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Energy Management Study Guide

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ENERGY MANAGEMENT STUDY GUIDE

Energy Management Study Guide
1st edition

ISBN 978-87-403-2747-2
Peer review: Erhard F. Joeres, Professor Emeritus, Civil & Environmental Engineering and Nelson Institute for Environmental Studies, UW-Madison

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PREFACE

Energy Management Study Guide contains a suite of solved problems designed to accompany the text entitled *Energy Management for Pollution Control* published by Bookboon.com in 2018. Pollution prevention and control is a big subject and you will learn more and more quickly if you vary what you read and how you read. Reading a textbook is not learning. Practicing –thinking about problems and solving them - is learning. So, here is the practice material.

Two kinds of practice are needed. One is directed toward mastering everyday calculations and procedures, such as calculating mass from a volume and concentration, or converting units from a volume basis to a mass basis, or from a wet basis to a dry basis. The second is discussion and open-ended questions. There are exercises of both kinds about water, wastewater, air and other gases, soil, and solid waste, and with varying degrees of difficulty.

To make the practice more interesting, many of the problems are given in an engineering context. The titles guide the student and instructor if there is a special area of interest. In a typical introductory course on pollution prevention and control, the more varied experience should be preferred. We believe this is true for engineers, and especially so for non-engineers.

If you are doing self-study, start by reading the problems; read as you would read a textbook to discover the context in which certain calculations are needed. Read them to discover new vocabulary and learn about systems and ideas that are not in the text. Then select a few problems to solve. Draw a diagram and show all the given information and only then start with the equations and calculations.

Solutions are not isolated in the back of the study guide; they appear with the questions. Work on your solution and then use our solution. There are often different paths to a correct answer so use ours as a guide and not a strict pattern to be followed.

The numbering of figures and tables is not sequential. It is keyed to the problems.

- Figure P6.14 and Table P6.14 are part of problem 6.14.
- Figure S6.14 and Table S6.14 are part of the solution of problem 6.14.

A Note to Instructors.

Some problems are short and quick, and some take a lot of work, so solve or carefully read the problems before making an assignment. Many of the problems should be enhanced by a quick explanation when they are assigned.

- Build professional vocabulary, not by listing and defining terms, but by working in context. Briefly describe the treatment process or system, and explain new vocabulary.
- Provide a context, "This problem is about heavy metals in compost that is made from sewage sludge. Heavy metals are toxic and we must be careful about moving them from a waste disposal site into someone's garden or park or playground."
- In short, try to make the problem interesting beyond the obvious calculations (which are necessary, but not interesting).
- Use problems as opportunities to teach the why and how of pollution prevention and control engineering.
- Tell students to be resourceful in finding information. Electronic dictionaries are great and should be used frequently. Wikipedia is a wonderful resource for concise explanations.
- Augment the problems and solutions with photos and pictures. It was our idea to use many photographs, one per problem would have been ideal, but there are difficulties with copyrights and permissions, so that idea was abandoned. If the problem mentions an electrostatic precipitator you can go to Google images and look at them. Having found a suitable photo, don't get sidetracked. Look fast and get back to work.

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October 2018

INTRODUCTION - THE MATERIAL BALANCE

The two fundamental tools for analysis of pollution prevention and control problems are the material balance and the energy balance. Our previous book, *Pollution Prevention and Control: Material and Energy Balances* (also published with Bookboon.com) has been expanded and republished in two parts. Every engineering design or analysis problem needs a material balance. Every design that involves heating, cooling, pumping, or the transfer of energy requires a material balance *and* an energy balance.

This section is a review of the most basic ideas about making a material balance.

It also reviews the units and measurements that will be useful in doing the energy balances, especially with gases.

The Material Balance

The law of conservation of mass states that matter is a neither created or destroyed within a process. (The exception is nuclear reactions). Materials can be transformed. Solid sodium chloride (NaCl) can change form by dissolving in water, or the chloride can become part of a new molecule, but the mass of chloride is conserved. The same is true of the sodium, the water, and every other substance. What enters the process must exit the process or be stored within the process. A steady-state process has no storage.

Example 1 is a steady-state sludge thickening process. There are three materials: sludge, water and solids; sludge is the mixture of water and solids. A material balance equation can be written for all three materials, but only two are needed.

EXAMPLE 1 - SLUDGE THICKENING

In Figure 1, the mass fraction of solids in the 1,000 kg/h feed to a sludge thickener is 0.03. The thickened sludge underflow has a solids fraction of 0.06. The thickener supernatant carries 1 kg/h of solids.

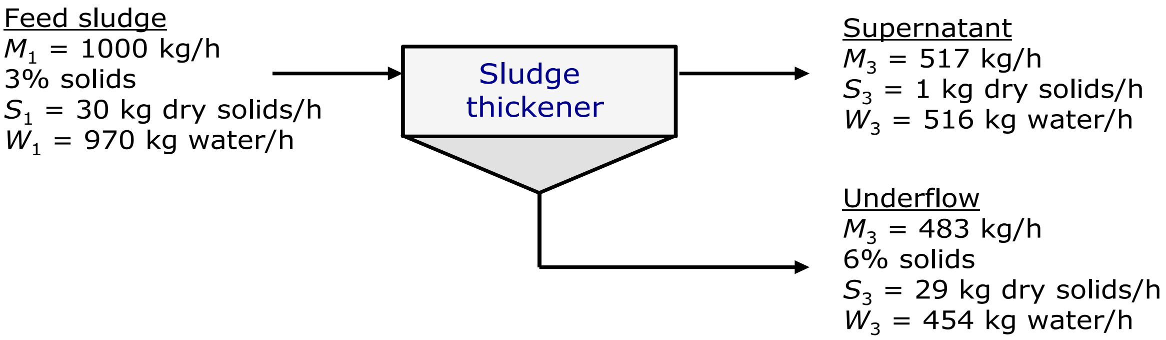


Figure 1 - Sludge thickening material balance

Using the numbers on the inputs and outputs, we can define

$$M_1 = 1{,}000 \text{ kg/h}$$

$$S_1 = 0.03(1{,}000 \text{ kg/h}) = 30 \text{ kg/h}$$

$$W_1 = (1.0 - 0.03)(1{,}000 \text{ kg/h}) = 970 \text{ kg/h}$$

Also $W_1 = M_1 - S_1 = 970$ kg/h

Material balance on solids

$$S_3 = S_1 - S_2 = 30 \text{ kg/h} - 1 \text{ kg/h} = 29 \text{ kg/h}$$

Using the definition of mass fraction

$$f_3 = \mathrm{S}_3/(\mathrm{S}_3 + \mathrm{W}_3) = 0.06$$

$$S_3 = 0.06\mathrm{S}_3 + 0.06\, W_3$$

$$W_3 = S_3(1.0 - 0.06)/0.06 = (29 \text{ kg/h})(0.94)/0.06 = 454.3 \text{ kg/h}$$

$$M_3 = S_3 + W_3 = 29 \text{ kg/h} + 454.3 \text{ kg/h} = 483.3 \text{ kg/h}$$

Units of Measurement

Material quantities, flow rates, and concentrations are expressed in a variety of units. It is most convenient to work entirely in SI units (liters, kilograms, and meters). Gallons, pounds, and feet are still used widely in the U.S., as they were once in the UK and some other countries. Converting units is a nuisance, but many engineers sooner or later will be retrofitting an old design that used these units. Therefore, some knowledge of both systems of units is a useful complement to one's skill set.

Volumetric flow rate is measured as liters per hour, cubic meters per second, gallons per hour, and so on. Temperature and pressure, within ordinary limits, have a negligible effect on the volume of liquids.

Material flows are expressed in terms of mass per time, such as kilograms per hour (kg/h), kg-moles per hour (kg mol/h), and lb/day. Mass flow is computed from the volumetric flow, density of the material, and the concentration of the pollutant in the material. Air and other gases expand and contract with changes in temperature and pressure and volume must be reported either at standard conditions or at the actual temperature and pressure of the gas.

A mixture is described by giving the concentration of each species in the mixture. Concentration can be expressed as mass per unit mass, mass per unit volume, or volume per unit volume. In solids it is common to report concentration as mass per unit mass, for example mg of pollutant per kg of dry solid material. Note that 1 mg/kg is one part per million (ppm) on a dry mass basis. In solids and liquids, ppm is always a mass ratio. In a gas, ppm indicates one part in a million parts based on volume, and it should be identified by ppmv instead of simply as ppm. Appendix 2 gives the most common units and conversion.

Liquids, Sludge and Solids

Concentrations in liquids are given as mass per volume concentrations, such as grams per liter (g/L), milligrams per liter (mg/L), and micrograms per cubic meter (μg/m^3). It can be convenient to use 1 mg/L = 0.001 kg/m^3. They may also be expressed as mass ratios, such as parts per million (ppm) or parts per billion (ppb).

When the specific gravity of the liquid is 1.000, mg/L and ppm are equivalent and either may be used for municipal sewage (which is 99.99% water), and for many industrial wastewaters, and dilute slurries of low-density solids. It should not be used for highly saline wastewater, sludge, soil, or sediments.

EXAMPLE 2 - SAMPLING AN AIR DUCT

A rectangular air duct has a total area of 3.2 m^2 that has been divided into four 0.8 m^2 sectors. Figure 2 shows the dust concentration (mg/m^3) and the air velocity (m/s) data, which are at 20° C and 1 atm pressure. Calculate the total air flow rate and the mass emission rate for dust.

Dust = 0.11 mg/m^3 Velocity = 4.0 m/s	Dust = 0.16 mg/m^3 Velocity = 4.4 m/s
Dust = 0.13 mg/m^3 Velocity = 4.1 m/s	Dust = 0.15 mg/m^3 Velocity = 4.2 m/s

Figure 2 Dust and velocity data

Example calculation for the top left sector

Air flow rate = (0.8 m^2)(4 m/s) = 3.2 m^3/s

Mass flow rate of dust = (3.2 m^3/s)(0.11 mg/m^3) = 0.352 mg/s

Total mass flow of dust

= (3.2 m^3/s)(0.11 mg/m^3) + (3.28 m^3/s)(0.13 mg/m^3) + (3.52 m^3/s)(0.16 mg/m^3)

+ (3.36 m^3/s)(0.15 mg/m^3)

= 0.352 mg/s + 0.4264 mg/s + 0.5632 mg/s + 0.504 mg/s = 1.8456 mg/s

Note: Multiplying the average air flow rate and the average dust concentration will give the wrong answer.

Average velocity = 4.175 m/s
Average air flow = 4(0.8 m^2)(4.175 m/s) = 13.36 m^3/s
Average dust concentration = 0.1375 mg/m^3
Mass flow of dust = (13.36 m^3/s)(0.1375 mg/m^3) = 1.837 mg/s

Mass Percentage and Mass Fraction

Mass/mass is the mass fraction. The mass fraction multiplied by 100% is the mass percent (often called weight percent).

Concentrations of pollutants in dense slurries, sludge, sediments, soil, and other solids are given as mass fractions – mass of pollutant per mass of total material. It is important to make clear whether the mass of bulk material is on a dry or wet basis. The best method is a dry mass basis. A concentration of 1 mg/kg means 1 milligram of pollutant in 1 kilogram of dry material; 1 µg/kg means 1 microgram of pollutant in 1 kilogram of dry material. Also, a concentration of 1 mg/kg means 1 part per million and 1 µg/kg means 1 part per billion, on a dry basis.

Concentration as a weight percent can be used for solids or liquids. To say that sludge is "4% solids by weight" means that 4% of the total sludge mass is dry solids. The total sludge mass includes the water and the solids. Thus, 4% solids by weight also means 96% water by weight. And it means 0.04 kg dry solids per kg of wet sludge.

EXAMPLE 3 - MASS PERCENTAGE OF SLUDGE SOLIDS

An industry is holding 600 m^3 of dense industrial sludge that has specific gravity 1.4. The sludge is 12% solids on a wet mass basis. Calculate the mass of solids in the 600 m^3 of sludge.

Density of sludge = 1.4(1000 kg/m^3) = 1,400 kg/m^3
Mass of wet sludge = (600 m^3)(1,400 kg/m^3) = 840,000 kg = 840 T
Mass of dry solids in the sludge = (0.12)(840 T) = 100.8 T

EXAMPLE 4 - WASTE GAS COMPOSITION

A gaseous mixture, with total mass of 1000 kg, is 5% benzene, 71% nitrogen, and 24% oxygen. These are mass fractions. The gas volume, at 25°C and 760 mm Hg, is 819,500 L = 819.5 m^3. Calculate the mass of each gas in the mixture and the concentration as mass per volume (mg/m^3)

The mass of each gas can be calculated from its mass fraction.

Gas component = (mass fraction)(total gas mass)
Benzene = 0.05(1,000,000 g) = 50,000 g
Nitrogen = 0.71(1,000,000 g) = 710,000 g
Oxygen = 0.24(1,000,000 g) = 240,000 g

Concentrations = (mass of gas)/(total volume of gas)
Benzene = (50,000 g)/(819.5 m^3) = 61.0 g/m^3
Nitrogen = (710,000 g)/(819.5 m^3) = 866.4 g/m^3
Oxygen = (240,000 g)/(819.5 m^3) = 292.8 g/m^3

Volume Fraction and Volume Concentration

Vo*lume concentration* and *volume fraction* are used for mixtures of gases. Common units are
m^3 pollutant /m^3 gas mixture
and ppmv = parts per million by volume (L/10^6 L or m^3/10^6 m^3)

The *volume fraction* of a mixture of gases equals the *mole fraction.*

The Ideal Gas Law

Energy balance calculations often involve the volumetric and mass flows of air and other gases. Gases expand as temperature is increased and compress as pressure is increased, so gas volume or volumetric flow rate have no useful meaning until the corresponding gas temperature and pressure are known.

The most used "standard conditions" are those of the International Union of Pure and Applied Chemistry (IUPAC) and the National Institute of Standards and Technology (NIST). Other organizations have adopted alternative definitions of standard conditions.

Normal cubic meters per hour (Nm^3/h) is the volumetric flow rate for gases at 0°C and 1 atm (101.325 kPa).

In the U.S. a common measure is scfm to indicate 'standard cubic feet per minute' or acfm to indicate 'actual cubic feet per minute'. The 'standard' refers to a reference condition known in chemistry and physics as standard temperature and pressure (STP). A similar reference condition in industrial hygiene and air pollution work is the normal condition (normal temperature and pressure, or NTP). Several widely used definitions for the reference, or "standard" conditions are given in Tab1e 1.

Discipline	Standard Conditions			Organization
	Temp.	Absolute Temp.	Pressure	
Chemistry/physics (STP)	0°C	273.15 K	100.000 kPa (1 atm)	IUPAC
Chemistry/physics (STP)	20°C	293.15 K	101.325 kPa (1 atm)	NIST & U.S. EPA
Industrial hygiene	60°F	519.67°R	14.696 psi (1 atm)	U.S. OSHA

IUPAC = International Union of Pure and Applied Chemistry
NIST = National Institute of Standards and Technology (NIST)

Table 1 - Standard conditions for various disciplines (dry air). (Source: Wikipedia)

Gas concentrations are usually measured as a volumetric ratio, typically parts per million by volume, ppmv. The ppmv concentration is independent of changes in pressure and temperature because all gases in a mixture expand or contract to the same extent. For example, if the concentration of SO_2 in air is 15 ppmv, then every million volumes of air contains 15 volumes of SO_2 regardless of how the gas mixture is compressed or expanded. This is one advantage of using ppmv units for air pollution work.

A mass concentration, say μg/m³ or mg/m³, is needed to make a material balance. The mass concentration is calculated using the molecular mass of the gaseous pollutant. Corrections for pressure and temperature may be required. These corrections are made using the ideal gas law:

$$PV = nRT$$

where P = pressure, atm
T = absolute temperature, K
V = gas volume, L
n = number of moles of gas
R = universal gas constant = 0.08205 L atm/mole K

The value of R depends on the units used for pressure, temperature, and volume, as given in Table 2. Molar volumes are given in Table 3.

R value and units	Pressure	Temp.	Absolute Temp.	Volume
0.08205 L-atm/mole K	1 atm	0°C	273.15 K	22.41 L/g mol
0.08205 L-atm/mole K	1 atm	25°C	298.15 K	22.45 L/g mol
0.73402 ft³-atm/lb mol- °R	1 atm	0°F	491.67°R	359 ft³/lb mol
Conversions (rounded)	K = °C + 273.15		°R = °F + 459.67	

Table 2 - Values and units of the universal gas constant *R* in the ideal gas law.

Molar Volume (V_m)	Temp.	Pressure
8.3145(273.15/101.325) = 22.414 m³/kg mol	0°C	101.325 kPa (1 atm)
8.3145(298.15/101.325) = 24.466 m³/kg mol	25°C	101.325 kPa
10.7316(519.67/14.696) = 379.48 ft³/lb mol = 0.8366 ft³/g mole	60°F	14.696 psi (1 atm)

Table 3 The molar volume of a gas calculated at various standard reference conditions (Wikipedia).

EXAMPLE 5 - MASS OF A GAS

Calculate the mass of the gas that occupies a volume of 2000 L at 20°C and 1.2 atm and has molar mass = 16 g/mole. For these units the universal gas constant is 0.08205 L atm/mol K.

Absolute temperature: = 20°C + 273°C = 293 K.

From the ideal gas law: $PV = nRT$

$(1.2\ \text{atm})(2{,}000\ \text{L}) = n\ (0.08205\ \text{L atm/mol K})(293\ \text{K})$

$n = 99.8\ \text{mol}$

Total mass of the gas = (99.8 mol) (16 g/mol) = 1600 g

EXAMPLE 6 - VENTING TOLUENE

A ventilation airflow of 40,000 m^3/h (at STP) from a printing company contains 2,200 ppmv toluene. (a) What is the flow of toluene in m^3/h? (b) The density of toluene is 4.12 kg/m^3. What is the mass flow of toluene in kg/h?

a) Volume fraction of toluene = 2,200 ppmv = 22,000 m^3/1,000,000 m^3

Volumetric flow of toluene = (40,000 m^3/h)(2,200 m^3/1,000,000 m^3) = 88 m^3/h.

b) Density of toluene = 4.12 kg/m^3 (at STP).

Mass flow of toluene = (88 m^3/h)(4.12 kg/m^3) = 362.6 kg/h

EXAMPLE 7 - SULFUR DIOXIDE

What is the concentration of sulfur dioxide (SO_2), expressed as ppmv, in combustion gas that 75% N_2, 7% O_2, 9.85% CO_2, 0.15% SO_2 and 8% H_2O

Since gas concentrations are provided as volume percent, use the following equation:

$$\text{ppmv for compound} = \frac{\text{Volume\% for compound}}{100\%} \text{x} 10^6$$

$$\frac{0.15\%\ SO_2}{100\%} \text{x} 10^6 = 1{,}500\ \text{ppmv}\ SO_2$$

Converting Volume and Mass Concentrations in Gases

Volume and mass concentrations (ppmv and mg/m^3) can be converted using the molar mass (*MM*) of the pollutant and the ideal gas law. One g-mole of an ideal gas occupies a volume 0.02241 m^3 (22.41 L) at standard temperature and pressure (0 °C = 273 K and 1 atm). Also, 1 m^3 of an ideal gas contains 1/0.02241 m^3 = 44.623 g-moles of the gas. One lb-mole occupies a volume of 359 ft^3 at STP.

The mass (mg) of a gas occupying 1 m^3 is

$$\frac{\text{mass of gas (mg)}}{\text{volume of gas (m}^3\text{)}} = \left(\frac{\text{MM(g/mol)}}{0.02241\ (\text{m}^3/\text{mol})}\right)\left(\frac{1{,}000\ \text{mg}}{\text{g}}\right) = \frac{\text{MM}(1{,}000)}{0.02241}$$

where MM is the molar mass of the gas (g/mole).

If a gas mixture contains a pollutant at a concentration of 1 ppmv, or 1 m^3 of pollutant in 1,000,000 m^3 of mixture, the mass concentration will be given by

$$\frac{\text{mg pollutant}}{\text{m}^3\text{ mixture}} = \left(\frac{\text{m}^3\text{ pollutant}}{10^6\text{ m}^3\text{ mixture}}\right)\left(\frac{\text{MM g/g-mol}}{0.02241\text{ m}^3\text{/g-mol}}\right)\left(\frac{1{,}000\text{ mg}}{\text{g}}\right) = \text{ppmv}\left(\frac{\text{MM g/mol}}{22.41\text{ L/mol}}\right)$$

EXAMPLE 8 - CONVERTING VOLUME CONCENTRATION TO MASS CONCENTRATION

The concentration of a gaseous pollutant in air is 15 ppmv. The molar mass of the pollutant is 16 g/mol. Find the concentration as mg/m^3 at standard conditions.

$$\frac{\text{mg pollutant}}{\text{m}^3\text{ mixture}} = \left(\frac{15\text{ m}^3\text{ pollutant}}{10^6\text{ m}^3\text{ mixture}}\right)\left(\frac{16\text{ g/g-mol}}{0.02241\text{ m}^3\text{/g-mol}}\right)\left(\frac{1{,}000\text{ mg}}{\text{g}}\right) = 10.7\ \frac{\text{mg}}{\text{m}^3}$$

EXAMPLE 9 - MASS CONCENTRATION IN GASES

A gaseous emission has an SO_2 concentration of 25 ppmv. The gas temperature and pressure are 25°C and 1.1 atm. The molar mass of SO_2 is 64 g/mol. The mass concentration of SO_2 at standard temperature and pressure (STP) of 1 atm and 0°C.

$$\left(\frac{\text{mg}}{\text{m}^3}\right)_{\text{STP}} = \text{ppmv}\left(\frac{\text{MM}}{22.41}\right) = \frac{(25\ \text{ppmv})(64\ \text{g/mol})}{22.41\ \text{L/mol}} = 71.4\ \text{mg/m}^3$$

Mass concentration at T = 25 °C and P = 1.1 atm is

$$\left(\frac{\text{mg}}{\text{m}^3}\right)_{\text{TP}} = \left(71.4\ \frac{\text{mg}}{\text{m}^3}\right)\left(\frac{273\ \text{K}}{273\ \text{K} + 25\ \text{K}}\right)\left(\frac{1.1\ \text{atm}}{1\ \text{atm}}\right) = 71.9\ \text{mg/m}^3$$

Molar Mass and Molar Concentration

Mass can also be measured in molar units, such as g mole, kg mole, and lb mole. Molar units are most convenient in chemical processes where the chemical species are known and the concentrations are high. The *mass percentage* (mass %) of an element in the compound is the fraction of the compound's mass contributed by that element, expressed as a percentage

$$\text{Mass\% of element } X = \frac{(\text{atoms of } X \text{ in compound})(\text{molar mass of } X)}{\text{molar mass of compound}} \text{ x } 100$$

EXAMPLE 10 - FREON-12

The chlorofluorocarbon known commercially as Freon-12 has the formula CCl_2F_2.

Atomic masses (g/g mol): C = 12, Cl = 35.453, and F = 18.998

Molar mass = CCl_2F_2 = 12 g/mol + 2(35.542 g/mol) + 2(18.998 g/mol)

= 120.91 g/mol

Mass fraction of Cl = 2(35.453 g/mol)/(120.91 g/mol) = 0.5864

Mass % of Cl = 58.64%

Adjusting Gas Compositions for Moisture or CO_2 Content

Air pollutant concentrations sometimes must be adjusted or 'corrected' to concentrations at specified reference conditions of moisture content, oxygen content or carbon dioxide content. For example, a regulation might limit the concentration in a dry combustion exhaust gas to 55 ppmv NO_x (at a specified reference temperature and pressure) corrected to 3 volume percent O_2 in the dry gas. Another regulation might limit the concentration of total particulate matter to 200 mg/m^3 of an emitted gas (at a specified reference temperature and pressure) corrected to a dry basis and further corrected to 12 volume percent CO_2 in the dry gas. The adjustments are explained by example.

Environmental agencies in the U.S. often use the terms *scfd* (or *dscf*) to denote a 'standard' cubic foot of *dry gas*. Likewise, *scmd* (or *dscm*) denotes a 'standard' cubic meter of gas. Since there is no universally accepted set of 'standard' temperature and pressure, such usage can be confusing. It is recommended that the reference temperature and pressure always be clearly specified when stating gas volumes or gas flow rates.

EXAMPLE 11 - ADJUSTING GAS COMPOSITION TO A DRY BASIS

A gaseous emission has a pollutant concentration of $C_{wet\ basis}$ = 40 ppmv and 10 volume percent of water vapor. The 40 ppmv should be designated as the "wet basis" pollutant concentration. The adjustment of the measured "wet basis" concentration to a "dry basis" concentration is done using

$$C_{\text{dry basis}} = \frac{C_{\text{wet basis}}}{1 - W}$$

where: C = concentration of the air pollutant in the emitted gas

W = fraction, by volume, of water vapor in the emitted gas

$$C_{\text{dry basis}} = \frac{40 \text{ ppmv}}{1 - 0.1} = 44.4 \text{ ppmv}$$

EXAMPLE 12 - ADJUSTING TO A REFERENCE CARBON DIOXIDE CONTENT

A dry gas has a measured particulate concentration is 200 mg/m^3 and a measured 8 volume % CO_2. This can be corrected to an equivalent pollutant concentration in an emitted gas that has a specified reference amount of 12 volume % of CO_2.

$$C_R = C_M \frac{(\%\ \text{CO}_2)_R}{(\%\ \text{CO}_2)_M} = \left(200 \text{ mg/m}^3\right)\left(\frac{12\%}{8\%}\right) = 300 \text{ mg/m}^3$$

where: C_R = corrected concentration of a dry gas having a reference volume % CO_2

C_M= measured concentration of a dry gas having a measured volume % CO_2

$(\%\ CO_2)_R$ = percentage of carbon dioxide in the reference volume

$(\%\ CO_2)_M$ = percentage of carbon dioxide in the measured volume

Conclusions

Pollutants have many physical and chemical forms. They may be carried by water or air, or other liquids and gases, or they may be part of a solid material, such as soil. They may be dissolved or particulate. This variety of pollutant forms and measurements generates the need to use a variety of units, such as mg/L in water, mg/kg in solids, and volume percent or ppmv in air and gases, depending on whether the concentration refers to water or wastewater, sludge, soil, or gas.

The unit of choice for water or wastewater is mg/L because mg/L is independent of the density of the solution. If the solution density is 1.00 or very close to it, as it is for fresh water and most wastewaters, mg/L and ppm are interchangeable. This approximation is less valid as the solution density deviates from 1.00.

Because of this, the concentration of a dense sludge or slurry is usually reported as a mass concentration, that is, mg/kg wet sludge, or kg/kg dry sludge solids.

The most convenient concentration measure for a mixture of gases is the volume fraction (vol/vol) and parts per million by volume (ppmv). For particulate solids in air the units typically will be g/m^3 or mg/m^3. The volume fractions for gases in a mixture do not change when the gas expands or contracts. This is not true for mass (e.g., g/m^3) concentrations.

1 ENERGY MANAGEMENT

These are open-ended questions that are meant to provoke discussion. No solutions are provided.

1.1 ENERGY AND MATERIAL FLOW

Explain why accounting for the flow of energy in a system requires an accurate accounting of the mass flow of materials.

1.2 SYNTHESIS AND ANALYSIS

Explain the difference between synthesis and analysis. Why does each synthesis create an analysis problem, and why is synthesis-analysis an iterative process?

1.3 SEPARATORS AND REACTORS

Give some everyday examples of separations and reactions. These might be from your school experience, your kitchen, or your garage.

2 THE LAWS OF THERMODYNAMICS

2.1 LOW-GRADE ENERGY

Figure P2.1 of the energy balance shows three outputs. Every system will have 'low-grade or waste energy' and one, or perhaps both, of the others. Explain what is meant by 'low-energy heat' or 'waste heat' and why it is inevitable.

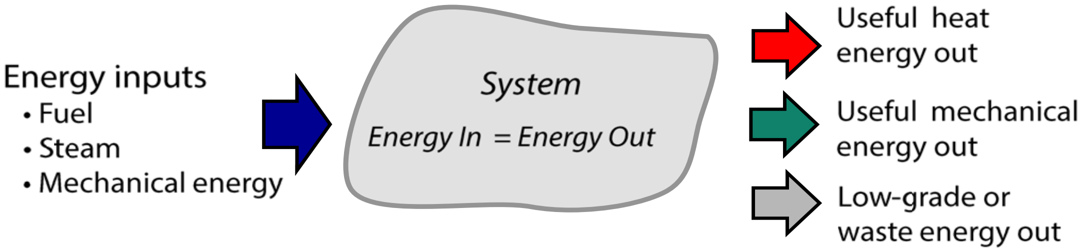


Figure P2.1 Schematic drawing of the energy balance

Solution

Low-grade energy is waste energy because it is in a form that cannot be used. It is liquid or gas that has too little heat content to be used for heating. It is energy lost through friction and other inefficiencies.

2.2 THE THREE R'S

The '3 Rs' - Reduce, Reuse, and Recycle – define a hierarchy of waste management. The Three R's of energy management might be: Reduce, Renew and Remedy. As with the other three, it implies a hierarchy - reduce your energy use, use renewable energy, and remedy the climate impacts of nonrenewable energy you use. Explain Reduce, Renew and Remedy in your own words. Give examples.

Solution

Reduce: When addressing your household, business, or city energy use the most important goal is to reduce energy use by purchasing energy-efficient appliances, light bulbs, cars, computers, etc., and by running them only when necessary.

Renew: Purchase as much renewable energy as possible, whether from a local utility program, by generating your own (say, by installing solar panels), or by using biofuels for your transportation needs.

Remedy: Finally, after you've used minimized energy use and, and maximized the use of renewable energy, remedy the climate impacts of the nonrenewable energy you use, by purchasing carbon offsets, perhaps in the form of "green tags."

A note on "offsets". Focusing on offsets as the principal strategy for addressing climate change impacts is the third choice. It's fine if you've already maximized your energy efficiency and purchases of renewables. But buying offsets for an energy-wasteful home or business and calling it environmentally responsible is akin to buying a Diet Coke to go with your double bacon cheeseburger and calling it a weight-loss program. And that's a big waste of energy.

2.3 POWER PLANT WASTE HEAT

A thermal electric power plant (Figure P2.3) burns 1,800,000 kg /day of coal that has a heating value of 9.5 kWh/kg (34.2 MJ/kg). The thermal efficiencies of the boiler, turbine, and generator are 80%, 45%, and 98%, respectively. Verify the energy balance on the power plant, and calculate the overall thermal efficiency. The losses are waste heat.

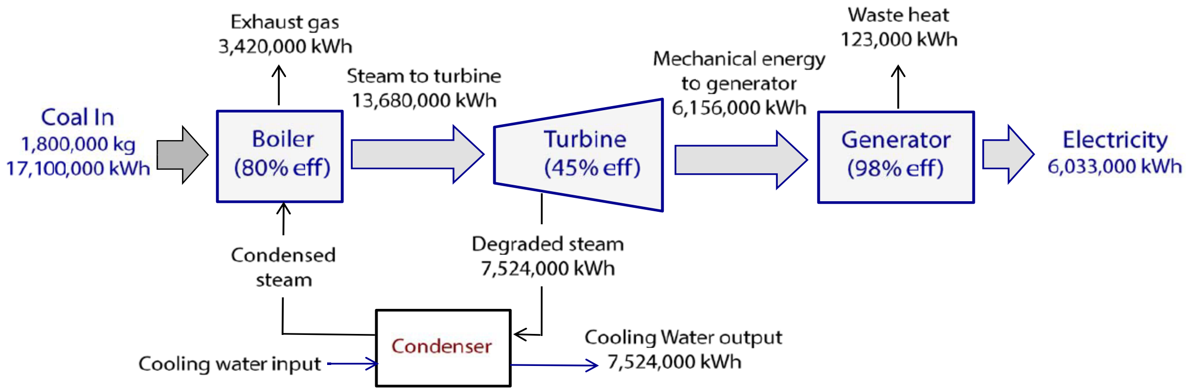


Figure P2.3 Thermal electric power plant

Solution

Basis: 1,800,000 kg coal

Coal input = (1,800,000 kg)(9.5 kWh/kg) = 17,100,000 kWh

= (1,800,000 kg)(34.2 MJ/kg) = 61,560,000 MJ

Boiler efficiency = 80%

Energy transmitted to the turbine = (0.80)(17,100,000 kWh)

= 13,680,000 kWh = 49,300,000 MJ

Energy lost with the exhaust gas = 17,100,000 kWh - 13,680,000 kWh

= 3,420,000 kWh = 12,300,000 MJ

Turbine efficiency = 45%

Energy transmitted to the generator = (0.45)(13,680,000 kWh)

= 6,156,000 kWh = 22,200,000 MJ

Energy lost with cooling water = 13,680,000 kWh - 6,156,000 kWh

= 7,524,000 kWh = 27,100,000 MJ

Generator efficiency = 98%

Energy produced = (0.98)(6,156,000 kWh) = 6,033,000 kWh = 21,700,000 MJ

Energy lost as waste heat = 6,156,000 kWh – 6,033,000 kWh

= 123,100 kWh = 443,000 MJ

The percentage of fuel energy input is converted to electricity is

= 100(6,033,000 kWh)/(17,100,000 kWh) = 35.3%

Almost two-thirds of the energy input is lost from the power plant to the environment, mostly by rejection to cooling water in the condensers. The waste heat absorbed by the cooling water is subsequently dissipated in the river or to the atmosphere via evaporation in a cooling tower.

2.4 CARNOT ENGINE I

What is the Carnot efficiency of a heat engine that operates between 20°C and 1200°C?

Solution

Convert temperatures to kelvins

$T_c = 20°\text{C} + 273°\text{C} = 293\text{ K}$

$T_h = 1200°\text{C} + 273°\text{C} = 1473\text{ K}$

$$\varepsilon_{\text{Carnot}} = \frac{T_h - T_c}{T_h} = \frac{1473\text{K - }293\text{K}}{1473\text{K}} = 0.80$$

2.5 CARNOT ENGINE II

The efficiency of a Carnot engine is $\epsilon_{\text{Carnot}} = 0.58$. The high operating temperature is T_h = 800°C (1073 K). What is the low temperature, T_c?

Solution

$$\varepsilon_{\text{Carnot}} = \frac{T_h - T_c}{T_h}$$

$$T_c = T_h(1 - \varepsilon_{\text{Carnot}}) = (1073\text{ K})(1 - 0.58) = 451\text{ K}$$

$$T_c = 451\text{ K} - 273\text{ K} = 178°\text{C}$$

3 ENERGY UNITS AND ENERGY CONVERSION

Tutorial Note

The table gives some frequently needed energy and power equivalence factors.

Most of the world measures energy in Joules and kilowatt-hours. The Joule is a small amount of energy. One Joule raises the temperature of 1 g of water by 0.239°C and it takes 4184 J to raise the temperature of 1 kg of water by 1°C. Also, 1 kWh = 3,600,000 J = 3,412 Btu. kilo-joules (kJ) or mega-joules (MJ) are more convenient units in most engineering problems.

The most commonly used units in the U.S. are kWh, Btu, and horsepower. Horsepower is widely used to measure the mechanical power of a motor or engine. Btu is a convenient measure of energy when mass is measured in pounds (lb), as one Btu will raise the temperature of one pound of water by one degree Fahrenheit (°F).

Energy unit	**Btu**	**kWh**	**kJ**
1 kilowatt-hour (kWh)	3412	1	3,600
1 kilojoule (kJ)	0.9478	2.778×10^{-4}	1
1 British thermal unit (Btu)	1.0	2.931×10^{-4}	1.055
1 horsepower-hour (hp-h)	2,544	0.7457	2,685
Fuel Unit	**Btu**	**kWh**	**kJ**
1 barrel petroleum (bbl = 42 US gal)	5.8×10^6	1700	6.117×10^6
1 cubic foot of natural gas	1050	0.308	1,087
1 US gallon automotive gasoline	126,000	36.9	132,000
1 US gallon #2 fuel oil	138,900	40.7	146,500
1 US gallon LPG	95,500	27.99	100,800
1 US gallon kerosene	134,800	39.5	1422800
1 tonne (1000 kg) coal equivalent	27.8×10^6	8,141	29.3×10^6
1 kg anthracite coal (HHV)	27,800	8.141	29,300
1 pound anthracite coal (HHV)	12,600	3.70	13,300

Power Unit	kW	hp	Btu/h
1 kW	1.0	1.341	3.412
1 hp	0.7457	1.0	2,544
1 Btu/h	$2.931\text{x}10^{-4}$	$3.930\text{x}10^{-4}$	1.0
1 kJ/h	$2.778\text{x}10^{-4}$	$3.723\text{x}10^{-4}$	0.9478
1 Ton of refrigeration	3.517	4.714	12,000

Table for Tutorial Note

3.1 U.S. HOUSEHOLD ENERGY USE

An average household in Minnesota (a state in the northern U.S.) uses 105,000 ft^3 of natural gas and 10,000 kWh of electricity per year, and operates two vehicles for a total of 12,500 miles that travel 22 miles per gallon of gasoline. Convert the three forms of energy into consistent units and the total annual energy use.

Solution

Express energy as kWh (alternates are Btu and kJ)

Natural gas: Use fuel value = 0.308 kWh/ft^3

(105,000 ft^3)(0.308 kWh/ft^3) = 32,340 kWh

Electricity = 10,000 kWh

Gasoline: Use fuel value = 36.9 kWh/gal

(12,500 mi)/(22 mi/gal) = 568 gal

(568 gal)(36.9 kWh/gal) = 20,960 kWh

Total = 63,300 kWh per year

3.2 HOME HEATING EFFICIENCY

Calculate the fuel input required to produce 100 units of useful heat output for each of the six heating methods in Table P3.2 that might be used in a home.

Heating Technology	Efficiency (%)
Home fireplace	10 - 40
Space heater	50 - 80
Gas furnace (low efficiency)	70 - 80
Oil burner heating system	70 - 85
Gas powered boiler	75 - 85
Gas furnace (high efficiency)	85 - 95

Table P3.2 Home heating technologies

Solution

Sample calculation for home fireplace

The units of energy can be kJ, Btu, or KWh

Input energy units = Output energy units/Efficiency

High end of range = 100 units/0.4 = 250 units

Low end of range = 100 units/0.1 = 1000 units

Values for all six methods are in Table S3.2.

Heating Technology	Efficiency (%)	Energy Input Units
Home fireplace	10 - 40	1000 – 250
Space heater	50 - 80	200 – 125
Residential gas furnace (low efficiency)	70 - 80	143 – 125
Oil burner heating system	70 - 85	143 – 118
Gas powered boiler:	75 - 85	133 – 118
High efficiency gas furnace	85 - 95	118 – 105

Table S3.2

3.3 EFFICIENCY OF HEATING WATER

Heating water is the second largest energy cost in the typical home. Water can be heated by burning natural gas in-home heating or by using electricity produced from natural gas to heat an electrical resistance element. Compare the energy of burning natural gas in a water heater or using an electric heating element to heat 500 liters (500 kg) of water from 10°C to 50°C. Assume the efficiency of converting heat from natural gas to electricity at a power plant is 32%. Assume the gas water heater transfers 62% of the fuel heat energy to the water.

Solution

The heating demand is proportional to mass of water heated and the difference between the hot and cold temperatures.

$$H_{\text{add}} \propto (\text{mass})(T_{\text{Hot}} - T_{\text{Cool}}) \propto (500\text{ kg})(50°\text{C} - 10°\text{C}) \propto 2000\text{ kg°C}$$

The proportionality coefficient is the heat capacity of water, c_p

$c_p = 4186\text{ J/kg°C} = 4.186\text{ kJ/kg°C}$

$H_{\text{add}} = (4.186\text{ kJ/kg°C})(500\text{ kg})(50°\text{C} - 10°\text{C}) = 83{,}720\text{ kJ}$

Natural gas heating energy = 83,720 kJ /0.62 = 135,000 kJ

Electricity heating energy = 83,720 kJ /0.32 = 261,600 kJ

3.4 FUEL CHOICES

West Virginia bituminous coal (3-5% ash, 1% S) packs a lot of energy, specifically 9.35 kWh/kg (4.25 kWh/lb or 14,500 Btu/lb). What mass of the following solid fuels must be burned to equal its energy release upon combustion? (a) Dry bagasse, (b) Natural gas, (c) Green oak, (d) Gasoline, (e) Sewage sludge digester gas. You may use Btu/lb, kWh/lb or kWh/kg.

Solution

If you look up the heating values, different sources will give different values, or a range of values. This is because of variation in the materials. Bagasse is a product of sugar cane manufacture and is not consistent at all times at all locations. The same is true for digester gas, wood, and even coal. Table S3.4 gives typical values.

Solid Fuel	Heating value			Mass Alternate Fuel
	Btu/lb	kWh/lb	kWh/kg	(kg fuel/kg WVcoal)
West Virginia bituminous coal	14,500	4.25	9.37	
Dry bagasse	8,000	2.34	5.17	9.37/5.17 = 1.81
Natural gas	20,300	5.95	13.12	9.37/13.12 = 0.71
Green oak	10,500	3.08	6.78	9.37/6.78 = 1.38
Gasoline	20,000	5.86	12.92	9.37/12.92 = 0.73
Digester gas	16,000	4.69	10.34	9.37/10.34 = 0.91

Table S3.4

3.5 A DROP IN THE BOILER

Calculate how long it takes a 100 MW power plant to consume 1,000 kg of coal that has a heat value of 36,000 kJ/kg = 10 kWh/kg

Solution

1000 kg of coal yields - (1000 kg)(10 kWh/kg) = 10,000 kWh
100 MW = 100,000 kW of electrical power
Basis: 1 hour of operation

Operating a 100 MW plant for 1 hour produces 100 MWh/h = 100,000 kWh/h
Energy input required assuming 34% conversion efficiency
= (100,000 kWh/h)/0.34 = 294,000 kWh/h
Coal input (294,000 kWh/h)/(10 kWh/kg) = 29,400 kg/h
Time to consume 1000 kg coal
= (1000 kg/29,412 kg/h) = 0.034 h = 2 min

3.6 POWER PLANT ASH I

A 500 MW power plant burns Wyoming sub-bituminous coal that has an energy value of 6.13 kWh/kg (9,500 Btu/lb)) with 6% ash content. Assume the fuel to electricity efficiency is 35%. Calculate the magnitude of the ash disposal problem (a) in U.S. tons/year and (b) in Tonnes per year (T/y).

Solution

Power output = 500 MW
Energy output = (500 MW)(24 h/d)(365 d/y) = 876,000 MWh/y
1 ton = 2000 lb; 1 Tonne = 1000 kg = 2,200 lb

a) Energy input @35% efficiency = (500 MW)/0.35 = 1,429 MW = 1,429,000 kW
   Wyoming coal at 9,500 Btu/lb = (9,500 Btu/lb)(kWh/3412 Btu) = 2.78 kWh/lb
   Mass input per day = (1,429,000 kW)(24h/d)/(2.78 kWh/lb) = 12,340,000 lb/d
   = (12,340,000 lb/d)/(2,000 lb/ton) = 6,168 ton/d
   At 6% ash = 0.06(6,168 ton/d) = 371 ton/d
   = (371 ton/d)(365 d/y) = 135,000 ton/y

b) Energy input @35% efficiency = 1,429,000 kW
   Wyoming coal = 6.13 kWh/kg = 6,130 kWh/T
   Mass input per day = (1,429,000 kW)(24h/d)/(6,130 kWh/T) = 5,595 T/d
   At 6% ash = 0.06(5,595 T/d) = 336 T/d =
   = (336 T/d)(365 d/y) = 123,000 T/y

3.7 POWER PLANT ASH II

How many tons per year of ash must be disposed of from a 100 MW power plant that burns anthracite coal with 3% ash content. The heating value of the coal is 8 kWh/kg. The thermal efficiency of the power plant (coal to electricity) is 40%.

Solution

Power plant output = (100 MW)(24 h/d)(365 d/y) = 876,000 MWh/y
Input at 40% conversion efficiency
(876,000 MWh/y)/0.4 = 2,190,000 MWh/y
Heating value of coal = 8 kWh/kg = 8 MWh/T
Mass of coal input = (2,190,000 MWh/y)/(8 MWh/T) = 274,000 T/y
Ash = 0.03(274,000 T/y) = 8,210 T/y

3.8 COMBINED HEAT AND POWER (CHP)

Combined heat and power (CHP), also called *cogeneration*, produces electricity *and* useful heat. A typical CHP system is 70 - 80% efficient. The separate generation of electricity and heat has a combined efficiency of about 50%. The fuel energy input to a CHP plant is one million kilojoules (1,000,000 kJ). (a) Assuming typical efficiencies, what amount of electricity and steam heat would one expect to produce? How many kJ are lost as waste heat? (b) Again assuming typical efficiencies, what fuel input would be needed to produce the same amount of electricity and steam heat with a conventional power plant and boiler plant?

Solution

a) Combined heat and power plant - Assume 35% conversion to electricity and 40% conversion to steam for heat recovery

Electricity = 0.35(1,000,000 kJ) = 350,000 kJ
Steam for heat = 0.4(1,000,000 kJ) = 400,000 kJ
Waste heat = 1,000,000 kJ – (350,000 kJ + 400,000 kJ) = 250,000 kJ
Overall efficiency = (100)(350,000 kJ +400,000 kJ)/(1,000,000 kJ) = 75%

b) Conventional power plant and boiler plant - Assume 35% conversion of fuel energy input to electricity

Input required = (350,000 kJ)/0.35 = 1,000,000 kJ
Waste heat = 1,000,000 kJ – 350,000 kJ = 650,000 kJ

Assume 85% conversion of fuel energy input to steam heat in boiler plant

Input required = (400,000 kJ)/0.85 = 470,600 kJ
Waste heat = 470,600 kJ – 400,000 kJ = 70,600 kJ
Total fuel energy input = 1,000,000 kJ + 470,600 kJ = 1,470,600 kJ
Useful output = 350,000 kJ + 400,000 kJ = 750,000
Overall efficiency = 100(750,000 kJ)/(1,470,600 kJ) = 51%

3.9 REFUSE TO ELECTRICITY

The municipal refuse from a city amounts to about 8 lb/capita (per person) per day. The heating value of refuse is approximately 5,000 Btu/lb. The average home uses 900 kWh per month. Assuming four residents per home, the per capita energy consumption in that city is 7.5 kWh per capita per day (7.5 kWh/cap-d). What percent of the per capita energy needs can be supplied by burning refuse in the city power plant to make electricity?

Solution

Basis = 1 day

Heating value of refuse = 5,000 Btu/lb

Per capita heating value of refuse

= (5,000 Btu/lb)(8 lb/d-cap) = 40,000 Btu/cap-d

Equivalent yield of in units of electricity

= (40,000 Btu/d-cap)/(3,412 Btu/kWh) = 11.72 kWh/ cap-d

An input of 11.72 kWh yields at 35% thermal efficiency

= 0.35(11.72 kWh) = 4.1 kWh/ cap-d

Per capita energy consumption = 7.5 kWh/cap-d

Percent of energy needs supplied from burning refuse

=100(4.1 kWh/ cap-d)/(7.5 kWh/ cap-d) = 55%

3.10 HISTORICAL EFFICIENCY OF PRODUCING ELECTRICITY

In the year 1900 it took about 19,000 kJ of fuel input to produce 1 kWh of electricity. Estimate the energy conversion efficiency and compare it with a typical value for today's power industry.

Solution

Convert kJ fuel input to kWh:

19,000 kJ (kWh/3600 kJ) = 5.28 kWh

Efficiency in 1900 was 100(1 kWh/5.28 kWh) = 19%

Efficiency today = 35% to 40%. This is double the 1900 efficiency.

Combined heat and power – at 80% efficiency – is 4 or 5 times better

3.11 150 YEARS AGO

One hundred fifty years ago, in *Scientific American*, July 1875, we find the following:

> *There is little doubt that the gas escaping from oil wells is of nearly or quite as much value as the oil itself. It is a matter of wonder that means have not long ago since been adopted to utilize this immense product of the earth. For years the gas has been allowed to pass away into the air uselessly. One well in the Pennsylvania oil region flows with a pressure of 300 pounds to the square inch and is estimated to yield a million cubic feet of gas every 24 hours.*

How many Btu of heating value could be obtained from this 1,000,000 ft^3/d? How many barrels of oil give the same heating value? How many gallons of water would this bring to boil? How many pounds of steam per day would this energy produce?

Solution

Heating value of escaping gas

1 ft^3 of natural gas = 1,050 Btu

1,000,000 ft^3/d of natural gas = 1,050,000,000 Btu/d

1 bbl (barrel) of petroleum = 5,800,000 Btu

(1,050,000,000 Btu/d)/(5,800,000 Btu/bbl) = 181 bbl/d

Volume of water brought to a boil

1 Btu will raise the temperature of 1 pound of water by 1°F

To heat water from, say 62°F to 212°F requires

= (1 Btu/lb°F)(212°F – 62°F) = 150 Btu/lb

1,000,000 ft^3/d of natural gas = 1,050,000,000 Btu/d

Mass of water that can be heated from 62°F to 212°F

= (1,050,000,000 Btu/d)/(150 Btu/lb) = 7,000,000 lb water/d

= (7,000,000 lb water/d)/(8.34 lb water/gal) = 839,000 gal water/d

Mass of steam production

To convert liquid water at 212°F to steam vapor requires 970 Btu/lb

To convert 62°F water to steam at 212°F requires

150 Btu/lb + 970 Btu/lb =1,120 Btu/lb

Steam produced = (1,050,000,000 Btu/d)/(1,120 Btu/lb) = 938,000 lb steam/d

3.12 ENERGY DEMAND GROWTH

From 1800 to the present the total demand for energy has grown at about 4.5% per year. If we could reduce this rate to 2.5%, by how much would the total energy demand increase from today until 2100?

Solution

Say the energy demand today, in 2018, is D_{2018}

One year later, at 4.5% growth, it is

$$D_{2019} = D_{2018} + 0.045\ D_{2018} = 1.045\ D_{2018}$$

After 2 years it is

$$D_{2020} = 1.045(1.045)\ D_{2018} = D_{2018}(1.045)^2 = 1.092D_{2018}$$

This is exponential growth. At 4.5% growth per year, for 82 years (to 2100) gives

$$D_{2100,\ 4.5\%} = D_{2018}\,(1 + 0.045)^{82} = D_{2018}\ (1.045)^{82} = 36.94\ D_{2018}$$

At 2.5% growth

$$D_{2100,\ 2.5\%} = D_{2018}\ (1 + 0.025)^{82} = D_{2018}\ (1.025)^{82} = 7.57\ D_{2018}$$

Total energy demand would be about five times less

$$(D_{2100,\ 2.5\%})/(D_{2100,\ 4.5\%}) = 7.57/36.94 = 0.205$$

At 2.5% growth per year, the 2100 demand is 7.6 times the 2018 rate. At 4.5% growth per year the demand will increase 7.6-fold in only 46 years. By 2100, the 4.5% growth give a demand that is 37 times more than the 2018 demand. A small change in the growth rate makes a big difference for exponential growth.

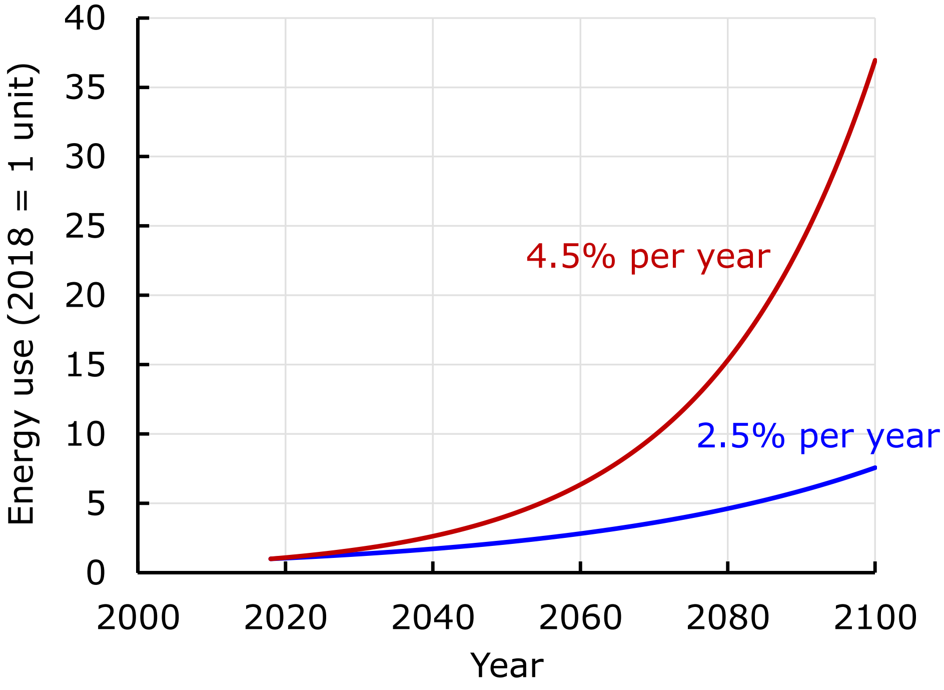


Figure S3.12 Energy demand growth

Tutorial Note

The standard volume unit for crude oil measurement, the 42-gallon barrel (bbl), dates back to the 1860s, when Pennsylvania producers actually stored and transported petroleum in wooden barrels. To this day you may hear a petroleum engineer say, "This field has reserves of 1 billion barrels and we expect to produce it for 20 years at a design rate of 150,000 bbl/day." In countries that use the SI or metric system, oil volumes may be measured in metric tonnes.

In Europe and especially the former Soviet Union, crude oil is measured in terms of weight and expressed in metric tonnes (T), where one T equals 2,204 lb. Although crude oils vary in density, a good "average" volume-to-weight conversion is 7.33 bbl/T. Based on this conversion factor, a Russian engineer would refer to production not as 150,000 bbl/day but as 20,464 T/day.

3.13 ALASKA PIPELINE

The 1,287 km (800 mile) oil pipeline from the Prudhoe Bay oil field to Valdez, Alaska, shipped 2.5x10^9 m^3 (16 billion barrels) of oil, as of 2010. The maximum flow rate in the pipeline is 339,600 m^3/d (2.14 Mbbl/d). The thermal energy content, or heating value**,** of crude oil depends on its composition, but generally averages about 6 million Btu per barrel. Use this value for Prudhoe Bay oil. If all this oil fueled electric power plants of 35% efficiency, how many 1000 MW plants could be fueled with this oil?

Solution

One maximum day of oil delivery = 2.136 x10^6 bbl
One day heating value = (2.14 x10^6 bbl/d)(5.8 x10^6 Btu/bbl) = 12.4 x10^{12} Btu/d
Electric equivalent = (12.4 x10^{12} Btu/d)/(3,412 kWh/Btu) = 3.63 x10^9 kWh/d
Electricity produced at 35% efficiency = 0.35(3.63 x10^9 kWh/d) = 1.27 x 10^9 kWh/d
A 1000 MW power plant produces (1,000,000 kW)(24 h/d) = 24,000,000 kWh/d
Number of 1000 MW plants = (1.27 x 10^9 kWh/d)/(24,000,000 kWh/d) = 529

3.14 WINDMILL POWER

There was once, 40 years ago, an ad on television that went something like this: (Scene – Windmill, its sails turning slowly in the wind.)

> *"Back in 1915, 3000 windmills helped light up the country of Denmark. America could generate electricity the same charming way. All we have to do is keep wasting our natural stores of energy. When it's gone we'll just turn on the windmills. A great idea until the wind dies down."*

There is some strange language here. Is this ad for or against wind power? Discuss the ad in light of the 21st century's technology and need for energy.

Figure P3.14 Danish windmills

Solution

This is an open-ended question that is meant to provoke discussion. No solution is provided.

3.15 WIND ENERGY TO ELECTRICAL ENERGY

A wind turbine has a rotor diameter of 150 m. Calculate the power for a wind velocity of 14 m/s and an air density of $\rho = 1.2\ \text{kg/m}^3$. The turbine efficiency, the amount of total wind power that is delivered as electricity, is 35%. What is the rated capacity for these conditions?

Solution

The swept rotor area is

$$A = \pi D^2/4 = \pi(150\ \text{m})^2/4 = 17{,}700\ \text{m}^2$$

The theoretical wind power is calculated using

$$P = 0.5\ \rho\ AV^3$$

$$P = 0.5(1.2\ \text{kg/m}^3)(17{,}700\ \text{m}^2)(14\ \text{m/s})^3 = 29{,}000{,}000\ \text{kW} = 29\ \text{MW}$$

Turbine efficiency = 30-35% (say 35% is delivered as electricity)
Rated capacity = (0.35)(29 MW) = 10 MW

3.16 WIND ENERGY I

The *rated power or nameplate power* of a wind turbine is the amount of electric power produced when the turbine operates at peak capacity. A wind turbine *rated* at 1000 kW will produce 1000 kilowatt hours (kWh) of electricity per hour of operation, when running at its maximum performance (i.e. at high winds above, say, 15 m/s). Denmark, for example, has, 1000 MW (1000 megawatts) of wind power installed. The turbines will usually be running 75 per cent of the hours of the year, but they will running at rated power for a lower percentage of the time. In order to find the annual energy production you have to know the distribution of wind speeds for each turbine. In Denmark's case, the average wind turbines will return 2,300 hours at the equivalent of full load operation per year. What is the total wind energy production?

Solution

Total wind energy production = 1000 MW of installed power with 2,300 hours of operation per year
= (1000 MW)(2300 h/y) = 2,300,000 MWh/y = 2,300,000,000 kWh/y

3.17 WIND ENERGY II

In Wales, Scotland, or Western Ireland there is likely to be about 3,000 hours annually of full load operation of a wind turbine. In Germany the figure is closer to 2,000 hours of full load operation. In Denmark it is about 2,300 hours. In each region, how much energy is generated per 1 MW of wind power installed?

Solution

Germany	(2,000 h/y)(1 MW) = 2,000 MWh/y
Denmark	(2,300 h/y)(1 MW) = 2,300 MWh/y
Scotland	(3,000 h/y)(1 MW) = 3,000 MWh/y

3.18 WIND TURBINE EVOLUTION

The rated power (nameplate power) is the power that will be produced per hour of operation when running at its maximum performance. Figure P3.18 shows how the size and rated power of wind turbines have grown from the 1980s to 2010. (a) What is the change in rated capacity of the typical unit in the 1980s and that in 2010? (b) Verify the rated capacity for the 1990 unit and the 2010 unit, using the rotor size shown in the diagram. Use a wind velocity of 15 m/s, air density = 1.2 kg/m^3, and conversion efficiency = 20%. (Source: Lantz, E et al. 2012, "Past and Future Cost of Wind Energy," NREL Conference Paper.)

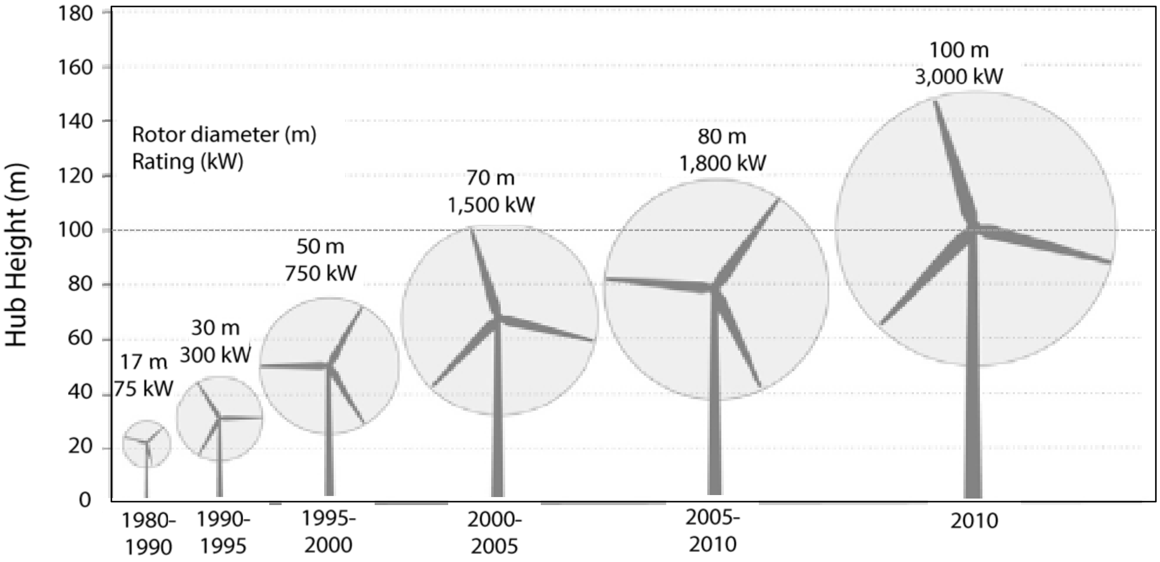


Figure P3.18 Rate capacity of wind turbines from 1980 to 2010

Solution

Change in rated capacity from 1980s to 2010

= 75 kW in 1980 to 3,000 kW in 2010, a 40 fold increase in power!

Note: Installed wind power capacity has changed by a much larger factor.

Rated capacity for 1990 unit. Assume wind velocity = 15 m/s and air density = 1.2 kg/m^3

1990 Rotor diameter = 30 m

Rated power = 300 kW

Rotor swept area = $A = \pi D^2/4 = \pi(30\text{ m})^2/4 = 707\text{ m}^2$

Theoretical wind power is calculated using

$$P = 0.5\,\rho\,AV^3$$

$$P = 0.5(1.2\text{ kg/m}^3)(707\text{ m}^2)(15\text{ m/s})^3 = 1{,}430{,}000\text{ W} = 1430\text{ kW}$$

Assume 20% conversion efficiency

$$P_{output} = (0.20)(1430\text{ kW}) = 286\text{ kW}$$

This is about 5% less than the rated 300 kW.

2010 Rotor diameter = 100 m

Rotor swept area = $A = \pi D^2/4 = \pi(100\text{ m})^2/4 = 7{,}854\text{ m}^2$

Theoretical wind power is calculated using

$$P = 0.5\,\rho AV^3$$

$$P = 0.5(1.2\text{ kg/m}^3)(7{,}854\text{ m}^2)(15\text{ m/s})^3 = 15{,}900{,}000\text{ W} = 15{,}900\text{ kW}$$

Assume 20% conversion efficiency

$$P_{output} = (0.20)(15{,}900\text{ kW}) = 3{,}180\text{ kW}$$

This is about 6% more than the rated 3000 kW

3.19 WIND TUBINE POWER RATING

Available wind resources is a function of yearly average wind velocity. *Resources* refers to the power present in the wind at 50 m above the ground surface. Calculate the available energy output from a wind turbine operating at an average wind velocity 15 m/s, with efficiency 20%, and operating 8000 hours per year. Figure P3.19 shows the wind speed vs. power curve for a typical wind turbine. The vertical axis is W/m^2, where the m^2 is the area swept by the turbine blades.

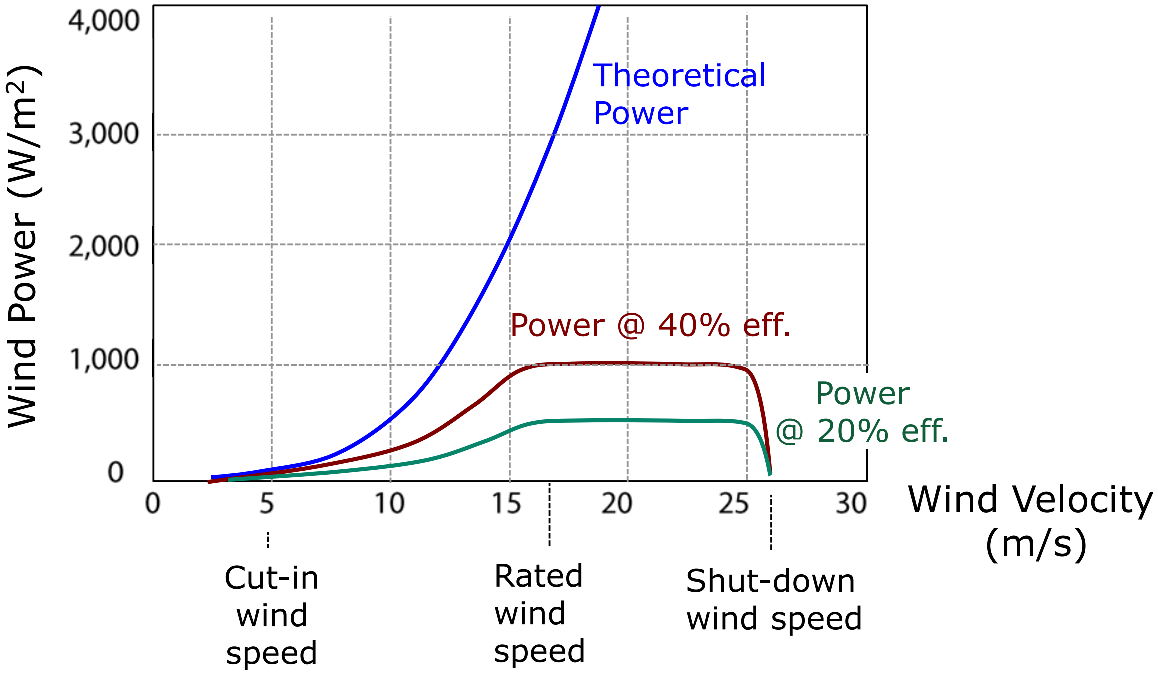


Figure P3.19 Available wind power as a function of wind velocity

Solution

Theoretical power $P = 0.5\rho A v^3$

Actual power $P = \eta(0.5\rho A v^3)$

where η = wind turbine efficiency (generally $\eta = 0.2 – 0.4$)

We do not have dimensions for the turbine, so use some values from Figure P3.19.
Power at 40% efficiency and 15 m/s, gives $P \approx 900$ W/m^2

Estimated annual energy production = (900 W/m^2)(8000 h/y)

= 7,200,000 Wh/m^2-y = 7,200 kWh/m^2-y

Power @ 20% efficiency and 15 m/s, give $P \approx 400 \text{ W/m}^2$

Estimated annual energy production = $(400 \text{ W/m}^2)(8000 \text{ h/y})$

= $3{,}200{,}000 \text{ Wh/m}^2\text{-y} = 3{,}200 \text{ kWh/m}^2\text{-y}$

3.20 WIND SPEED VARIATION AND POWER GENERATION

Figure P3.20 shows the rated power capacity for a wind turbine to be installed at a location that has the wind speed distribution shown by the histogram. Estimate the annual output of electrical energy. (The values read from the graphs may vary from person to person. Don't worry about that lack of precision. You are making an estimate.)

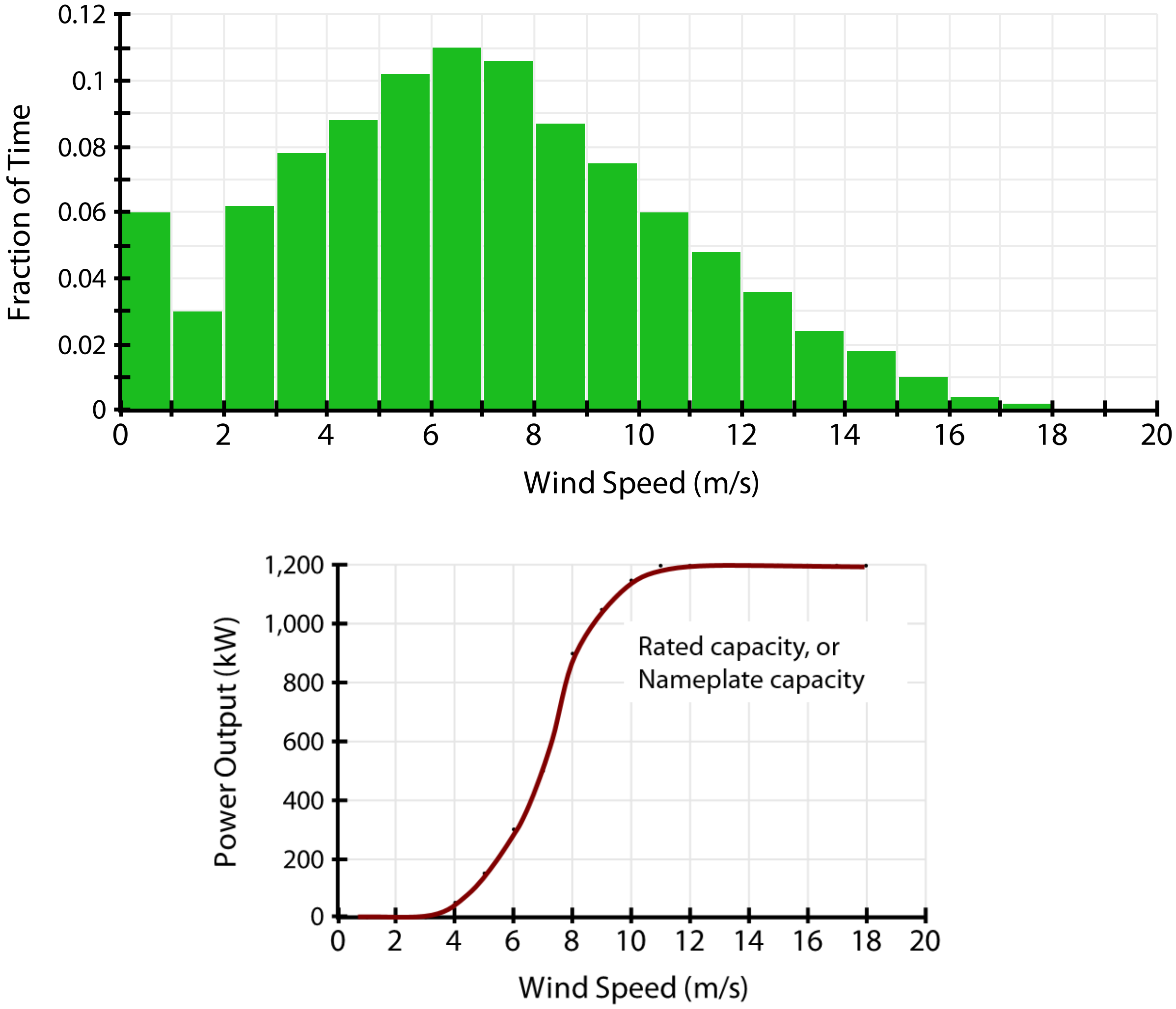


Figure P3.20 Variation of wind speed and power output at a wind turbine site

Solution

Construct a table using the fraction of time and power output data from Figure P3.20.

Sample calculation:

Wind speed = 4-5 m/s
Days per year = (fraction of time)(365 d/y) = 0.088(365) = 32.1 d
Power output at 4-5 m/s = 150 kW
Energy produced = (150 kW)(32.1 d)(24 h/d)
=115,600 kWh = 116 MW (rounded)

Wind Speed	Fraction of time	Time	Power Output	Electricity Produced		Percent of Total	Cumulative Percent
(m/s)		(days/y)	(kW)	(kWh)	(MWh)	(%)	(%)
< 1	0.060	21.9	0	0	0	0.0	0.0
1-2	0.030	11.0	0	0	0	0.0	0.0
2-3	0.062	22.6	0	0	0	0.0	0.0
3-4	0.078	28.5	50	34,164	34	0.6	0.6
4-5	0.088	32.1	150	115,632	116	2.1	2.8
5-6	0.102	37.2	300	268,056	268	5.0	7.7
6-7	0.110	40.2	500	481,800	482	8.9	16.6
7-8	0.106	38.7	900	835,704	836	15.4	32.0
8-9	0.087	31.8	1050	800,226	800	14.8	46.8
9-10	0.075	27.4	1150	755,550	756	14.0	60.8
10-11	0.060	21.9	1200	630,720	631	11.6	72.4
11-12	0.048	17.5	1200	504,576	505	9.3	81.8
12-13	0.036	13.1	1200	378,432	378	7.0	88.7
13-14	0.024	8.8	1200	252,288	252	4.7	93.4
14-15	0.018	6.6	1200	189,216	189	3.5	96.9
15-16	0.010	3.7	1200	105,120	105	1.9	98.8
16-17	0.004	1.5	1200	42,048	42	0.8	99.6
17-18	0.002	0.7	1200	21,024	21	0.4	100.0
Totals				*5,414,556*	*5,415*	*100*	

Table S3.20

The wind turbine operates at peak capacity at wind speeds over 11 m/s but there are few such days and the power generated is only 27% of the available total.

Just 7.7% of the annual total (5,415 MWh) is produced when the wind speed is below 7 m/s;

That means that 65.3% of the annual output is generated at wind speeds between 7 m/s and 11 m/s.

3.21 PHOTOVOLTAIC CONVERSION OF SOLAR ENERGY TO ELECTRICAL ENERGY

Solar electric power will be installed in house that receives an average of 5 hours of sun per day to provide an output of 2,000 Watt-h/day (Wh/d). The wattage output is 80% of the collected solar energy. What is the required system output?

Solution

Wattage collection requirement = (2,000 Wh/d)/0.8 = 2,500 Wh/d
Daily power requirement = (2,000 Wh/d)/(5 h/d) = 400 W (rounded up)
Energy must be purchased from the grid for 19 h/d unless some battery storage is provided.

3.22 VALUE OF ENERGY IN SUNLIGHT

The energy flux from the sun varies from place to place and it depends on weather conditions. Without an atmosphere 1.4 kW/m^2 is available, but at the earth's surface we can only count on 1 kW/m^2 on a clear sunny day. How much is 3 hours of sunlight on one square meter (or 1 hour of sunlight on 3 m^2) worth?

Solution

Energy from the sun falling onto 3m^2 for 1 hour = (1 kW/m^2)(3 m^2)(1 h) = 3kWh. How much is 3 kWh of energy worth?

As electricity:
Let's say that electricity is worth \$0.10/kWh. Then 3 kWh is worth \$0.30. Photovoltaic (PV) panels have a radiant energy conversion rate of about 20% or less, so one hour of sunlight on three square meters of a solar panel is worth about \$0.06

As heat:
1 kWh = 3400 Btu, so 3 kWh = 10,200 Btu.
Since one gallon of fuel oil contains 150,000 Btu, 10,200 Btu is the equivalent of 0.07 gallons of fuel oil. If fuel oil is selling for \$2.00/gallon, the value 10,200 Btu is about \$0.14.

You might think this is an unfair comparison since we're not taking into account the heat conversion efficiency factor like we did with the solar panel. I'm glad to see you're paying attention and you are right about this. The heat transfer efficiency of a solar hot water system is between 50% and 70%, the same as oil burner heat transfer efficiency. Since the heat transfer efficiency for an oil burner is about the same as solar collector, then the value of one hour of sunlight on three square meters is worth about (0.6)(\$0.14) = \$0.08.

3.23 SOLAR ENERGY – ROOF COLLECTION

The solar collection area of a roof, which is tilted south at a pitch to maximize heat gain, is 90 m^2. What is the value of the solar energy falling onto a roof of a house over the period of one year? Assume the energy output is 70% of the collected solar energy.

Solution

Surface area of the roof = 90 m^2.
Available solar energy available (for north central U.S.) = 1500 kWh/m^2-y
Energy collected from (90 m^2)(1500 kWh/m^2-y) = 135,000 kWh/y
Energy yield = (0.7)(135,000 kWh/y) = 94,500 kWh/y

At \$0.1/kWh the solar roof could save \$9,450/y.
Problem 3.1 stated that an average family in Minnesota uses about 63,000 kWh per year.

3.24 ETHANOL ENERGY BALANCE

Figure P3.24 shows the net energy value for corn ethanol as calculated in a number of studies. The "net energy value" is defined as the Btu content of a gallon of ethanol minus the fossil fuel energy used to produce a gallon of ethanol. More recent studies are on the right-hand side of the chart, and these are about half positive and half negative. (a) Investigate how these estimates are made and what factors may differ to account for the wide range of net energy values. (b) The most recent estimate shown was developed more than 10 years ago. Technology changes, usually to become more efficient, so look for newer data to add to the chart.

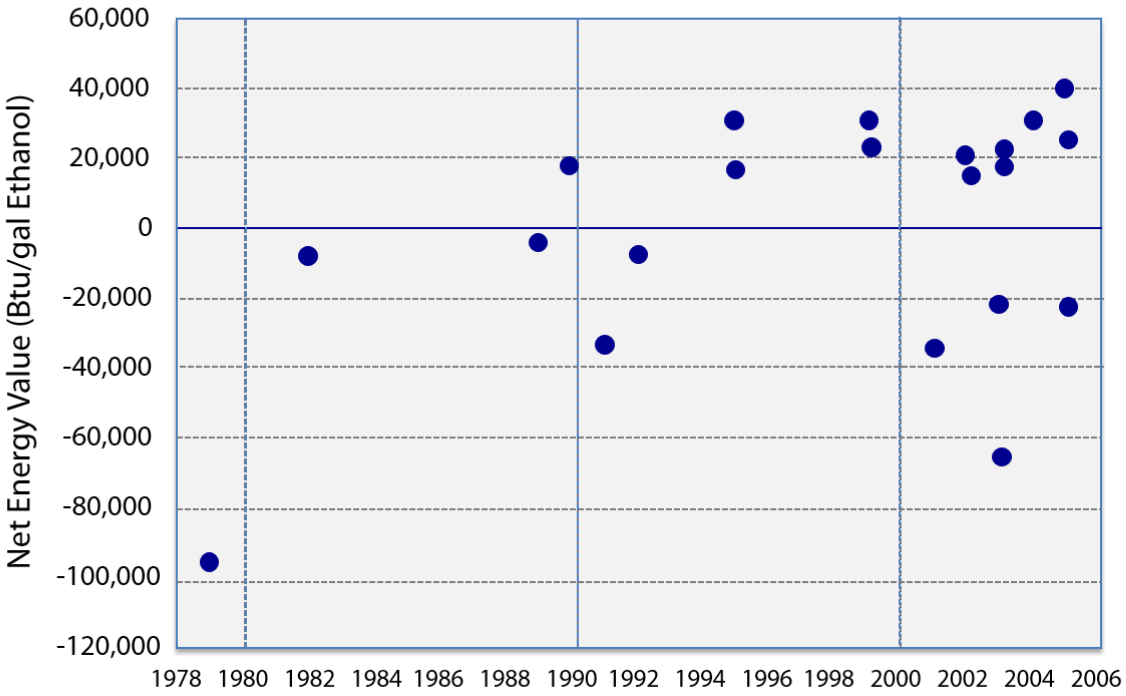


Figure P3.24 Net energy value for corn ethanol. (Source: Ethanol Energy Debate Continues *The Energy Blog*, Sept 1, 2005; http://thefraserdomain.typepad.com/energy/2005/09).

Solution

This is an open-ended question meant to stimulate research and discussion. No solution is provided.

4 THE ENERGY BALANCE AND ENTHALPY

4.1 ENTHALPY OF EVAPORATION

Which of the four liquids in Table P4.1 would be most efficient in cooling a hot gas stream? The heat capacities (specific heats) are:

Liquid	Heat Capacity	
	kJ/kg-°C	Btu/lb-°F
Water	4.19	1
Light oil	1.8	0.43
Hexane	2.24	0.535
Ethylene glycol	2.36	0.56

Table P4.1 Heat capacity of four liquids

Solution

A higher heat capacity means the liquid can absorb and carry more enthalpy (heat). The most effective is water, followed by ethylene glycol.

4.2 POWER PLANT COOLING WATER

A thermal electric power plant discharges 10 million kWh per year of waste heat to cooling water. Calculate the amount of cooling water required for a once through cooling system if the increase in cooling water temperature is $\Delta T = 15°$ C.

Solution

Specific heat of water = 4.187 kJ/kg°C
Density of water = 1000 kg/m^3

$$m = \frac{Q}{c_p \Delta T} = \left(\frac{10{,}000{,}000 \text{ kWh}}{(4.187 \text{ kJ/kg°C})(15°\text{C})} \right) \left(\frac{3{,}600 \text{ kJ}}{\text{kWh}} \right) = 573 \times 10^6 \text{ m}^3$$

4.3 MAKING STEAM

Eighty thousand pounds per hour of water at 100°F is heated to make steam at 212°F and 1 atmosphere pressure. (a) Calculate the amount of heat required using the specific heat of water and the latent heat of vaporization. (b) Calculate the amount of heat required using the enthalpy of water and steam.

Solution

Method 1 - Use the specific heat (1 Btu/lb°F) and the latent heat of vaporization (970 Btu/lb)

Basis: m = 80,000 lb
Heating the water from 100°F to 212°F requires

$$Q = mc_p(T_2 - T_1) = (80{,}000 \text{ lb/h})(1 \text{ Btu/lb°F})(212°\text{F} - 100°\text{F}) = 8{,}960{,}000 \text{ Btu/h}$$

Changing the 212°F water to 212°F steam requires

$$Q = mH_v = (80{,}000 \text{ lb/h})(970 \text{ Btu/lb}) = 77{,}600{,}000 \text{ Btu/h}$$

Total heat required is

8,960,000 + 77,600,000 = 86,560,000 Btu/h

Method 2 - Use enthalpy. The amount of heat required is equal to the change in enthalpy of the incoming water and the exiting steam.

From Appendix 5

Enthalpy of liquid water at @ 100°F and 1 atm H_1 = 67.97 Btu/lb
Enthalpy of water vapor (steam) @ 212°F and 1 atm H_2 = 1,150.4 Btu/lb

Change in enthalpy and the total amount of heat required to make the steam

$$Q = m(H_2 - H_1) = (80{,}000\text{ lb/h})\,(1{,}150.4\text{ Btu/lb} - 67.97\text{ Btu/lb})$$
$$= 86{,}594{,}000\text{ Btu/h}$$

This answer is slightly different than the 86,560,000 Btu/h (0.04%) calculated by Method 1 because the enthalpy values from the steam tables are more precise than we calculate using a specific heat of 1.00 Btu/lb°F and a latent heat of 970 Btu/lb. The difference is not important in our understanding of the basic principles of making an energy balance.

4.4 HIGH TEMPERATURE STEAM (U.S. UNITS)

Calculate the change in enthalpy of per pound mass of water as it is heated (a) from 60°F to 212°F, (b) as it vaporizes to steam at 212°F, and (c) as the water vapor is heated to 400°F.

Solution

Latent heat of vaporization = 970 Btu/lb of water evaporated
Heat capacity of water = c_P = 1 Btu/lb°F

a) Sensible energy as the temperature rises from 60°F to 212°F

$$\Delta H \text{ of } H_2O = (1\text{ Btu/lb°F})(212°F - 60°F) = 152\text{ Btu/lb}$$

b) Enthalpy of vaporization at 212°F = 970.3 Btu/lb

c) Sensible energy as steam temperature rises from 212°F to 400°F

$$H_{212°F} = 1150.4\text{ Btu/lb}$$
$$H_{400°F} = 1173.7\text{ Btu/lb}$$
$$\Delta H = H_{400°F} - H_{212°F} = 1150.4\text{ Btu/lb} - 1173.7\text{ Btu/lb} = 23.3\text{ Btu/lb}$$

Total change from 60°F to 400°F = 152 Btu/lb + 970.3 Btu/lb + 23.3 Btu/lb

= 1145 Btu/lb

4.5 HIGH TEMPERATURE STEAM (SI UNITS)

Calculate the change in enthalpy of per kilogram mass of water as it is heated (a) from 20°C to 100°C, (b) as it vaporizes to steam at 100°C, and (c) as the water vapor is heated to 150°C.

Solution

Latent heat of vaporization = 2,257 kJ/kg evaporated
Heat capacity of water = c_p = 4.187 kJ/kg°C

a) Sensible energy as the temperature rises from 20°C to 100°C

$$\Delta H \text{ of } H_2O = (4.187 \text{ kJ/kg°C})(100°C - 20°C) = 335.0 \text{ kJ/kg}$$

b) Vaporization at 100°C = 2,256.5 kJ/kg

c) Sensible energy as steam temperature rises from 100°C to 150°C

$$H_{100°C} = 2{,}675.6 \text{ kJ/kg}$$
$$H_{150°C} = 2{,}745.9 \text{ kJ/kg}$$
$$\Delta H = H_{150°C} - H_{100°C} = 2{,}745.9 \text{ kJ/kg} - 2{,}675.6 \text{ kJ/kg} = 70.3 \text{ kJ/kg}$$

Total change from 20°C to 150°C = 335.0 kJ/kg + 2,256.5 kJ/kg + 70.3 kJ/kg
= 2,662 kJ/kg

4.6 COOLING AIR WITH WATER (U.S. UNITS)

When air is cooled with a water spray the temperature of the water is unchanged but a small amount evaporates to remove heat from the air (Figure P4.6). Use a basis of 100 lb of dry air that enters at 100°F and assume that moist air leaves at 68°F. (a) How much water is evaporated to accomplish the cooling? The specific heat of dry air is 0.25 Btu/lb°F. (b) Does the amount of water evaporated result in the relative humidity of the output air exceeding a target level of 50%? The humidity ratio of saturated air at 68°F = 0.0147 lb H_2O/lb dry air.

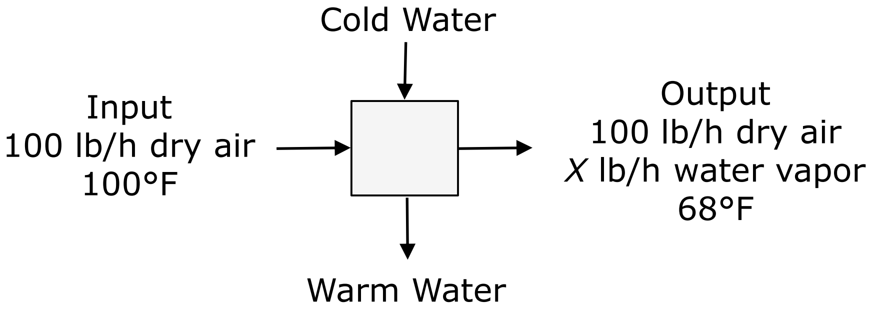


Figure P4.6 Cooling air with a water spray (U.S. units)

Solution

Basis: 1 hour operation = 100 lb dry air
Specific heat of air = 0.25 Btu/lb°F
Heat of vaporization of water = 970 Btu/lb
Define X = mass of water evaporated (lb/h)

a) Mass of water evaporated.
Heat energy removed from water to cool air from 100°F to 68°F

$$Q_{\text{Cool}} = mc_p(T_2 - T_1) = (100 \text{ lb/h})(0.25 \text{ Btu/lb°F})(100\text{°F} - 68\text{°F}) = 800 \text{ Btu/h}$$

Heat energy transferred to water to evaporate X lb/h

$$Q_{\text{Heat}} = (X)(970 \text{ Btu/lb})$$

Energy balance: $Q_{\text{Cool}} = Q_{\text{Heat}}$

$$800 \text{ Btu/h} = (X)(970 \text{ Btu/lb})$$

$$X = (800 \text{ Btu/h})/(970 \text{ Btu/lb}) = 0.825 \text{ lb/h of water evaporated}$$

b) Relative humidity of cooled air.
Mass of moist air exiting = 100 lb dry air+ 0.825 lb water vapor= 100.825 lb moist air
This is 0.825 lb H_2O in 100 lb dry air = 0.00825 lb H_2O/lb dry air
Humidity ratio of saturated air at 68°F = 0.0147 lb H_2O/lb dry air
The relative humidity of the cooled air is

$$= (0.00825 \text{ lb } H_2O/\text{lb dry air})/(0.0147 \text{ lb } H_2O/\text{lb dry air}) = 0.56 = 56\%$$

The output water content is well below the saturated air moisture ratio, but has a relative humidity that exceeds the target of 50% by about 6 percentage points.

4.7 COOLING AIR WITH WATER (SI UNITS)

Air is cooled with a water spray (Figure P4.7). The temperature of the water is unchanged but a small amount evaporates to remove heat from 500 kg/h of dry air that enters at 50°C and assume that 500 kg/h of moist air leaves at 20°C. (a) How much water is evaporated to accomplish the cooling? The specific heat of dry air is 1.006 kJ/kg°C. (b) Does the amount of water evaporated result in the relative humidity of the output air exceeding a target level of 50%? The humidity ratio of saturated air at 20°C = 0.0147 kg H_2O/kg dry air.

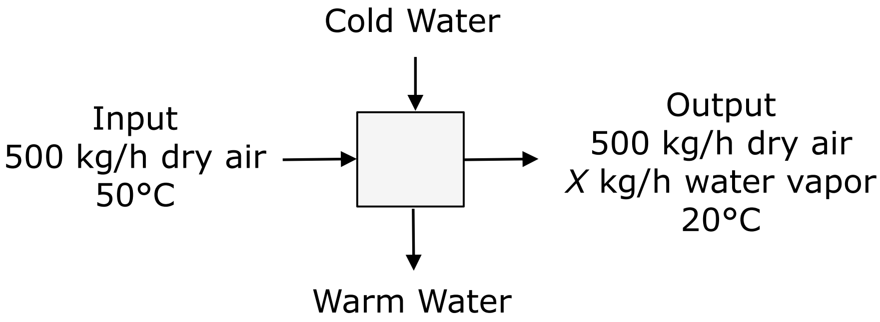


Figure P4.7 Cooling air with a water spray (SI Units)

Solution

Basis: 1 hour operation = 500 kg dry air
Specific heat of air = 1.006 kJ/kg°C
Heat of vaporization for water = 2,256.5 kJ/kg
Define X = mass of water evaporated (kg)

a) Mass of water evaporated
Heat energy removed from water to cool air from 50°C to 20°C

$$Q_{Cool} = mc_P(T_2 - T_1) = (500 \text{ kg/h})(1.006 \text{ kJ/kg°C})(50°C - 20°C) = 15{,}090 \text{ kJ/h}$$

Heat energy transferred to water to evaporate X kg/h

Q_{Heat} = (X)(2,256.5 kJ/lkg)

Energy balance: $Q_{Cool} = Q_{Heat}$

15,090 kJ/h = (X)(2,256.5 kJ/kg)

X = (15,090 kJ/h)/(2,256.5 kJ/kg) = 6.69 kg/h water evaporated

b) Relative humidity of cooled air.

Mass of moist air exiting = 500 kg dry air + 6.69 kg water vapor = 506.69 kg moist air

This is 6.69 kg H_2O in 500 kg dry air = 0.0134 kg H_2O/kg dry air

Humidity ratio of saturated air at 20°C = 0.0147 kg H_2O/kg dry air

Relative humidity of the cooled moist air is

= (0.0134 kg H_2O/kg dry air)/(0.015 kg H_2O/kg dry air) = 0.91 = 91%

The output cooled moist air has a relative humidity of 91%, which is nearly double the target of 50%.

Tutorial Note

This abbreviated table of enthalpies for water is useful for the next problems.

T (°C)	Vapor Pressure (kPa)	Enthalpy, kJ/kg			T (°F)	Vapor Pressure (kPa)	Enthalpy, Btu/lb		
		Sat. Liquid	ΔH_v	Sat. Vapor			Sat. Liquid	ΔH_v	Sat. Vapor
0	0.62	0	2500.9	2500.9	32	0.0060	0	1075.1	1075.1
5	0.87	21.02	2489.1	2510.1	40	0.0083	8.05	1070.5	1078.6
10	1.23	42.02	2477.2	2519.2	50	0.0121	18.07	1064.8	1082.9
15	1.71	62.98	2465.4	2528.4	60	0.0174	28.07	1059.1	1087.2
20	2.34	83.92	2453.6	2537.5	70	0.0247	38.05	1053.4	1091.5
25	3.17	104.84	2441.7	2546.5	80	0.0345	48.02	1047.8	1095.8
30	4.25	125.75	2429.9	2555.6	90	0.0475	58.00	1042.1	1100.1
35	5.63	146.64	2418.0	2564.6	100	0.0646	67.97	1036.4	1104.4
40	7.38	167.54	2406.0	2573.5	110	0.0867	77.94	1030.9	1108.8
45	9.59	188.44	2394.1	2582.5	120	0.115	87.91	1025.3	1113.2
50	12.35	209.34	2382.0	2591.3	130	0.151	97.89	1019.5	1117.4

4.8 ENTHALPY OF HUMID AIR (SI UNITS)

Moist air is a mixture of dry air and water vapor. The water vapor content of atmospheric air ranges from 0 to 3% by mass. At relative humidity (RH) of 100% air is saturated with water vapor. The enthalpy of moist air is the sum of sensible heat and latent heat of vaporization, and can be estimated using

$$H_{x,T^\circ\text{C}} = c_{P,\,\text{air}}T + x\left(c_{P,\,\text{water vapor}}T + H_{v,\,\text{water, }0^\circ\text{C}}\right)$$

where: x = humidity ratio of moist air, kg water vapor/ kg dry air

T = air temperature, °C (0°C is used as the reference temperature).

Calculate the enthalpy of moist air at 50°C at (a) 100% relative humidity (RH) and at (b) 50% RH. Air saturated with water vapor air at 50°C has a humidity ratio of x = 0.087 kg H_2O/kg dry air. The heat capacity of dry air is 1.006 kJ/kg°C. The heat capacity of water vapor is 1.84 kJ/kg°C. The heat of vaporization of water at 0°C = 2501 kJ/kg. The enthalpy of dry air at T = 0°C is 0.0 kJ/kg.

Solution

Basis = 1 kg dry air at 0°C
Specific heat of dry air = 1.006 kJ/kg°C
Specific heat of water vapor = $c_{P\text{-water vapor}}$ = 1.84 kJ/kg°C
Humidity ratio at 50°C = 0.087 kg H_2O/kg dry air
Heat of vaporization of water at 0°C = 2501 kJ/kg

a) Enthalpy of moist air at 50°C and 100% relative humidity (RH)

$$H_{x,T^\circ\mathrm{C}} = c_{P,\ \mathrm{air}}T + x\left(c_{P,\ \mathrm{water\ vapor}}T + H_{v,\ \mathrm{water,\ 0^\circ C}}\right)$$

$$H_{Sat,\ 50^\circ\mathrm{C}} = \left(1.006\frac{\mathrm{kJ}}{\mathrm{kg\ air\ ^\circ C}}\right)(50^\circ\mathrm{C})$$

$$+\left(0.087\frac{\mathrm{kg\ H_2O}}{\mathrm{kg\ air}}\right)\left[\left(1.84\frac{\mathrm{kJ}}{\mathrm{kg\ H_2O\ ^\circ C}}\right)(50^\circ\mathrm{C})+2{,}501\frac{\mathrm{kJ}}{\mathrm{kg\ H_2O}}\right]$$

$$= 50.3 + 8.0 + 217.6 = 275.9\frac{\mathrm{kJ}}{\mathrm{kg\ moist\ air}}$$

b) Enthalpy of moist air at 50°C and 50% relative humidity.

At 50% RH the humidity ratio is
x = (0.087 kg H_2O/kg dry air)/2 = 0.0435kg H_2O/kg dry air

$$H_{RH=50\%,\ 50^\circ\mathrm{C}} = \left(1.006\frac{\mathrm{kJ}}{\mathrm{kg\ air^\circ C}}\right)(50^\circ\mathrm{C})$$

$$+\left(0.0435\frac{\mathrm{kg\ H_2O}}{\mathrm{kg\ air}}\right)\left[\left(1.84\frac{\mathrm{kJ}}{\mathrm{kg\ H_2O^\circ C}}\right)(50^\circ\mathrm{C})+2{,}501\frac{\mathrm{kJ}}{\mathrm{kg\ H_2O}}\right]$$

$$= 50.3 + 8.0 + 217.6 = 275.9\frac{\mathrm{kJ}}{\mathrm{kg\ moist\ air}}$$

Notes:
The second term for 50% RH is half the value for 100% RH
112.8 kJ/kg = 0.5(225.6 kJ/kg)
The sensible heat of the water vapor (8.0 kJ/kg and 4.0 kJ/kg) is small, 2.5 to 3%, of the total enthalpy.

4.9 ENTHALPHY OF HUMID AIR (U.S. UNITS)

Moist air is a mixture of dry air and water vapor. The water vapor content of atmospheric air ranges from 0 to 3% by mass. At relative humidity (RH) of 100% air is saturated with water vapor. The enthalpy of moist air is sensible heat and latent heat of vaporization.

$$H_{x,T°\mathrm{F}} = c_{P,\ \mathrm{air}}(T - 32°\mathrm{F}) + x\left(c_{P,\ \mathrm{water\ vapor}}(T - 32°\mathrm{F}) + H_{v,\ \mathrm{water},\ 32°\mathrm{F}}\right)$$

where: x = humidity ratio of moist air, lb water vapor/ lb dry air
T = temperature, °F (Note: reference temperature is 32°F).

Calculate the enthalpy of moist air at 122°F (50°C) at (a) 100% relative humidity (RH) and at (b) 50% RH. Air saturated with water vapor air at 122°F has a humidity ratio of x = 0.087 lb H_2O/lb dry air. The specific heat of dry air is 0.240 Btu/lb°F. The specific heat of water vapor is 0.446 Btu/lb°F. Heat of vaporization of water at 0°F = 1061 Btu/lb (reference www.engineeringtoolbox.com).

Solution

Basis = 1 lb dry air at reference temperature of 32°F
Specific heat of dry air = 0.240 Btu/lb°F.
Specific heat of water vapor = $c_{P\text{-water vapor}}$ = 0.446 Btu/lb°F
Humidity ratio at 122°F = 0.0.087 lb H_2O/lb dry air
Heat of vaporization of water at 32°F = 1075.1 Btu/lb

a) Enthalpy of moist air at 122°F and 100% relative humidity (RH)

$$H_{Sat,\ 122°\mathrm{F}} = \left(0.240\frac{\mathrm{Btu}}{\mathrm{lb\ air\ °F}}\right)(122°\mathrm{F} - 32°\mathrm{F}) + \left(0.087\frac{\mathrm{lb\ H_2O}}{\mathrm{lb\ air}}\right)\left[\left(0.446\frac{\mathrm{Btu}}{\mathrm{lb\ H_2O\ °F}}\right)(122°\mathrm{F} - 32°\mathrm{F}) + 1{,}075.1\frac{\mathrm{Btu}}{\mathrm{lb\ H_2O}}\right]$$

$$= 21.6 + 3.5 + 93.5 = 119\ \frac{\mathrm{Btu}}{\mathrm{lb\ moist\ air}}$$

b) Enthalpy of moist air at 122°F and 50% relative humidity.
At 50% RH the humidity ratio is
x = (0.087 lb H_2O/lb dry air)/2 = 0.0435 lb H_2O/lb dry air

$$H_{Sat,\ 122°\mathrm{F}} = \left(0.240\frac{\mathrm{Btu}}{\mathrm{lb\ air\ °F}}\right)(122°\mathrm{F} - 32°\mathrm{F}) + \left(0.0435\frac{\mathrm{lb\ H_2O}}{\mathrm{lb\ air}}\right)\left[\left(0.446\frac{\mathrm{Btu}}{\mathrm{lb\ H_2O\ °F}}\right)(122°\mathrm{F} - 32°\mathrm{F}) + 1{,}075.1\frac{\mathrm{Btu}}{\mathrm{lb\ H_2O}}\right]$$

$$= 21.6 + 1.7 + 46.8 = 70\ \frac{\mathrm{Btu}}{\mathrm{lb\ moist\ air}}$$

Notes:
The second term for 50% RH is half the value for 100% RH

48.5 Btu/lb = 0.5(97 Btu/lb)

The sensible heat of the water vapor (3.5 Btu/lb and 1.7 Btu/lb) is small, 2.5 to 3%, of the total enthalpy.

4.10 SPECIFIC HEAT OF A NITROGEN-OXYGEN MIXTURE

A gaseous mixture is 50% nitrogen and 50% oxygen, by volume. Calculate the specific heat of the mixture (a) in Btu/lb°F and (b) kJ/kg°C. The specific heats are:

Nitrogen = 0.25 Btu/lb°F (1.04 kJ/kg°C)
Oxygen = 0.22 Btu/lb°F (0.919 kJ/kg°C)

Solution

The specific heat of the mixture is calculated as the weighted mass average of the specific heats of nitrogen and oxygen.

Note: For gas mixtures, mole fraction = volume fraction

Basis = 1 mole of mixed gas
Table S4.10 is valid for U.S units (lb and lb mole) and SI units (kg and kg mol).

	Nitrogen	Oxygen	Total
Volume fractions	0.50	0.50	1.00
Mole of gas	0.5	0.5	1.00
Molar mass (lb/mol or kg/mol)	28	32	
Mass (lb or kg)	14.0	16.0	30.0
Mass Fractions	14/30 = 0.467	16/30 = 0.533	1.00

Table S4.10

a) Specific heat of mixture = (0.467)(0.25 Btu/lb°F) + (0.533)(0.22 Btu/lb°F)
= 0.234 Btu/lb°F

b) Specific heat of mixture = (0.467)(1.04 kJ/kg°C) + (0.533)(0.919 kJ/kg°C)
= 0.976 kJ/kg°C

4.11 HEAT RECOVERY

Steam that has been used in a process or a boiler is condensed with cooling water and the condensate is used to heat air, as shown in Figure P4.11. The cooling water entering the condenser is 10°C and leaves at 30°C. The 800 kg/h steam entering the condenser is at 120°C. The condensate enters the air heater at 100°C and leaves at 50°C. Air enters at 10°C and exits at 45°C. Calculate the amount of cooling water, *X*, that is needed and the amount of air, *Y*, that can be heated. Ignore heat loss from the walls of the condenser, air heater, or piping.

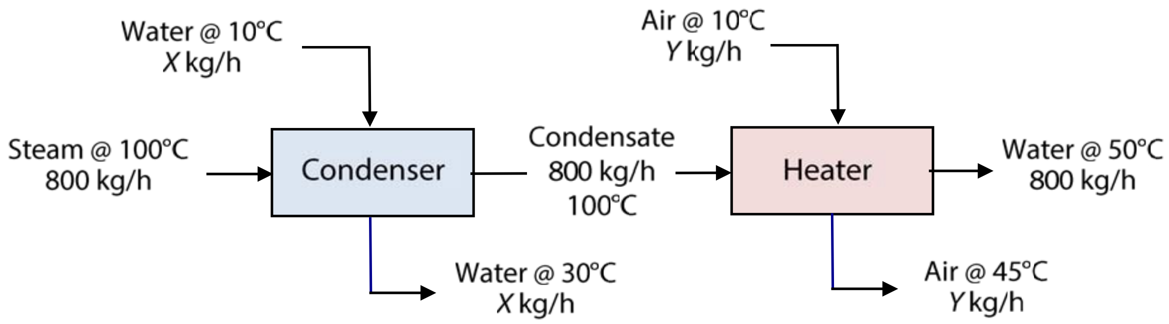


Figure P4.11 Condenser and air heater

Solution

There are two unknowns so two energy balance equations are needed. The possibilities are:

a. Energy balances on the condenser and on the heater
b. Overall energy balance plus an energy balance on the condenser
c. Overall energy balance plus an energy balance on the heater.

Basis: 1 hour
We use option (a) Energy balances on the condenser and on the heater

The relevant thermodynamic data

Water at 10°C	H = 42.02 kJ/kg
Water at 30°C	H = 125.75 kJ/kg
Water at 50°C	H = 209.34 kJ/kg
Condensate water at 100°C	H = 419.10 kJ/kg
Saturated steam at 120°C	H = 2675.6 kJ/kg

Heat capacity of air = c_p = 1.006 kJ/kg°C
Density of dry air at 45°C and 1 atm = 1.118 kg/m^3

Energy balance on the condenser will give the mass flow rate of cooling water, X (kg/h)
ΔH for condenser cooling water (10°C to 30°C) = ΔH for steam (120°C to 100°C)
Condenser cooling water = $m\Delta H$ = X (125.75 kJ/kg – 42.02 kJ/kg)
= X (83.73 kJ/kg)
Steam = $m\Delta H$ = (800 kg/h)(2675.9 kJ/kg – 419.10 kJ/kg) = 1,805,000 kJ/h
Energy balance:
X (83.73 kJ/kg) = 1,805,000 kJ/h
X = (1,805,000 kJ/h)/(83.73 kJ/kg) = 21,560 kg water/h

Energy balance on the heater will give the airflow rate, Y (kg/h)
Enthalpy absorbed by air (10°C to 45°C)
= enthalpy given up from condensate (100°C to 50°C)
Air = $mc_p\Delta T$ = Y (1.006 kJ/kg°C)(45°C – 10°C) = Y (35.21kJ/kg)
Condensate = $m\Delta H$ = (800 kg/h)(419.10 kJ/kg – 209.34 kJ/kg) = 167,800 kJ/h
Energy Balance:
Y (35.21kJ/kg) = 167,800 kJ/h
Y = (167,800 kJ/h)/(35.21 kJ/kg) = 4,766 kg air/h

Volume of air heated = (4,677 kg/h)/(1.118 kg/m^3) = 4,264 m^3 air/h

4.12 CONDENSING ETHANOL

A flow of 1500 kg/h of ethyl alcohol (ethanol) vapor at 90°C is to be condensed and cooled to 20°C. The boiling point of ethanol is 78.3°C so the vapor needs cooling before condensation will occur. The latent heat of vaporization is 855.5 kJ/kg; this is the amount of heat that must be removed to accomplish the phase change from vapor to liquid. The specific heat of liquid ethanol is c_p = 2.85 kJ/kg°C. The specific heat of ethanol vapor is 1.68 kJ/kg°C. Cooling water is available at 10°C and can be heated to no more than 35°C. The specific heat of water is c_p = 4.187 kJ/kg°C. How much cooling water, in kg/h, is needed.

Solution

Cool ethanol vapor from 100°C to 78.3°C

$$Q = mc_p\Delta T = (1500\ \text{kg/h})(1.68\ \text{kJ/kg°C})(100°\text{C} - 78.3°\text{C}) = 54{,}684\ \text{kJ/h}$$

Condense the ethanol vapor to liquid ethanol

$$Q = mH_v = (1{,}500\ \text{kg/h})(855.5\ \text{kJ/kg}) = 1{,}283{,}250\ \text{kJ/h}$$

Cool liquid ethanol from 78.3°C to 20°C

$$Q = mc_p\Delta T = (1500\ \text{kg/h})(2.85\ \text{kJ/kg°C})(78.3°\text{C} - 20°\text{C}) = 249{,}232\ \text{kJ/h}$$

Total energy removed from ethanol

$$= 56{,}684\ \text{kJ/h} + 1{,}283{,}250\ \text{kJ/h} + 249{,}232\ \text{kJ/h} = 1{,}587{,}166\ \text{kJ/h}$$

Energy balance on water, assuming the water is heated from 10°C to 35°C.

Energy absorbed by cooling water = energy removed from ethanol
Let X = mass of cooling water needed.
$Q = Xc_p\Delta T = X$ (4.187kJ/kg°C)(35°C - 10°C) = 1,587,166 kJ/h
X = (1,587,166 kJ /h)/(35°C – 10°C)(4.187 kJ/kg°C) = 15,163 kg/h

4.13 CHEESE MAKING – AMMONIA CONDENSATION

A cheese factory needs to condense and cool 6.22 T/h gaseous ammonia. This requires cooling the gaseous ammonia from 114°C to the condensation temperature of 28°C, condensing it at 28°C, and then additional cooling to a final temperature of 20°C. Cooling is available at the rate of 24 T/h at 18°C. The cooling water is used in another process so the maximum water temperature allowed is 35°C. Table P4.13 summarizes the data.

Stream	Type	Source (°C)	Target (°C)	m (T/h)	c_p (kJ/kg°C)
Cooling the gaseous ammonia	Hot	114	28	6.22	3.25
Condensing the gaseous ammonia	Hot	28	28	6.22	
Cooling the liquid ammonia	Hot	28	20	6.22	4.75
Cooling water	Cold	18	35	24.0	4.19

Table P4.13

Solution

Normally c_p is given as kJ/kg°C; i.e. 3.25 kJ/kg°C.
Here is it more convenient, because the mass flow is given in T/h, to use 3.25 MJ/T°C

Expand the table to include the enthalpy change for each stream.
Negative (–) indicates heat is removed; positive (+) indicates heat will be added.
Change in enthalpy (MJ/h) = $\Delta H = mc_p\,\Delta T$ with units of (T/h)(MJ/T°C)(°C)

Stream	Source (°C)	Target (°C)	*m* (T/h)	c_P (MJ/T°C)	mc_P (MJ/°C)	Δ*H* (MJ/h)
Cooling gaseous ammonia	114	28	6.22	3.25	20.215	-1,738.5
Condensing gaseous ammonia	28	28	6.22			-1980.0
Cooling liquid ammonia	28	20	6.22	4.75	29.545	-236.4
Cooling water	18	35	24.0	4.19	100.56	+1,709.5

Table S4.13

Total demand for cooling is 1,738.5 MJ/h + 1,980 MJ/h + 236.4 MJ/h = 3,954.9 MJ/h.
Cooling potential of the makeup water = 1,709.5 MJ/h

Additional cooling needed = 3,954.9 MJ/h - 1,709.5 MJ/h = 2,245 MJ/d

4.14 COMBUSTION AIR PRE-HEATER I

A furnace operates at 1600°F, using ambient temperature combustion air, for 8,000 hours per year and produces flue gas with an average of 10 million British thermal units (MMBtu) per hour. Flue gas leaves the convection section of the heater at around 750°F (400°C), after heat recovery by the economizer. Ambient air feed to the boiler is heated to 570-660°F (300-350°C). This results in a flue gas temperature drop of 445-480°F (230-250°C), thus resulting in 10% increase in efficiency. The flue gas temperature can further be brought down to around 320°F (160°C) or less in a second-stage, which results in a further efficiency improvement of 2% or more.

Boilers are equipped with economizers and pre-heaters, shown in Figure P4.14, to recover heat from flue gas. An economizer heats boiler feedwater. A preheater heats inlet air for the boiler combustion chamber. Preheater thermal efficiencies of 90-92% are expected with modern equipment, and in some cases as high 94% has been achieved.

The fuel cost (natural gas) is $6 per million Btu. How much could be saved by using air that has been preheated to 800°F? Use the data in Table P4.14.

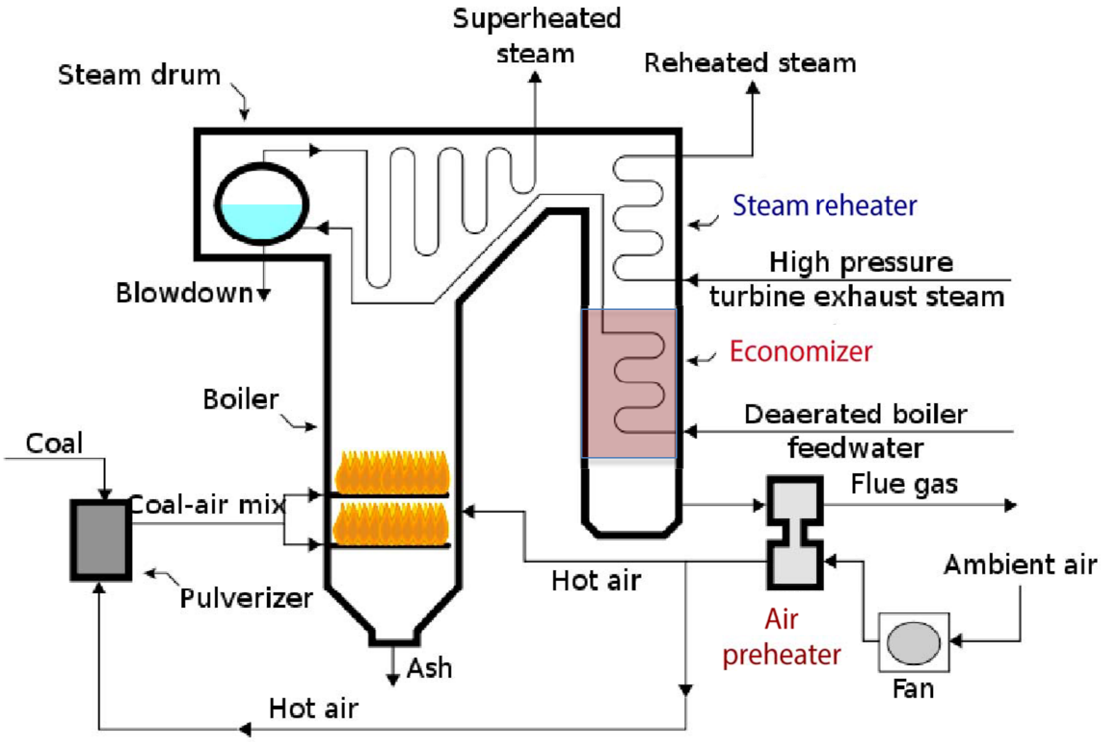


Figure P4.14 Furnace with an air preheater (Source: Wikipedia)

Furnace Exhaust Temperature		Preheated Air Temperature					
(°F)	(°C)	600°F (316°C)	800°F (427°C)	1,000°F (538°C)	1,200°F (649°C)	1,400°F (760°C)	1,600°F (871°C)
1,000	538	13	18	—	—	—	—
1,200	649	14	19	23	—	—	—
1,400	760	15	20	24	28	—	—
1,600	871	17	22	26	30	34	—
1,800	982	18	24	28	33	37	40
2,000	1093	20	26	31	35	39	43
2,200	1204	23	29	34	39	43	47
2,400	1316	26	32	38	43	47	51

Table P4.14 Estimated percent fuel savings gained from using preheated combustion air. (Source: U.S. Dept of Energy, 2007. 'Preheated Combustion Air", Energy Tips-Process Heating; *Combustion Technology Manual*, Industrial Heating Equipment Association (IHEA), Arlington, VA)

Solution

From Table P4.14 find that using preheated air at 800° F in a furnace that operates at 1800°F will result in 24% fuel savings.

Cost per hour = (10 million Btu/h)($6/million Btu) = $60/h
Annual fuel cost = ($60/h)(8,000 h/y) = $480,000
Fuel savings = 0.24($480,000) = $115,200 per year

4.15 COMBUSTION AIR PREHEATER II

Flue gas is cooled from 450°C to 140°C to heat boiler feed air from 30°C to 380°C. Figure P4.15 shows the arrangement. What is the mass ratio of air to flue gas?

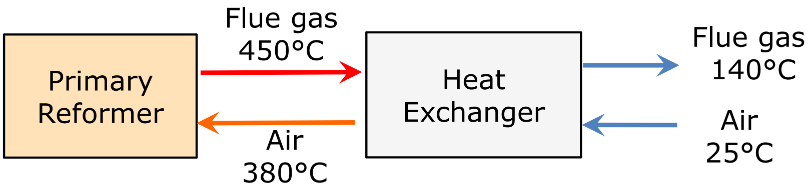


Figure P4.15 A heat exchanger for preheating air

	Flue Gas		**Dry Air**	
T **(°C)**	**Density** ρ **(kg/m3)**	**Specific heat** c_P **(kJ/kg K)**	**Density** ρ **(kg/m3)**	**Specific heat** c_P **(kJ/kg K)**
0	1.295	1.042	1.2930	1.005
100	0.95	1.068	0.9461	1.009
200	0.748	1.097	0.7461	1.026
300	0.617	1.122	0.6159	1.047
400	0.525	1.151	0.5243	1.068
500	0.457	1.185	0.4565	
600	0.405	1.214		
700	0.363	1.239		
800	0.33	1.264		

Table P4.15 Properties of flue gas and dry air

Solution

Basis: 1000 kg flue gas

For an approximate solution, assume that the density of the flue gas = density of the air and that air and flue gas have the same specific heat

An energy balance requires heat transferred to air = heat supplied by fuel gas.

Let subscript *a* = air and subscript *f* = flue gas

Heat transferred to air: $Q_a = m_a c_{P,a} \Delta T_a$

Heat supplied by flue gas: $Q_f = m_f c_{P,f} \Delta T_f$

For $c_{P,a} = c_{P,f}$, the mass ratio of flue gas to air is

$$m_a/m_f = \Delta T_f/\Delta T_a = (450°C - 140°C)/(380°C - 25°C) = 0.873$$

Mass ratio is determined by the temperature differences.

For the specified temperatures, 1000 kg/h of flue gas will heat about 873 kg/h of air.

For a more exact solution, use data from the table

For the flue gas (Note: reference temperature for enthalpy is 0°C)

Specific heat of flue gas at 450°C (interpolate) = 1.160 kJ/kg°C

Enthalpy of flue gas at 450°C $= m_f c_{P,f} \Delta T_f = (m_f)$(1.160 kJ/kg°C)(450°C)

= (522 m_f) kJ/kg

Specific heat of flue gas at 140°C (interpolate) = 1.108 kJ/kg°C

Enthalpy of flue gas at 140°C = (m_f)(1.108 kJ/kg°C)(140°C) = (155.1 m_f) kJ/kg

Heat transferred to air = ΔH_f = (522 m_f) kJ/kg – (155.1 m_f) kJ/kg

= (366.9 m_f) kJ/kg

For the dry air

Specific heat of dry air at 380°C (interpolate) = 1.064 kJ/kg°C

Enthalpy of dry air at 380°C $= m_a c_{P,a} \Delta T_a = (m_a)$(1.064 kJ/kg°C)(380°C)

= (404.3 m_a) kJ/kg

Specific heat of dry air at 25°C = 1.006 kJ/kg°C

Enthalpy of dry air at 25°C = (m_a)(1.006 kJ/kg°C)(25°C) = (25.2 m_a) kJ/kg

Heat absorbed by air = ΔH_a = (404.3 m_a) kJ/kg– (25.2 m_a) kJ/kg

= (379.1 m_a) kJ/kg

Energy balance

$$\Delta H_f = (366.9\ m_f)\ \text{kJ/kg} = \Delta H_a = (379.1\ m_a)\ \text{kJ/kg}$$

Mass ratio

$$m_a/m_f = 366.9/379.1 = 0.968$$

For the specified temperatures, 1000 kg/h of flue gas will heat 968 kg/h of air.

The difference between the approximate and more exact solutions is about 10%.

4.16 COTTON TEXTILES

Soft water is heated from 29°C to 78°C to supply the finishing (rinsing and dying) department of a textile factory, as shown in Figure P4.16. This is done using 105°C steam. Wastewater at 75°C, from the finishing department is being discharged to waste treatment. The mass of 75°C wastewater and 29°C soft water supply are in a proportion that substantial heat transfer is possible. The soft water can be heated from 29°C to 66°C while the wastewater is cooled from 75°C to 38°C. This cooling benefits the wastewater treatment process, while reducing the cost of soft water heating. Steam is still needed for heating from 68°C to 78°C.

a) The heat recovery system saved 7.73 GWh/y of heat energy. How much soft water was heated?

b) How much wastewater from the finishing department was being cooled?

c) Calculate the percent steam energy savings by heating the soft water with wastewater from the finishing department.

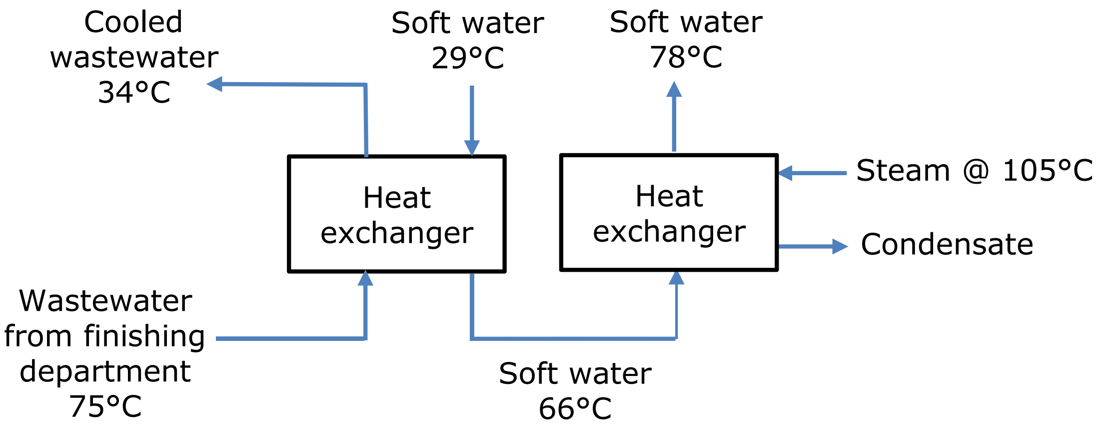


Figure P4.16 Heating soft water with wastewater from a textile finishing department

Solution

Define: Mass flow of soft water heated = m_{SW}
Mass flow of finishing water cooled = m_{FW}
Specific heat of water = 4.187 kJ/kg°C

Energy savings = 7.73 GWh/y
Note: 3,600 kJ/kWh = 3,600 GW/GWh
(3,600 GJ/GWh)(7.73 GWh/y) = 27,828 GJ/y = 27,828,000,000 kJ/y

a) Mass flow of soft water, m_{SW}

Energy savings = Heat absorbed from finishing wastewater

$= m_{SW}(4.187\text{ kJ/kg°C})(66°\text{C} - 29°\text{C}) = m_{SW}(4.187\text{ kJ/kg°C})(37°\text{C})$

$27{,}828{,}000{,}000\text{ kJ/y} = m_{SW}(4.187\text{ kJ/kg°C})(37°\text{C})$

$m_{SW} = 179{,}600{,}000\text{ kg/y} = 492{,}000\text{ kg/d}$

b) Mass flow of finishing wastewater, m_{FW}.

Energy savings = Heat transferred from finishing wastewater

$= m_{FW}(4.187\text{ kJ/kg°C})(75°\text{C} - 34°\text{C}) = m_{FW}(4.187\text{ kJ/kg°C})(41°\text{C})$

$27{,}828{,}000{,}000\text{ kJ/y} = m_{FW}(4.187\text{ kJ/kg°C})(41°\text{C})$

$m_{FW} = 162{,}100{,}000\text{ kg/y} = 444{,}000\text{ kg/d}$

Mass ratio of finishing wastewater to soft water is equal to the ratio of the temperature differences

Energy added to soft water: $Q_{SW} = m_{SW}\, c_P \Delta T_{SW}$

Energy removed from finishing wastewater: $Q_{FW} = m_{FW}\, c_P \Delta T_{FW}$

Energy balance: $Q_{SW} = m_{SW}\, c_P \Delta T_{SW} = Q_{FW} = m_{FW}\, c_P \Delta T_{FW}$

$m_{FW}/m_{SW} = \Delta T_{SW}/\Delta T_{FW}$

$m_{FW}/m_{SW} = (66°\text{C} - 29°\text{C})/(75°\text{C} - 34°\text{C}) = 37°\text{C}/41°\text{C} = 0.90$

Heating 1 kg of soft water to 66°C requires 0.90 kg finishing department wastewater.

b) Percent steam saved.

$$\%\text{ Steam savings} = 100\,\frac{\text{energy savings with heat recovery}}{\text{energy required without heat recovery}}$$

Energy required without heat recovery from finishing wastewater

$m_{SW}(4.187\text{ kJ/kg°C})(78°\text{C} - 29°\text{C}) = m_{SW}(4.187\text{ kJ/kg°C})(49°\text{C})$

Energy savings with heat recovery from finishing wastewater

$m_{SW}(4.184\text{ kJ/kg°C})(66°\text{C} - 29°\text{C}) = m_{SW}(4.187\text{ kJ/kg°C})(37°\text{C})$

or, using the finishing wastewater stream

$$m_{FW}(4.184\ \text{kJ/kg°C})(75\text{°C} - 34\text{°C}) = m_{FW}(4.187\ \text{kJ/kg°C})(41\text{°C})$$

$$\%\ \text{Steam savings} = 100\left(\frac{m_{SW}}{m_{SW}}\right)\frac{(4.187\ \text{kJ/kg°C})(66\text{°C} - 29\text{°C})}{(4.187\ \text{kJ/kg°C})(78\text{°C} - 29\text{°C})}$$

$$= 100\left(\frac{37\text{°C}}{49\text{°C}}\right) = 75.5\%$$

or, using the finishing wastewater stream

$$\%\ \text{Steam savings} = 100\left(\frac{m_{FW}}{m_{SW}}\right)\frac{(4.187\ \text{kJ/kg°C})(75\text{°C} - 34\text{°C})}{(4.187\ \text{kJ/kg°C})(78\text{°C} - 29\text{°C})}$$

$$= 100\ (0.9)\left(\frac{41\text{°C}}{49\text{°C}}\right) = 75.5\%$$

Energy consumption for the production of one unit (m^2) of cotton fabric in this company decreased from 18.55 MJ/m^2 to 16.18 MJ/m^2 (EU target level =14.1MJ/ m^2)

Economic effect

Investment = 312,000 EUR.
Savings due to reduction of environmental cost = 180,200 EUR/y
Pay-back period = 1.7 years

4.17 HEAT EXCHANGE FOR WASTEWATER SLUDGE

Digested sludge leaves a thermophilic anaerobic digester at a temperature of 60°C. Some heat energy can be extracted from this to warm boiler feed water. (Alternately, it could be used to warm the feed sludge to the digester.) In the heat exchanger, inlet and outlet temperatures of water are 18°C and 35°C. The digested sludge flow is 20 m^3/h. The sludge enters the heat exchanger at 60°C and leaves at 45°C. Assume equal densities for the sludge and the water. The heat capacities are: $c_p = 4.1$ kJ/kg°C for sludge and $c_p = 4.187$ kJ/kg°C for water. The sludge contains solids that have a heat capacity less than water so the heat capacity of the mixture is less than water. (a) Show the given information on a diagram. (b) What mass of water can be heated?

Solution

a) Block diagram of heat exchange process.

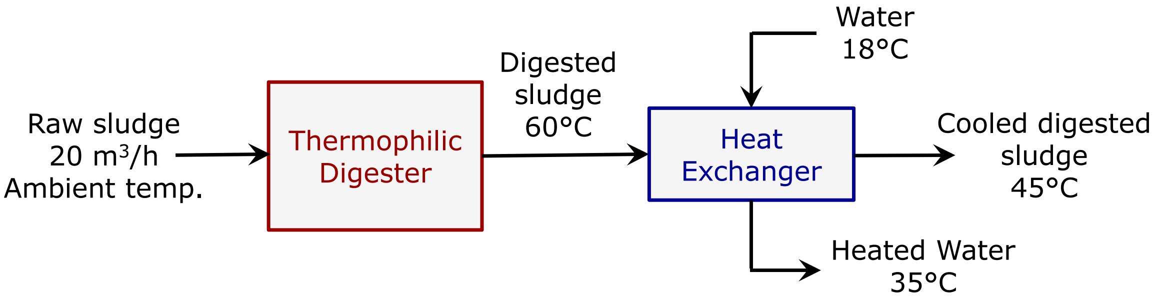


Figure S4.17

b) Mass of water heated

Basis: One hour of operation

Let m_s = mass flow rate of digested sludge = 20 m^3/h = 20,000 kg/h

m_w = mass flow rate of water

Energy balance on heat exchanger

Heat transferred to water = Heat transferred from sludge

Heat transferred to water

$= Q_w = m_w c_{P,W} \Delta T_w = m_w(4.187\ \text{kJ/kg°C})(35°\text{C} - 18°\text{C})$

$= m_w(71.2\ \text{kJ/kg})$

Heat transferred from sludge

$= Q_s = m_s c_{P,S} \Delta T_s = (20{,}000\ \text{kg/h})(4.1\ \text{kJ/kg°C})(60°\text{C} - 45°\text{C})$

$= 1{,}230{,}000\ \text{kJ/h}$

$m_w = (1{,}230{,}000\ \text{kJ/h})/(71.2\ \text{kJ/kg}) = 17{,}300\ \text{kg/h}$

4.18 AIR-TO-FLUE GAS HEAT EXCHANGER

Flue gas (after cooling) will be used to heat air in a counterflow single-pass heat exchanger. The heat exchanger transfers 1,350,000 kJ/h. The flue gas side has an inlet temperature of 300°C and an outlet temperature of 150°C. The flue gas flow is 9,000 kg/h. The airflow is 8,200 kg/h, and inlet temperature of 20°C and an outlet temperature of 180°F. . (a) Show the given information on a diagram. (b) Do these temperatures work to satisfy the energy balance on the heat exchanger? (c) Optional: To what temperature could the air be heated?

Useful data

Specific heat of flue gas at 150°C = $c_{P\text{-gas}}$ = 1.082 kJ/kg°C
Specific heat of flue gas at 300°C = $c_{P\text{-gas}}$ = 1.122 kJ/kg°C
Specific heat of air at 20°C = $c_{P\text{-air}}$ = 1.006 kJ/kg°C
Specific heat of air at 180°C = $c_{P\text{-air}}$ = 1.023 kJ/kg°C

Solution

a) Block diagram of heat exchange process.

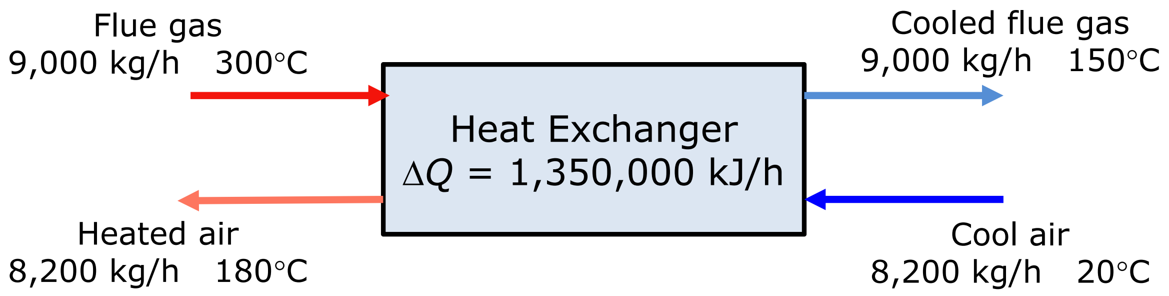


Figure S4.18

b) Do these temperatures satisfy the energy balance?

Energy Balance
Decrease in enthalpy of flue gas = Increase of enthalpy of air
Calculate enthalpies using $H = mc_p\Delta T$ and a reference temperature of 0°C
Decrease in flue gas enthalpy
= (9,000 kg/h) (1.122 kJ/kg°C)(300°C) – (9,000 kg)(1.082 kJ/kg°C)(150°C)
= 1,569,000 kJ/h
Increase in air enthalpy
= (8,200 kg/h)(1.023 kJ/kg°C)(180°C) - (8,200 kg/h)(1.006 kJ/kg°C)(20°C)
= 1,345,000 kJ/h

The flue gas carries more energy than is need to heat 8,200 kg/h of air.

c) Optional: To what temperature could the air be heated?

Available heat energy = 1,569,000 kJ/h

$$1{,}569{,}000\ \text{kJ/h} = (8{,}200\ \text{kg/h})(1.023\ \text{kJ/kg°C})\ T_{air} - (8{,}200\ \text{kg/h})(1.006\ \text{kJ/kg°C})(20°\text{C})$$

$$1{,}569{,}000\ \text{kJ/h} = (8{,}389\ \text{kJ/h°C})\ T_{air} - 165{,}000\ \text{kJ/h}$$

$$T_{air} = (1{,}734{,}000\ \text{kJ/h})/(8{,}389\ \text{kJ/h°C}) = 207°\text{C}$$

This calculation used an exit air specific heat for 180°C. Refine the calculation by using a value closer to the estimated air temperature of 207°C (or a bit lower, say 200°C).

Specific heat of air at 200°C = $c_{P\text{-}air}$ = 1.026 kJ/kg°C

$$1{,}569{,}000\ \text{kJ/h} = (8{,}200\ \text{kg/h})(1.026\ \text{kJ/kg°C})\ T_{air} - (8{,}200\ \text{kg/h})(1.006\ \text{kJ/kg°C})(20°\text{C})$$

$$1{,}569{,}000\ \text{kJ/h} = (8{,}413\ \text{kJ/h°C})\ T_{air} - 165{,}000\ \text{kJ/h}$$

$$T_{air} = (1{,}734{,}000\ \text{kJ/h})/(8{,}413\ \text{kJ/h°C}) = 206°\text{C}$$

The refinement didn't have much effect on the temperature estimate because the specific heat of air changes very little over a 180°C – 210°C temperature range.

4.19 INTERNET TECHNICAL CHAT ON SLUDGE HEATING

The discussion below comes from an Internet technical chat room. (a) Is the *question* a good question? *Good* means, can it be answered with the information given? (b) Is there a helpful answer? (c) Can you calculate the BTU's using any of the answers to the question?

> *Question - Need to calculate BTU's necessary raise temp 25 degrees? I am drawing a blank. I need to raise the temp of sludge from ambient to 132°F, through a heat exchanger. How do I calculate my BTU's necessary to do this? The sludge is WWTP sludge, needs to be heated to between 130–134°F for the natural bacteria to activate and start the TPAD process. (Note: TPAD is a two-stage anaerobic digester process.)*

There were four responses:

1) Why do you want to put sludge through a heat exchanger? Unless the viscosity is low, it will probably thicken inside the tubes and plug the unit.
2) In a heat exchanger, you typically deal with flows, so the Q and m terms are Qdot and mdot (heat rate and mass flow rate).
   Qdot = mdot • C_p • ΔT UNITS [Btu = lb_m * Btu/lb_m-°F]
3) There are types of exchangers that can handle sludge, depending upon its composition and viscosity. I personally have no experience with them, however. I have designed heat exchangers in the refrigeration and chemical/petrochemical industries for 8 years.
4) You need to know the heat capacity of the sludge.

Solution

a) This is not a good question. Needs to raise temp by 25 degrees. And raise it to 132°F. OR to between 130-134°F. Unless ambient is 107°F this is conflicting information.
b) Are the answers helpful?
   Answer 1 is nonsense.
   Answer 4 makes a correct statement, but it is useless.
   Answer 3 makes a correct statement – there are such heat exchangers – but it is useless.
   Answer 2 gives some useful information, but not enough. Doesn't define c_p or ΔT, and one should not expect the question writer will know these things.
c) It is not possible to calculate anything with the given information. Our students should be able to give a precise and helpful answer.

4.20 HEAT RECOVERY FROM CENTRIFUGED SLUDGE

Wastewater treatment plant sludge at 15°C and 10,000 kg/d passes through to a heat exchanger prior being fed to an anaerobic digester, as shown in Figure P4.20. The digested sludge temperature is 35°C. Assume that the centrate temperature is 35°C. Assume that 85% heat transfer is possible from the centrate to the digester feed sludge (This means that 15% is lost as waste heat). (a) Make the material balance on solids. (b) Calculate the temperature of the feed sludge to the digester if no additional heat is added. (c) Summarize the heat balance around the heat exchanger to show that the total enthalpy in = total enthalpy out.

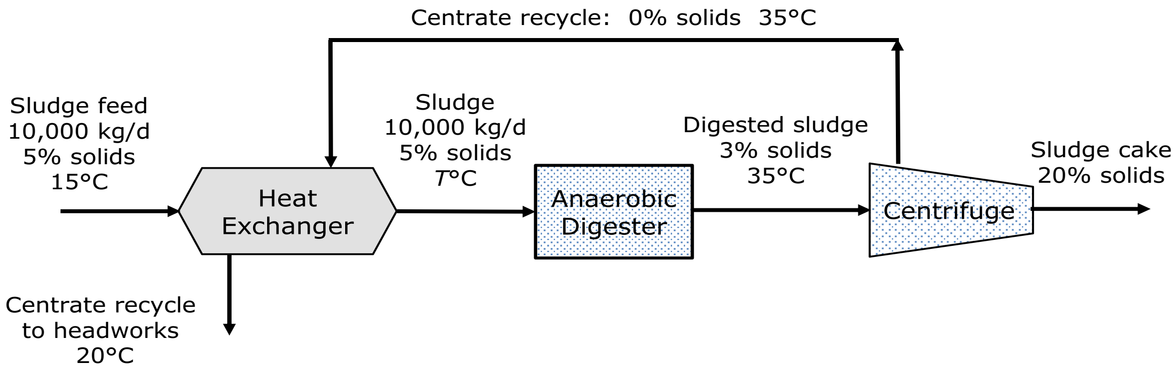


Figure P4.20 Preheating sludge with warm recycle from a centrifuge

Solution

Basis = 10,000 kg wet sludge feed to centrifuge
Assume all solids are captured in the sludge cake
Define T = temperature of the sludge leaving the heat exchange

a) Material balance on solids

Sludge to heat exchanger

Solids = (10,000 kg)(0.05 kg/kg solids) = 5,000 kg solids

Water = 10,000 – 5,000 = 9,500 kg

Sludge out of digester

Water = 9,500 kg

Solids/(9,500 kg + Solids) = 0.03

Solids = (0.03)(9,500 kg)/0.97 = 294 kg

Total sludge mass = 9,500 kg + 294 kg = 9,794 kg

Sludge to centrifuge

294 kg solids – all captured in sludge cake

Cake = 20% solids

Cake solids/(cake solids + cake moisture) = 0.2

(294 kg)/(294 kg + cake moisture) = 0.2

Cake moisture = (0.8)(294 kg)/0.2 = 1,176 kg

Centrate = Feed water – Cake Moisture = 9,500 – 1,176 = 8,325 kg

b) Temperature of feed sludge to digester

Assume the specific heat of the feed sludge, digested sludge, and centrate are the same as water: c_p = 4.187 kJ/kg°C

Energy balance (Values rounded to nearest 1000)

85% transfer of energy from centrate

Enthalpy change of sludge = Enthalpy change of centrate

Enthalpy change of centrate = $m\, c_p \Delta T$

= (0.85)(8,325 kg)(4.187 kJ/kg°C)(35°C – 20°C) = 444,000 kJ

Enthalpy change of sludge

= (10,000 kg)(4.187 kJ/kg°C)(T – 15°C) = (41,870 kJ/°C)(T – 15°C)

T – 15°C = (444,000 kJ)/(41,870 kJ/°C) = 10.6°C

T = 25.6°C

c) Summary of the heat exchanger energy balance

Enthalpy of feed sludge = (10,000 kg)(4.187)(15°C) = 628,000 kJ

Enthalpy of feed centrate = (8,325 kg)(4.187 kJ/kg°C)(35°C) = 1,220,000 kJ

Energy transfer from centrate to feed sludge, at 85%

= (0.85)(8,325 kg)(4.187 kJ/kg°C)(35°C – 20°C) = 444,000 kJ

Enthalpy lost in heat exchanger

= (0.15)(8,325 kg)(4.187 kJ/kg°C)(35°C – 20°C) = 78,000 kJ

Enthalpy of centrate recycled to headworks at 20°C

= (8,325 kg)(4.187 kJ/kg°C)(20°C) = 697,000 kJ

Enthalpy of sludge to digester

= (10,000 kg)(4.187 kJ/kg°C)(25.6°C) = 1,072,000 kJ

Total enthalpy in = 628,000 kJ + 1,220,000 kJ = 1,848,000 kJ

Total enthalpy out = 1,072,000 kJ+ 697,000 kJ + 78,000 kJ = 1,847,000 kJ

4.21 HEAT EXCHANGER DUTY

Before a process change, the product stream was sent to storage at 55°C. Now the temperature of that product stream is 71°C. A new cooler will be added to bring the temperature back down to 55°C for safe operation. The total product stream flow rate is 25,000 kg/h. The heat capacity of the product at 63°C, the midpoint of the cooling duty (average of 55°C and 71°C) is 3.43 kJ/kg°C. The cooling liquid will be water. Cooling tower water is available at 31°C during the warmest summer month. The cooling tower water can undergo a 15°C temperature rise in the exchanger. (a) Show the given information on a diagram. (b) What mass of cooling water is required?

Solution

a) Block diagram of heat exchange process.

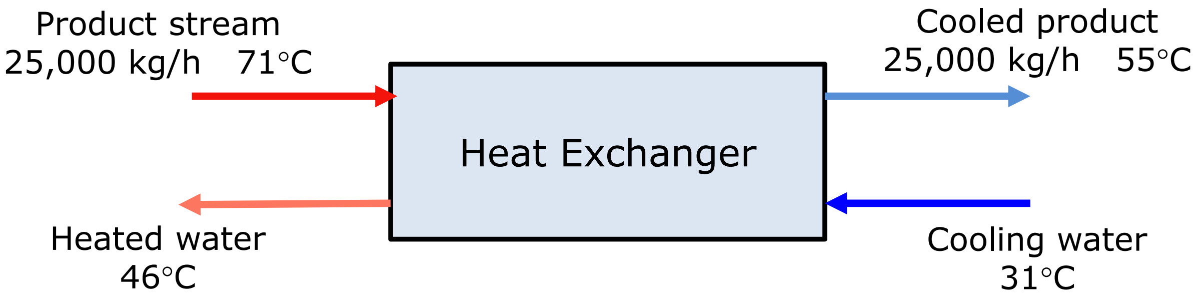


Figure S4.21

b) Mass of cooling water

Basis: 25,000 kg/h product stream

Assume: Heat transferred on the hot and cold sides of the heat exchanger are equal.

The subscripts indicate: *H* = hot fluid (product) and *C* = cold fluid (cooling water)

Heat capacity of the cooling tower water is 4.187 kJ/kg°C.

Heat transfer duty for the hot fluid (the fluid being cooled).

$$Q_H = m_H\, c_{P,H}\, (T_{H,\,\mathrm{In}} - T_{H,\,\mathrm{Out}})$$
$$= (25{,}000\ \mathrm{kg/h})(3.43\ \mathrm{kJ/kg°C})(71°\mathrm{C} - 55°\mathrm{C}) = 1{,}372{,}000\ \mathrm{kJ/h}$$

Heat transfer duty for the cold fluid (cooling water).

Temperature rise of water through the heat exchanger = $\Delta T = 15°\mathrm{C}$

$$Q_C = m_C\, c_{P,C}\, (T_{C,\,\mathrm{In}} - T_{C,\,\mathrm{Out}})$$
$$= m_C\, (4.187\ \mathrm{kJ/kg°C})(15°\mathrm{C}) = m_C\, (62.8\ \mathrm{kJ/kg})$$

Energy balance: $Q_H = Q_C$

$$m_C = (1{,}372{,}000\ \mathrm{kJ/h})/(62.8\ \mathrm{kJ/kg}) = 21{,}800\ \mathrm{kg/h}$$

4.22 PRECOOLING AIR FOR BAGHOUSE FILTER

Hot dirty air at 10,000 scfm (1 atm and 500°F) is blown by a fan into a heat exchanger and then into a baghouse filter to remove dust particles. The dirty air is cooled to 130°F using 65°F water. The water is heated to 90°F. Calculate the amount of water required.

Data:	Air density at 500°F	$\rho_{\mathrm{air}} = 0.0412\ \mathrm{lb/ft^3}$
	Air specific heat (average)	$c_{P,\,\mathrm{air}} = 0.241\ \mathrm{Btu/lb°F}$
	Water specific heat	$c_{P,\,\mathrm{water}} = 1.0\ \mathrm{Btu/lb°F}$
	Air enthalpy at 500°F	$H_{\mathrm{air},\,500°\mathrm{F}} = 231.1\ \mathrm{Btu/lb}$
	Air enthalpy at 130°F	$H_{\mathrm{air},\,130°\mathrm{F}} = 141.1\ \mathrm{Btu/lb}$

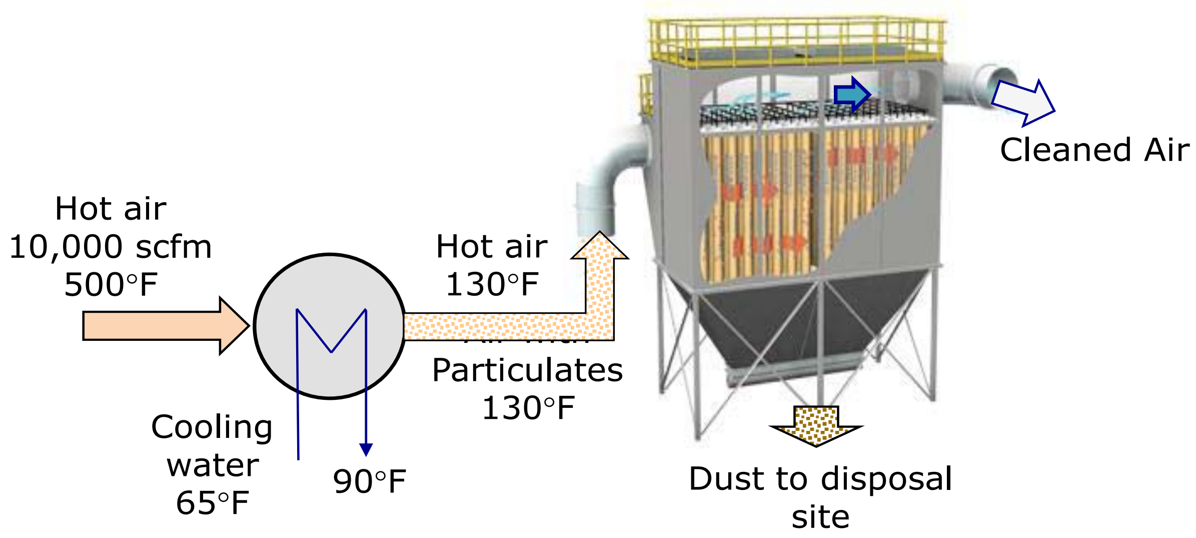


Figure P4.22 Precooling air prior to particulate removal with a baghouse filter

Solution

Basis: 10,000 scfm of hot air

Convert volumetric air flow to mass flow.

Mass flow rate = (volumetric flow rate) (density).

$$m_{\text{air}} = (10{,}000\ \text{ft}^3/\text{min})(0.0412\ \text{lb/ft}^3) = 4{,}120\ \text{lb/min}$$

Energy balance: Heat removed from hot air = heat absorbed by cooling water

$$\text{Heat removed from hot air} = m_{\text{air}}\,(H_{\text{hot air}} - H_{\text{cold air}})$$

$$= (4{,}120\ \text{lb/min})(231.1\text{Btu/lb} - 141.1\text{Btu/lb}) = 370{,}800\ \text{Btu/min}$$

$$\text{Heat absorbed by cooling water} = m_{\text{water}}\,(c_{P\ \text{water}})(T_{\text{hot water}} - T_{\text{cold water}})$$

$$= m_{\text{water}}(1\ \text{Btu/lb°F})(90°\text{F} - 65°\text{F}) = m_{\text{water}}(25\ \text{Btu/lb})$$

Equating heat removed and heat absorbed

$$m_{\text{water}} = (370{,}800\ \text{Btu/min})/(25\ \text{Btu/lb}) = 14{,}800\ \text{lb/min}$$

As a check, the sensible heat energy removed from the hot air – using average specific heat of air is

$$\Delta H = m_{\text{air}}\ c_{P,\text{air}}\ (T_{\text{hot air}} - T_{\text{cold air}})$$

$$= 4{,}120\ \text{lb/min})(0.241\ \text{Btu/lb°F})(500°\text{F} - 130°\text{F}) = 367{,}400\ \text{Btu/min}$$

which is within 1% of the value (370,800 Btu/min) computed from the change in enthalpies.

4.23 GAS STREAM COOLING REQUIREMENTS

A hot gas stream of 20,000 acfm (dry gas and actual cubic feet per minute) will be cooled from 600°F to 140°F to condense some organic vapor contaminants before it goes to an air pollution control device that will remove fine particulates (Figure P4.23). The inlet gas temperature of 600°F and an inlet pressure of 0.975 atm. Cooling and condensation will be done by evaporation of a water spray water that is provided at 60°F water. The cooled gas will be saturated with water vapor. The water leaving the cooler/condenser is contaminated and is identified as wastewater. Calculate the required amount of cooling water. Assume that the properties of air can be used to describe the gas that is flowing through the cooler.

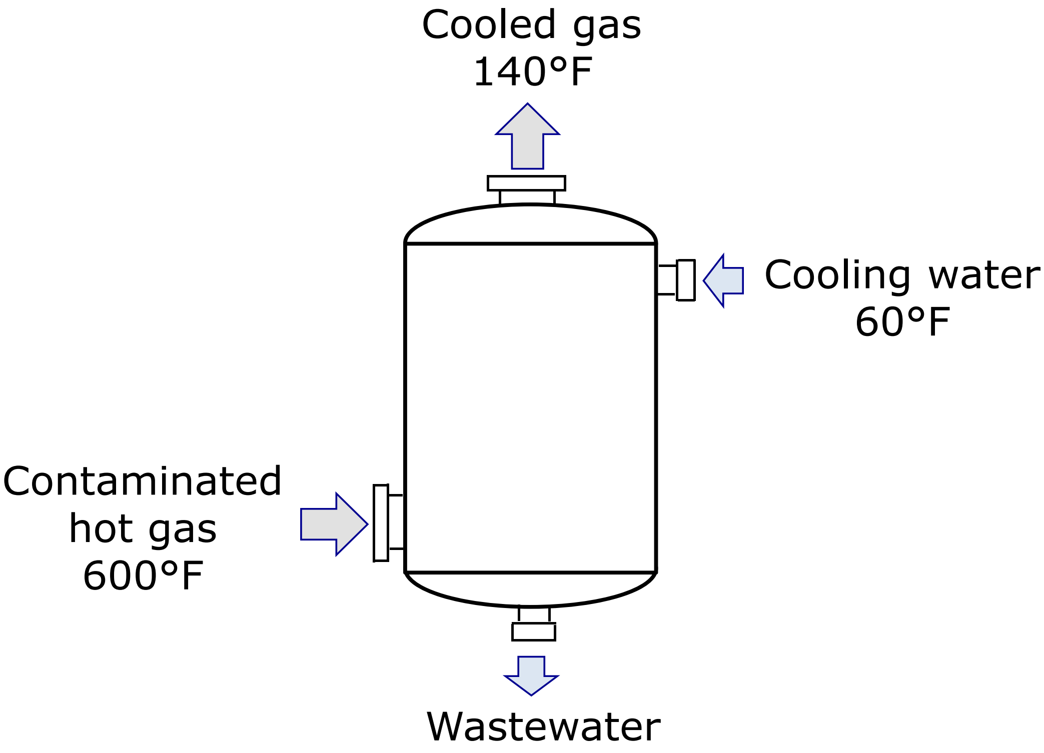


Figure P4.23 Gas treatment by cooling and condensation.

Solution

Basis = Inlet air at 20,000 acfm and 600°F

Energy balance

Convert the gas flow rate from acfm to scfm. From the ideal gas law

$$V_{\mathrm{STP}} = V_{\mathrm{Actual}}\left(\frac{T_{\mathrm{Std}}}{T_{\mathrm{Actual}}}\right)\left(\frac{P_{\mathrm{Actual}}}{P_{\mathrm{Std}}}\right)$$

where STP indicates standard temperature and pressure (T = 68°F and P = 1 atm)

Temperature is in degrees Rankin (°R) where °R = °F + 460

T_{Inlet} = 600°F + 460 = 1060°R

T_{Std} = 68°F + 460 = 528°R

$$V_{\text{STP}} = (20{,}000 \text{ acfm})\left(\frac{528°\text{R}}{1060°\text{R}}\right)\left(\frac{0.975 \text{ atm}}{1 \text{ atm}}\right) = 9{,}713 \text{ cfm}$$

Mass flow rate of inlet gas flow rate (lb/min)

Moleclar mass of air = 29 lb/mol

Molar volume of air at STP = 385 ft^3/mol

$$\text{Inlet mass flow rate} = 9{,}713\frac{\text{ft}^3}{\text{min}}\left(\frac{1 \text{ lb mol}}{385 \text{ ft}^3}\right)\left(\frac{29 \text{ lb}}{\text{lb mol}}\right) = 731 \text{ lb/min}$$

Change in enthalpy (Δ*H*) of the air as it is cooled from 600°F to 140°F.

$$\Delta H_{\text{air}} = m_{\text{air}}\left(H_{\text{air, 600°F}} - H_{\text{air, 140°F}}\right)$$

Enthalpies: $H_{\text{dry air,600°F}}$ = 258 Btu/lb

$H_{\text{dry air, 160°F}}$ = 60.4 Btu/lb

ΔH_{air} = (731 lb/min)(258.2 Btu/lb°F – 60.4 Btu/lb°F) = 144,600 Btu/min

Enthalpy absorbed by the water and water vapor

Assume the water and vapor are in temperature equilibrium with the exiting gas.

Enthalpy transferred to water as it is heated from 60°F to 140°F and evaporated.

Sensible energy as the temperature rises from 60°F to 140°F

$\Delta H = m_{\text{water}}\, c_p\, \Delta T = m_{\text{water}}$ (1 Btu/lb°F)(140°F – 60°F) = m_{water} (80 Btu/lb)

Enthalpy of evaporation at 140°F (Appendix 5): $\Delta H_{\text{V, 140°F}}$ =1013.7 Btu/lb

$\Delta H = m_{\text{water}}$ (1013.7 Btu/lb)

Total change from 60°Fwater to 140°F vapor.

$\Delta H_{\text{water}} = m_{\text{water}}$ (80 Btu/lb +1013.7 Btu/lb) = m_{water} (1093.7 Btu/lb)

Quantity of water required to cool the gas.

Energy balance: $\Delta H_{\text{water}} = \Delta H_{\text{air}}$

m_{water} (1093.7 Btu/lb) = 144,600 Btu/min

m_{water} = 132 lb/min

At 8.34 lb/gal this is (132 lb/min)/(8.34 lb/gal) = 15.8 gal/min

4.24 AIR CONDITIONING

An air conditioner system with 3,000 tons of refrigeration (TR = 3,000) capacity removes 36,000,000 Btu/h. The average seasonal load is 50% and the actual average efficiency is 0.70 kW/ton. The energy cost is $0.15/kWh.

a) Calculate the seasonal energy requirement and the seasonal operating cost.
b) If the seasonal operation is 3,200 h/y, what is the seasonal energy consumption (in kWh) and what is the annual energy cost?
c) If scale builds up in the air conditioner condenser and reduces the efficiency by 8%, how much is the annual operating cost increased?

Solution

a) Average seasonal load = (3,000 ton)(0.7 kW/ton)(0.5 load factor) = 1,050 kW
Operating cost = ($0.15/kWh)(1,050 kW)(1 h) = $157.50/h
b) Annual energy requirement = (1,050 kW)(3,200 h/y)= 3,360,000 kWh/y
Actual annual energy cost = (3,360,000 kWh)($0.15/kWh) = $504,000/y
c) Efficiency decreases by 8%, increasing the kW/ton from 0.7kW/ton to
(0.7 kW/ton)/0.92 = 0.761 kW/ton
Average load = (3000 ton)(0.761 kW/ton)(0.5) = 1,142 kW
New annual energy requirement = (1,142 kW)(3,200 h/y) = 3,654,400 kWh/y
New annual cost = (3,654,400 kWh/y)($0.15/kWh) = $548,160/y
Cost increase = $548,160/y - $504,000/y = $44,160/y
% cost increase = 100($44,160/y)/($504,000/y) = 8.8%

4.25 VENTILATION & HEATING

A factory brings in fresh outside air for ventilation at a rate of 285 Nm^3/min. This air must be heated to the indoor temperature of 20°C. Ventilation air is needed only when the factory is in production, which is 120 h/week during the heating season. Fuel for heating the air costs \$6 per million kilojoule of heat delivered to the air. (a) Calculate the heating cost for a month with an average outside temperature of 4°C. (b) Calculate the annual cost. Assume heating is needed for 6 months at an average temperature T_{Ave} = 8°C during the heating season.

A convenient measure of the amount of air heating needed is degree-days, defined as

Degree-hours per year (°C-h/y)= (h/y of heating needed)(20°C – T_{Ave})

Solution

Basis: 285 Nm^3/min

Nm^3 = means volume in m^3 at 0°C

The volume of air will change as the temperature changes but the mass will not.

Convert the volumetric air flow rate to a mass flow rate.

Assume that outdoor air at cold temperatures will contain negligible moisture; it is dry air.

Density of dry air at 0°C = 1.294 kg/m^3

Specific heat of dry air = $c_{P\text{-air}}$ = 1.006 kJ/kg°C

Mass flow rate of air = m_{air} = (285 Nm^3/min)(1.294 kg/m^3) = 368.8 kg/min

a) Cost for a month with $T_{Outside}$ = 4°C and T_{Inside} = 20°C

Q = heat input required = $m_{air}\ c_{P\text{-air}}\ \Delta T$

= (369 kg/min)(1.006 kJ/kg°C)(20°C – 4°C) = 5,936 kJ/min

Operating time - Use 4 weeks per month

= (120 h/week)(4 week/month) = 480 h/month = 28,800 min/month

Monthly cost = (28,800 min/month)(5,936 kJ/min)(\$6/1,000,000 kJ)

= \$1,026/month

b) Annual cost

Degree-hours per year (°C-h/y) = (h/y of heating needed)(20°C – T_{Ave})

Given: T_{Ave} = 8°C during the heating season.

Hours of heating per year = (120 h/week)(4 week/month)(6 month/y) = 2,880 h/y

Degree-hours (°C-h/y) = (2,880 h/y)(20°C – 8°C) = 34,560 °C-h/y

Annual heating requirement = (m_{air})($c_{P\text{-air}}$)(degree-hours)

Mass flow rate of air (kg/h) = (368.8 kg/min)(60 min/h) = 22,128 kg air/h

Annual heating requirement

= (22,128 kg air/h)(1.006 kJ/kg°C)(34,560 °C-h/y)

= 769,300,000 kJ/y (rounded)

Annual cost = (769.3 x 10^6 kJ/y)($6/$10^6$ kJ) = $4,616/y

4.26 BOILER

A boiler, Figure P4.26, produces 300,000 lb/day of steam, which is (300,000)(1,184.6 Btu/lb) = 355.38 million Btu/day. The boiler operating pressure is 75 psig and the efficiency is 80%. The fuel source is natural gas at $4.50/1000 ft^3 and 1,000 Btu/ft^3. The condensate returning to the boiler is 80% of the steam output and is at 200°F. The blowdown rate is 10% of the condensate return. The operating season is 150 days/y. Water costs $1.50/1000 gal. Boiler blowdown is a loss of water already heated, which means a loss of both water and energy. How much can be saved by reducing blowdown from 10% to 5%?

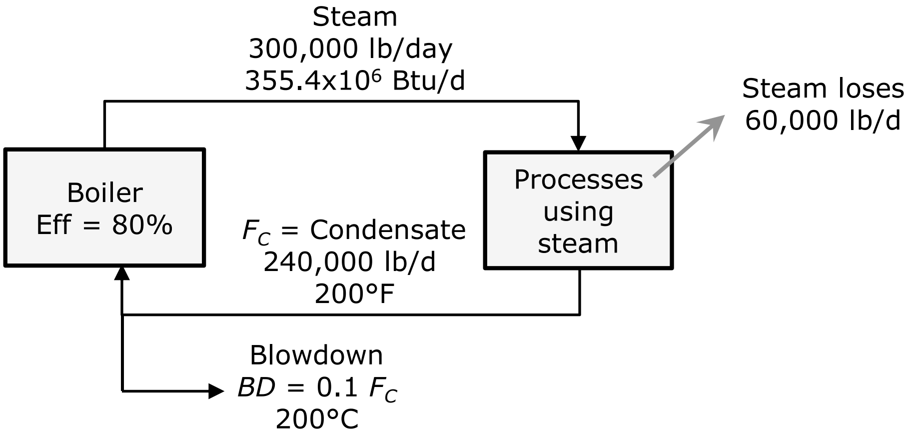


Figure P4.26 Steam from a boiler is used in processing, with a 20% loss.

Solution

Condensate return = 0.8(300,000 lb/d) = 240,000 lb/d

Blowdown mass = 0.1(240,000 lb/d) = 24,000 lb/d

Blowdown energy loss = (24,000 lb/d)(1 Btu/lb°F)(200*F) = 4,800,000 Btu/d

Natural gas used to heat blowdown

= (4,800,000 Btu/d)/(1050 Btu/ft^3 gas) = 4,571 ft^3/day

Natural gas cost for blowdown

= (4,571 ft^3/day)($4.50/1000 ft^3 gas) = $20.57/day

Annual cost for natural gas

= ($20.57/day)(150 day/y) = $3,086

Volume of blowdown = (24,000 lb/d)/(8.34 lb/gal) = 2,878 gal/d
Cost of blowdown water = (2,878 gal/d)($1.50/1000 gal) = $4.32/d = $648/y

Total annual cost for blowdown
Natural gas + Water = $3,086/y + $648/y = $3,734/y
Cutting the blowdown in half from 10% to 5% will halve the cost.
Total annual savings = $0.5($3,734/y) = $1,245/y

NOTE: The reduction in natural gas consumption also means a reduction in CO_2 emissions to the atmosphere.

4.27 COOLING TOWER RANGE AND APPROACH

A cooling tower operates with a warm water input at 35°C, a cool water output of 20°C, and a wet bulb temperature of 17°C. Calculate the *Range* and the *Approach* for the tower.

Solution

Definitions

Range = $T_{\text{Warm}} - T_{\text{Cool}}$

Approach = T_{Cool} - T_{WB}

where T_{Warm} = inlet temperature of water to the tower (°C, °F)

T_{Cool} = outlet temperature of water from the tower (°C, °F)

T_{WB} = wet bulb temperature of entering air (°C, °F)

Range = 35°C – 20°C = 15°C

Approach = 20°C – 17°C = 3°C

The *range* is normally 6°C to 16°C (approx. 10 – 30°F).

4.28 COOLING TOWER EFFICIENCY

The cooling tower efficiency, η_{CT}, is usually 70 - 75%. Will a cooling tower operating at these temperatures have an efficiency within that range.

T_{Warm} = inlet temperature of water to the tower = 38°C

T_{Cool} = outlet temperature of water from the tower = 22°C

T_{WB} = wet bulb temperature of entering air = 16°C

Solution

Calculate the cooling tower efficiency.

$$\eta_{CT} = \frac{100(T_{\text{Warm}} - T_{\text{Cool}})}{T_{\text{Warm}} - T_{\text{WB}}} = \frac{100(38°\text{C} - 22°\text{C})}{38°\text{C} - 16°\text{C}} = 73\%$$

So the tower operates in the 70-75% efficiency range.

Note that the efficiency can also be calculated in terms of Range and Approach.

Range = $T_{\text{Warm}} - T_{\text{Cool}}$ = 38°C – 22°C = 16°C

Approach = T_{Cool} - T_{WB} = 22°C – 16°C = 6°C

$$\eta_{CT} = 100\frac{\text{Range}}{\text{Range + Approach}} = 100\left(\frac{16°\text{C}}{16°\text{C} + 6°\text{C}}\right) = 73\%$$

4.29 COOLING CAPACITY

A cooling tower evaporates 1000 kg of water per day. The temperature difference of the warm water in and the cooled water out is 11°C. Calculate the cooling capacity of the tower and the mass of water circulating through the tower.

Solution

The cooling capacity of a tower is the heat rejected kJ/h or TR (refrigeration tons; 1 TR = 12,000 Btu/h = 12,660 kJ/h), and is determined by

$$\text{Cooling capacity} = m_{CW}\, c_P (T_{\text{Warm}} - T_{\text{Cool}})$$

This must equal

$$\text{Heat lost via evaporation} = m_{\text{evap}}\, H_V$$

where m_{CW} = mass flow rate of cooling water through the tower (kg/h, lb/h)
c_P = specific heat of water (kJ/kg°C, Btu/lb°F)
$T_{\text{Warm}} - T_{\text{Cool}} = \Delta T$ = temperature difference of warm and cool streams, (°C, °F)
m_{evap} = mass of water evaporated (lb/h, kg/h)
H_V = latent heat of vaporization of water = 970 Btu/lb or 2260 kJ/kg

From a simplified heat balance around the cooling tower, the latent heat of evaporation is provided from the water that is circulating through the tower.

$$m_{evap}\, H_v = m_{CW}\, c_p\, \Delta T$$

For m_{evap} = 1000 kg/d H_V = 2,260 kJ/kg
ΔT = 11°C c_P = 4.187 kJ/kg°C

Cooling capacity = $H_V\, m_{\text{evap}}$ = (1,000kg/d)(2,260 kJ/kg) = 2,260,000 kJ/d

Energy balance gives the mass flow rate of circulating water

$$m_{\text{evap}}\, H_V = m_{CW}\, c_P\, \Delta T$$

$$(1000 \text{ kg/h})(2{,}260 \text{ kJ/kg}) = m_{CW}(4.187 \text{ kJ/kg°C})(11°\text{C})$$

$$m_{CW} = 49{,}000 \text{ kg/d}$$

4.30 TON OF REFRIGERATION

A ton of refrigeration (commonly abbreviated as TR) is defined as a unit of power (12,000 Btu/h) that describes the heat extraction capacity of cooling equipment. It is equivalent to the consumption of one ton (2000 lb) of ice per day and originated during the transition from stored natural ice to mechanical refrigeration. More precisely, it is the heat of fusion (H_f= 144 Btu/lb or 333 kJ/kg) absorbed by melting 1 ton (2,000 lb or 907 kg) of pure ice per day at 32°F (0°C). Show that the stated power equivalent (12,000 Btu/h) is correct.

Solution

A ton of cooling is the removal of 12,000 Btu/h (3.517 kW = 12,660 kJ = 12.66 MJ/h) from water.

$$\mathrm{TR} = m_{\mathrm{water}}\, H_f = (2000\ \mathrm{lb/day})(144\ \mathrm{Btu/lb})(\mathrm{d}/24\mathrm{h}) = 12{,}000\ \mathrm{Btu/h}$$

A mechanical chiller adds approximately 3,000 Btu/h (.879 kW or 3.165 MJ/h) of parasitic heat load. Therefore, a ton of cooling in a cooling tower is the removal of 15,000 Btu/h (4.396 kW or 15.83 MJ/h). An absorption chiller generates 18,000 Btu of heat for each ton of chilled water produced. Thus a cooling tower for an absorption chiller must remove 30,000 Btu/h (8.792 kW or 31.65 MJ/h).

4.31 TON OF REFRIGERATION – RULES OF THUMB

Verify these rules of thumb for refrigeration.

a) One ton of cooling by a mechanical chiller means that 15,000 Btu/h of heat must be removed from the water, and for ΔT = 10°F, that requires a 3 gal/min flow of water (1 gal water = 8.34 lb).
b) Removing 15,000 Btu/h using a mechanical chiller requires evaporating 1.85 gal/h of water.

Solution

Rule of thumb (a)

15,000 Btu/h = $m_{CW} c_P \Delta T = m_{CW}$(1 Btu/lb°F)(10°F)
m_{CW} = (15,000 Btu/h)/(10 Btu/lb) = 1500 lb/h
At 8.34 lb/gal this is (1500 lb/h)/(8.34 lb/gal) = 180 gal/h = 3 gal/min

Rule of thumb (b)

Let E = evaporation rate (lb/h)
Evaporation of 1 lb of water takes about 970 Btu of heat.
15,000 Btu/h = (E) (970 Btu/lb)
E = (15,000 Btu/h)/(970 Btu/lb) = 15.5 lb/h
At 8.34 lb/gal this is (15.5 lb/h)/(8.34 lb/gal) = 1.85 gal/h

Note: Operating an absorption chiller requires the removal of twice the amount of heat and twice the amount of water must be evaporated.

4.32 BOILER HORSEPOWER

A boiler generating 30,500 lb/h of steam at 155 lb/in^2 has a factor of evaporation of F_E = 1.02. Calculate the boiler horsepower.

Solution

Boiler horsepower

$$\text{BHP} = \frac{F_E(\text{lb steam/h})}{34.5} = \frac{1.02(30{,}500\ \text{lb steam/h})}{34.5} = 902\ \text{HP}$$

4.33 BOILER FUEL CONSUMPTION

A boiler produces 8,000 lb/h of steam using diesel fuel (F_{HV} = 130,000 Btu/gal) with a feedwater temperature of 140°F. The enthalpy of the steam is 1,190 Btu/lb (at 100 psi). How much fuel is required?

Solution

Boiler fuel consumption is

$$F = \frac{S(H_S - H_{FW})}{\eta_{Boiller} F_{HV}}$$

where F = fuel consumption (gal/h)
S = steam production (lb/h)
H_S = enthalpy of steam at stated temperature and pressure (Btu/lb)
H_{FW} = enthalpy of feedwater at saturation temperature (Btu/lb)
η_{boiler} = boiler efficiency (typically 80%)
F_{HV} = fuel heating value (Btu/gal)

Enthalpy is referenced to 32°F
Enthalpy of feedwater = (1 Btu/lb°F)(140°F – 32°F) = 108 Btu/lb

$$F = \frac{S(H_S - H_{FW})}{\eta_{Boiller} F_{HV}} = \frac{(8{,}000 \text{ lb steam/h})(1{,}190 \text{ Btu/lb - } 108 \text{ Btu/lb})}{0.8(130{,}000 \text{ Btu/gal})} = 83 \text{ gal/h}$$

5 COMBUSTION OF MUNICIPAL REFUSE

5.1 COMBUSTION OF ORGANICS

An organic material consisting of carbon, hydrogen, oxygen, nitrogen and sulfur has an empirical chemical formula $C_aH_bO_cN_dS_e$. Write a balanced reaction for the complete combustion of this material.

Solution

$$C_aH_bO_cN_dS_e + x\,O_2 \rightarrow a\,CO_2 + (b/2)\,H_2O + d\,NO_2 + e\,SO_2$$

Balance the oxygen: $2x + c = 2a + b/2 + 2d + 2e$

$x = a + b/4 - c/2 + d + e$

$$C_aH_bO_cN_dS_e + (a + b/4 - c/2 + d + e)\,O_2 \rightarrow a\,CO_2 + (b/2)\,H_2O + d\,NO_2 + e\,SO_2$$

5.2 INCINERATION OF HYDROCARBONS

How much oxygen and air are needed for combustion of 1 kg of these generic aliphatic and aromatic compounds?

a) Aliphatic Compound: $C_3H_7 + 4.75\ O_2 \rightarrow 3\ CO_2 + 3.5\ H_2O$

b) Aromatic Compound: $CH + 1.25\ O_2 \rightarrow CO_2 + 0.5\ H_2O$

Solution

a) Aliphatic compound

	C_3H_7	+	$4.75\ O_2$	→	$3\ CO_2$	+	$3.5\ H_2O$
Molar mass (kg)	43		32				

Theoretical amount of O_2 needed for complete combustion

$$4.75(32\text{ kg }O_2)/(43\text{ kg }C_3H_7) = 3.535\text{ kg }O_2/\text{kg }C_3H_7$$

Air is 23.2% oxygen by weight, the air requirement is

$(3.535 \text{ kg } O_2/\text{kg } C_3H_7)/(0.232 \text{ kg air/kg } O_2) = 15.24 \text{ kg air/kg } C_3H_7$

Density of air at STP = 1.293 kg/m^3

Volume of air required

$= (15.24 \text{ kg air/kg } C_3H_7)/(1.293 \text{ kg air/m}^3) = 11.79 \text{ m}^3 \text{ air/kg } C_3H_7$

b) Aromatic compound

	CH	+	$1.25\ O_2$	→	CO_2	+	$0.5\ H_2O$
Molar mass (kg)	13		32				

Theoretical amount of O_2 needed for complete combustion

$1.25(32 \text{ kg } O_2)/(13 \text{ kg } CH) = 3.077 \text{ kg } O_2/\text{kg } CH$

Air is 23.2% oxygen by weight, the air requirement is

$(3.077 \text{ kg } O_2/\text{kg } CH)/(0.232 \text{ kg air/kg } O_2) = 13.26 \text{ kg air/kg } CH$

Density of air at STP = 1.293 kg/m^3

Volume of air required

$= (13.26 \text{ kg air/kg } CH)/(1.293 \text{ kg air/m}^3) = 10.26 \text{ m}^3 \text{ air/kg } CH$

5.3 COMBUSTION OF MUNICIPAL REFUSE

A dried municipal refuse has the following empirical chemical composition, $C_{59}H_{93}O_{39}N$. The combustion products are carbon dioxide, water vapor, and NO_2. (a) Write a balanced stoichiometric equation for the combustion reaction. (b) Find the mass of oxygen required to completely combust 1000 kg/h of this material. (c) Calculate the theoretical mass of air that will contain the required mass of oxygen.

Solution

a) Balanced combustion reaction

$$C_{59}H_{93}O_{39}N + a\,O_2 \rightarrow x\,CO_2 + y\,H_2O + z\,NO_2$$

Mass balance on atoms

C $x = 59$
H $2y = 93 \rightarrow \quad y = 46.5$
O $39 + 2a = 2x + y + 2z$
N $z = 1$

Solve for a: $39 + 2a = 2(59) + 46.5 + 2(1)$ $a = 63.75$

Balanced reaction:	$C_{59}H_{93}O_{39}N$	+	$63.75\,O_2$	→	$59\,CO_2$	+	$46.5\,H_2O$	+	NO_2
Reacting Masses (kg)	1439		2040		2596		837		46

b) Stoichiometric oxygen requirement

$= 2040$ kg O_2/1439 kg refuse $= 1.418$ kg O_2/kg refuse

mass O_2 = (1000 kg refuse/h)(1.418 kg O_2/kg refuse) = 1,418 kg O_2/h

c) Mass of air that will supply this amount of oxygen

Air is 23.2% O_2 by weight:
Mass of air = (1,418 kg O_2/h)/(0.232 kg O_2/kg air) = 6,110 kg air/h

Some excess air beyond the stoichiometric requirement will be needed to have complete combustion.

5.4 EMPIRICAL FORMULA FOR A MIXED SOLID WASTE

Large quantities of mixed solid waste are available as a fuel. A representative sample of the waste has this as-delivered (wet) composition: 30 kg food waste, 40 kg paper, 10 kg cardboard, 10 kg plastics, and 10 kg wood. Use the data in Table P5.4 for the elemental composition of the dry solids to determine an empirical stoichiometric formula for the mixed solid waste of the form $C_aH_bO_c$. Ash is nonreactive and it is not included. The waste does include nitrogen and sulfur, but in relatively small amounts, so do not include them in your formula.

Composition of solid waste	Wet mass (kg)	Water %	Dry solids (kg)	Water (kg)	Elemental Composition of Dry Solids (kg)					
					C	H	O	N	S	Ash
Food	30	70	9	21	4.32	0.58	3.38	0.23	0.04	0.45
Paper	40	18	32.8	7.2	14.27	1.97	14.43	0.10	0.07	1.97
Cardboard	10	5	9.5	0.5	4.18	0.56	4.24	0.03	0.02	0.48
Plastics	10	1	9.9	0.1	5.94	0.71	2.26			0.99
Yard wastes	10	65	3.5	6.5	1.67	0.21	1.33	0.12	0.01	0.16
Total	100	35.3	64.7	35.3	30.38	4.03	25.64	0.48	0.13	4.04

Table P5.4 Moisture content and elemental composition of solid waste components of solid waste components

Solution

The sulfur and nitrogen are irrelevant to the combustion of this material and the simplest formulation is sufficient.

The elemental composition of each component is used to calculate the moles of each element. Sample calculations for carbon:

Total mass of C (five components) = 30.38 kg
Moles of C = (30.38 kg)(12 kg/mol) = 2.532 moles

Element	Mass (kg)	Atomic Mass (kg/kg mol)	Moles	Mole Ratios O = 1
C	30.38	12	2.532	1.6
H	4.03	1	4.027	2.5
O	25.64	16	1.603	1
N	0.48	14	0.0343	
S	0.13	32	0.0041	

Table S5.4

The empirical stoichiometric composition is

$C_{1.6}H_{2.5}O$

5.5 REFUSE AS FUEL

A refuse processing plant shreds 980 T/d of raw refuse in a hammermill. Metals are removed at the rate of 74 T/d. The remaining 906 T/d of solid material is mixed with coal according to heating value in proportions of 10% refuse and 90% coal and burned in an electric generating plant boiler. The refuse heating value is 5,000 Btu/lb and the coal heating value is 12,000 Btu/lb. (a) Calculate the amount of coal that must be added to the sorted refuse in order to burn the all of the refuse. (b) Calculate the fuel value of the mixture. (c) Calculate the electricity production if the thermal to electric conversion efficiency is 40%.

Solution

Basis = 1 day of operation = 980 T raw refuse.

a) Amount of coal to be added to the refuse

Refuse after metal is removed

= 980 T raw refuse – 74 T metal = 906 T free of metal

Heat value of refuse = (906 T)(2,000 lb/T)(5,000 Btu/lb) = 9,060 x 10^6 Btu

Heat value of coal = (9 Btu coal/btu refuse)(9,060 x 10^6 Btu) = 81,540 x 10^6 Btu

Mass of coal to be added

= (81,540 x 10^6 Btu)/(12,000 Btu/lb coal) = 6,795 x 10^6 lb = 3.4 x 10^3 T

b) Fuel value of the mixture

= 9,060 x 10^6 Btu + 81,540 x 10^6 Btu = 90,600 x 10^6 Btu

c) Electricity production

At 40% energy conversion, the electricity generated daily (24 h) should be about

(0.4)(90,600 x 10^6 Btu)/(3412 Btu/kWh) = 10.6 x 10^6 kWh

The energy from the refuse, accounts for ten percent of this total. The true energy yield of the refuse is lower because of the energy consumed in the shredding, sorting, and hauling.

5.6 HEATING VALUE OF MUNICIPAL REFUSE

Table P5.6 gives data on the heating value of refuse for 12 cities in Thailand. The proximate analysis looks at simple measures of the bulk material. The ultimate analysis looks at the elemental make up of the material. The proximate analysis is easy to do; the ultimate analysis is not. Make some simple plots of the data (for example heating value as a function of volatile solids) to see if there is a useful relationship.

City	Proximate analysis (mass % ; dry basis)				Ultimate analysis (mass % ; dry basis)							High Heating Value
	Moisture (%)	Volatile Solids	Ash	Fixed Carbon	C	H	N	S	O	C/H	C/O	kJ/kg
1	6.1	53.0	38.4	8.6	31.1	4.2	3.3	1.1	24.3	7.45	1.31	13,900
2	5.1	51.2	42.0	6.7	27.5	4.1	4.0	1.1	23.3	6.72	1.18	13,200
3	5.4	50.0	43.0	7.0	26.4	4.1	4.3	0.9	23.7	6.46	1.13	12,600
4	6.4	47.6	48.4	4.0	23.9	3.9	3.8	1.3	21.8	6.08	1.10	11,000
5	3.7	42.2	51.8	6.0	20.9	3.4	3.3	0.9	21.7	6.20	0.97	10,100
6	4.1	34.5	61.8	3.7	18.0	2.9	2.3	0.8	16.7	6.21	1.08	9400
7	3.4	39.0	56.0	5.0	19.5	3.2	3.1	0.8	19.4	6.13	1.03	8700
8	3.9	33.3	63.5	3.2	14.5	2.6	2.6	1.2	18.1	5.51	0.82	6900
9	3.7	32.9	64.0	3.1	15.3	2.5	2.3	0.5	17.7	6.05	0.87	6500
10	3.2	30.6	67.6	1.8	12.7	2.0	1.8	0.6	17.5	6.34	0.74	5700
11	4.4	24.8	72.9	2.2	10.6	2.0	1.6	0.4	15.7	5.38	0.69	4300
12	8.9	23.4	74.2	2.4	9.0	2.2	1.5	1.6	18.2	4.06	0.50	3500

Table P5.6 Data for the fuel value of refuse in 12 cities of Thailand. (Thipkhunthod, et al.)

Solution

Here is a plot of high heating values as a function of volatile solids (mass % on a dry solids basis). There is a clear linear relationship. The fitted equation is

$$\text{HHV (MJ/kg)} = 0.339\ \text{VS (\% dry basis)} - 4.05$$

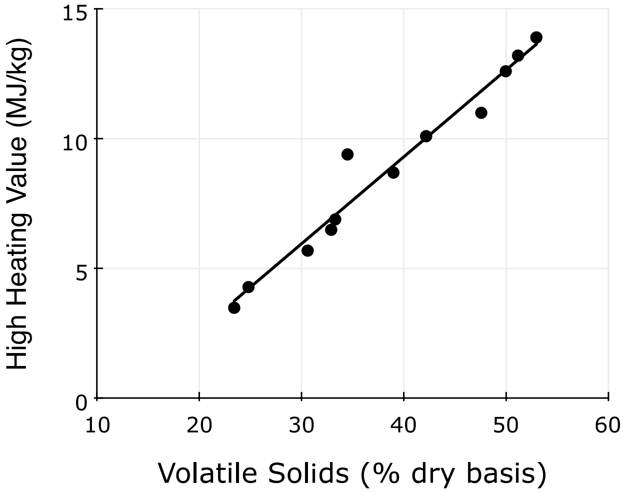


Figure S5.6 Fitted model for fuel value of municipal refuse (Thailand)

5.7 REFUSE DERIVED FUEL

Refuse derived fuel (RDF) is shredded municipal refuse that has been processed to remove metals and glass. It can be burned in boilers and power plants. An input of 1000 kg raw refuse typically yields 704 kg of refuse derived fuel (RDF) and 296 kg of rejected material. Table P5.7 gives proximate and elemental analysis of the refuse, RDF, and rejects. Calculate the mass of sulfur, chloride, lead, cadmium and mercury in the raw refuse and in the RDF. The elemental analysis is on a dry solids basis, i.e. 0.28% sulfur means 0.0028 kg S/kg dry solids.

Component	Refuse	RDF	Reject
Total Mass	100%	70.4%	29.6%
Moisture content (% by mass)	27.9	21.0	44.3
Dry mass (% by mass)	72.1	79.0	55.7
Ash content (% dry mass)	30.5	22.2	58.5
Volatile content (% dry mass)	69.5	77.8	41.5
Carbon, C (% dry mass)	48.0	34.5.	93.5
Nitrogen, N (% dry mass)	2.1	0.74	6.7
Sulfur, S (% dry mass)	0.28	0.18	0.62
Chloride, Cl (% dry mass)	0.38	0.40	0.31
Lead, Pb (mg/kg dry mass)	110	6	460.9
Cadmium, Cd (mg/kg dry mass)	12	1.7	46.8
Mercury, Hg (mg/kg dry mass)	0.4	0.4	0.4

Table P5.7 Proximate and elemental analysis of a municipal refuse

Solution

Basis: 1000 kg Refuse

Refuse yield = 70.4% of Refuse

RDF = (0.704)(1000 kg) = 704 kg RDF

Rejects = 1000 kg – 704 kg = 296 kg

Moisture in Refuse = (0.279)(1000 kg) = 279 kg water

Dry solids in Refuse = 1000 kg – 279 kg = 721 kg dry solids

Moisture in RDF = (0.21)(704 kg) = 148 kg water

Dry solids in RDF = 704 kg – 148 kg = 556 kg dry solids
Moisture in Rejects = (0.44)(296 kg) = 131 kg water
Dry solids in Reject = 296 kg – 132 kg = 165 kg dry solids
Mass of Sulfur in Refuse = (0.0028 kg S/kg dry solids)(721 kg dry solids) = 2.0 kg sulfur
Mass of Lead in Refuse = (110 mg/kg)(721 kg)/(1,000,000 mg/kg) = 0.0793 kg

Table S5.7 summarizes the calculated masses.

Component	Refuse (kg)	RDF (kg)	Reject (kg)
Total Mass	1000	704	296
Moisture content	279	148	131
Dry mass	721	556	165
Ash content	220	123	96
Volatile content	501	433	68
Carbon, C	346	192	154
Nitrogen, N	15.1	4.1	11.0
Sulfur, S	2.0	1.0	1.0
Chloride, Cl	2.7	2.2	0.5
Lead, Pb	0.0793	0.0033	0.0760
Cadmium, Cd	0.0087	0.0009	0.0077
Mercury, Hg	0.00029	0.00022	0.00007

Table S5.7

6 ENERGY RECOVERY FROM BIOGAS

6.1 STOICHIOMETRIC COMBUSTION OF METHANE

The most common oxidizer is air. The chemical equation for stoichiometric combustion of methane (CH_4) with air is

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2\,O + 7.52N_2$$

If more air is supplied some of the air will not be involved in the reaction. The additional air is termed *excess air*. Write the balanced chemical reaction for burning methane with 15% and 25% excess air.

Solution

For 15 % excess air

$$CH_4 + (1.15)2(O_2 + 3.76\ N_2) \rightarrow CO_2 + 2H_2\,O + 0.3O_2 + 8.65N_2$$

For 25% excess air

$$CH_4 + (1.25)2(O_2 + 3.76\ N_2) \rightarrow CO_2 + 2H_2\,O + 0.5O_2 + 9.4N_2$$

6.2 LANDFILL GAS

Gas will be collected from a landfill that receives the solid waste from a city of 200,000 people. Assuming 900 kg of refuse per year per person, the landfill has been receiving 180,000,000 kg/y, or about 500,000 kg/d. Each kg of municipal refuse put into a landfill yields 0.41 m^3 of landfill gas that is about 50 percent methane and 50 percent carbon dioxide. What is the equivalent energy as electricity (kWh/d) of the methane in the landfill gas?

Solution

From Appendix 4, the lower heating value of methane is 31.7 MJ/m^3 (8.8 kWh/m^3).

Expected landfill gas production = (500,000 kg/d)(0.41 m^3/kg) = 205,000 m^3/d

Expected methane production = 0.5(205,000 m^3/d) = 102,500 m^3/d

Electricity value of the methane produced

= (102,500 m^3/d)(8.8 kWh/m^3) = 902,000 kWh/d

6.3 METHANE PRODUCTION IN A LANDFILL

Figures P6.3a and P6.3b show the general pattern of gas production from birth to old age of a landfill. The fraction of generated methane that is recovered changes over the life of the landfill. This is true during the operating period (when refuse is being deposited) and after the landfill has been closed and capped. Discuss the lifetime of a landfill and the potential for using extracted methane in terms of this diagram.

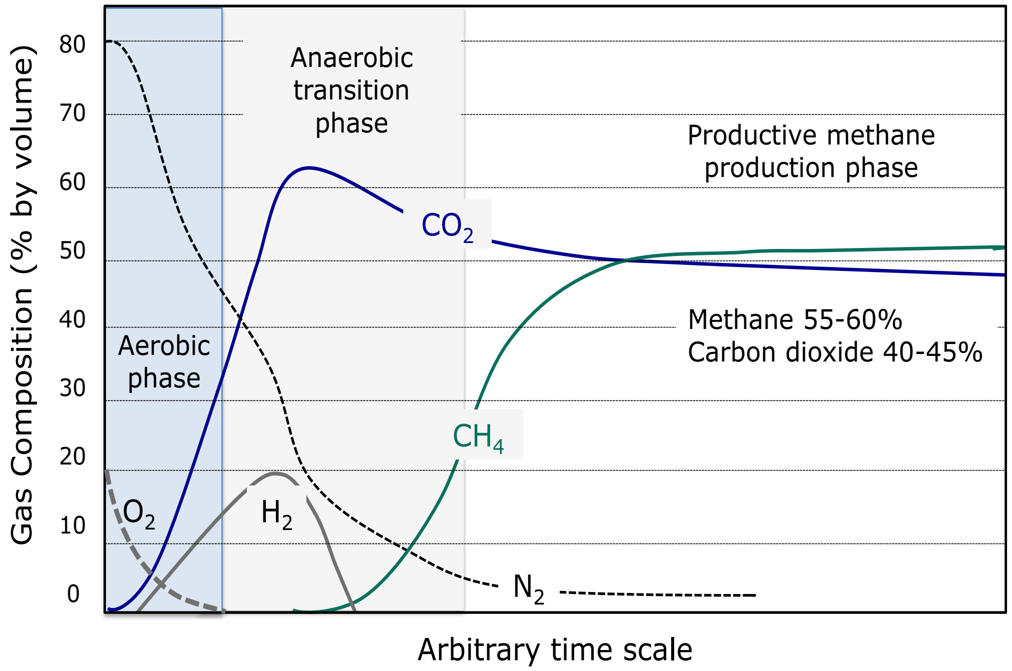


Figure P6.3a Development of landfill gas production

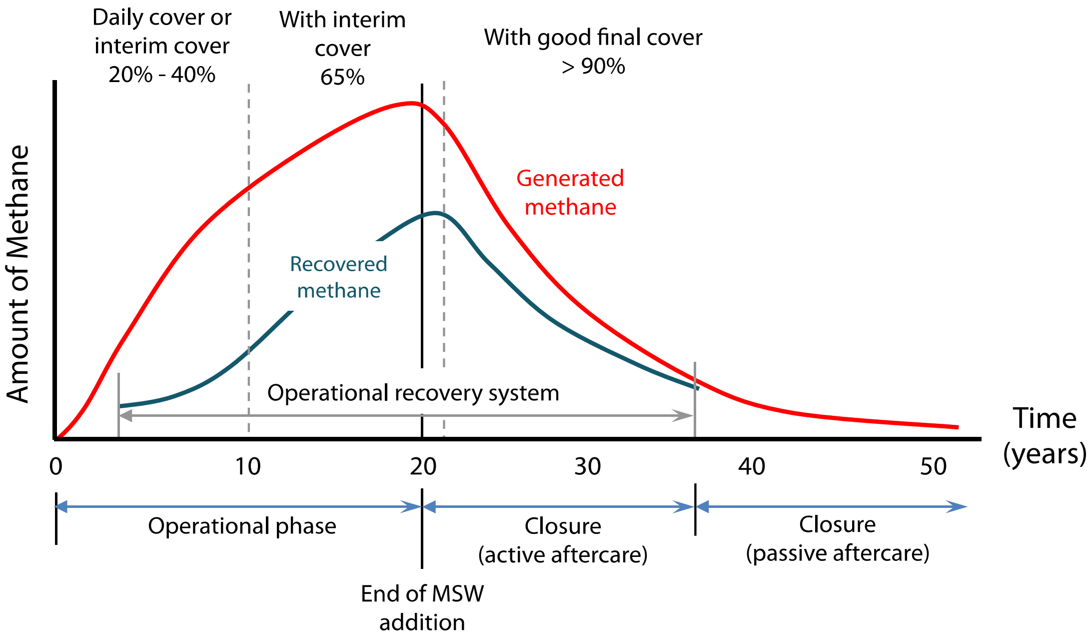


Figure P6.3b Methane gas production over the life of a landfill

Solution

This is an open-ended question that is meant to provoke discussion. No solution is provided.

6.4 LANDFILL GAS PRODUCTION CAPACITY

A rough estimate of the maximum amount of landfill gas that can be extracted from solid organic matter is 0.8-1.4 m^3/kg (dry weight) or 0.6 – 0.9 m^3/kg of putrescible matter. (a) Estimate the gas production over an 18-year lifetime of a landfill of 1,000,000 T (dry mass) of municipal refuse at 40% putrescible organic matter. (b) If gas were produced at a uniform rate (it is not, see Figure 6.3a) what would be the average rate per hour (m^3/h). (c) If 50% of the gas is methane, and 50% of the landfill gas can be recovered, what would be the average yield of methane gas?

Solution

a) Life time gas production

Putrescible matter (40% of refuse)

= 0.4(1,000,000,000 kg) = 400,000,000 kg deposited during life of landfill

Gas yield (low)

= (400,000,000 kg)(0.6 m^3/kg)

= 240,000,000 m^3 of gas over the 18-y life of the landfill.

Gas yield (high)

= (400,000,000 kg)(0.9 m^3/kg)

= 360,000,000 m^3 of gas over the 18-y life of the landfill.

b) Average production rate over an 18-year life, for the assumption (unrealistic) of uniform production

18 y = (18 y)(365 d/y)((24 h/d) = 157,680 h

Low gas yield: (240,000,000 m^3)/(157,680 h) = 1,500 m^3/h (rounded)

High gas yield: (360,000,000 m^3)/(157,680 h) = 2,300 m^3/h (rounded)

c) Actual recoverable rate, assuming uniform production over 18 years and a methane content of 50% and that 50% of the landfill gas is recoverable, is more in the order of

Low methane yield = (0.5)(0.5)1,500 m^3/h = 375 m^3 /h

High methane yield = (0.5)(0.5)2,300 m^3/h = 575 m^3 /h

Comment: Gas is not produced at a uniform rate. From Figure P6.3 we can see that there is a lag-period of a few years before any landfill gas is produced from the initial deposit. Then there is a 7-11 year period when the production peaks and begins its slow decline, followed by an 11 to 40-year period where the production declines to negligible levels. The total gas production is roughly the same in each of the rising and declining phases.

6.5 MODEL FOR LANDFILL GAS PRODUCTION

The rate of decomposition of a waste mass in a landfill is quick initially but it slows over time. A useful approximation is the exponential decay model, also known as a first-order model.

$$M_t = M_0 e^{-kt}$$

where M_0 = the initial waste mass (T), M_t = the mass remaining at time t (T), and k = a first order decay coefficient (t^{-1})

Define L_0 as the potential CH_4 generation capacity (m^3 methane/T waste). The methane potential volume at time $t = 0$ is $M_0 L_0$. The amount of gas that remains to be generated at time t is

$$L_t = L_0 M_0 e^{-kt}$$

The cumulative CH_4 generation is calculated by subtracting L_t from $M_0 L_0$, giving

$$Q_{\mathrm{CH4},t} = M_0 L_0 (1 - e^{-kt})$$

a) Use this model to predict the methane production from a landfill that has M_0 = 1,500,000 T, k = 0.05/y, and L_0 = 190 m³/T at one year intervals.

b) What is the half-life for gas production? That is, when does gas production decrease to half the original value.

Solution

a) Methane production

Sample calculation, using a time interval of 1 year

Waste mass, M

$$M_t = M_0 e^{-kt} = (1{,}500{,}000\ \text{T})\ e^{-(0.05/\text{y})\ t}$$

$$M_1 = (1{,}500{,}000\ \text{T})\ e^{-(0.05/\text{y})(1\ \text{y})} = 1{,}426{,}844\ \text{T}$$

$$M_2 = (1{,}500{,}000\ \text{T})\ e^{-(0.05/\text{y})\ (2\ \text{y})} = 1{,}357{,}256\ \text{T}$$

Cumulative methane generated, Q

$$Q_{\text{CH4},t} = M_0 L_0 (1 - e^{-kt}) = (190\ \text{m}^3/\text{T})(1{,}500{,}000\ \text{T})(1 - e^{-(0.05/\text{y})(t)})$$

$$Q_{\text{CH4},1} = (285{,}000{,}000\ \text{m}^3)(1 - e^{-(0.05/\text{y})(1\ \text{y})}) = 13.9 \times 10^6\ \text{m}^3$$

$$Q_{\text{CH4},2} = (285{,}000{,}000\ \text{m}^3)(1 - e^{-(0.05/\text{y})(2\ \text{y})}) = 27.1 \times 10^6\ \text{m}^3$$

Annual methane production, $Q_{\text{CH4},t} - Q_{\text{CH4},t\text{-}1})$

Year 1 = 13.9 x 10^6 m³

Year 2 = 27.1 x 10^6 m³ - 13.9 x 10^6 m³ = 13.2 x 10^6 m³

Complete calculations are in Table S6.6

Year	Mass of Waste	Cumulative methane produced	Annual methane production	Year	Mass of Waste	Cumulative methane produced	Annual methane production
	(T)	(10^6 m³)	(10^6 m³)		(T)	(10^6 m³)	(10^6 m³)
0	1,500,000	0	0				
1	1,426,844	13.9	13.9	21	524,907	185.3	5.11
2	1,357,256	27.1	13.2	22	499,307	190.1	4.86
3	1,291,062	39.7	12.6	23	474,955	194.8	4.63
4	1,228,096	51.7	12.0	24	451,791	199.2	4.40
5	1,168,201	63.0	11.4	25	429,757	203.3	4.19
6	1,111,227	73.9	10.8	26	408,798	207.3	3.98
7	1,057,032	84.2	10.3	27	388,860	211.1	3.79
8	1,005,480	94.0	9.79	28	369,895	214.7	3.60
9	956,442	103.3	9.32	29	351,855	218.1	3.43
10	909,796	112.1	8.86	30	334,695	221.4	3.26

11	865,425	120.6	8.43	31	318,372	224.5	3.10
12	823,217	128.6	8.02	32	302,845	227.5	2.95
13	783,069	136.2	7.63	33	288,075	230.3	2.81
14	744,878	143.5	7.26	34	274,025	232.9	2.67
15	708,550	150.4	6.90	35	260,661	235.5	2.54
16	673,993	156.9	6.57	36	247,948	237.9	2.42
17	641,122	163.2	6.25	37	235,856	240.2	2.30
18	609,854	169.1	5.94	38	224,353	242.4	2.19
19	580,112	174.8	5.65	39	213,411	244.5	2.08
20	551,819	180.2	5.38	40	203,003	246.4	1.98

Table S6.5

b) Half-life for methane gas production.
This is the time when the estimated annual methane production is half the initial value of 13.9 x 10^6 m^3/y. Half this value is 6.95 x 10^6 m^3/y, which (from the calculations table) occurs at about 15 years.

6.6 EPA LANDGEM METHANE PRODUCTION FORECASTS

Refuse is deposited in a landfill at the rate of 1000 T/y for 10 years. After 10 years no more refuse is deposited but the buried material continues to decompose and produce methane. The rate of decomposition is k = 0.04/y and the methane formation potential is L_0 = 170 m^3/T. Use the U.S EPA *Landfill Gas Emissions Model* (LandGEM) to estimate the expected volume of methane produced over a 50-year time span.

A brief tutorial on the LandGEM Model.

The LandGEM model predicts methane production, not the total volume of landfill gas.

- The model predicts methane production. It does not predict how much of that methane can be extracted from the landfill for beneficial use.
- It assumes that the landfill gas is 50% methane.
- Using this value would predict total landfill gas production a two times the methane production.
- The quantity of methane is needed to make economic decisions about utilization of the landfill gas.
- The quantity of landfill gas (methane plus CO_2 and other components) is needed to actually design a system to extract, purify, and use the landfill gas.

Here is a quick derivation. For each deposit of wet refuse, define

M_0 = mass of wet refuse placed in the landfill at time t = 0, (T)
M_t = mass remaining after M_0 has been decomposing for time t, (y)
(The EPA recommends intervals of 0.1 year)
$Q_{CH4,\, t}$ = estimated production of methane at time t, (m^3/y)
k = biodegradation rate (1/y)
L_0 = potential methane generation capacity (m^3 CH_4/T of wet refuse in landfill)
n = number of years of methane production in the landfill

The model assumes that the rate of decomposition at time t is proportional to the mass of refuse remaining at time t. The rate of decomposition at the beginning of a period is

$$\Delta M_t/\Delta t = -kM_t$$

The rate of gas production is proportional to the rate of decomposition

$$\Delta Q_{CH4,\, t}/\Delta t = -kL_oM_t$$

where $M_t = M_0 \exp(-kt)$

The accumulated methane production over n time intervals is

$$Q_{\mathrm{CH4}} = \sum_{i=1}^{n} kL_0 M_0 \exp(-kt_i)$$

The model is usually run with 10 intervals per year. The model tends to over predict when the time interval is one year.

Solution

Deposition rate and data:

- Refuse is deposited in the landfill for 10 years
- Annual deposit of wet refuse for years 1 to 10 = 1000 T/y
- Deposit of refuse after 10 years = 0
- After 10 years the refuse in place continues to decompose and methane continues to be generated
- The rates of decomposition and methane production both decrease after deposition ends.

L_o = 170 m^3/T k = 0.04/y n = 50

The use of the model will be illustrated using time intervals of 1 year. (The model is usually run with 10 intervals per year. The model tends to over predict when the time interval is one year.)

Figure S6.6 shows the methane production over the 50-year life of the landfill. Methane production increases over the 10 years when fresh material is being buried and then decreases with time.

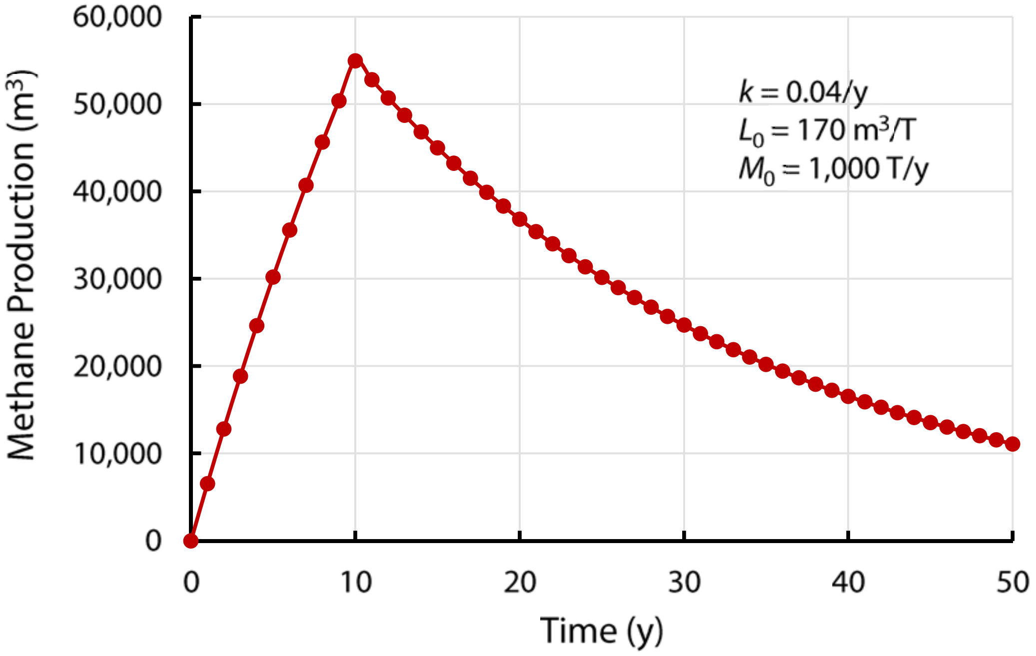


Figure S6.6 Methane production in a landfill

The methane produced in year 1 from the first year refuse is landfilled is

$$Q_{CH4,1} = k\, L_0\, M_0 \exp(-k\, t_1)$$

$$= (0.04/y)(170\ m^3/T)(1000\ T)\exp[-(0.04/y)(1\ y)] = 6{,}533\ m^3/y$$

The methane produced in year 2 from the first year's refuse deposit is

$$Q_{CH4,2} = (0.04/y)(170\ m^3/T)(1000\ T)\exp[-(0.04/y)(2\ y)] = 6{,}277\ m^3/y$$

And for year 10

$$Q_{CH4,10} = (0.04/y)(170\ m^3/T)(1000\ T)\exp[-(0.04/y)(10\ y)] = 4{,}558\ m^3/y$$

The pattern is that less methane is produced each year.

In year 2 another 1000 T of refuse is placed in the landfill and the calculations under "Year 2 of refuse placement" follow the same pattern as for the refuse placement in Year 1.

For time = 3, Year = 2 the calculation is

$$= (0.04/y)(170\ m^3/T)(1000\ T)\exp[-(0.04/y)(2\ y)] = 6{,}277\ m^3/y$$

The "2 years" in the exponent is the 2 years that placement of refuse had been in the landfill.

The total methane production during a given time equals the sum of the methane production from each refuse placement at that time. So for time = 2,

Total methane = methane from deposit 1 + methane from deposit 2
= 6,533 m^3 + 6,277 m^3 = 12,810 m^3

There is typically a lag period before a new landfill starts to produce usable volumes of gas. This lag is not shown in the diagram or in the table of calculated values (see below).

This is not the amount of methane that can be recovered from or extracted from the landfill. Perhaps 50% to 70% can be extracted, depending on the design of the gas collection system (how many collection wells, their location, etc.)

The model predicts methane production and *not* total gas production. The landfill gas is typically 40-60% methane, with the rest being mostly carbon dioxide but with small amounts of other gases. Also, the gas is not dry – it contains substantial amounts of water vapor.

From the standpoint of gas utilization, the most important *trace gases* are sulfur compounds, especially hydrogen sulfide (H_2S) because it is corrosive and toxic. From an air pollution standpoint, the landfill gas may carry many kinds of regulated chemicals, including ones that are toxic or carcinogenic.

Gas as it comes from the landfill is *low grade*. It can be burned but the fuel value is low. It can be improved to *high grade* or *very high grade* by removing H_2S, carbon dioxide, and water vapor.

Table S6.6 shows the calculations for the first 20 years of the landfill life. This table is the model for a spreadsheet calculation. The U.S. EPA does have a computer program to do the calculations, but we opted not to use it.

The values in the table are annual methane production from the placement of that year. The column on the right is the collected methane production for all the years when refuse was being added to the landfill.

Time	Year of Refuse Placement in the Landfill										Volume of Methane (m^3)
	1	2	3	4	5	6	7	8	9	10	
1	6533										6,533
2	6277	6533									12,810
3	6031	6277	6533								18,841
4	5795	6031	6277	6533							24,636
5	5567	5795	6031	6277	6533						30,203
6	5349	5567	5795	6031	6277	6533					35,552
7	5139	5349	5567	5795	6031	6277	6533				40,691
8	4938	5139	5349	5567	5795	6031	6277	6533			45,629
9	4744	4938	5139	5349	5567	5795	6031	6277	6533		50,373
10	4558	4744	4938	5139	5349	5567	5795	6031	6277	6533	54,932
11	4379	4558	4744	4938	5139	5349	5567	5794	6031	6277	52,778
12	4208	4379	4558	4744	4938	5139	5349	5567	5794	6031	50,708
13	4043	4208	4379	4558	4744	4938	5139	5349	5567	5794	48,720
14	3884	4043	4208	4379	4558	4744	4938	5139	5349	5567	46,810
15	3732	3884	4043	4208	4379	4558	4744	4937	5139	5349	44,974
16	3586	3732	3884	4043	4208	4379	4558	4744	4937	5139	43,211
17	3445	3586	3732	3884	4043	4208	4379	4558	4744	4937	41,516
18	3310	3445	3586	3732	3884	4043	4208	4379	4558	4744	39,888
19	3180	3310	3445	3586	3732	3884	4043	4207	4379	4558	38,324
20	3055	3180	3310	3445	3586	3732	3884	4042	4207	4379	36,822

Table S6.6 Landfill gas predictions.

6.7 OPEN FLARE BURNING OF WASTE LANDFILL WASTE GAS

Open-flare burning landfill gas was once a common practice. Today landfills are extracting the gas for beneficial use. One reason is unacceptable atmospheric emissions from open flares (an open combustor without enclosure or shroud). Emission factors for landfill gas are used if site-specific data are not available. (Emission factors for industrial flares should not be used.) An active landfill gas collection system provides open waste gas flare with 5 million ft^3 of dry landfill gas per year at 55°F and 8 psig. The landfill gas is 55% methane. Use the data in Table P6.7 to estimate the annual atmospheric emissions if the gas is flared

Pollutant	Emission Factors
CO	750 lb per million ft^3 methane gas burned*
NO_X	40 lb per million ft^3 methane gas burned*
PM_{10}, Primary	17 lb per million ft^3 methane gas burned*
$PM_{2.5}$, Primary	1.7 lb per million ft^3 methane gas burned*
SO_X	7.8 lb per million ft^3 landfill gas burned**
VOC	5.6 lb per million ft^3 methane gas burned*

* waste gas burned = dry methane generated at standard conditions
** MMCF landfill gas burned = dry landfill gas generated at standard conditions
Listed SO_X emission factor is based on the default concentration for total reduced sulfur (TRS) in landfill gas (46.9 ppmv).

Table P6.7 Air pollution emission factors for open-flare burning of landfill gas from an active gas collection system. (Source: Emission Calculation Fact Sheet #9844 (Rev. 11/06), Michigan Department of Environmental Quality)

Solution

Basis: 1 year = 5,000,000 ft^3 of landfill gas

Operating conditions = 8 psig, 55°F, 20% relative humidity.

Standard conditions = dry gas at 14.7 psia and 68°F (1 atm and 528°R)

Correct to standard conditions

8 psig = 14.7 psi + 8 psi = 22.7 psi

55°F = 55°F + 460 = 515°R

Landfill gas production per year (at standard conditions)

$$\text{Standard ft}^3/\text{y} = (5{,}000{,}000 \text{ ft}^3)\left(\frac{528°\text{R}}{515°\text{R}}\right)\left(\frac{22.7 \text{ psi}}{14.7 \text{ psi}}\right) = 7{,}916{,}000 \text{ ft}^3/\text{y}$$

Methane gas production per year, assuming landfill gas is 55% methane.

= (0.55)(7,916,000 ft^3/y) = 4,354,000 standard ft^3/y

Annual CO emissions = $(4.354\text{x}10^6 \text{ ft}^3\ CH_4/\text{y})(750 \text{ lb CO}/10^6 \text{ ft}^3)$ = 3,266 lb CO/y

Pollutant	Emission Factors	Annual Emissions (lb/y)
CO	750 lb/10^6 ft^3 methane burned*	3,266
NO_X	40 lb/10^6 ft^3 methane burned	175
PM_{10}	17 lb/10^6 ft^3 methane burned	74
$PM_{2.5}$	1.7 lb/10^6 ft^3 methane burned	7.4
SO_X	7.8 lb/10^6 ft^3 landfill gas burned	61.7
VOC	5.6 lb/10^6 ft^3 methane burned	24.4

Table S6.7 Emission from landfill gas flares

6.8 ENERGY BALANCE FOR MESOPHILIC ANAEROBIC DIGESTION

Raw (undigested) sludge at 10°C must be heated to 35°C when it is fed to a mesophilic digester. Some heat energy can be recovered from the warm sludge that leaves the digester. Additional heat must be added from a boiler to raise the inlet feed to 35°C. Heat (25 GJ/d) is also lost through the floor, cover, and walls of the digester. The system is shown in Figure P6.8. The specific heat of the sludge is 4.2 kJ/kg°C (0.0042 GJ/T°C).

a) The heating potential of the gas generated in the digester is 400 GJ/d. Calculate how much of this is needed for the boiler and how much can be used for other purposes.
b) The heating value of methane = 0.037 GJ/m^3 CH_4. Calculate the volume of methane that must be produced to meet the demand of the boiler.
c) Methane production = 0.7 m^3/kg volatile solids (VS) destroyed in the digester. Calculate the mass of volatile solids that must be destroyed in the digester to meet the demand of the boiler.

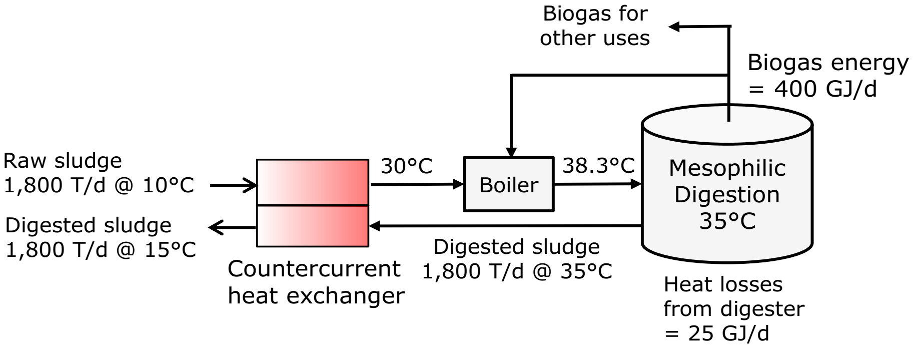


Figure P6.8 Energy balance with heat recovery for a mesophilic anaerobic digester.

Solution

Basis: 1,800 T/d of raw sludge at 10°C

a) Sludge heating requirement (T = 10°C to T = 35°C)

$= mc_p(\Delta T)$ = (1800 T/d)(0.0042 GJ/T°C)(35°C – 10°C) = 189 GJ/d

Add heat losses of 25 GJ/d

Total heating requirement = 189 GJ/d + 25 GJ/d = 214 GJ/d

Because of heat losses in the digester, the feed sludge must be heated to a temperature greater than 35°C in order for the digester contents to be 35°C. This temperature is

ΔT = (214 GJ/d)/[(1800 T/d)(0.0042 GJ/T°C)] = 28.3°C

$\Delta T = T_{Out} - T_{In}$

$T_{Out} = T_{In} + \Delta T$ = 10°C + 28.3°C = 38.3°C

Energy supplied from heat recovery

= (1800 T/d)(0.0042 GJ/T°C)(35°C – 15°C) = 151 GJ/d

Assume 100 % of the recovered energy is transferred to the feed sludge. This will raise the feed sludge temperature by 20°C, because the temperature of the warm sludge was reduced by 20°C and the mass flows are equal.

Temperature of sludge into boiler = 10°C + 20°C = 30°C

Energy supplied to sludge by boiler = total heating required – heat recovered

= 214 GJ/d – 151 GJ/d = 63 GJ/d

Energy available for other uses = 400 GJ/d - 63 GJ/d = 334 GJ/d

b) Methane demand for boiler energy

Heating value of methane = 0.037 GJ/m^3

Required volume of methane = (63 GJ/d)/(0.037 GJ/m^3 CH_4) = 1,700 m^3/d

c) Volatile solids destruction required to meet boiler energy demand

Methane production = 0.7 m^3 per kg volatile solids (VS) destroyed in the digester.

Heat value per kg VS destroyed = (0.037 GJ/m^3CH_4)(0.7 m^3 CH_4/kg VS destroyed

= 0.0259 GJ/kg VS destroyed

Required VS destruction to produce the required gas

(63 GJ/d)/(0.0259 GJ/kg VS destroyed) = 2430 kg VS destroyed/d

Alternate calculation

Methane requirement for boiler = 1,700 m^3

Required VS destruction = (1,700 m^3/d)/(0.7 m^3/kg VS destroyed)

= 2,430 kg VS destroyed/d

6.9 THERMOPHILIC ANAEROBIC DIGESTION

A mesophilic anaerobic digester receives partially digested sludge from a thermophilic digester (Figure P6.9). The operating temperatures are 37°C in the mesophilic digester and 55°C in the thermophilic. *Thermophilic* means *heating loving* or *heat tolerant* and it refers to the microorganisms in the digester that produce methane. The digester gas is used for heating, running engines and generating electricity. Gas would be used to heat the water that is supplied to the sludge/water heat exchanger.

The specific heat of the sludge is 4.2 kJ/kg°C. (a) Make the energy balance on the heat exchanger that uses warm sludge (55°C) from the thermophilic digester to heat the raw sludge feed (15°C). (b) Calculate the heat supplied to the thermophilic digester from external heating unit.

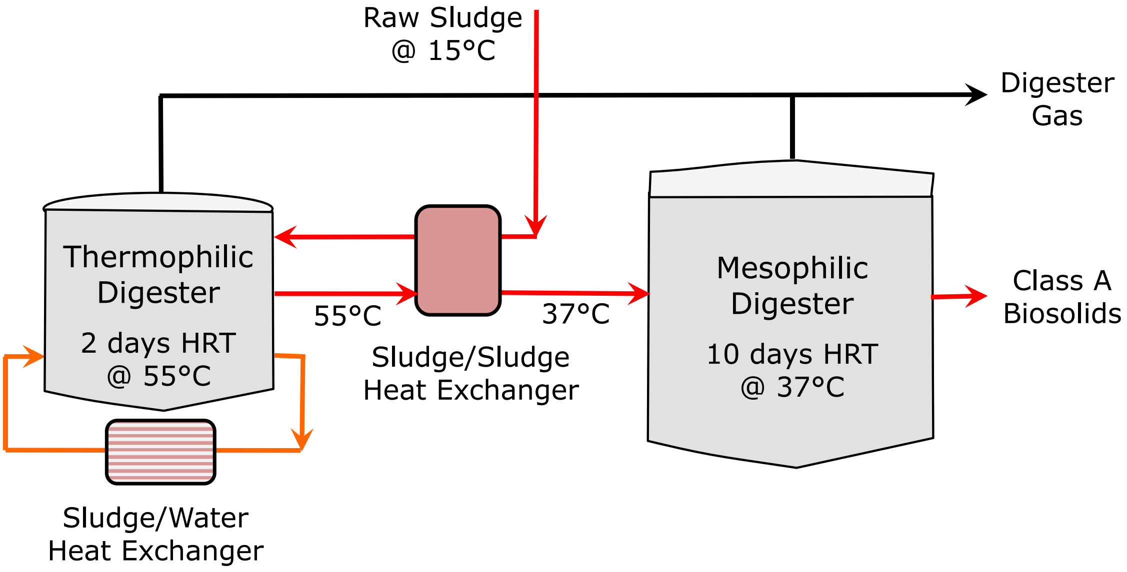


Figure P6.9 Two-stage thermophilic-mesophilic anaerobic digester system

Solution

Basis = 1 kg raw sludge feed

Assumption: About 30% of the volatile solids in the feed sludge will be converted to gas in the thermophilic digester. Assume the loss of solids will not change the specific heat of the sludge. That is, $c_P = 4.2$ kJ/kg°C for the sludge entering and leaving the TAD.

a) Energy balance on heat exchanger.

Define:

T = temperature of raw sludge leaving the heat exchanger and entering the TAD

Energy balance on the heat exchanger

$Q = mc_P(\Delta T)$ and $Q_{\text{Feed sludge}} = Q_{\text{Thermophilic sludge}}$

$(1 \text{ kg sludge})(4.2 \text{ kJ/kg°C})(T - 15°\text{C}) = (1 \text{ kg})(4.2 \text{ kJ/kg°C})(55°\text{C} - 37°\text{C})$

$T = 18°\text{C} + 15°\text{C} = 33°\text{C}$

b) Heat supplied to thermophilic digester from the external heat source

Raise temperature of sludge from 33°C to 55°C

$(1 \text{ kg})(4.2 \text{ kJ/kg°C})(55°\text{C} - 33°\text{C}) = 92.4 \text{ kJ/kg}$

Added to the 92.4 kJ/kg will be heat requires to make up for losses from the digester. These are not negligible, but they are small relative to sludge heating, and will not be calculated here.

6.10 ENERGY FROM MANURE

Figure P6.10 shows a manure digestion system in which biogas from the digester is cleaned, compressed, and then stored or directly used as fuel. (a) Why does the gas need to be cleaned? What compounds or substances are removed from it? (b) What are the possible uses for the biogas?

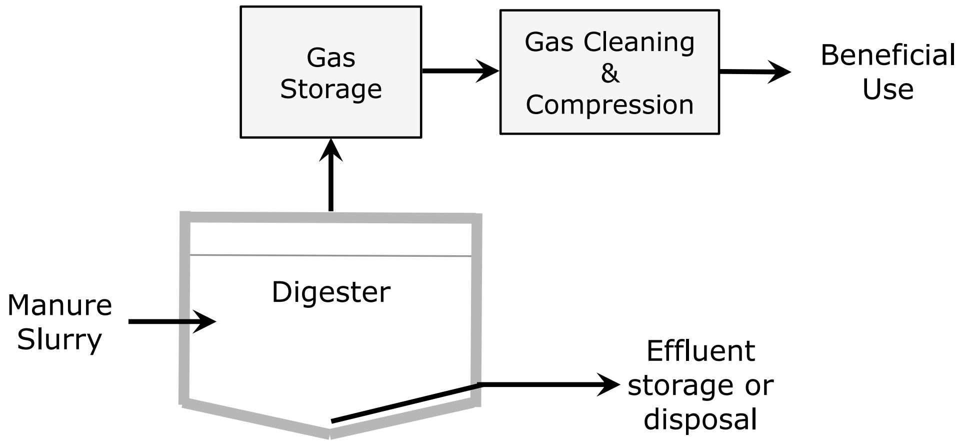


Figure P6.10 Manure digestion system

Solution

a) The digester gas contains hydrogen sulfide (H_2S) that must be removed because it reacts with moisture in the gas and in combustion products to form corrosive sulfuric acid (H_2SO_4). Other sulfur compounds will be in the gas, but in much lower concentrations. They may be of more concern because of odors than corrosion.

b) The biogas from manure digestion typically is about 50% carbon dioxide (CO_2) and 50% methane (CH_4). Gas of this composition can be burned to produce heat or electricity, but the fuel value per cubic meter is only half the value for natural gas. Some plants will upgrade the gas by removing CO_2.

6.11 GAS UTILIZATION OPTIONS

Figure P6.11 shows energy sources and energy demands for a wastewater treatment plant. Electricity costs \$0.12/kWh. Gas costs \$0.34/m^3 and has a heating value of 8.5 Mcal/m^3.

a) Calculate the annual cost for electricity and natural gas

b) Digester gas, which has a thermal value of 5.5 Mcal/m^3, is not being used. Suggest ways that purchased electricity and natural gas can be reduced and estimate the annual savings in energy costs.

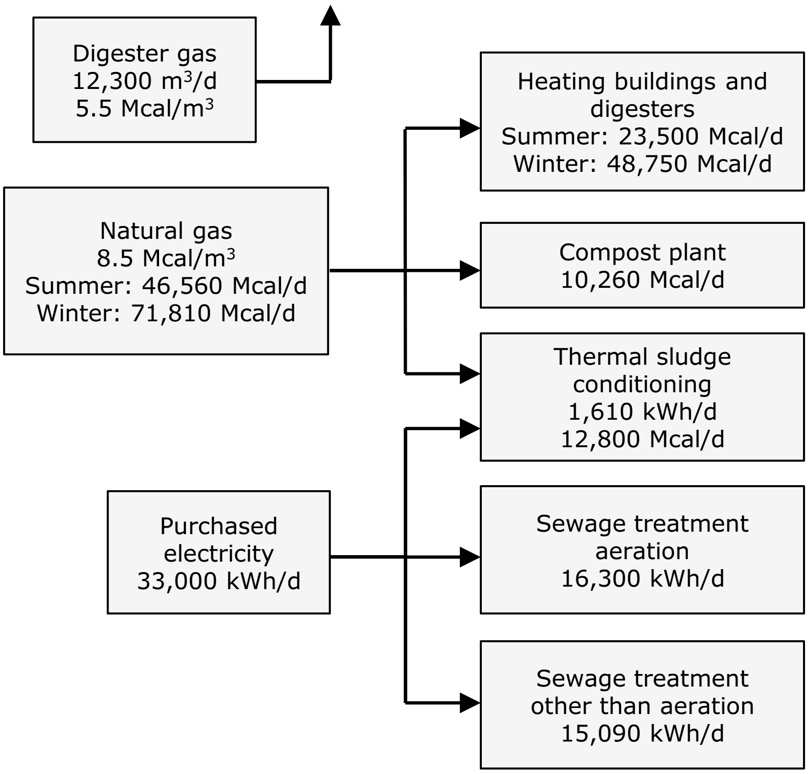


Figure P6.11

Solution

a) Annual cost of electricity and natural gas

Electricity use = 33,000 kWh/d

Unit cost = $0.12/kWh

Cost of electricity = (33,000 kWh/d)(365 d/y)($0.12/kWh) = $1,445,400/y

Natural gas use: Summer (193 d/y) = 46,560 Mcal/d

Winter (192 d/y) = 71,810 Mcal/d

Unit cost = ($0.34/m^3)/(8.5 Mcal/m^3) = $0.04/Mcal

Cost of natural gas

Summer: (46,560 Mcal/d)(193 d/y)($0.04/Mcal) = $359,400/y

Winter: (71,810 Mcal/d)(192 d/y)($0.04/Mcal) = $551,500/y

Total cost of natural gas = $359,000/y + $551,500/y = $910,900/y

Total cost of electricity and gas = $1,445,000/y + $910,900/y = $2,356,300/y

b) Potential use of digester gas for energy

Digester gas (currently unused) = (12,300 m^3/d)(5.5 Mcal/m^3) = 67,650 Mcal/d. The digester gas has the potential to supply the demand for natural gas in the summer and to cover 90+% of the winter demand.

We say "potential" because neither the supply nor the demand for gas is constant and it may not be possible to use all the digester gas within the plant. Figure S6.11 shows how the variations can be significant.

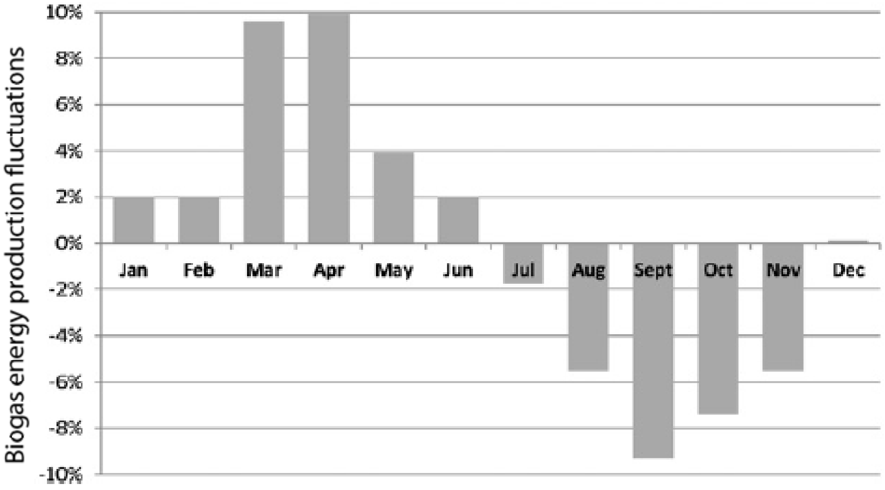


Figure S6.11 Biogas energy production fluctuations (%)

6.12 DIGESTER GAS FOR MICROTURBINE ELECTRICITY GENERATION

An anaerobic digester produces enough gas (70% CH_4 and 30% CO_2) to operate 5 microturbines, each of which has a power rating of 45 kW, for a total of 180 kW. The turbines will operate 7,800 hours per year and produce 1.5 units of heat energy for each unit of electrical energy. Electric energy is worth $0.15/kWh and the recovered heat energy is worth $8 per million kJ. Calculate the electrical energy output, the heat energy recovered, and the value of the electrical and heat energy produced per year.

Solution

Microturbine power rating = 45 kW
Electrical generating potential = (5 turbines)(45 kW/turbine) = 225 kW
Annual utilization rate = 7,800 h/y

Electric energy output = (225 kW)(7,800 h/y) = 1,755,000 kWh/y
Value of electricity generated, at $0.15/kWh
= ($0.15/kWh)(1,755,000 kWh/y) = $263,250/y

Heat energy produced, at 1.5 unit per unit of energy.
= 1.5(1,755,000 kWh/y) = 2,632,500 kWh equivalent heat energy/y
Convert to kJ, at 1 kWh = 3,600 kJ
= (3,600 kJ/kWh)(2,632,500 kWh/y) = 9,477 x 10^6 kJ/y
Value of recovered heat energy, at \$8 per 10^6 kJ
= (\$8/10^6 kJ)(9,477 x 10^6 kJ/y) = \$75,816/y

Total value of energy produced from utilized digester gas
= \$263,000/y + \$76,000/y = \$339,000/y

7 THERMAL INCINERATION OF WASTE GAS

Tutorial Note

In SI units we usually work in kg and kg-moles. In U.S. we use lb and lb-mole. For convenience we shall drop the kg from kg-mol and lb-from lb-mol. It will be clear from the context which molar mass is being used.

7.1 LOWER EXPLOSIVE LIMIT OF TOLUENE

Solvent vapors are drawn from workplace ventilation hoods at a concentration of 10,000 ppmv toluene. Discuss safety in managing the ventilation air.

Solution

The LEL for toluene is 12,700 ppmv. For safety in the ventilation system, the waste air stream must be diluted with fresh air so the toluene concentration is not more than 25% of the LEL, or 3,175 ppmv. The dilution ratio is

= 10,000 ppmv/3,175 ppmv = 3.15

This will more than triple the volume of contaminated air that must be handled as well as the size of the incinerator or any other process that is used to clean the gas. It will also increase the amount of fuel needed to heat the incoming air. The alternative is to somehow reduce the toluene concentration at the source.

7.2 LOWER EXPLOSIVE LIMIT OF A VOC MIXTURE

A waste gas flow of 20,000 scfm is air contaminated with 1000 ppmv benzene (BZ) and 1000 ppmv methyl chloride (MC). The LEL values are $\mathrm{LEL}_{\mathrm{BZ}}$ = 13,500 ppmv and $\mathrm{LEL}_{\mathrm{MC}}$ = 107,000 ppmv. Calculate the LEL of the mixture. Is there an explosive hazard?

Hint: Gas i has volume fraction f_i and LEL_i. The total volume fraction of combustibles is the sum of the individual values of f_i.

$$\frac{\sum x_i}{\mathrm{LEL}_{\mathrm{mixture}}} = \frac{x_1}{\mathrm{LEL}_1} + \frac{x_2}{\mathrm{LEL}_2} + \ldots.. + \frac{x_n}{\mathrm{LEL}_n}$$

Solution

The volume fraction of all combustible gases is

$$\sum x_i = x_{\mathrm{BZ}} + x_{\mathrm{MC}} = \text{1,000 ppmv} + \text{1,000 ppmv} = \text{2,000 ppmv}$$

From Le Chatelier's formula, the LEL of the mixture is

$$\frac{\text{2,000 ppmv}}{\mathrm{LEL}_{\mathrm{mixture}}} = \frac{\text{1,000 ppmv BZ}}{\text{13,500 ppmv}} + \frac{\text{1,000 ppmv MC}}{\text{107,000 ppmv}} = 0.0741 + 0.0094 = 0.0835$$

$$\mathrm{LEL}_{\mathrm{mixture}} = \frac{\text{2,000 ppmv}}{0.0835} = \text{23,950 ppmv}$$

25% of $\mathrm{LEL}_{\mathrm{mixture}}$ = (0.25)(23,950 ppmv) = 5,988 ppmv

The mixture LEL is well below 25% so no dilution air is needed and there is no explosive hazard.

7.3 COMBUSTION OF HYDROCARBONS

A mixture of hydrocarbons plus impurities is burned. The empirical composition is C_8H_{18}. Calculate the amount of oxygen required for stoichiometric combustion.

Solution

Basis = 1 kg hydrocarbon mixture

The balanced chemical reaction for complete oxidation of C_8H_{18} is

$$C_8H_{18} + 12.5\ O_2 \rightarrow 8\ CO_2 + 9H_2O$$

reacting masses (kg) 114 400

The oxygen requirements are

12.5 moles of oxygen per mole of C_8H_{18}

400 kg O_2 per 114 kg C_8H_{18}

3.51 kg O_2 per kg C_8H_{18}

7.4 COMBUSTION OF GASOLINE

Gasoline having composition of C_8H_{16} will be used as fuel in an engine. (a) How much air is required per kg of gasoline? (b) Calculate the air to fuel ratio (kg air/kg gasoline).

Solution

Basis: 1 kg gasoline
Air is 23.2% oxygen by mass.

a) The balanced chemical reaction for complete oxidation of C_8H_{16} is

$$C_8H_{16} + 12\ O_2 \rightarrow 8\ CO_2 + 8H_2O$$

reacting masses (kg) 112 384

The oxygen requirements are

384 kg O_2 per 112 kg C_8H_{16}
3.42 kg O_2 per kg C_8H_{16}

Air is 23.2% O_2. Mass of air = (3.42 kg O_2)/0.232 = 14.74 kg air/kg gasoline

b) Air to fuel ratio

A/F ratio = 14.74 kg air/kg gasoline

7.5 BURNING ETHANE

Normally non-reactive compounds are not included in the balanced stoichiometric equation. In the special case of combustion in air, nitrogen (which is non-reactive) accounts for a large proportion of the exit gases, and it can be convenient to include it in the equation.

a) Show that this combustion reaction is correct for the combustion of ethane (C_2H_6) in dry air.

$$C_2H_6 + 3.5(O_2 + 3.76N_2) \rightarrow 2CO_2 + 3H_2O + 13.16N_2$$

b) Ethane (C_2H_6) is burned with dry air that contains 5 mol O_2 for each mole of ethane. Show that this combustion equation correctly accounts for the excess air.

$$C_2H_6 + 5(O_2 + 3.76N_2) \rightarrow 2CO_2 + 3H_2O + 1.5O_2 + 18.8N_2$$

c) Calculate the percentage of excess air in part (b).

Solution

a) When the oxygen is provided by air, the equation can modified to reflect the mass balance of all the gases passing through the combustion chamber. Nitrogen comes in with the oxygen. It does not react – it just passes through – but it is an important component in the mass and volume of gas flow.

The stoichiometric equation for the combustion (oxidation) of ethane is

$$C_2H_6 + 3.5O_2 \rightarrow 2CO_2 + 3H_2O$$

The theoretical oxygen requirement is 3.5 mol O_2/mol ethane.

The $3.5(O_2 + 3.76\ N_2)$ term carries the non-reactive nitrogen along with the oxygen in the proportions that they are found in dry air.

The value of 3.76 mol N_2 per mole O_2 comes from assuming the molar composition of dry air is 79% N_2 and 21% O_2.

$$(0.79 \text{ mol } N_2)/(0.21 \text{ mol } O_2) = 3.76 \text{ mol } N_2/\text{mol } O_2$$

If we use a few of the other gases found in air, the volume composition of dry air 78.09% nitrogen (N_2), 20.95% oxygen (O_2) 0.93% argon (Ar), 0.039% carbon dioxide (CO_2) and traces of other gases. The volume fraction of a gas equals the mole fraction, giving air a nitrogen to oxygen ratio of (0.7809 mol N_2)/(0.2095 mol O_2) = 3.73mol N_2/mol O_2. This small difference has no engineering significance and the 3.76 value is commonly used.

b) Verify the mass balance of the elements of reactants and products.
The $5(O_2 + 3.76\ N_2)$ term is present because it is given that the supply of O_2 is 5 moles per mole of ethane. Only 3.5 moles of O_2 react with the ethane, leaving an excess of 1.5 moles that shows up as a product. The nitrogen in the system must be proportional to the 5 moles of oxygen.

c) There is excess air because the process is provided with 5 mol O_2 rather than the 3.5 mol O_2 that is consumed in the combustion reaction.

Percent excess air = (1.5 mol excess)/(3.5 mol required) = 0.429
= 42.9% excess air.

7.6 BURNING A MIXTURE OF GASES

A fuel mixture of 60% methane (CH_4), 30% ethane (C_2H_6), and 10% propane (C_3H_8) by volume is burned with dry air. (a) Write the balanced stoichiometric combustion reaction. (b) Calculate the mass flow rate of air for complete combustion of 5 kg fuel per hour.

Solution

Basis = 1 mol of fuel = 0.6 mol CH_4, 0.3 mol C_2H_6, and 0.1 mol C_3H_8

a) The combustion reaction is

$$0.6CH_4 + 0.3C_2H_6 + 0.1\,C_3H_8 + a(O_2 + 3.76N_2) \rightarrow bCO_2 + cH_2O + dN_2$$

We find a, b, c, and d by balancing the various elements as follows:

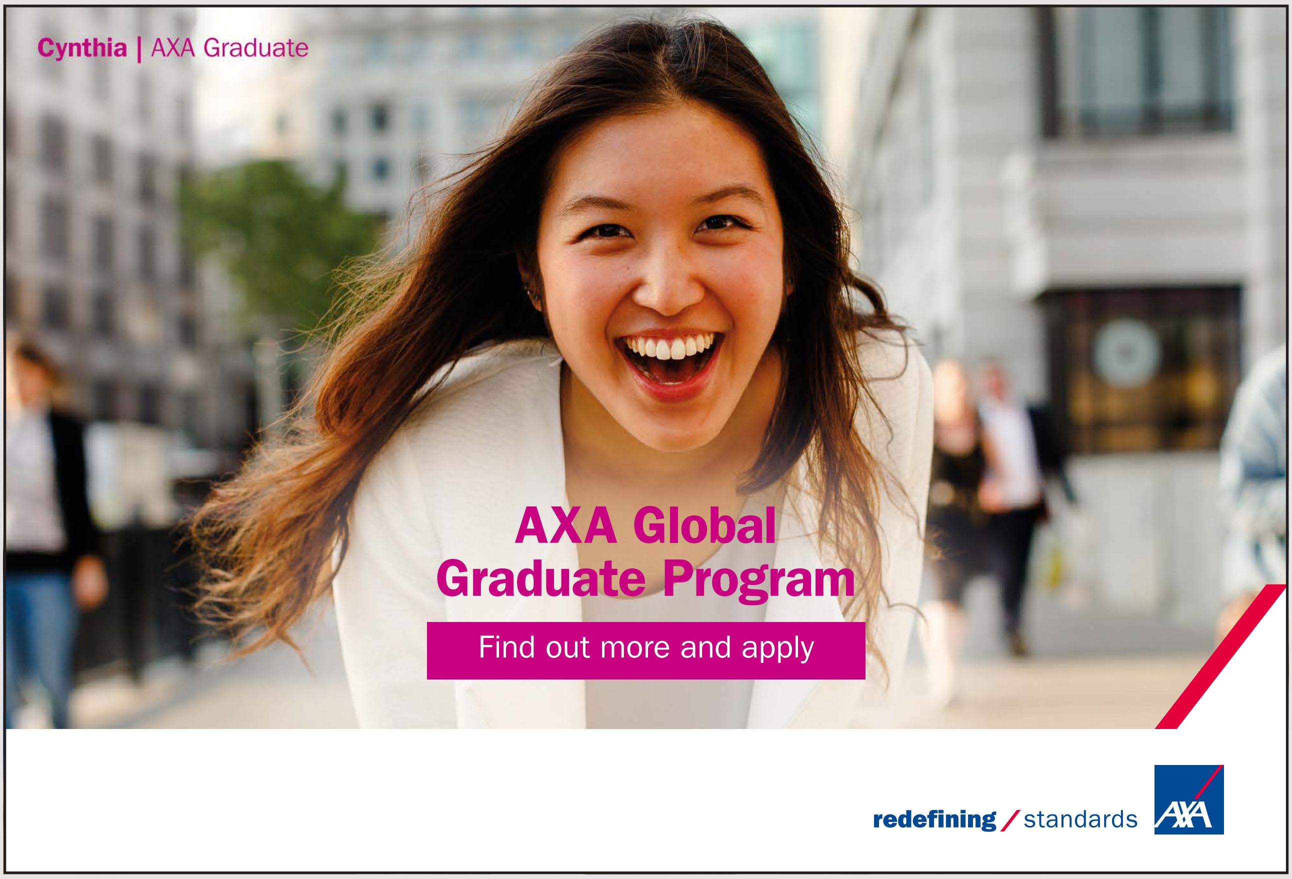
C: $0.6 + 0.6 + 0.3 = b$ $b = 1.5$
H: $2.4 + 1.8 + 0.8 = 2c$ $c = 2.5$
O: $2a = 2b + c$ $a = 2.75$
N: $2(3.76a) = 2d$ $d = 10.34$

$$0.6CH_4 + 0.3C_2H_6 + 0.1\,C_3H_8 + 2.75(O_2 + 3.76N_2) \rightarrow 1.5CO_2 + 2.5H_2O + 10.34N_2$$

b) Molar masses:

CH_4 = 16.042 kg/mol → 16 kg/mol
C_2H_6 = 30.069 kg/mol → 30 kg/mol
C_3H_8 = 44.095 kg/mol → 44 kg/mol

We will use the rounded masses of 16, 30 and 44 kg/mol



Mass of fuel reacted

= (0.6 mol CH_4)(16 kg/mol) + (0.3 mol C_2H_6)(30 kg/mol) + (0.1 mol C_3H_8)(44 kg/mol)
= 23 kg - fuel/mol

5 kg/h fuel reacted = (5 kg-fuel/h)/(23 kg-fuel/mol) = 0.217 mol-fuel/h reacted

Mole of oxygen reacted = (0.217 mol fuel/h)(2.75 mol O_2/mol fuel) = 0.598 mol O_2/h
Mass of O_2 reacted = (0.598 mol O_2/h)(32 kg O_2/kg-mol O_2) = 19.13 kg O_2/h
Moles of N_2 carried along = (3.76 mol N_2/mol O_2)(0.598 mol O_2/h) = 2.248 mol N_2/h
Mass of N_2 carried along = (2.248 mol N_2/h)(28 kg/kg-mol N_2) = 62.96 kg N_2/h

Mass of air = 19.13 kgO_2/h + 62.96 kg N_2/h = 82.09 kg air/h

7.7 COMBUSTION OF A HYDROCARBON MIXTURE I

A combustible gas is a mixture of these empirical aliphatic and aromatic compounds.

Aliphatics: $C_3H_7 + 4.75\ O_2 \rightarrow 3\ CO_2 + 3.5\ H_2O$
Aromatics: $CH + 1.25\ O_2 \rightarrow CO_2 + 0.5\ H_2O$

Calculate the theoretical masses of oxygen and air for complete combustion of 1000 kg of the following mixtures of these gases.

a) The mole fractions of the mixture are aliphatics = 0.5 and aromatics = 0.5
b) The mole fractions of the mixture are aliphatics = 0.7 and aromatics = 0.3

Solution

Basis: 1000 kg of gas mixture

a) The mole fractions are equal so 1 mole of gas mixture contains 0.5 mole of aliphatics and 0.5 mole of aromatics. Or, more simply, 2 moles of mixture contains 1 mole of each and the stoichiometry of the combustion is

Aliphatics: $C_3H_7 + 4.75\ O_2 \rightarrow 3\ CO_2 + 3.5\ H_2O$
Aromatics: $CH + 1.25\ O_2 \rightarrow CO_2 + 0.5\ H_2O$

Overall reaction: $C_3H_7 + CH + 6\ O_2 \rightarrow 4\ CO_2 + 4\ H_2O$
or $C_4H_8 + 6\ O_2 \rightarrow 4\ CO_2 + 4\ H_2O$
Masses 56 kg 192 kg

Theoretical amount of O_2 needed for complete combustion of this gas mixture

$$6(32 \text{ kg } O_2)/(56 \text{ kg gas}) = 192 \text{ kg } O_2/(56 \text{ kg gas}) = 3.429 \text{ kg } O_2/\text{kg gas}$$

For 1000 kg of gas mixture, the oxygen required

$$(1000 \text{ kg gas})(3.429 \text{ kg } O_2/\text{kg gas}) = 3{,}429 \text{ kg } O_2$$

The mass fraction of oxygen in dry air is 0.232, so the mass of air required is

$$(3{,}429 \text{ kg } O_2)/0.232 = 14{,}780 \text{ kg air}$$

b) To keep the numbers simple, use a basis of 10 moles of gas mixture.

10 moles total = 7 moles of aliphatics + 3 moles of aromatics

The empirical stoichiometry is

Aliphatics: $7\ C_3H_7 + 7(4.75)\ O_2 \rightarrow 7(3)\ CO_2 + 7(3.5)\ H_2O$

$C_{21}H_{49} + 33.25\ O_2 \rightarrow 21\ CO_2 + 24.5\ H_2O$

Aromatics: $3\ CH + 3\ (1.25\ O_2) \rightarrow 3CO_2 + 3(0.5\ H_2O)$

$C_3H_3 + 3.75\ O_2 \rightarrow 3\ CO_2 + 1.5\ H_2O$

Overall reaction: $C_{24}H_{52} + 37\ O_2 \rightarrow 24\ CO_2 + 26\ H_2O$

Masses 340 kg 1,184 kg

Theoretical amount of O_2 needed for complete combustion of this gas mixture

$$(1{,}184 \text{ kg } O_2/340 \text{ kg gas}) = 3.482 \text{ kg } O_2/\text{kg gas}$$

For 1000 kg of gas, the oxygen required

$$(1000 \text{ kg gas})(3.482 \text{ kg } O_2/\text{kg gas}) = 3{,}482 \text{ kg } O_2$$

The mass fraction of oxygen in dry air is 0.232, so the mass of air required is

$$(3{,}482 \text{ kg } O_2)/0.232 = 15{,}010 \text{ kg air}$$

7.8 COMBUSTION OF A HYDROCARBON MIXTURE II

A combustible gas is a mixture of equal parts (by volume) of these generic aliphatic and aromatic compounds.

Aliphatics: $CH_3 + 1.75\ O_2 \rightarrow CO_2 + 1.5\ H_2O$

Aromatics: $CH + 1.25\ O_2 \rightarrow CO_2 + 0.5\ H_2O$

Use a basis of 1000 kg of gas mixture and

a) Calculate the stoichiometric amount of O_2 required, CO_2 produced, and H_2O produced for the combustion reaction.
b) If dry air is used for the oxidation, calculate the mass and volume of the dry gaseous exhaust from the combustion chamber.
c) Calculate the mass and volume of the dry gaseous exhaust from the combustion chamber assuming 10% excess air has been used to get a complete reaction.

For parts (b) and (c) assume all the exhaust gases behave as ideal gases. Do not include the water vapor. Report the volume as the standard conditions of 0°C and 1 atm.

Solution

a) The overall reaction is

$$C_2H_4 + 3\ O_2 \rightarrow 2\ CO_2 + 2\ H_2O$$

or $CH_2 + 1.5\ O_2 \rightarrow CO_2 + H_2O$

Masses (kg) 14 48 44 18

Stoichiometric amounts of oxygen, carbon dioxide, and water vapor

O_2 required = 48 kg O_2/(14 kg gas) = 3.429 kg O_2/kg gas
CO_2 produced = 44 kg CO_2/14 kg gas = 3.143 kg CO_2/kg gas
H_2O produced = 18 kg H_2O/14 kg gas = 1.286 kg H_2O/kg gas

Masses for combustion of 1000 kg of generic gas

O_2 required = (1000 kg gas)(3.429 kg O_2/kg gas) = 3,429 kg O_2
CO_2 produced = (1000 kg gas)(3.143 kg CO_2/kg gas) = 3,143 kg CO_2
H_2O produced = (1000 kg gas)(1.286 kg H_2O/kg gas) = 1,286 kg H_2O

b) Stoichiometric combustion with dry air

The mass fraction of oxygen in dry air is 0.232, so the mass of air required is

(3,429 kg O_2)/0.232 = 14,780 kg air

The mass fraction of nitrogen in dry air is 0.768, so the mass of nitrogen in the combustion is

0.768(14,780 kg air) = 11,350 kg N_2

Total exhaust gas = CO_2 + N_2 = 3,143 kg CO_2 + 11,350 kg N_2 = 14,493 kg exhaust gas

Moles of gas
1000 kg generic gas = 1000 kg/(14 kg/mol) = 71.43 mol
CO_2 produced = 71.43 kg mol CO_2 (1 mole per mole of generic gas)
O_2 consumed = (1.5 kg mol O_2/mol gas)(71.428 kg mol gas) = 107.14 mol O_2
N_2 in combustion air = (11,350 kg N_2)/(28 kg N_2/kg mol N_2) = 405.4 mol N_2
Total moles exhaust gas = 71.43 mol CO_2 + 405.4 mol N_2 = 477 mol exhaust gas

At normal temperature and pressure (0°C and 1 atm) one g-mole of any ideal gas has a volume of 22.4 L. One kg-mol has a volume of 22,400 L = 22.4 m^3.

Volume of exhaust gas at 0°C and 1 atm
= (22.4 m^3/kg mol)(477 kg mol exhaust gas)
= 10,680 m^3 exhaust gases (nitrogen plus carbon dioxide)

c) Adding 10% excess air will yield unburned oxygen in the exhaust gas stream and it will increase the nitrogen by 10%. The mass of CO_2 will not be changed.

Exhaust gas composition, by mass

Excess Oxygen = 0.1(3,429 kg O_2) = 342.9 kg O_2
Nitrogen = 1.1(11,350 kg N_2) = 12,485 kg N_2
CO_2 = 3,143 kg CO_2
Total mass = 15,971 kg exhaust gas

Exhaust gas composition, by volume

Excess Oxygen = (0.1)(107.14 kg mol O_2) = 10.71 kg mol unburned O_2

N_2 in combustion air = 1.1(405.4 kg N_2) = 445.9 kg mol N_2

CO_2 = 71.43 mol CO_2

Total exhaust gas = 528.1 mol

Volume of exhaust gas = (22.4 m^3/mol)(528.1 mol) = 11,830 m^3 exhaust gas

Mass fraction of dry exhaust gas:	78.2% N_2, 19.7% CO_2, 2.1% O_2
Volume fraction of dry exhaust gas:	84.4% N_2, 13.5% CO_2, 2.1% O_2

7.9 COMBUSTION STOICHIOMETRY

High temperature combustion with dry air involves hundreds of separate chemical reactions that are occurring simultaneously. We avoid dealing with this complexity by using an empirical stoichiometric relation, for example

$$C_xH_yS_zO_w + (x + y/4 + z - w/2)\ O_2 + (0.79/0.21)(x + y/4 + z - w/2)N_2$$
$$\rightarrow x\ CO_2 + 0.5y\ H_2O + z\ SO_2 + (0.79/0.21)(x + y/4 + z - w/2)N_2$$

Notice that nitrogen is non-reactive. Writing the reaction equation this way is a convenient means of including nitrogen in the mass balance. Usually sulfur dioxide is the dominant reaction product of sulfur, but there may be small amounts of other sulfur compounds, some of which will form vapor phase sulfuric acid when the combustion gas cools below 320°C (600°F). If chlorine or fluorine atoms are present they will form HCl. Our chemistry here ignores these possibilities, and it also ignores the formation of nitrogen oxides. For a gaseous mixture with empirical chemical formula $C_5H_{14}SO_2$ write the balanced combustion reaction and determine the oxygen requirement and sulfur dioxide production.

Solution

Balanced chemical reaction:

$x = 5$, $y = 14$, $z = 1$ and $w = 2$

$(x + y/4 + z - w/2) = 5 + 14/4 +1 - 2/2 = 8.5$

$(0.79/0.21)(x + y/4 + z - w/2) = (0.79/0.21)(8.5) = 32$

$$C_5H_{14}SO_2 + 8.5\ O_2 + 32\ N_2 \rightarrow 5\ CO_2 + 7\ H_2O + SO_2 + 32\ N_2$$

Empirical molar mass of gas

5(12 g C/mol C) + 1(14 g N/mol N)) + 32 g S/mol S + 2(16 g O/mol O)

= 138 g gas/mol gas

Oxygen requirement

8.5(32 g O_2/138 g gas) = 1.97 g O_2/g gas = 1.97 kg O_2/ kg gas

Molar mass of SO_2 = 32 g S/mol S + 2(16 g O/mol O) = 64 g SO_2/mol SO_2

Sulfur dioxide production

64 g SO_2/138 g gas = 0.464 g SO_2/g gas = 0.464 kg SO_2/kg gas

7.10 HAZARDOUS WASTE INCINERATION STOICHIOMETRY

A hazardous chlorinated hydrocarbon ($C_6H_3Cl_2$) is to be burned in air. (a) Write a balanced stoichometric equation for comlete combustion, including the nitrogen that is carried with the oxygen in the feed air. (b) The air quality standard is that the destruction percentage of this hydrocarbon is 99.99%. What concentration is emitted when the stack gas is adjusted to an oxygen content of 4% (molar basis).

Solution

a) The balanced combustion reaction

$$C_6H_3Cl_2 + a\,(O_2 + 3.76\,N_2) \rightarrow b\,CO_2 + c\,H_2O + d\,HCl + a(3.76)\,N_2$$

Balancing the elements:

C: $6 = b$ H: $3 = 2c + d$

Cl: $2 = d$ O: $2a = 2b + c$

from which $b = 6$, $d = 2$, $c = (3 - d)/2 = 0.5$, and $a = (2b + c)/2 = 6.25$

$$C_6H_3Cl_2 + 6.25\,(O_2 + 3.76\,N_2) \rightarrow 6\,CO_2 + 0.5\,H_2O + 2\,HCl + 23.5\,N_2$$

b) Stack gas hydrocarbon concentration at 4% oxygen

Total moles in the stack gas with no excess oxygen

= 6 + 0.5 + 2 + 23.5 = 32.5 mol gas

Let E = the added fraction of excess oxygen

$6.25E$ moles of O_2 are in the stack gas.

$6.25E(3.76)$ moles of N_2 in the stack gas.

Total moles in the stack gas products with excess oxygen

= 32.5 + 6.25E + 6.25E(3.76) mol gas

Specification is 4% oxygen in stack gas.

This is a volume fraction, which is also the mole fraction

Mole fraction oxygen in stack gas: $$0.04 = \frac{6.25\,E}{32.5 + 6.25\,E + 6.25(3.76\,E)}$$

Excess oxygen = $6.25E = 6.25(0.257) = 1.61$ mol O_2

Total moles oxygen input = 6.25 mol O_2 + 1.61 mol O_2 = 7.86 mol O_2

Balanced combustion reaction with excess oxygen (air)

$$C_6H_3Cl_2 + 7.86\,(O_2 + 3.76\,N_2) \rightarrow 6\,CO_2 + 0.5\,H_2O + 1.61\,O_2 + 2\,HCl + 29.55\,N_2$$

Total moles out with excess oxygen added = 6 + 0.5 + 1.61 + 2 + 29.55 = 39.66 mol gas

Check mole fraction O_2 = (1.61 mol O_2)/(39.66 mol gas) = 0.4 OK

At 99.99% hydrocarbon ($C_6H_3Cl_2$) destruction,

Moles $C_6H_3Cl_2$ in stack gas = 0.0001(1 mol Input) = 0.0001 mol $C_6H_3Cl_2$

Mole fraction $C_6H_3Cl_2$ in stack gas = (0.0001 mol $C_6H_3Cl_2$)/(39.66 mol gas) = 2.52×10^{-6}

ppmv concentration = mole fraction (10^6) = 2.52 ppmv

7.11 COMBUSTION TEMPERATURES

The necessary gas temperature for combustion is the *auto-ignition temperature* of the compounds that are most difficult to oxidize. For complete combustion thermal oxidizers operate at temperatures of at least 90°C–150°C above the auto-ignition temperatures, which would be in the range of 590°C–650°C, but higher temperatures are often used.

A mixture of the chemicals listed in Table P7.11 will be destroyed in a thermal oxidizer. (a) What is the minimum necessary temperature for combustion? (b) Recommend an operating temperature that will ensure complete combustion.

Compound	Auto-Ignition Temperature	
	(°F)	(°C)
Acetone	870	466
Acetonitrile	970	521
Isopropyl alcohol	780	416
Methanol	878	470
Methyl ethyl ketone (MEK)	759	404
Toluene	867	464

Table P7.11 Auto Ignition temperature of various chemicals

Solution

a) Acetonitrile controls at 521°C.
b) Add 150°C to get an operating temperature of 671°C

7.12 COMBUSTION CHAMBER VOLUME

The flow into a combustion chamber is 5.83 Nm^3/s, Combustion will occur at 900°C. What volume is required for the combustion chamber to have a residence time of one second?

Solution

The required volume of the combustion chamber is based on the actual volume of gas passing through the combustion chamber. The combustion is extremely fast and the gas temperature everywhere in the combustion chamber is 900°C. Therefore the actual gas volume flowing through the incinerator is the output flow of carbon dioxide, water vapor, sulfur dioxide gas, oxygen and nitrogen, which is 20,989 Nm^3/h = 350 Nm^3/min = 5.83 Nm^3/s

Convert from standard conditions (T = 0°C = 273K and 1 atm) to actual conditions.
Standard conditions are P_{Std} = 1 atm and T_{Std} = 0°C = 273K. Convert 900°C to Kelvins: T_{Actual} = 900 + 273 = 1173K. Assuming an actual pressure of P_{Actual} = 1.2 atm, the actual volumetric flow rate, Q_{Actual}, is

$$Q_{Actual} = Q_{STP}\,\frac{P_{Std}T_{Actual}}{P_{Actual}T_{Std}} = (5.83\ \text{m}^3/\text{s})\left(\frac{1\ \text{atm}}{1.2\ \text{atm}}\right)\left(\frac{1173\ \text{K}}{273\ \text{K}}\right) = 20.9\ \text{m}^3/\text{s}$$

The required volume of the combustion chamber for a residence time of θ = 1 second is

Combustion chamber volume = $V = Q_{Actual}/\theta$ = (20.9 m^3/s)/(1 s) = 20.9 m^3

7.13 HAZARDOUS WASTE INCINERATION

U. S. Federal performance standards require a 99.99 destruction and removal efficiency (DRE) of organic hazardous constituents, such as benzene, chlorobenzene, and toluene. Emissions of HCl are limited to 1.82 kg/h or 99% control. Particulates are restricted to 185 mg/m^3 (dry Normal cubic meters, dNm^3), corrected to 7% O_2. The gas mixture in Table P7.13 is being incinerated at 2000°F with 50% excess air and a residence time of 2.1 seconds. The flow rate of flue gas from the incinerator is 355 m^3/min. The O_2 concentration in the flue gas is 7%. (a) Calculate the DRE for each compound. (b) Determine if the emission meets the requirement for organics, particulates, and HCL.

Compound	Formula	Molar Mass (kg/kg mole)	Inlet (kg/h)	Outlet (kg/h)
Benzene	C_6H_6	78.11	916	0.24
Chlorobenzene	C_6H_5Cl	112.5	237.6	0.05
Ethylbenzene	C_8H_{10}	106.17	1014	0.34
Toluene	C_7H_8	92.10	289.5	0.01
Xylene	C_8H_{10}	106.17	10.7	0.06
Hydrochloric acid	HCl	36.45	35.7	0.10
Particulates			23.4	4.1

Table P7.13 Composition of mixture to be incinerated

Solution

a) Destruction and Removal Efficiency

$$DRE(\%) = 100\left(\frac{\text{Inlet - Outlet}}{\text{Inlet}}\right)$$

$$\text{DRE for benzene} = 100\left(\frac{916\text{ kg/h} - 0.24\text{ kg/h}}{916\text{ kg/h}}\right) = 99.9738$$

DRE < 99.99% so benzene emission does not meet the regulatory requirement.

The DREs for the remaining constituents are in Table S7.14. Only toluene meets the DRE.

Compound	Formula	Molar Mass (kg/mol)	Inlet (kg/h)	Outlet (kg/h)	DRE (%)
Benzene	C_6H_6	78.11	916	0.24	99.9738
Chlorobenzene	C_6H_5Cl	112.5	237.6	0.05	99.9790
Ethylbenzene	C_8H_{10}	106.17	1014	0.34	99.9665
Toluene	C_7H_8	92.10	289.5	0.01	99.9966
Xylene	C_8H_{10}	106.17	10.7	0.06	99.4393
Hydrochloric acid	HCl	36.45	35.7	0.10	
Particulates			23.4	4.1	

Table S7.13 DRE for emissions

b) Particulates out = (4.1 kg/h)/(60 min/h) = 0.0683 kg/min
(0.0683 kg/min)(10^6 mg/kg)/(355 m^3/min) = 192.5 mg/m^3
This does not meet the standard of 185 mg/m^3.
Concentration that will meet the standard is 3.94 kg/h.

c) The HCl emission rate is 0.10 kg/h, which does meet the requirement.

7.14 THERMAL OXIDATION

The combustion chamber of a thermal oxidation system has a volume of 0.2 m^3. It is fed a mixture of methane in air. Calculate the residence time for these two conditions.

a) The actual flow rate of 0.1 m^3/s.
b) The flow rate is 0.1 m^3/s at 0°C and 1 atm (STP). The conditions in the combustion chamber are 800 K and 2.5 atm.

Solution

a) Residence time for actual flow rate of 0.1 m^3/s

$$\text{Residence time} = \frac{\text{Volume of combustion chamber}}{\text{Actual volumetric flow rate}} = \frac{0.2\ \text{m}^3}{0.1\ \text{m}^3/\text{s}} = 2\ \text{s}$$

b) Calculate the actual flow rate at the conditions in the combustion chamber.
Standard conditions: $T_{\text{Std}} = 0°\text{C} = 273\ \text{K}$, $P_{\text{Std}} = 1\ \text{atm}$
Actual conditions: $T_{\text{Actual}} = 800\ \text{K}$, $P_{\text{Actual}} = 2.5\ \text{atm}$

$$Q_{\text{Actual}} = Q_{\text{STP}} \frac{P_{\text{Std}} T_{\text{Actual}}}{P_{\text{Actual}} T_{\text{Std}}} = (0.1\ \text{m}^3/\text{s})\left(\frac{1\ \text{atm}}{2.5\ \text{atm}}\right)\left(\frac{800\ \text{K}}{273\ \text{K}}\right) = 0.117\ \text{m}^3/\text{s}$$

$$\text{Residence time} = \frac{0.2\ \text{m}^3}{0.117\ \text{m}^3/\text{s}} = 1.71\ \text{s}$$

7.15 THERMAL INCINERATION

A thermal oxidizer treats 5,000 acfm of a 120°F air mixture that contains 1500 ppmv benzene (C_6H_6) and 500 ppmv carbon tetrachloride (CCl_4). The oxidizer fuel is methane (CH_4) and the operating temperature of the oxidizer is 1,400°F. The combustion of carbon tetrachloride releases chlorine that reacts with moisture in the exhaust gas to form hydrochloric acid (HCl).

a) How much methane fuel is required to achieve the combustion temperature?
b) Is there sufficient oxygen in the air mixture to operate at 125% of the stoichiometric air requirement to burn the methane?
c) Calculate the concentration of HCl in the exhaust gas.

Solution

Basis: 1 minute of operation
Assume a gross heating value for methane = 1050 Btu/scf
Standard conditions: 68°F and 1 atm
Properties of the air mixture are the same as air
Density of dry air = 0.075 lb/ft^3 at 68°F
Dry air is 21% O_2 and 79% N_2 by volume
The gas mixture and components act as ideal gases; 385.4 scf/lb mol.

Calculate the volumetric and molar flow rates of the components of the air mixture at standard conditions (68°F and 1 atm).

$$\text{Air mixture flow (scfm)} = (5{,}000\ \text{acfm})\left(\frac{460°\text{R} + 68°\text{F}}{460°\text{R} + 120°\text{F}}\right) = 4{,}522\ \text{scfm}$$

The air mixture consists of the benzene and carbon tetrachloride contaminants and air (oxygen and nitrogen). The volumetric flow rates are:

Benzene = (1500 ppmv)(4,552 scfm)/1,000,000 = 6.8 scfm
Carbon tetrachloride = (500 ppmv)(4,552 scfm)/1,000,000 = 2.3 scfm
Air = 4,552 scfm – 6.8 scfm – 2.3 scfm = 4,543 scfm
Oxygen = 0.21(4,543 scfm) = 954 scfm
Nitrogen = 0.79(4,543 scfm) = 3,589 scfm

The molar flow rates are:

Benzene = (6.8 scfm)/(385.4 scf/lb mol) = 0.0176 lb mol/min
Carbon tetrachloride = (2.3 scfm)/(385.4 scf/lb mol) = 0.0060 lb mol/min
Oxygen = (954 scfm)/(385.4 scf/lb mol) = 2.4753 lb mol/min
Nitrogen = (3589 scfm)/(385.4 scf/lb mol) = 10.0140 lb mol/min

a) Methane fuel requirement.

Mass flow rate of air mixture:

$m = (4{,}552 \text{ scfm})(0.075 \text{ lb/ft}^3) = 341 \text{ lb/min}$

Heat input required $Q = mc_p(\Delta T)$

The specific heat of air varies from about 0.24 Btu/lb°F at 100°F to about 0.275 Btu/lb°F at 1,400°F, so use an average of 0.257 for the calculation.

$Q = mc_p(\Delta T)$
$= (341 \text{ lb/min})(0.257 \text{ Btu/lb°F})(1{,}400\text{°F} – 120 \text{°F}) = 112{,}200 \text{ Btu/min}$

Methane required at standard conditions = (112,200 Btu/min)/(1050 Btu/scf) = 107 scfm
= (107 scfm/(385.4 scf/lb-mol) = 0.278 lb mol CH_4/min

b) Can combustion oxygen requirements be met by oxygen in air mixture?

Combustion reactions

Methane $CH_4 + 2\,O_2 \rightarrow CO_2 + 2H_2O$
Benzene $C_6H_6 + 7.5O_2 \rightarrow 6CO_2 + 3H_2O$
Carbon tet. $CCl_4 + 2H_2O \rightarrow CO_2 + 4\,HCl$

Stoichiometric amount of oxygen required for combustion

Methane requires 2 mol O_2 per 1 mol of CH_4
(2 mol O_2/mol CH_4)(0.278 mol CH_4/min) = 0.556 mol O_2/min
Benzene requires 7.5 mol O_2/mol benzene
(7.5 mol O_2/mol benzene)(0.0176 mol benzene/min) = 0.132 mol O_2/min
Total = 0.556 + 0.132 - = 0.688 lb mol O_2/min

Oxygen available in gas stream = 2.4753 lb mol/min
Yes, the available oxygen is over three times the required amount.

c) Concentration of HCl in exhaust gas

Composition of exhaust gas

= N_2 and excess O_2 in heated air and combustion products CO_2, H_2O, and HCl.

Nitrogen = 10.0140 lb mol/min

Oxygen = 2.4753 lb mol/min - 0.688 lb mol/min = 1.79 lb mol O_2/min

Carbon dioxide

From CH_4: (1 mol CO_2/mol CH_4)(0.278 mol CH_4/min) = 0.278 mol CO_2/min

From C_6H_6: (6 mol CO_2/mol C_6H_6)(0.0176 mol C_6H_6/min) = 0.1056 mol CO_2/min

From CCl_4: (1 mol CO_2/mol CCl_4)(0.0060 mol CCl_4/min) = 0.006 mol CO_2/min

Total CO_2 = 0.390 lb mol/min

Water vapor

From CH_4: (2 mol H_2O/mol CH_4)(0.278 mol CH_4/min) = 0.556 mol H_2O /min

From C_6H_6: (3 mol H_2O /mol C_6H_6)(0.0176 mol C_6H_6/min) = 0.053 mol H_2O /min

Lost to CCl_4: (2 mol H_2O/mol CCl_4)(0.0060 mol CCl_4/min) = 0.012 mol H_2O /min

Total H_2O = 0.556 + 0.053 – 0.012 = 0.60 lb mol H_2O/min

Hydrochloric acid

From CCl_4: (4 mol HCl/mol CCl_4)(0.0060 mol CCl_4/min) = 0.024 mol HCl/min

Total mol in exhaust gas = 10.01 + 1.79 +0.390 + 0.60 + 0.024 = 12.81 mol

Mole fraction HCl = (0.024 mol HCl)/(12.81 mol gas) = 0.001873 = 1873 ppmv

7.16 CATALYTIC COMBUSTION

The time-temperature requirements for 99% destruction by catalytic oxidation for four chemicals are given in Table P7.16.

a) What is the minimum residence time operating temperature for combustion a mixture of (1) benzene and carbon tetrachloride, (2) benzene and MEK, and (3) acetaldehyde and carbon tetrachloride?

b) For each mixture in part (a) calculate the required residence time for a flow of 10 Nm^3/s. The pressure of the feed stream and the combustion chamber is 4 atm. Calculate the required volume of the catalytic oxidation chamber for each mixture.

Compound	Temperature (°C)	Residence Time (s)
Benzene	235	0.1
Carbon tetrachloride	370	0.23
Methyl ethyl ketone (MEK)	320	0.1
Acetaldehyde	260	0.17

Table P7.16 Temperature and time requirements for 99% DRE

Solution

a) Minimum residence time operating temperature for various mixtures (higher values control).

1) Benzene and carbon tetrachloride 370°C for 0.23 sec
2) Benzene and MEK 320°C for 0.1 sec
3) Acetaldehyde and carbon tetrachloride 370°C for 0.23 sec

b) Given a flow of 10 Nm^3/s and 4 atm, the actual flow rate for the mixture of benzene and carbon tetrachloride is

$$Q_{\text{Actual}} = Q_{\text{Std}} \frac{P_{\text{Std}}}{P_{\text{Actual}}} \frac{T_{\text{Actual}}}{T_{\text{Std}}} = \left(10\ \text{m}^3/\text{s}\right)\left(\frac{1\ \text{atm}}{4\ \text{atm}}\right)\left(\frac{370°\text{C} + 273\ \text{K}}{273\ \text{K}}\right) = 5.89\ \text{m}^3/\text{s}$$

Combustion chamber volume

$$\text{Volume} = (\text{Actual flow rate})(\text{Reaction time}) = (5.89\ \text{m}^3/\text{s})(0.23\ \text{s}) = 1.35\ \text{m}^3$$

Calculations for the remaining mixtures are in Table S7.16.

Compound	Temp. (°C)	Time (s)	Flow (m^3/s)	Volume (m^3)
Benzene + Carbon tetrachloride	370	0.23	5.89	1.35
Benzene + Methyl ethyl ketone (MEK)	320	0.1	5.43	0.54
Acetaldehyde + Carbon tetrachloride	370	0.23	5.89	1.35

Table S7.16

7.17 MEAT PACKING PLANT ODOR CONTROL

The 5000 acfm air exhaust from a meat processing plant causes an odor problem in the neighborhood. The company plans to oxidize the odorous compounds using natural gas to raise the waste gas from a temperature of 90°F to the required temperature of 1200°F. The higher heating value (HHV) of natural gas is 1,059 Btu/scf. Assume no heat losses. How much natural gas (scfm) is required for this oxidation?

Solution

Basis: 1 hour of operation
Standard conditions: 68°F and 1 atm
Density of dry air = 0.075 lb/ft^3 at 68°F
Convert the gas flow rate to standard conditions (68°F and 1 atm) to calculate mass flow rate

$$\text{Gas flow (scfm)} = (5{,}000\text{ acfm})\left(\frac{460°\text{R} + 68°\text{F}}{460°\text{R} + 90°\text{F}}\right)\left(\frac{60\text{ min}}{\text{h}}\right) = 288{,}000\text{ ft}^3/\text{h}$$

Mass flow rate:

$$M = (288{,}000\text{ ft}^3/\text{h})(0.075\text{ lb/ft}^3) = 21{,}600\text{ lb/h}$$

Heat input required $Q = mc_p(\Delta T)$

Specific heat of air varies from 0.24 Btu/lb°F at 32°F to 0.27 Btu/lb°F at 1,200°F.
Use an average of 0.255 Btu/lb°F.

$$Q = mc_p(\Delta T) = (21{,}600\text{ lb/h})(0.255\text{ Btu/lb°F})(1{,}200°\text{F} – 90\text{ °F}) = 6{,}114{,}000\text{ Btu/h}$$

Natural gas required at standard conditions

= (6,114,000 Btu/h)/(1059 Btu/scf) = 5,773 scf/h = 96.2 scf/m

7.18 PULPING PLANT ODOR CONTROL

The actual 500 m^3/min exhaust from a pulping plant causes an odor problem in the neighborhood. The company plans to oxidize the odorous compounds using natural gas to raise the waste gas from a temperature of 35°C to the required temperature of 800°C. The gross heating value of natural gas is 39 MJ/Nm^3. Assume no heat losses. How much natural gas (Nm^3/min) is required for this oxidation?

Solution

Basis: 1 hour of operation

Standard conditions: 0°C and 1 atm

Density of dry air at 1 atm and 0°C = 1.17 kg/m^3

Convert the gas flow rate to standard conditions (0°C and 1 atm) to calculate mass flow rate

$$\text{Gas flow (Nm}^3\text{/min)} = (500\ \text{m}^3\text{/min})\left(\frac{273\ \text{K}}{273\ \text{K} + 35^\circ\text{C}}\right)\left(\frac{60\ \text{min}}{\text{h}}\right) = 26{,}590\ \text{Nm}^3/\text{h}$$

Mass flow rate:

$$m = (26{,}590\ \text{Nm}^3\text{/h})(1.17\ \text{kg/Nm}^3) = 31{,}100\ \text{kg/h}$$

Heat input required $Q = mc_p(\Delta T)$

Specific heat of air varies from 1.005 kJ/kg°C at 0°C to 1.12 kJ/kg°C at 800°C;
Use an average of 1.06 kJ/kg°C.

$$Q = mc_p(\Delta T) = (31{,}100\ \text{kg/h})(1.06\ \text{kJ/kg}^\circ\text{C})(800^\circ\text{C} - 35\ ^\circ\text{C})$$
$$= 25{,}220{,}000\ \text{kJ/h} = 25{,}220\ \text{MJ/h}$$

Natural gas required (standard conditions) = (25,220 MJ/h)/(39 MJ/Nm^3)
= 647 Nm^3/h = 10.8 Nm^3/min

7.19 BURNING WASTE GAS

A waste gas at temperature 30° contains methane (CH_4) hydrogen sulfide (H_2S), methyl mercaptan (CH_3SH) and dimethyl sulfide (CH_3SCH_3) in the amounts shown in Table P7.19 The odorous sulfur compounds will be destroyed by thermal oxidation at 900°C, with a 1 second reaction time in the combustion chamber.

Inputs			Outputs	
Component	**Flow rate (Nm³/h)**	**HHV (kJ/kg)**	**Component**	**c_P (kJ/kg°C)**
Waste Gas			Combustion Gas	
CH_4	50	50,090	CO_2	1.062
H_2S	5	15,230	H_2O	2.201
CH_3SH	30	23,520	SO_2	0.765
CH_3SCH_3	40	23,270	O_2	1.017
Air	2,000	NA	N_2	1.122
			Air	1.098
Total	2,125			
c_P is the average value over the temperature range 30°C to 900°C				

Table P7.19 Flow and thermodynamic data for waste gas and combustion products

a) Use the material balance to compute the stoichiometric oxygen requirement for complete combustion of the waste gases. Is there sufficient oxygen in the waste gas air to meet the stoichiometric requirement? Complete the entries in Table P7.19(a) to show air requirements, including additional air if needed, and the output combustion products.

Inputs				Outputs		
Component	Flow rate (Nm^3/h)	Flow rate (kg/h)	Oxygen Required (kg/h)	Component	Flow rate (Nm^3/h)	Flow rate (kg/h)
Waste Gas				Output Gas		
CH_4	50			CO_2		
H_2S	5			H_2O		
CH_3SH	30			SO_2		
CH_3SCH_3	40					
Waste Gas Air	2,000					
O_2 in waste gas				O_2		
N_2 in waste gas				N_2		
Additional Air for O_2 Stoichiometry						
O_2 in added air				O_2		
N_2 in added air				N_2		
Total						

Table P7.19(a) Material balance for waste gas combustion

b) Using the input and output flows from the material balance, make a preliminary energy balance by completing the entries in Table P7.19(b). Then refine the balance by adding in the amount of dilution air or auxiliary fuel (methane) required to balance the energy inputs and outputs.

Inputs				
Component	**Flow rate (Nm³/h)**	**Flow rate (kg/h)**	**Heating value (kJ/kg)**	**Energy released (kJ/h)**
Waste Gas				
CH_4	50		50,090	
H_2S	5		15,230	
CH_3SH	30		23,520	
CH_3SCH_3	40		23,270	
Waste Gas Air	2,000		NA	
O_2 in waste gas air			NA	
N_2 in waste gas air			NA	
Totals				
Outputs				
Component	**Flow Rate (Nm³/h)**	**Flow Rate (kg/h)**	**c_p (kJ/kg°C)**	**Energy in exit gases (kJ/h)**
CO_2			1.062	
H_2O			2.201	
SO_2			0.765	
O_2			1.017	
N_2			1.122	
Totals				
(a) Inlet temperature of gases = 30°C; Outlet temperature = 900°C, ΔT = 900-30 = 870°C				

Table P7.19(b) Energy balance for waste gas combustion

Solution

a) Material balance

Balanced combustion equations for the four waste gas components

Methane	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
Hydrogen sulfide	$H_2S + 1.5O_2 \rightarrow H_2O + SO_2$
Methyl mercaptan	$CH_3SH + 3O_2 \rightarrow CO_2 + 2H_2O + SO_2$
Dimethyl sulfide	$CH_3SCH_3 + 4.5O_2 \rightarrow 2CO_2 + 3H_2O + SO_2$

First, calculate the mass flows of the four waste gas components.

Methane	$(50\ Nm^3/h)(1\ mol/22.41\ Nm^3)(16\ kg/mol) = 35.7\ kg/h$
Hydrogen sulfide	$(5\ Nm^3/h)(1\ mol/22.41\ Nm^3)(34\ kg/mol) = 7.6\ kg/h$
Methyl mercaptan	$(30\ Nm^3/h)(1\ mol/22.41\ Nm^3)(48\ kg/mol) = 64.3\ kg/h$
Dimethyl sulfide	$(40\ Nm^3/h)(1\ mol/22.41\ Nm^3)(62\ kg/mol) = 110.7\ kg/h$

Second, calculate the stoichiometric oxygen requirements for each waste gas component.

The oxygen requirements are computed from the balanced stoichiometric reaction for each waste gas component and their mass flow rates. For example, the combustion of methyl mercaptan (CH_3SH) is

	CH_3SH	+	$3\ O_2$	$\rightarrow$	CO_2	+	$2\ H_2O$	+	SO_2
Molar masses (kg/mol)	48		3(32)		44		2(18)		64
Mass flow rates (kg/h)	64.3		128.5		58.9		48.2		85.7

The mass flow rate of methyl mercaptan in the waste gas is 64.3 kg/h and the quantities of the other constituents, obtained by simple proportion with their molar masses, are 128.5 kg/h O_2, 58.9 kg/h CO_2, 48.2 kg/h H_2O, and 85.7 kg/h SO_2.

Summing over all waste gas components stream gives 539 kg O_2/h.

Third, calculate the mass of oxygen in the waste gas air. Assume air is 20.9% O_2 and 79.1% N_2 by volume.

$$\text{Oxygen in waste gas air} = 2000\ Nm^3/h\ (0.209) = 418\ Nm^3/h$$
$$= (418\ Nm^3/h)(1\ mol/22.41\ Nm^3)(32\ kg/mol) = 597\ kg\ O_2/h$$

The air in the waste gas stream (597 kg O_2/h) is well above the stoichiometric requirement (539 kg O_2/h) to combust all the waste compounds, so no additional air is required.

Table S7.19(a) gives the air requirements and combustion products.

Inputs				**Outputs**		
Component	**Flow rate (Nm^3/h)**	**Flow rate (kg/h)**	**Oxygen Required (kg/h)**	**Component**	**Flow rate (Nm^3/h)**	**Flow rate (kg/h)**
Waste Gas	50	35.7	142.8	Output Gas	160	314.1
CH_4				CO_2		
H_2S	5	7.6	10.7	H_2O	285	228.9
CH_3SH	30	64.3	128.5	SO_2	75	214.2
CH_3SCH_3	40	110.7	257.0			
Waste Gas Air (a)	2,000	2,574				
O_2 in waste gas	418	597		O_2	40.5	57.8
N_2 in waste gas	1,582	1,977		N_2	1,582	1,977
Additional Air for O_2 Stoichiometry	None					
O_2 in added air				O_2		
N_2 in added air				N_2		
Total		2,792	539			2,792
(a) Calculations made assuming air is 20.9% oxygen and 79.1% nitrogen by volume.						

Table S7.19(a)

b) Energy Balance

Preliminary energy balance

First, calculate the input energy released from the combustion of the waste gas components, for example for the methane component.

Energy released = (Mass flow rate)(Heat of combustion)
= (35.7 kg/h)(50,100 kJ/kg) = 1,788,000 kJ/h

Second, calculate the energy in the exiting gases, for example for CO_2

Exiting energy = (Mass flow rate)(Specific heat)(Temperature difference)

$= mc_P\Delta T$

= (314.1 kg/h)(1.062 kJ/kg°C)(900°C – 30°C) = 290,200 kJ/h

The preliminary energy balance results (spreadsheet calculations) for all inputs and outputs are shown in Table S7.19(b)

Inputs				
Component	**Flow rate (Nm³/h)**	**Flow rate (kg/h)**	**Heating value (kJ/kg)**	**Total heat released (kJ/h)**
Waste Gas				
CH_4	50	35.7	50,090	1,788,000
H_2S	5	7.6	15,230	116,000
CH_3SH	30	64.3	23,520	1,511,000
CH_3SCH_3	40	110.7	23,270	2,575,000
Waste Gas Air	2,000	2574	NA	
O_2 in waste gas air	418	597	NA	
N_2 in waste gas air	1,582	1977	NA	
Totals	2,125	2792		5,990,000

Outputs[a]				
Component	Flow Rate (Nm³/h)	Flow Rate (kg/h)	c_p (kJ/kg°C)	Total heat increase (kJ/h)
CO_2	160	314.1	1.062	290,000
H_2O	285	228.9	2.201	438,000
SO_2	75	214.2	0.765	143,000
O_2	40	57.8	1.017	51,000
N_2	1,582	1977	1.122	1,929,000
Totals	2,125	2,792		2,852,000

(a) Inlet temperature of gases = 30°C; Outlet temperature = 900°C, ΔT = 900-30 = 870°C

Table S7.19(b)

The preliminary balance shows that more heat energy is released in the combustion than is in the exiting gases. This means the temperature in the combustion chamber cannot be kept at 900°C, but will increase and potentially damage the equipment. Dilution air must be added to absorb the excess combustion heat energy to maintain the desired temperature.

Excess heat energy = 5,990,000 kJ/h – 2,852,000 kJ/h = 3,138,000 kJ/h

Required mass flow of air = $m = Q/c_p\Delta T$
= (3,138,000 kJ/h)/[(1.098 kJ/kg°C)(900°C – 30°C)] = 3,285 kg air/h
= (3,285 kg/h)/(28.84 kg/kg mol) = 114 kg-mol/h
= (114 kg-mol/h)(22.41 Nm^3/kg-mol) = 2,553 Nm^3/h

The mass flow of air is then partitioned into O_2 and N_2 to complete the revised energy balance. Assume composition of air by mass 23.1% O_2 and 76.9% N_2

Mass flow of O_2 = (0.231 kg O_2/kg air)(3,285 kg air/h) = 759 kg O_2/h
Mass flow of N_2 = (0.769 kg N_2/kg air)(3,285 kg air/h) = 2,526 kg N_2/h

These amounts of oxygen and nitrogen are added to the input and output gases. They have no heating value, but absorb heat from the combustion reaction. The nitrogen in the air, and the oxygen not used in the combustion reaction pass through the combustion chamber unaffected.

The final energy balance results (spreadsheet calculations) for all inputs and outputs are shown in Table S7.19(c).

Inputs				
Component	**Flow rate (Nm^3/h)**	**Flow rate (kg/h)**	**Heating value (kJ/kg)**	**Total heat released (kJ/h)**
Waste Gas				
CH_4	50	35.7	50,090	1,788,000
H_2S	5	7.6	15,230	116,000
CH_3SH	30	64.3	23,520	1,511,000
CH_3SCH_3	40	110.7	23,270	2,575,000
Waste Gas Air	2,000	2574	NA	
O_2 in waste gas air	418	597	NA	
N_2 in waste gas air	1,582	1977	NA	
Dilution air	2,553	3,285	NA	
O_2 in dilution air	531	759		
N_2 in dilution air	2022	2,526		
Totals		6,077		5,990,000

Outputsa				
Component	**Flow Rate (Nm³/h)**	**Flow Rate (kg/h)**	**c_P (kJ/kg°C)**	**Total heat increase (kJ/h)**
CO_2	160	314.1	1.062	290,000
H_2O	285	228.9	2.201	438,000
SO_2	75	214.2	0.765	143,000
O_2	40	57.8	1.017	51,000
N_2	1,582	1977	1.122	1,929,000
Dilution air				
O_2 in dilution air	531	759	1.017	671,000
N_2 in dilution air	2,022	2,526	1.122	2,466,000
Totals		6,077		5,989,000
(a) Inlet temperature of gases = 30°C; Outlet temperature = 900°C, ΔT = 900-30 = 870°C				

Table S7.19(c)

7.20 HEAT RECOVERY I

Waste gas (Figure P7.20) is pre-heated from 20°C to 350°C before injection into a thermal oxidizer that exhausts flue gas at 600°C. The volumetric flow of flue gas, measured as Nm^3, is 50% more than the preheated waste gas, also measured as Nm^3. Estimate the *thermal recovery efficiency* of the preheater.

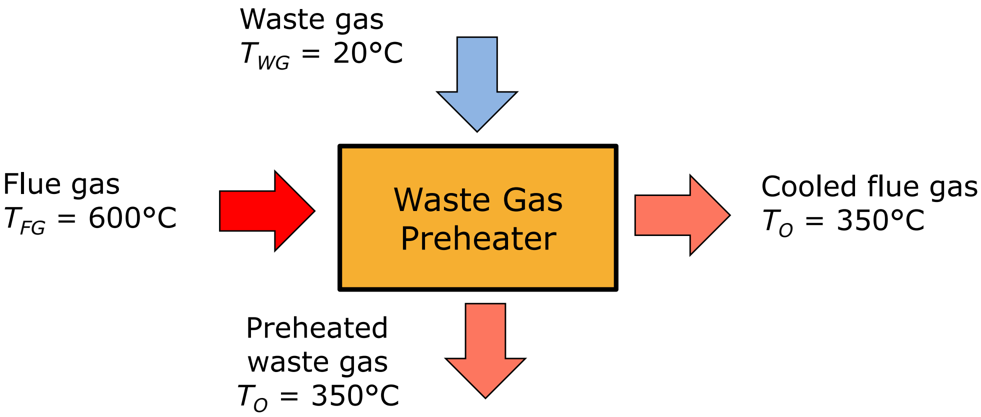


Figure P7.20 Preheating waste gas for thermal oxidation

Solution

For convenience in estimating the efficiency, assume that the cooled flue gas temperature is the same as the heated waste gas temperature, T_O= 350°C.

Because the waste gas and flue gas are nearly 100% air the densities and specific heats can be assumed nearly equal. The thermal recovery efficiency simplifies to

$$\eta_{TRE} = \frac{Q_{\text{Actual}}}{Q_{\text{Max possible}}} = \frac{F_{WG}\left(T_O - T_{WG}\right)}{F_{FG}\left(T_{FG} - T_{WG}\right)}$$

For $F_{FG} = 1.5F_{WG}$, T_{WG} = 20°C. T_O = 350°C, and T_{FG} = 600°C

$$\eta_{TRE} = \frac{F_{WG}\left(350°\text{C} - 20°\text{C}\right)}{1.5\,F_{WG}\left(600°\text{C} - 20°\text{C}\right)} = 0.38$$

7.21 HEAT RECOVERY II

Waste gas (Figure P7.21) is pre-heated from 30°C before injection into a thermal oxidizer that exhausts flue gas at 650°C. The volumetric flow of flue gas, measured as Nm^3, is the same as the preheated waste gas, also measured as Nm^3. For a *thermal recovery efficiency* of 70%, estimate the preheated waste gas temperature. T_O.

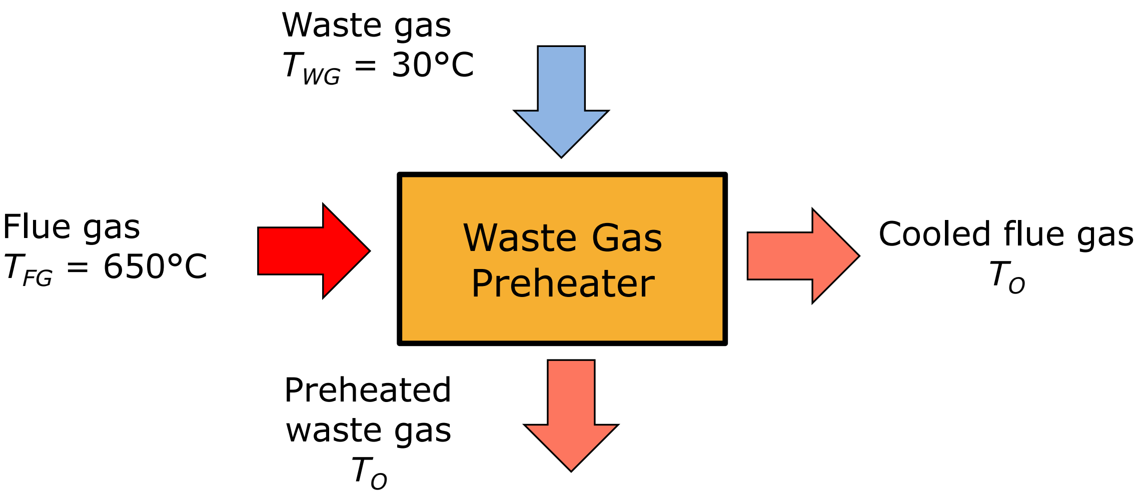


Figure P7.21 Preheating waste gas for thermal oxidation

Solution

The simplified equation for thermal recovery efficiency is

$$\eta_{TRE} = \frac{Q_{\text{Actual}}}{Q_{\text{Max possible}}} = \frac{F_{WG}\left(T_O - T_{WG}\right)}{F_{FG}\left(T_{FG} - T_{WG}\right)}$$

For $F_{FG} = F_{WG}$, T_{WG} = 30°C, T_{FG} = 650°C, and $\eta_{TRE} = 0.7$

$$\eta_{TRE} = 0.70 = \frac{\left(T_O - 30°\text{C}\right)}{\left(650°\text{C} - 30°\text{C}\right)} \quad \rightarrow \quad T_O = 464°\text{C}$$

7.22 COMBUSTION FUEL REQUIREMENT

Preheated waste gas (F_{WG} = 18,000 scfm, T_{WG} = 1000°F) is to be burned with methane (T_F = 80°F) in a combustion chamber operating at 1650°F, as shown in Figure P7.22. Determine the methane requirement (scfm), assuming 10% heat loss in the combustion chamber. The preheated waste gas has a heating value of 5.5 Btu/scf, with density (0.0739 lb/scf) and specific heat (0.255 Btu/lb°F) similar to air.

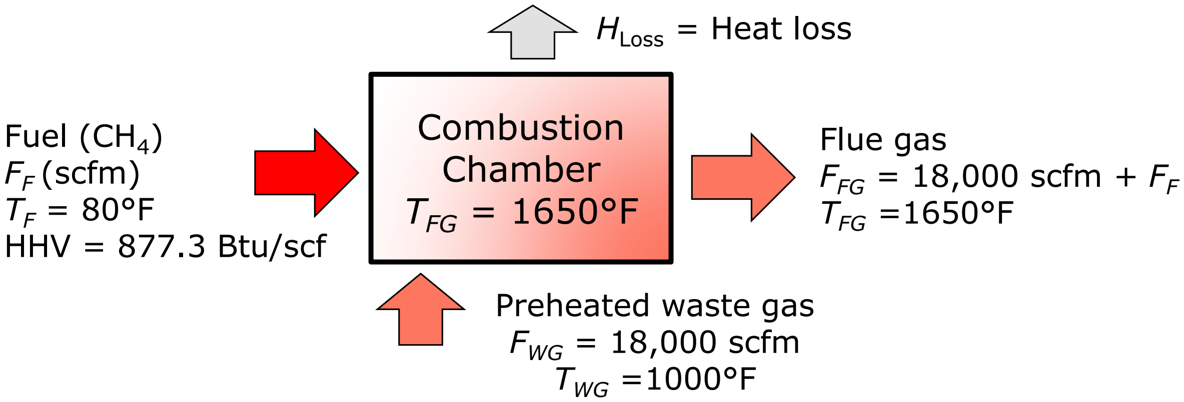


Figure P7.22 Definition diagram for the energy balance on the combustion chamber to calculate the methane fuel requirement (scfm).

Solution

The overall energy balance is

$$H_{WG} + H_F = Q_{FG} + H_{Loss}$$

where

H_{WG} is the heat from combustion of the waste gas (benzene and methyl chloride)
H_F is the heat supplied by the methane fuel
Q_{FG} = sensible heat flow in the flue gas (Btu/min)
The subscripts indicate waste gas (*WG*), flue gas (*FG*), and fuel (*F*)

The heat loss (H_{Loss}) is assumed as 10% of the heat energy in the combustion chamber flue gas ($0.1Q_{FG}$), so the energy balance simplifies to

$$H_{WG} + H_F = 1.1Q_{FG}$$

The quantities are

$$H_{WG} = (18{,}000 \text{ scfm})(5.5 \text{ Btu/scf}) = 99{,}000 \text{ Btu/min}$$

$$H_F = (F_F)(877.3 \text{ Btu/scf}) = 877.3(F_F) \text{ Btu/scf}$$

$$\begin{aligned} Q_{FG} &= (18{,}000 \text{ scfm})(0.0739 \text{ lb/scf})(0.255 \text{ Btu/lb°F})(1650°\text{F} - 1000°\text{F}) \\ &\quad + (F_F)(0.0739 \text{ lb/scf})(0.255 \text{ Btu/lb°F})(1650°\text{F} - 80°\text{F}) \\ &= 220{,}480 + 29.6F_F \end{aligned}$$

$$H_{\text{Loss}} = 0.1Q_{FG} = 22{,}048 + 2.96F_F$$

Using these values in the energy balance equation gives

$$99{,}000 + 877.3F_F = 220{,}480 + 29.6F_F + 22{,}048 + 2.96F_F$$

$$F_F = 143{,}528/844.7 = 170 \text{ scfm}$$

7.23 WASTE GAS OXIDATION

Benzene, toluene, ethylbenzene, and xylene are present in a ventilation gas, Figure P7.23, at concentrations of 500 ppmv, 400 ppmv, 200 ppmv, and 300 ppmv, respectively. The total ventilation gas flow rate is 500 Nm^3/min.

a) Is there any risk of explosion in the ventilation system?
b) Calculate the heating value (kJ/Nm^3) of the waste ventilation gas.
c) The waste ventilation gas is preheated from 35°C before being burned in a thermal oxidizer that exhausts flue gas at 700°C. If the thermal recovery efficiency of the preheater is 65% find the exit temperature of the preheated waste gas prior to injection into the thermal oxidizer.
d) Preheated waste gas is burned with methane (T_{Fuel} = 25°C) in a combustion chamber operating at 700°C. Determine the methane requirement (Nm^3/min), assuming 12% heat loss in the combustion chamber.

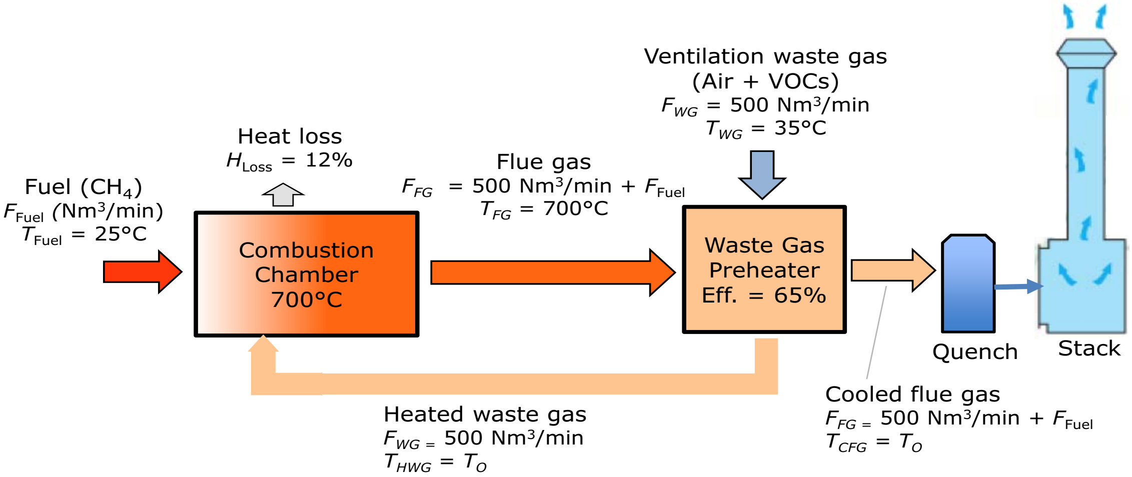


Figure P7.23

Solution

a) Explosive risk. LEL values are from Appendix 7.
The concentrations of all gases in the ventilation gas are well below the 25% LEL values and do not present any risk of explosion or accidental fires in the ventilation system.

Gas	LEL (ppmv)	25% LEL (ppmv)	Concentration (ppmv)
Benzene	13,500	3,375	500
Toluene	12,700	3,175	400
Ethylbenzene	10,000	2,500	200
Xylene	10,000	2,500	300

Table S7.23(a)

b) Heating value of ventilation gas: KJ/Nm^3. Heating values are from Appendix 4. Convert heating values from mass basis to volume basis.

Volumetric heating value = (mass heating value)(molar mass)/(22.41 Nm^3/mol)
Sample calculation for benzene
= (40,147 kJ/kg)(78 kg/mol)/(22.41 Nm^3/mol) = 139,735 kJ/Nm^3

Gas	Molar mass (kg/kg-mol)	Heat value (kJ/kg)	Heat value (kJ/Nm^3)
Benzene	78	40,147	139,735
Toluene	93	40,519	168,151
Ethylbenzene	106	40,938	193,638
Xylene	106	40,705	192,536
Methane	16	50,000	35,698

Table S7.23(b)

The ventilation gas composition is given by the ppmv concentrations
Volume fractions: 0.05% benzene, 0.04% toluene, 0.02% ethylbenzene, 0.03% xylene, and 99.86% air.

The heating value for the ventilation gas is the concentration weighted sum of the individual component heating values

$$= (0.0005)(139{,}735 \text{ kJ/Nm}^3) + (0.0004)(168{,}151 \text{ kJ/Nm}^3) + (0.0002)(193{,}638 \text{ kJ/Nm}^3) + (0.0003)(192{,}536 \text{ kJ/Nm}^3)$$

$$= 234 \text{ kJ/Nm}^3$$

c) Find T_O

The simplified equation for thermal recovery efficiency is

$$\eta_{TRE} = \frac{Q_{\text{Actual}}}{Q_{\text{Max possible}}} = \frac{F_{WG}\left(T_O - T_{WG}\right)}{F_{FG}\left(T_{FG} - T_{WG}\right)}$$

Assume the fuel requirement F_F will be small compared to the waste gas flow rate F_{WG} so that $F_{FG} = F_{WG}$. For $T_{WG} = 35°C$, $T_{FG} = 700°C$, and $\eta_{TRE} = 0.65$

$$\eta_{TRE} = 0.65 = \frac{\left(T_O - 35°C\right)}{\left(700°C - 35°C\right)} \quad \rightarrow \quad T_O = 467°C$$

d) Methane requirement

Densities and average specific heats are needed for the waste gas and methane over the temperature range of the combustion. The waste ventilation gas is mostly air, so use air values for the waste gas.

Gas	Density (kg/Nm³)	Specific heat (kJ/kg°K)		
	STP	T = 30°C	T = 400°C	T = 700°C
Air	1.293	1.012	1.075	1.144
Methane	0.717	2.226	2.525	3.602

Table S7.23(c)

The overall energy balance for the combustion chamber is

$$H_{WG} + H_{\text{Fuel}} = Q_{FG} + H_{\text{Loss}}$$

H_{WG} = heat supplied by combustion of the ventilation gas (kJ/min)

$$H_{WG} = (F_{WG})(\text{heat value}) = (500\ \text{Nm}^3/\text{min})(234\ \text{kJ/Nm}^3) = 116{,}810\ \text{kJ/min}$$

H_{Fuel} = heat supplied by the methane fuel (kJ/min)

$$H_{\text{Fuel}} = (F_{\text{Fuel}})(35{,}698\ \text{kJ/Nm}^3)$$

Q_{FG} = sensible heat flow in the flue gas (kJ/min)

$$Q_{FG} = F_{FG}(\rho_{FG})(c_{P,FG}) + F_{\text{Fuel}}(\rho_{\text{Fuel}})(c_{P,\text{Fuel}})$$

The densities are for standard conditions, and the specific heats are an average over the temperature range of the combustion.

For the flue gas $\rho_{FG} = 1.293\ \text{kg/Nm}^3$

Average $c_{P,FG} = (1.075 + 1.144)/2 = 1.110$ kJ/kg°K

For methane $\rho_{\text{Fuel}} = 0.717\ \text{kg/Nm}^3$

Average $c_{P,\text{Fuel}} = (2.226 + 3.602)/2 = 2.914$ kJ/kg°K

This gives

$$\begin{aligned} Q_{FG} &= (500\ \text{Nm}^3/\text{min})(1.293\ \text{kg/Nm}^3)(1.110\ \text{kJ/kg°K})(700°\text{C} - 467°\text{C}) \\ &\quad + (F_{\text{Fuel}})(0.717\ \text{kg/Nm}^3)(2.914\ \text{kJ/kg°K})(700°\text{C} - 25°\text{C}) \\ &= 167{,}200\ \text{kJ/min} + (1{,}410\ \text{kJ/Nm}^3)(F_{\text{Fuel}}) \end{aligned}$$

$H_{\text{Loss}} = (0.12)\ Q_{FG}$

Substitute in the energy balance and solve for the methane requirement F_{Fuel}

$$H_{WG} + H_{\text{Fuel}} = 1.12\ Q_{FG}$$

$$\begin{aligned} &116{,}810\ \text{kJ/min} + (F_{\text{Fuel}})(35{,}698\ \text{kJ/Nm}^3) \\ &\quad = 1.12[167{,}200\ \text{kJ/min} + (1{,}410\ \text{kJ/Nm}^3)F_{\text{Fuel}}] \end{aligned}$$

$$(34{,}119\ \text{kJ/Nm}^3)\ F_{\text{Fuel}} = 70{,}454\ \text{kJ/min}$$

$$F_{\text{Fuel}} = 2.06\ \text{Nm}^3/\text{min}$$

Note: Check assumption in part (c). $F_{\text{Fuel}} = 2.06\ \text{Nm}^3/\text{min}$ is less than 1% of $F_{WG} = 500\ \text{Nm}^3/\text{min}$, so that assumption that $F_{FG} = F_{WG}$ is OK.

8 ENERGY CONSERVATIVE DESIGN

8.1 COUNTERCURRENT HEAT EXCHANGER AREA

The countercurrent heat exchanger in Figure P8.1 will transfer Q = 28,000 MJ/h. The heat exchange coefficient is U = 1.6 MJ/h-m^2-°C. The operating temperatures are $T_{H,\text{In}}$ = 180°C, $T_{H,\text{Out}}$ = 80°C, $T_{C,\text{Out}}$ = 80°C , and $T_{C,\text{In}}$ = 20°C. Calculate the area of the heat transfer interface.

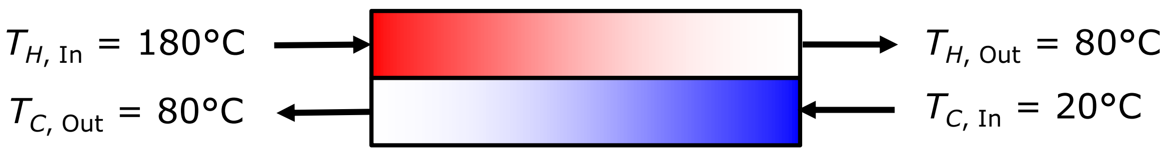


Figure P8.1 Countercurrent heat exchanger

Solution

Calculate the log-mean temperature difference to use in $Q = AU\Delta T_m$

$T_{H,\,\mathrm{In}}$ = 180°F $T_{H,\,\mathrm{Out}}$ = 80°F $T_{C,\,\mathrm{In}}$ = 20°F $T_{C,\,\mathrm{Out}}$ = 80°F

$T_{\mathrm{Max}} = T_{H,\,\mathrm{In}} - T_{C,\,\mathrm{Out}}$ = 180°F - 80°F = 100°F

$T_{\mathrm{Min}} = T_{H,\,\mathrm{Out}} - T_{C,\,\mathrm{In}}$ = 80°C – 20°C = 60°C

$$\Delta T_m = \frac{T_{\mathrm{Max}} - T_{\mathrm{Min}}}{\ln\left(T_{\mathrm{Max}} / T_{\mathrm{Min}}\right)} = \frac{100°\mathrm{C} - 60°\mathrm{C}}{\ln(100°\mathrm{C}/60°\mathrm{C})} = \frac{40°\mathrm{C}}{0.511} = 78.3°\mathrm{C}$$

$Q = AU\Delta T_m$ = (28,000 MJ/h) = A (1.6 MJ/h-m^2-°C)(78.3°C) = 125.3 A

A = 223 m^2

8.2 CO-CURRENT HEAT EXCHANGER AREA

The co-current heat exchanger in Figure P8.2 will transfer Q = 18,000 MJ/h. The heat exchange coefficient U = 2.0 MJ/h-m^2-°C. The operating temperatures are $T_{H,\,\mathrm{In}}$ = 90°C, $T_{H,\,\mathrm{Out}}$ = 40°C, $T_{C,\,\mathrm{In}}$ = 15°C, and $T_{C,\,\mathrm{Out}}$ = 30°C. Calculate the area of the heat transfer interface.

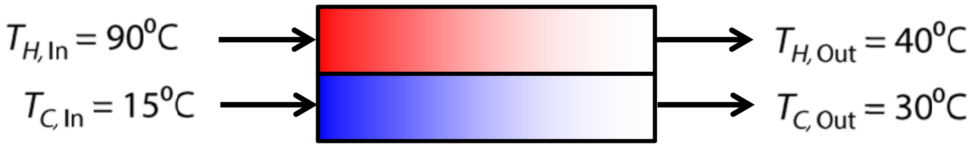


Figure P8.2 Co-current heat exchanger

Solution

$Q = A\ U\ \Delta T_m$

$T_{H,\,\mathrm{In}}$ = 90°C $T_{H,\,\mathrm{Out}}$ = 40°C $T_{C,\,\mathrm{In}}$ = 15° $T_{C,\,\mathrm{Out}}$ = 30°C

$T_{\mathrm{Max}} = T_{H,\,\mathrm{In}} - T_{C,\,\mathrm{In}}$ = 90°C - 15°C = 75°C

$T_{\mathrm{Min}} = T_{H,\,\mathrm{Out}} - T_{C,\,\mathrm{Out}}$ = 40°C – 30°C = 10°C

$$\Delta T_m = \frac{T_{\mathrm{Max}} - T_{\mathrm{Min}}}{\ln\left(T_{\mathrm{Max}}/T_{\mathrm{Min}}\right)} = \frac{75°\mathrm{C} - 10°\mathrm{C}}{\ln(75°\mathrm{C}\ /\ 10°\mathrm{C})} = \frac{65°\mathrm{C}}{2.015} = 32.3°\mathrm{C}$$

$A = Q/U\Delta T_m$ = (18,000 MJ/h)/[(2 MJ/h-m^2-°C)(32.3°C)] = 279 m^2

8.3 HEAT TRANSFER AREA

Calculate the heat transfer surface area of a heat exchanger that must transfer 5,000 Btu/min if the heat transfer coefficient is U = 28 Btu/h-ft^2-°F. The inlet temperature of the hot liquid is 140°F. The inlet cooling water temperature is 40°F. The temperatures of the hot liquid after cooling is 70°F. The exiting cooling water is a 52°F, respectively. Assume countercurrent flow of the liquid and the cooling water, as shown in Figure P8.3.

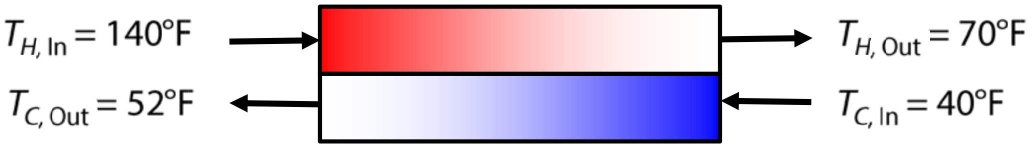


Figure P8.3 Countercurrent heat exchanger

Solution

$Q = A\ U\ \Delta T_m$

$T_{H, In}$ = 140°F $T_{H, Out}$ =70°F $T_{C, Out}$ = 52°F $T_{C, In}$ = 40°F

$T_{Max} = T_{H, In} - T_{C, Out}$ =140°F - 52°F = 88°F

$T_{Min} = T_{H, Out} - T_{C, In}$ = 70°F – 40°F = 30°F

$$\Delta T_m = \frac{T_{Max} - T_{Min}}{\ln(T_{Max}/T_{Min})} = \frac{88°F - 30°F}{\ln(88°F/30°F)} = \frac{50°F}{1.076} = 53.9°F$$

Q = (5,000 Btu/min)(60 min/h) = 300,000 Btu/h

A = (300,000 Btu/h)/((28 Btu/h-ft^2-°F)(53.9°F))

A = 199 ft^2

8.4 ODOR CONTROL

A wastewater treatment process vents 18,000 kg/h of 100°C steam at 2,257 kJ/kg heat energy. Heat energy can be recovered by condensing the steam and cooling it to 30°C. At the same time, this will solve a serious odor problem by condensing offensive compounds that are emitted with the steam. A condenser having a heat transfer coefficient U = 2400 kJ/h-m^2- °C can operate at a log mean temperature difference ΔT_m = 60°C. (a) How much heat energy must be removed to condense and cool the steam? (b) What is the required surface area of the heat exchanger.

Solution

Basis = 18,000 kg/h steam

a) Heat energy to be removed to condense and cool the steam/water

Latent heat to condense 100°C steam to 100°C liquid water = ΔH_v = 2,257 kJ/kg

$$Q_{\text{Cond}} = m\Delta H_v = (18{,}000\ \text{kg/h})(2{,}257\ \text{kJ/kg}) = 40{,}626{,}000\ \text{kJ/h}$$

To cool the 100°C water to 30°C (c_p = 4.167 kJ/kg°C)

$$Q_{\text{Cool}} = mc_p\Delta \text{T} = (18{,}000\ \text{kg/h})(4.167\ \text{kJ/kg°C})(100\text{°C} - 30\text{°F}) = 5{,}250{,}000\ \text{kJ/h}$$

Total heat transfer requirement

$$Q_{\text{Total}} = 40{,}626{,}000\ \text{kJ/h} + 5{,}250{,}000\ \text{kJ/h} = 45{,}876{,}000\ \text{kJ/h}$$

b) Surface area of heat exchanger

$$Q_{\text{Total}} = A\ U\ \Delta T_m$$

$$45{,}876{,}000\ \text{kJ/h} = A\ (2400\ \text{kJ/h-m}^2\text{- °C})(60\text{°C})$$

$$A = 319\ \text{m}^2$$

8.5 HEAT EXCHANGERS IN SERIES

The two heat exchangers in Figure P8.5 have equal heat exchange areas and are used in series to cool 1,500 kg/h of a fluid from 80°C to 64°C. The heat exchangers have the same heat exchange capacity. The heat capacity of this fluid is $c_{P,\ \mathrm{Hot}}$ = 3.5 kJ/kg/°C. The cold stream has $c_{P,\ \mathrm{Cold}}$ = 4 kJ/kg/°C. (a) Calculate the overall energy balance and determine the mass flow of cold fluid, m_{Cold}. (b) Calculate the temperatures T_C and T_H. (c) Is there any advantage to using heat exchangers in series rather than one larger unit?

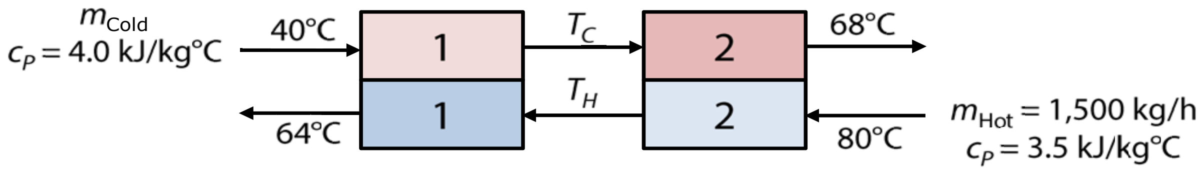


Figure P8.5 Heat exchangers in series

Solution

a) Overall energy balance

Energy In = Energy Out

Energy lost from hot stream = Energy gained by cold stream

$m_{\mathrm{Cold}}\ c_{P,\ \mathrm{Cold}}\ \Delta T_{\mathrm{Cold}} = m_{\mathrm{Hot}}\ c_{P,\ \mathrm{Hot}}\ \Delta T_{\mathrm{Hot}}$

m_{Cold} (4 kJ/kg°C)(68°C – 40°C) = m_{Hot} (3.5 kJ/kg°C)(80°C – 64°C)

112 m_{Cold} = 56 m_{Hot}

m_{Cold} = 0.5 (1,500 kg/h) = 750 kg/h

b) Calculate intermediate temperatures

m_{Hot} = 1500 kg/h

Heat removed from hot stream

ΔH_{Hot} = (1500 kg/h)(3.5 kJ/kg°C)(80°C – 64°C) = 84,000 kJ/h

Half of this will be removed in each exchanger:

42,000 kJ/h in unit 1 and 42,000 kJ/h in unit 2

Heat exchanger 1

(1500 kg/h)(3.5 kJ/kg°C)(T_H– 64°C) = 42,000 kJ/h

($T_{H\text{-}}$ 64°C) = (42,000 kJ/h)/(5,250kJ/h°C) = 8°C

T_H= 72°C (halfway between 80°C and 64°C

Likewise, T_C= 54°C is halfway between 40°C and 68°C

c) There is no thermodynamic advantage to having two heat exchangers. It may be desirable if the heat exchange capacity had to be doubled and the existing unit (say heat exchanger 1) was in good condition and replacing it with a larger unit costs more than adding one of the same size. Or there might be a space limitation, or the desired output temperatures may have changed, or the cooling water availability or temperature changed.

8.6 RECIRCULATING SYSTEM

An 8 kg/s stream and a 14 kg/s stream, both having c_p = 4 kJ/kg°C, are heated and cooled by a 22 kg/s recirculating heat transfer fluid as shown in Figure P8.6 The specific heat of the recirculating fluid is 2.8 kJ/kg°C. (a) Calculate the temperature of the cooled 14 kg/s stream, T_{C2}. (b) Assume the circulating fluid leaves heat exchanger 1 at 20°C. Calculate T_B.

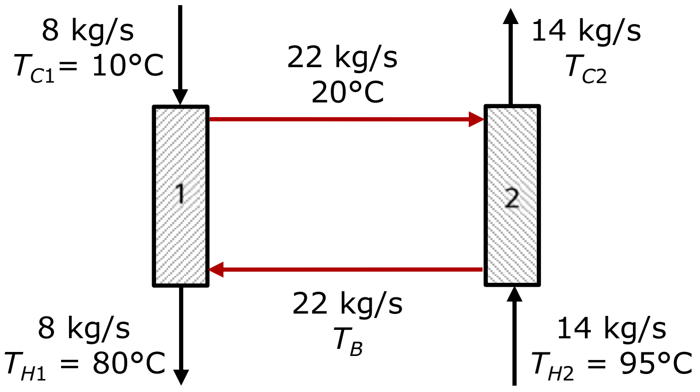


Figure P8.6 Recirculating heat exchangers

Solution

a) Temperature of cooled stream, T_{C2}

Overall energy balance

Heat added to stream 1 = Heat removed from stream 2

(8 kg/s)(4 kJ/kg°C)(80°C – 10°C) = (14 kg/s)(4 kJ/kg°C)(95°C – T_{C2})

(95°C – T_{C2}) = (2,240 kJ/s)/(56 kJ/s°C) = 40°C

T_{C2} = 55°C

b) Temperature of recirculating fluid leaving exchanger 2, T_B

Energy balance on unit 1

(8 kg/s)(4 kJ/kg°C)(80°C – 10°C) = (22 kg/s)(2.8 kJ/kg°C)(T_B – 20°C)

(T_B – 20°C) =2,240 kJ/s)/(61.6 kJ/s°C) = 36.4°C

T_B = 56.4°C

8.7 HEATING AND COOLING A REACTOR I

The influent to the reactor in Figure P8.7 is heated from 20°C to 60°C by adding steam. The reaction releases heat that raises the reactor contents (and the effluent) to 80°C. To facilitate the next step in the process the reactor output temperature is reduced to 20°C using cooling water. Calculate (a) the heat energy added by means of the steam heat exchanger, (b) the amount of heat removed by the cooling water, and (c) the amount of heat added by the exothermic reaction. The specific heat of the material flowing into the reactor is c_p = 3.5 kJ/kg°C. The material leaving the reactor has c_p = 3.9 kJ/kg°C. The c_p values are different because the reaction has changed the composition of the material.

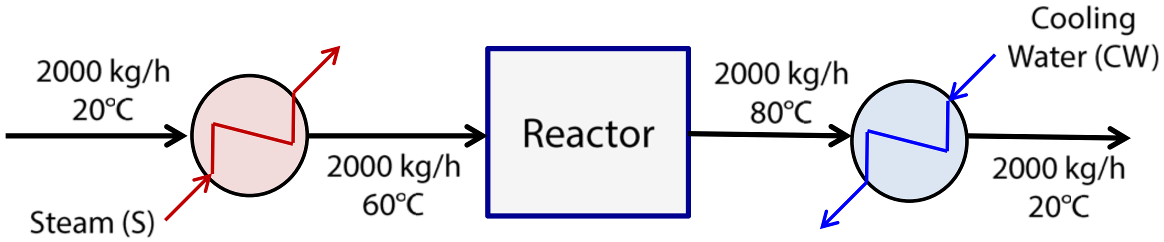


Figure P8.7 Heating and cooling reactor flows

Solution

Basis: 2000 kg/h of reactor input.

a) Heat added from steam

$Q_{In} = m\ c_P\ \Delta T$ = (2000 kg/h)(3.5 kJ/kg°C)(60°C – 20°C) = 280,000 kJ/h

b) Heat removed by cooling water

$Q_{Out} = m\ c_P\ \Delta T$ = (2000 kg/h)(3.9 kJ/kg°C)(80°C – 20°C) = 468,000 kJ/h

c) Heat added by exothermic reaction

Q_{Rxn} = Enthalpy of output stream – Enthalpy of input stream

$H_{In} = m\ c_{P,In}\ T_{In}$ = (2000 kg/h)(3.5 kJ/kg°C)(60°C) = 420,000 kJ/h

$H_{Out} = m\ c_{P,Out}\ T_{Out}$ = (2000 kg/h)(3.9 kJ/kg°C)(80°C) = 624,000 kJ/h

$Q_{Rxn} = H_{Out} - H_{In}$ = -624,000 kJ/h - 420,000 kJ/h = 204,000 kJ/h

8.8 REACTOR SYSTEM REDESIGN

Redesign the reactor system in problem 8.7 to reduce the amount of heating and cooling that is needed. You might first try the simple re-arrangement in Figure P8.8. Instead of steam, use the heated reactor output to heat the input stream. Is this arrangement feasible? Is it efficient? Assume perfect heat transfer – heat removed from one stream is absorbed by the other.

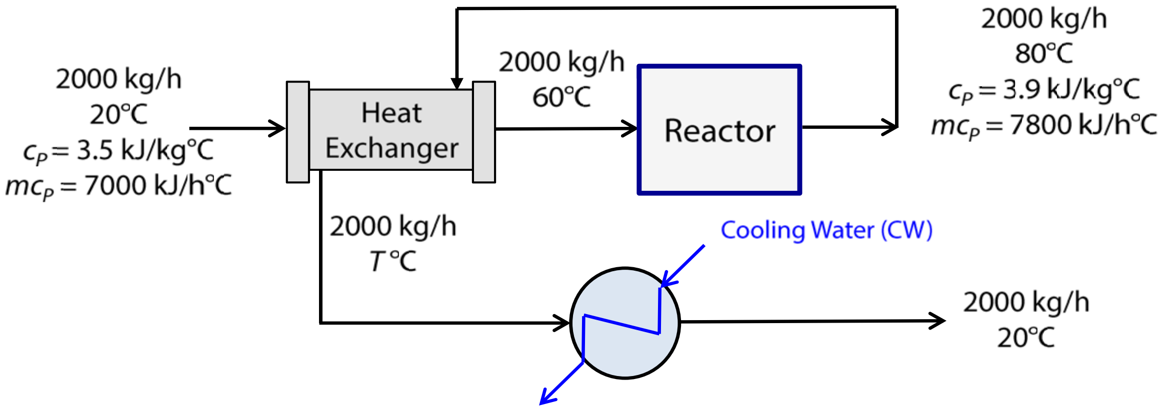


Figure P8.8 Reactor system redesign

Solution

Basis: 2000 kg/h of reactor feed

Let T =temperature of reactor effluent after passing through the heat exchanger

a) Energy balance on heat exchanger

Heat added to input from recycled reactor output

$Q_{In} = m\, c_P \Delta T$ = (2000 kg/h)(3.5 kJ/kg°C)(60°C – 20°C) = 280,000 kJ/h

Heat removed from recycled reactor output

$Q_{Out} = m\, c_P \Delta T$ = (2000 kg/h)(3.9 kJ/kg°C)(80°C – T°C)

= 624,000 kJ/h – (7,800 kJ/h°C)T

$Q_{In} = Q_{Out}$ = 280,000 kJ/h = 624,000 kJ/h – (7,800 kJ/h°C)T

T = 44.1°C

b) Heat energy removed by cooling water

= (2000 kg/h)(3.9 kJ/k°C)(44.1°C – 20°C) = 188,000 kJ/h

c) Savings

Need for steam is eliminated.

Cooling water reduced from 468,000 to 188,000 kg/h, a savings of 60%.

8.9 HEATING AND COOLING A REACTOR II

The reactor system shown in Figure P8.9 consumes steam to bring the 5000 kg/d feed to the reactor to 90°C. An additional inflow of 1000 kg/h at 20°C is added to the reactor. No heat is generated or lost in the reaction (the reactor is isothermal). The operating temperature of 69°C. The reactor effluent is cooled to 20°C. (a) Make the energy balance on the system to determine the energy added as steam and the energy removed by cooling water. (b) Redesign the system to reduce the need for steam, cooling water, or both.

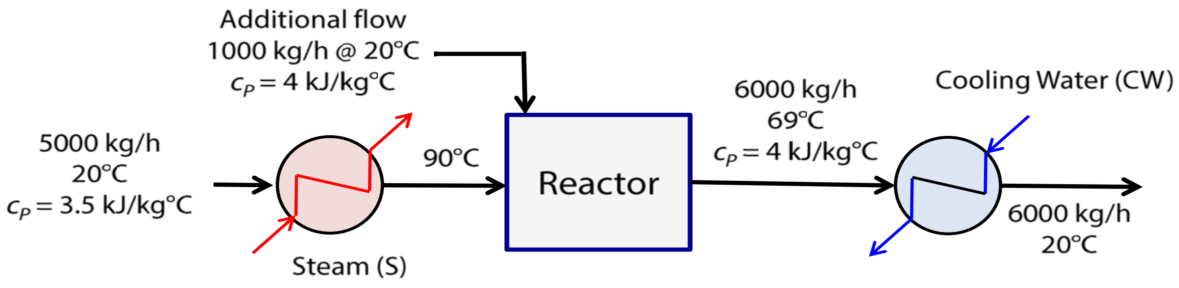


Figure P8.9 Heating and cooling in a reactor system

Solution

a) Energy flows: $Q = mc_p\Delta T$

Energy balance on the steam heat exchanger

Energy in feedstock + Energy in steam added = Energy in heat exchanger output

Energy in feedstock = (5000 kg/h)(3.5 kJ/kg°C)(20°C) = 350,000 kJ/h

Energy in heat exchanger output

= (5000 kg/h)(3.5 kJ/kg°C)(90°C) = 1,575,000 kJ/h

Steam heat required = 1,575,000 kJ/h - 350,000 kJ/h = 1,225,000 kJ/h

Energy balance on the reactor

Energy in feed + Energy in additional flow = Energy in reactor effluent

Energy in feed = 1,575,000 kJ/h

Energy in additional flow = (1000 kg/h)(4 kJ/kg°C)(20°C) = 80,000 kJ/h

Energy in reactor effluent = 1,575,000 kJ/h + 80,000 kJ/h = 1,656,000 kJ/h

Check: (6000 kg)(4 kJ/kg°C)(69°C) = 1,656,000 kJ/h

Energy balance on cooling water

Energy in reactor output – Energy removed by cooling water
= Energy in cooled product

Energy in reactor output = 1,656,000 kJ/h

Energy in cooled product = (6000 kg/h)(4 kJ/kg°C)(20°C) = 480,000 kJ/h

Energy removed in cooling water
= 1,656,000 kJ/h – 480,000 kJ/h = 1,176,000 kJ/h

Energy balance on the steam heat exchanger

Steam heat required = (5000 kg/h)(3.5 kJ/kg°C)(90°C - 20°C) = 1,225,000 kJ/h

Energy balance on the cooling water

Cooling required = (6000 kg/h)(3.5 kJ/kg°C)(69°C - 20°C) = 1,176,000 kJ/h

Check the overall energy balance

Feed + Steam + Added flow = Water + Product

350,000 kJ/h + 1,225,000 kJ/h + 80,000 kJ/h = 1,176,000 kJ/h + 480,000 kJ/h

1,655,000 kJ/h vs. 1,656,000 kJ/h

This discrepancy of 1000 kJ/h is because the reactor output temperature as calculated from an energy balance on the reactor, is 68.96°C, instead of the rounded 69°C shown on the diagram

b) Possible Redesign

The reactor output could be used to add some heat to the reactor feed. This would reduce steam and cooling water.

The feedstock can be heated to 59°C, if a minimum temperature difference of 10°C is required between the heat exchanger input (the reactor output) and the warmest heat exchanger output (the feedstock). Additional heating with steam will be needed for the reactor input, and some further cooling of the product will be needed. The proposed flow diagram is Figure S8.9 .

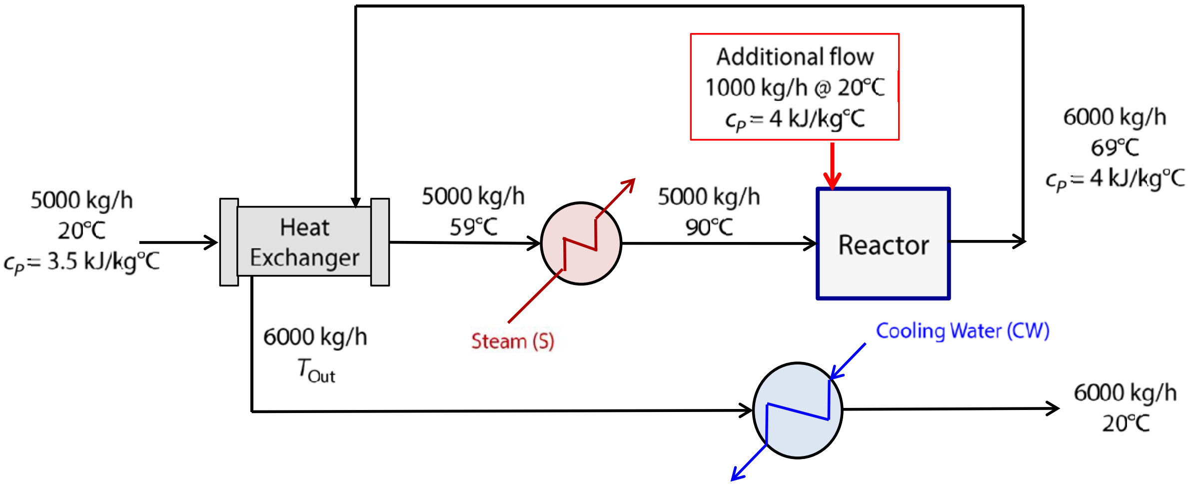


Figure S8.9

Heat recovered and transferred to feedstock

= (5000 kg/h)(3.5 kJ/kg°C)(59°C – 20°C) = 682,500 kJ

Temperature of cooled reactor output (energy balance on heat exchanger)

Heat transferred from reactor output = $mc_p\Delta T$ = 682,500 kJ

ΔT = 69°C $-T_{Out}$ = (682,500 kJ)/(6,000 kg/h)(4.0kJ/kg°C) = 28.4°C

T_{Out} = 40.6°C

Steam required = Original – Recovered = 1,225,000 kJ/h – 628,500 kJ/h = 596,500 kJ/h

Cooling water load = (6000 kg/h)(4 kJ/kg°C)(40.6°C – 20°C) = 494,400 kJ/h

Steam is reduced from 1,225,000 kJ/h to 596,500 kJ/h

Cooling water is reduced from 1,176,000 kJ/h to 494,400 kJ/h

8.10 COOLING A REACTOR

The reactor system in Figure P8.10 has a heavy cooling load. The feed to the reactor must be cooled from 60°C to 20°C. Exothermic reactions in the reactor increase the outflow temperature to 50°C, and most of this heat must be removed to reduce the output temperature to 30°C that is required facilitate effluent purification. All streams have the same heat capacity. Determine the total cooling requirement. Is there a way to reduce the cooling load?

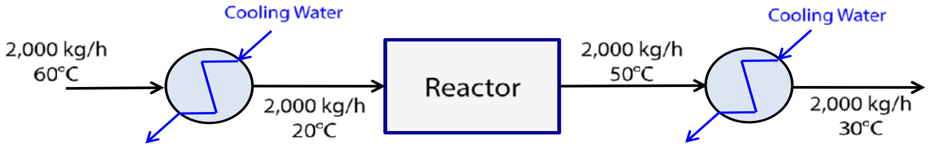


Figure P8.10 Reactor network requiring cooling

Solution

Because all streams have the same heat capacity we can simplify energy balance calculations by assuming c_p = 1 kJ/kg°C.

Overall energy balance:
Energy in feed + Energy produced in reactor - Cooling = Energy in effluent

Heat energy in feed = $(m\Delta T)$(1 kJ/kg°C) = (2,000 kg/h)(60°C)(1 kJ/kg°C) = 120,000 kJ/h
Heat energy produced in the reactor = (2,000 kg/h)(50°C – 20°C)(1 kJ/kg°C)
= 60,000 kJ/h

Heat energy in effluent = (2,000 kg/h)(30°C)(1 kJ/kg°C) = 60,000 kJ/h

Balance: 120,000 kJ/h + 60,000 kJ/h – cooling = 60,000 kJ/h
Cooling requirement = 120,000 kJ/h
This is divided as follows:

Cool the feed	(2,000 kg/h)(60°C – 20°C) = 80,000 kJ
Cool the output	(2,000 kg/h)(50°C – 30°C) = 40,000 kJ/h

There is no opportunity for reducing the cooling requirement.

Tutorial Note

The next few problems are about designing simple heat exchange networks. The important design factor is mc_p, the product of the mass flow rate, m, and the specific heat, c_p, of each stream in the network. Using mc_p removes the need to keep track of both m and c_p for each stream. If there are no phase changes (e.g. condensation of steam) the change in enthalpy of a stream is

$$\Delta H = mc_p \, \Delta T.$$

ΔH is directly proportional to the change in temperature, ΔT. The proportionality factor is mc_p. *Values of mc_p can be reported in energy units as kJ/h°C, MJ/h°C, Btu/h°F, etc., or in power units, say as kW/°C, MW/°C, hp/°F, etc.*

8.11 HEAT EXCHANGER NETWORK DESIGN I

A heat exchanger network will handle two cold streams and two hot streams, as described in the Table P8.11. The values of mc_p are given for each stream. Design an efficient heat exchange system.

Stream	Supply Temp (°C)	Target Temp (°C)	mc_p (MJ/h°C)	Heat added (+) or removed (–) (MJ/h)
H1	180	105	2	2(105 – 180) = –150
H2	245	180	1	1(180 – 245)= – 65
C1	70	120	3	3(120 – 70) = +150
C2	50	215	1	1(215 – 50) = +165

Table P8.11 Specifications for heat exchanger network

Solution

Basis = 1 hour of operation

From Table P8.11, the overall energy balance is

Heat removed from hot streams = –(150 MJ/h + 65 MJ/h) = – 215 MJ/h

Heat added to cold streams = +(150 MJ/h + 165 MJ/h) = 315 MJ/h

The best we can do is a network with 315 MJ/h – 215 MJ/h = 100 MJ/h of heating.

There is a perfect heat flow match for H1 and C1.

C1 requires 150 MJ/h added and H1 requires 150 MJ/h removed.

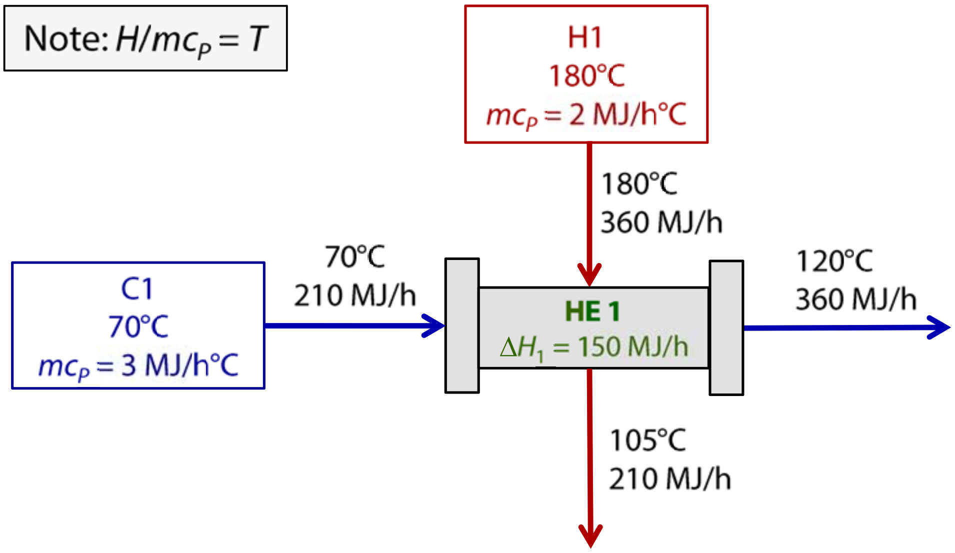


Figure S8.11a

That leaves a match of H2 and C2.

H2 can provide 65 MJ/h of the 165 MJ/h need to heat C2.

Thus, 165 MJ/h – 65 MJ/h = 100 MJ/h must be provided by external heating (steam).

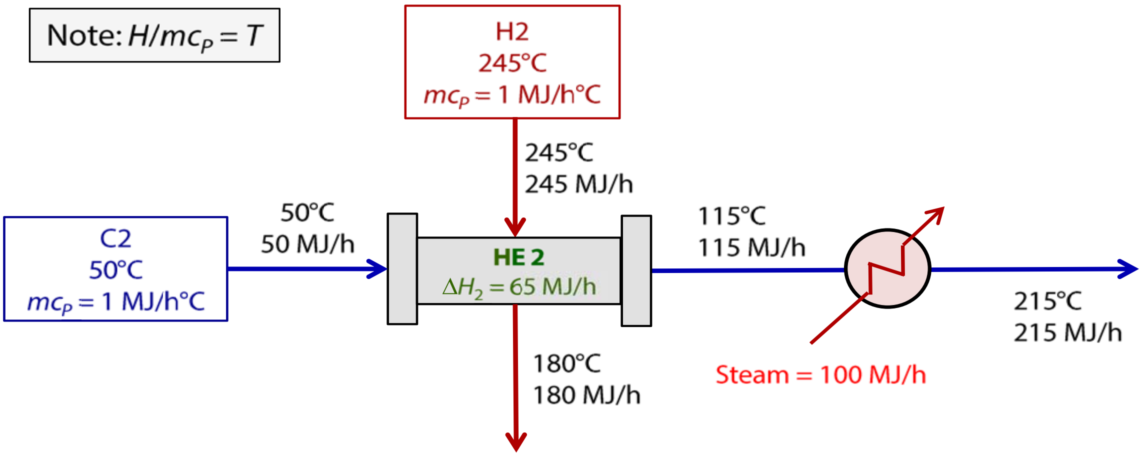


Figure S8.11b

8.12 HEAT EXCHANGER NETWORK DESIGN II

A heat exchanger network will handle two cold streams and two hot streams, as described in the Table P8.12. The values of mc_p are given for each stream. Design an efficient heat exchange system.

Stream	Supply Temp (°C)	Target Temp (°C)	mc_p (kW/°C)	Heat added (+) or removed (–) (kW)
H1	180	100	3	3(100 – 180) = –240
H2	245	180	2	2(180 – 245) = – 130
C1	70	200	2	2(200 – 70) = +260
C2	50	215	1	1(215 – 50) = +165

Table P8.12 Specifications for heat exchanger network

Solution

Basis: 1 hour of operation.
From Table P8.11, the overall energy balance is

Heat removed from hot streams = –(240 kW + 130 kW) = –370 kW
Heat added to cold streams = +(260 kW + 165 kW) = 425 kW
The best we can do is a network with 425 kW – 370 kW = 55 kW of heating.

The heat flows for H1 and C1 nearly match. C1 requires 260 kW added and H1 requires 240 kW removed. However, at 180°C, H1 is not hot enough to raise C1 to its target temperature of 200°C. Using the 10°C rule, it can raise C1 to about 170°C.

Thus only (2 kW/°C)(170°C - 70°C) = 200 kW can be exchanged in the heat exchanger
External heat (60 kW) will be required to raise C1 from 170°C to its target of 200°C.
External cooling (40 kW) will be required to lower H1 to its target of 100°C.

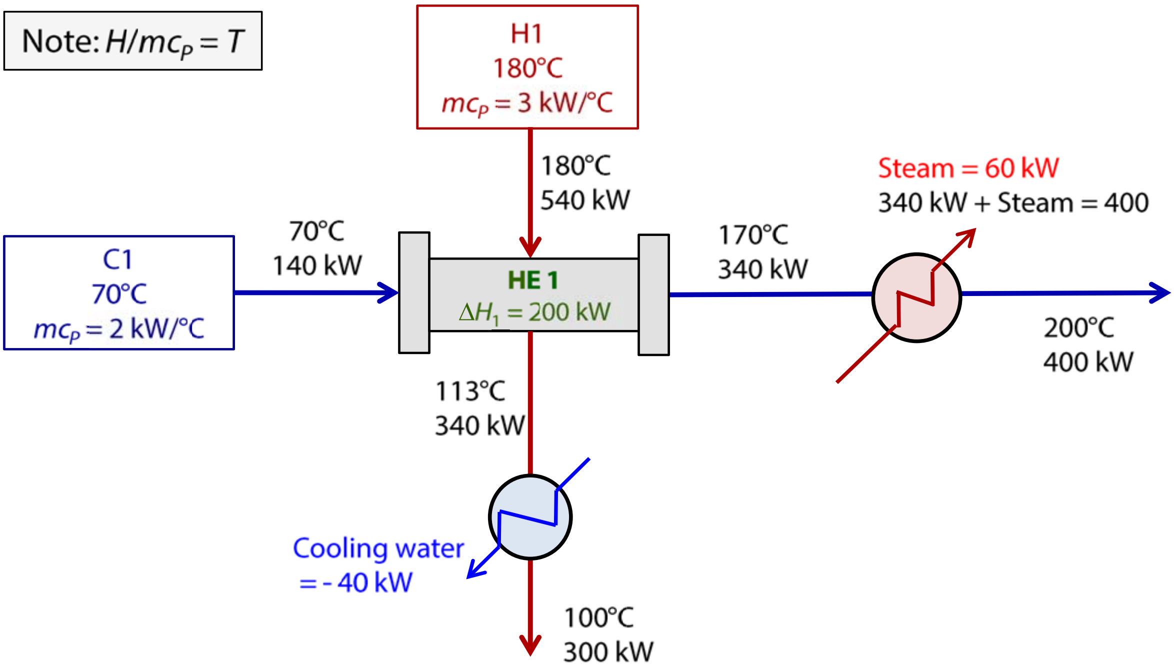


Figure S8.12a

That leaves a match of H2 and C2.

H2 can provide 130 kW of the 165 KW needed to heat C2.
Thus, 165 kW – 130 kW= 35 kW must be provided by external heating (steam).

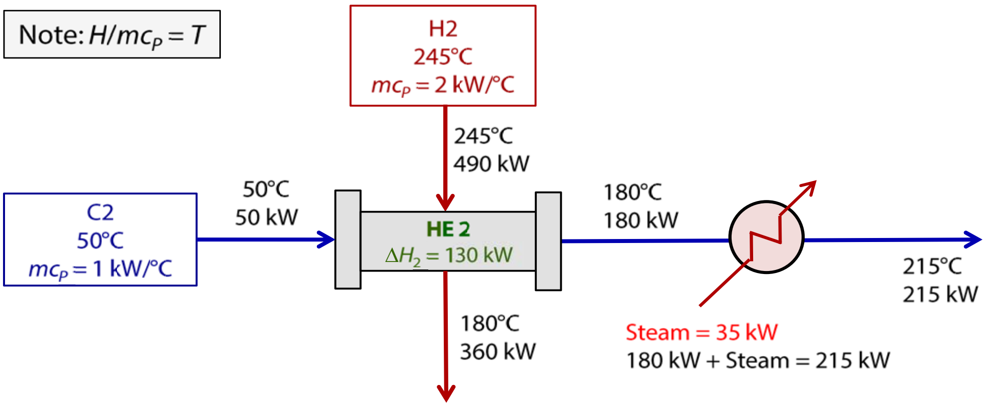


Figure S8.12b

The total amount of external heating is 60 kW + 35 kW = 95 kW. This is 40 kW more than the minimum because stream H1 requires 40 kW of cooling after HE1 to meet its target temperature.

Optional: If a third heat exchanger were available, can the hot stream exiting HE1 (113°C, 340 kW) be used to heat C2 prior to entering HE2 to reduce the cooling water and steam requirements of the current solution?

8.13 HEAT EXCHANGE NETWORK

The heat exchange network (HEN) in Figure P8.13 has three heat exchangers (labeled HE1, HE2, and HE3), two hot streams (H1 and H2) and two cold streams (C1 and C2). The objective is to achieve target temperatures for the hot and cold streams with the least use of steam or cold water. Table P8.13 shows initial and target stream temperatures and the flow heat capacities (mc_p), given in MW/°C, for the four streams. (a) Analyze the existing network to determine the intermediate temperatures and the requirements for steam and cooling water.(b) Improve the heat exchange network.

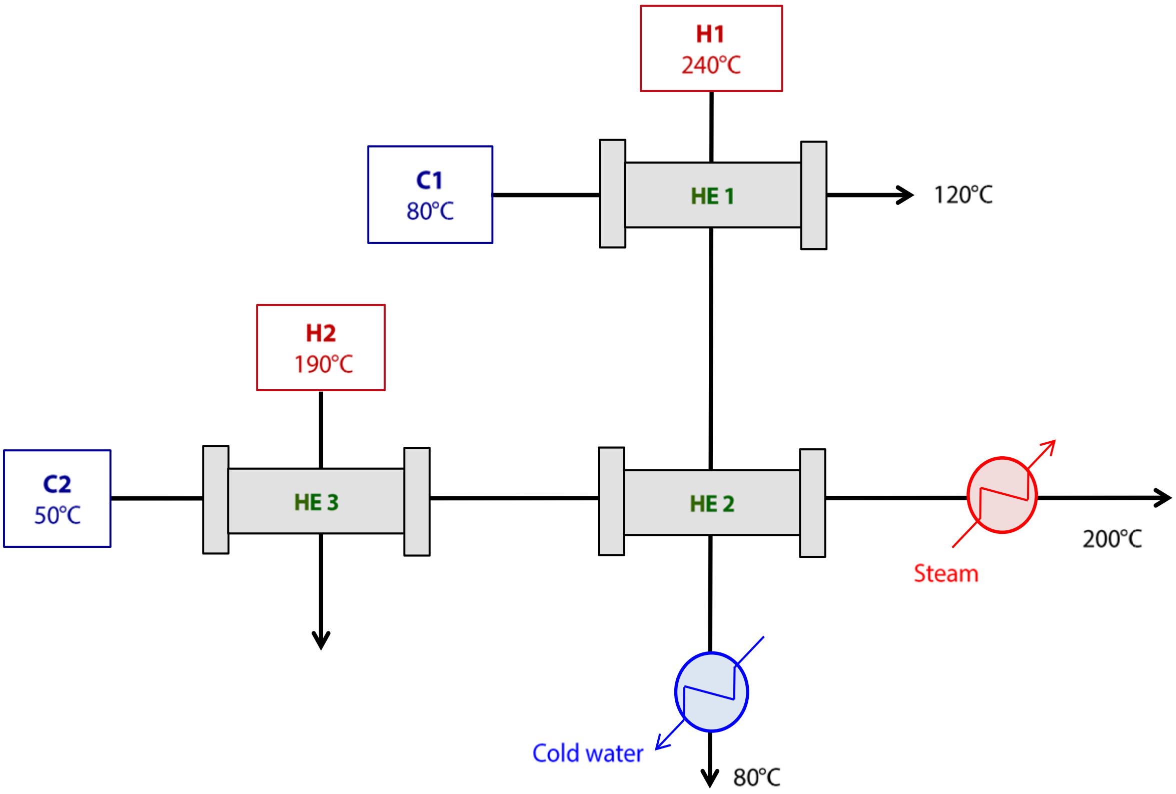


Figure P8.13 Heat exchange network

Stream	Supply Temp (°C)	Target Temp (°C)	mc_p (MW/°C)
H1	240	80	0.1
H2	190	100	0.3
C1	70	120	0.1
C2	50	200	0.4

Table P8.13 Specifications for heat exchanger network

Solution

Basis = 1 hour of operation.

Figure P8.13 summarizes the information needed to do the energy balance calculations.

Heat added or removed = $mc_p\Delta T$

Stream	Supply Temp (°C)	Target Temp (°C)	mc_p (MW/°C)	Heat added (+) or removed (–) (MW)
H1	240	80	0.1	0.1(80 - 240) = -16
H2	190	100	0.3	0.3(190 – 100) = 27
C1	70	120	0.1	0.1(120 – 70) = 5
C2	50	200	0.4	0.4(200 – 50) = 60

Table S8.13

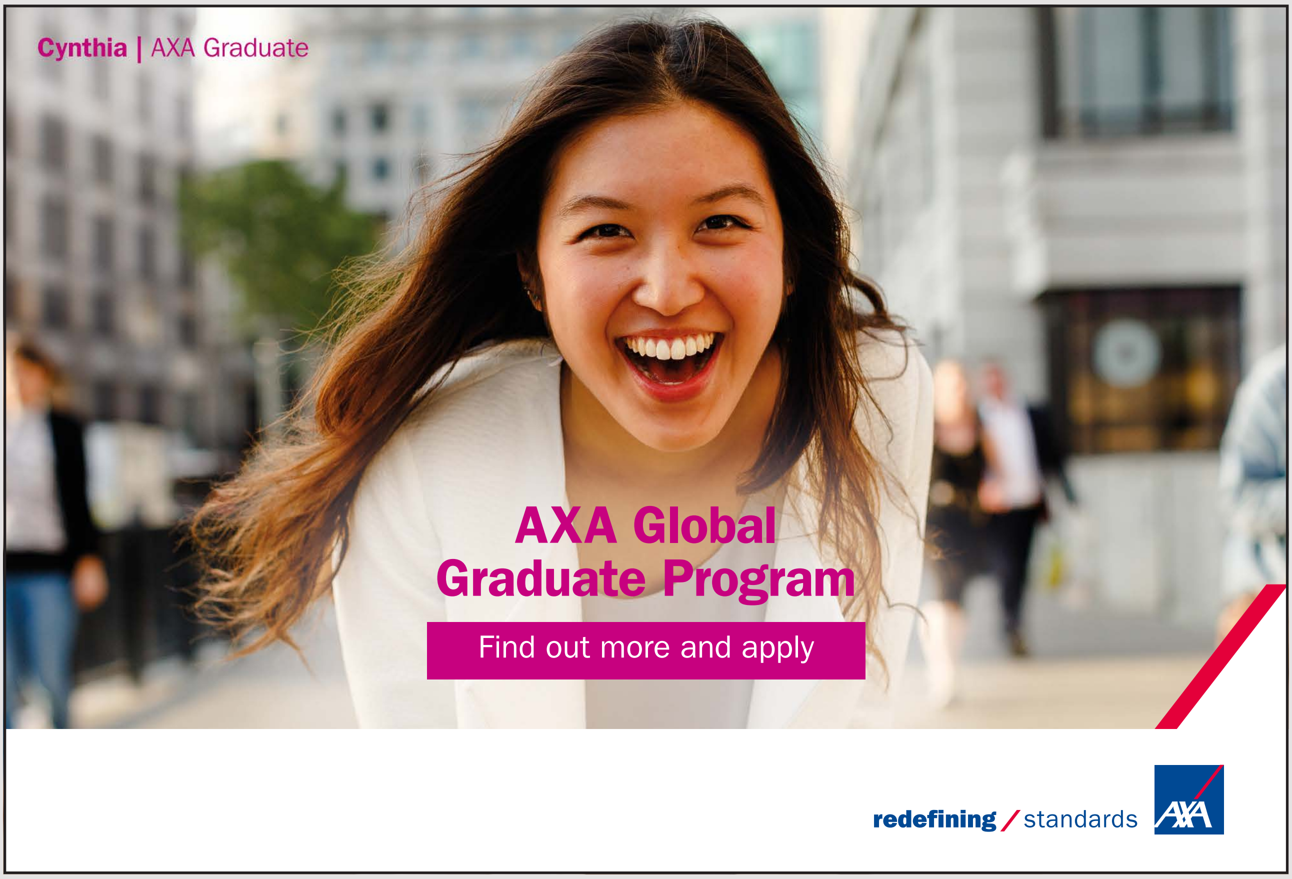
a) Energy Balance for the original heat exchange network

Heat input to C1 and C2

$$Q_{In} = 5 \text{ MW} + 60 \text{ MW} = 65 \text{ MW}$$

Heat removed from H1 and H2

$$Q_{Out} = 16 \text{ MW} + 27 \text{ MW} = 43 \text{ MW}$$



The heat required by the cold streams exceeds what is available from the hot streams by
65 MW – 43 MW = 22 MW.

It may not be able to extract all the heat energy from the hot streams because of the practical technical limitation is that the minimum temperature difference between a hot stream and a cold stream is 10°C.

Heat exchanger 1
Energy change of C1 = 12 MW – 7 MW = 5 MW
Energy change of H1 = 24 MW – 5 MW = 19 MW
The outlet temperature of H1 is (19 MW)/(0.1 MW/°C) = 190°C

Heat exchanger 3
Energy change of H1 = 57 MW – 30 MW = 27 MW
Energy change of C2 = 20 MW + 27 MW = 47 MW
The outlet temperature of C2 is (47 MW)/(0.4 MW/°C) = 117.5°C

Heat exchanger 2
The inlet temperature of C2 is determined by heat exchanger 3 to be 117.5°C.
The 10°C rule limits the output temperature of H1 from HE2 to 117.5°C + 10°C = 127.5°C,
Heat flow = (0.1 MW/°C)(127.5°C) = 12.75 MW.

Thus, the heat exchanged in HE2 is limited to 19MW – 12.75 MW = 6.25 MW.
C2 increases by 6.25 MW and H1 decreases by 6.25 MW.

Additional heating and cooling
C2 requires an additional (80 MW – 53.25 MW) = 26.75 MW heating to meet its target temperature of 200°C.
H1 requires an additional (8 MW – 12.75 MW) = -4.75 MW coolingto meet its target temperature of 80°C.

The energy balance for the original network is shown in Figure S8.13a

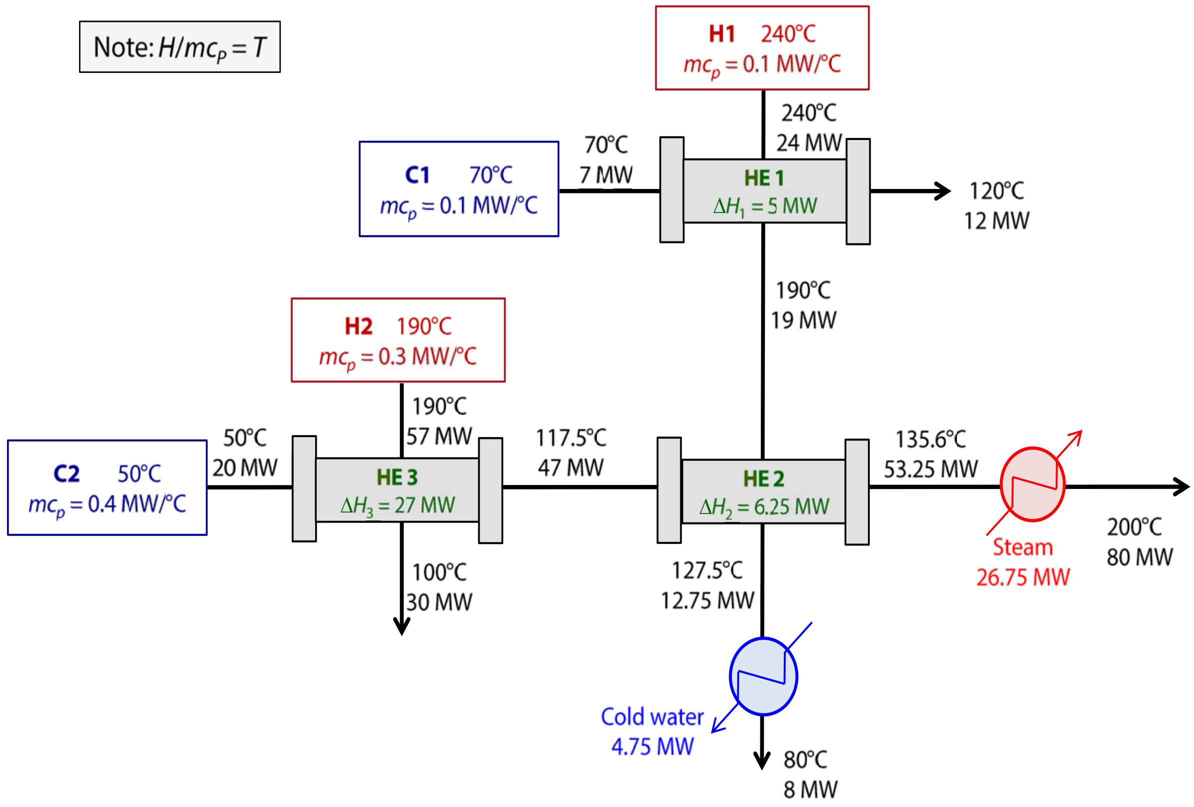


Figure S8.13a

b) Figure S8.13a shows an improved network.
The output of C2 from HE3 is fed to HE1 for heat exchange with H1.
C1 is fed directly to HE2.
No cooling water is needed. The steam load is reduced from 26.75 MW to 22 MW.

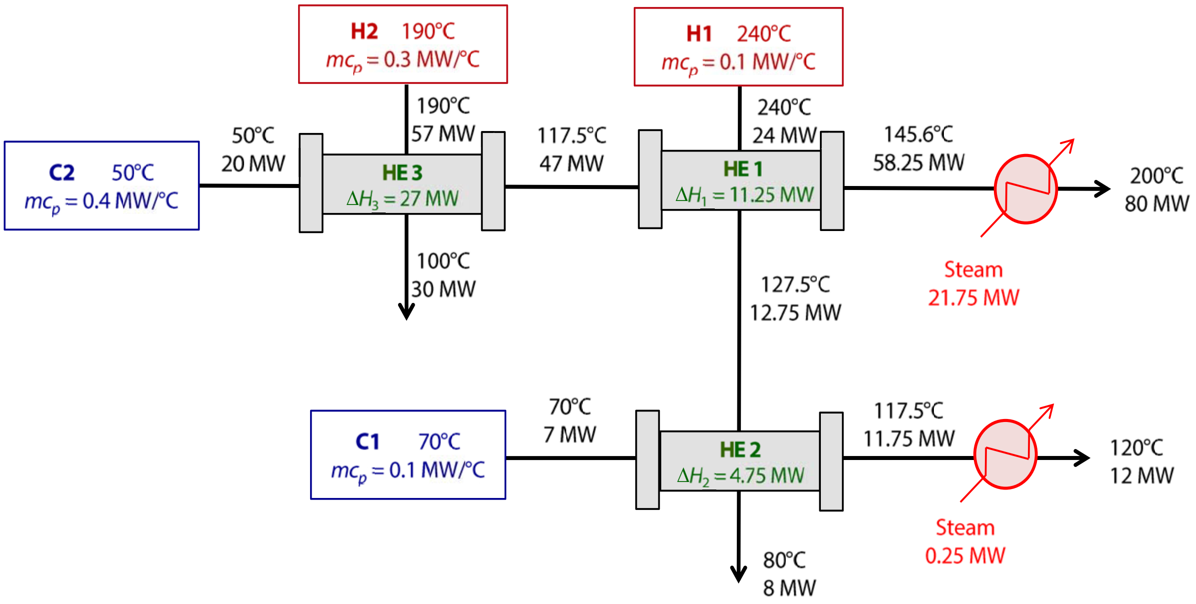


Figure S8.13b

9 ENERGY CONSUMPTION BY PUMPING

Some Useful Technical Data

Pressure is the resistance a pump works against. It is measured as kPa, kg/m^2, or lb/ft^2.
Pressure = (water height)(water density) → $P = H\rho$

A water depth of 2 ft is equivalent to
P = (2 ft)(62.4 lb/ft^3) = 124.8 lb/ft^2 = 0.867 lb/in^2

A water depth of 2 m is equivalent to
P = (2 m)(1000 kg/m^3) = 2000 kg/m^2 = 0.2 kg/cm^2

Another common term for this resistance – a curious term called *head (H)* - needs to be defined. Head is pressure expressed as an equivalent water depth and it is measured in meters or feet. This is convenient because the main job of a pump is to lift water, and it is natural to think of the lift as so many meters or feet.

Pressure and *head* measure the same thing in different units; they are interchangeable.
1 atmosphere of pressure = 14.7 lb/in^2 = 2,116 lb/ft^2 = 10,330 kg/m^2 = 101.35 kPa
1 atmosphere of pressure = 33.9 ft = 10.33 m of water
A water depth of 1 m = 1,000 kg/m^2 = 9.807 kPa
A water depth of 1 foot = 62.4 lb/ft^2 = 0.433 lb/in^2 = 0.433 psi

Power

Power in horsepower	(1 hp = 550 ft-lb/s)	$P_o = \rho gHQ/550$	$P_o = 32.2\rho HQ/550$
Power in kW	(1 kW = 0.7457 hp)	$P_o = 0.0437\ \rho HQ$	
Power in kW	$P_o = \rho gHQ/1000$	$P_o = 9.81\rho Q/1000$	

where P_o = power delivered by the pump (kW, hp)
ρ = density of water (kg/m^3, lb/ft^3)
g = acceleration of gravity (9.81 m/s^2, 32.2 ft/s^2)
H = total head loss (m, ft)
Q = flow rate (m^3/s, ft^3/s)

9.1 SYSTEM HEAD CURVE

On the pump head-discharge and efficiency curves shown in Figure P9.1, draw a system head curve starting at 20 m static pressure that will operate at the best efficiency point.

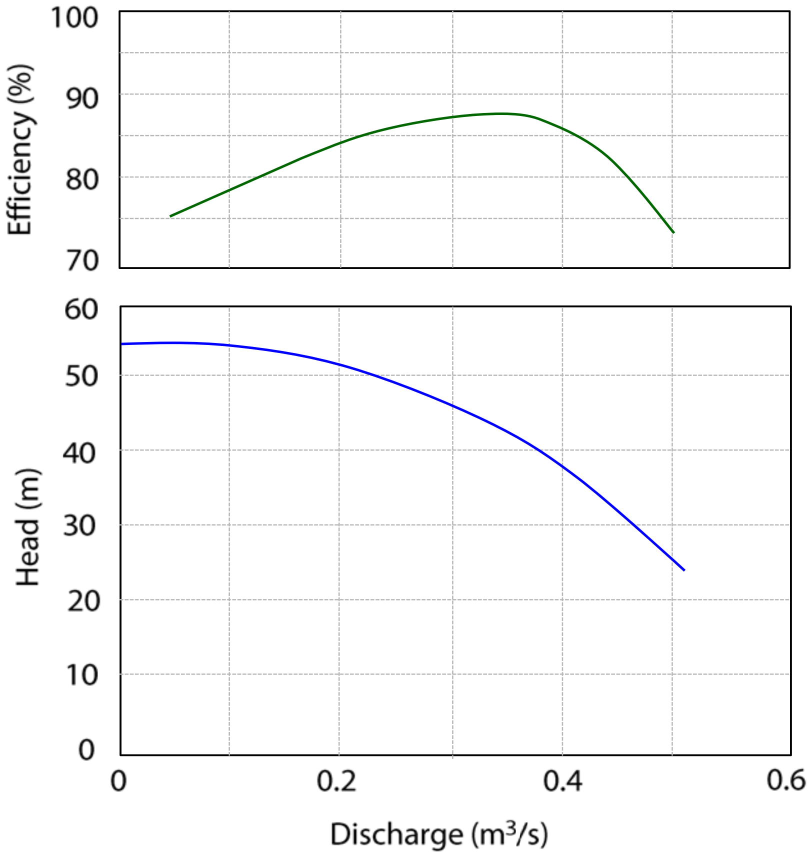


Figure P9.1 Pump discharge and efficiency curves

Solution

The system head curve should intersect the pump curve at the discharge that gives the maximum efficiency.

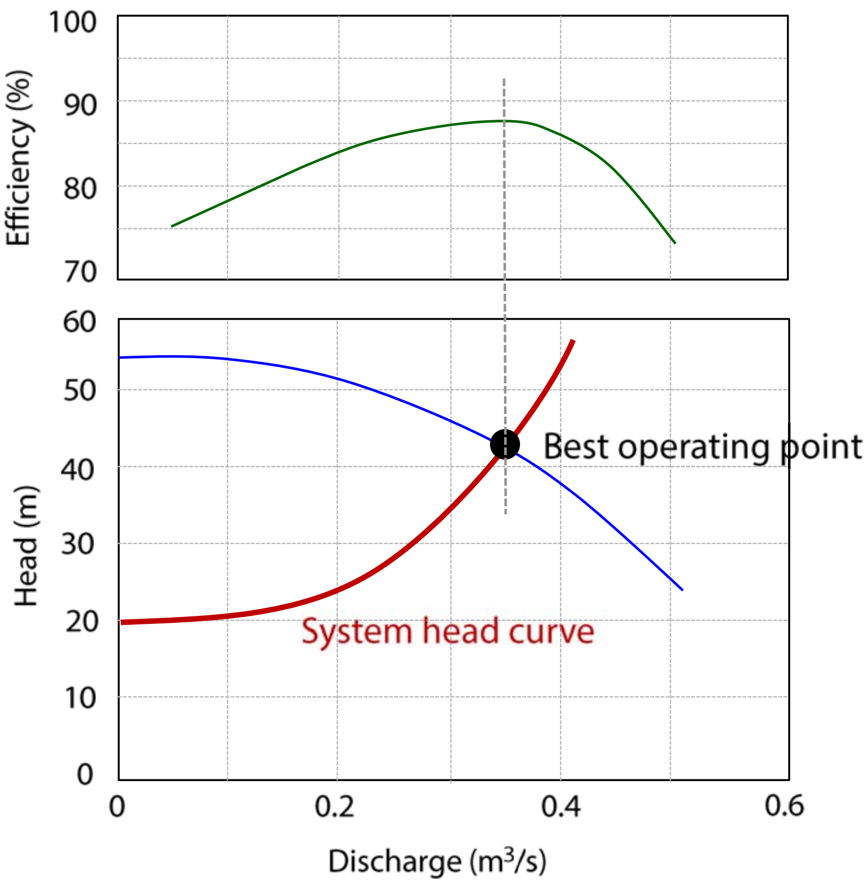


Figure S9.1

9.2 CHANGE IN PUMP EFFICIENCY

When installed, a pump had operating characteristics given by the head-discharge and efficiency curves shown in Figure P9.2. Corrosion in piping and valves has increased the total operating head to 100 m. Draw the new system curve. For the new system curve, indicate the shut off head, the static head, and other head losses, the new duty point, and the new pump efficiency.

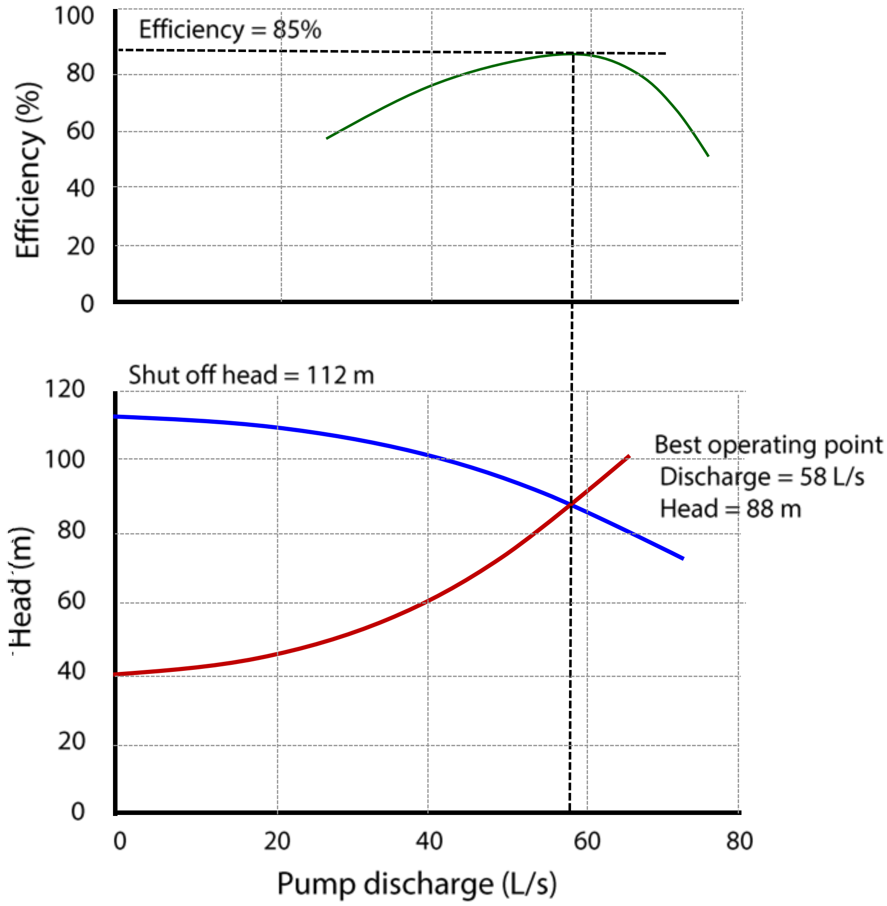


Figure P9.2 Pump operating characteristics

Solution

- The pump curve does not change, so the shut off head will not change.
- The static head does not change – it is determined by the elevation difference between the two ends of the pipe.
- The new system curve (Figure S9.2) will intersect the pump curve at 100 m total head, which corresponds to a discharge rate of about 42 L/s
- The new duty point is (42 L/s, 100 m)
- The dynamic head changes from (88 m - 40 m) = 48 m to (100 m – 40 m) = 60 m.
- The additional head of 12 m is due to corrosion and other physical changes in the piping and valves.
- The new pump efficiency is about 78%.

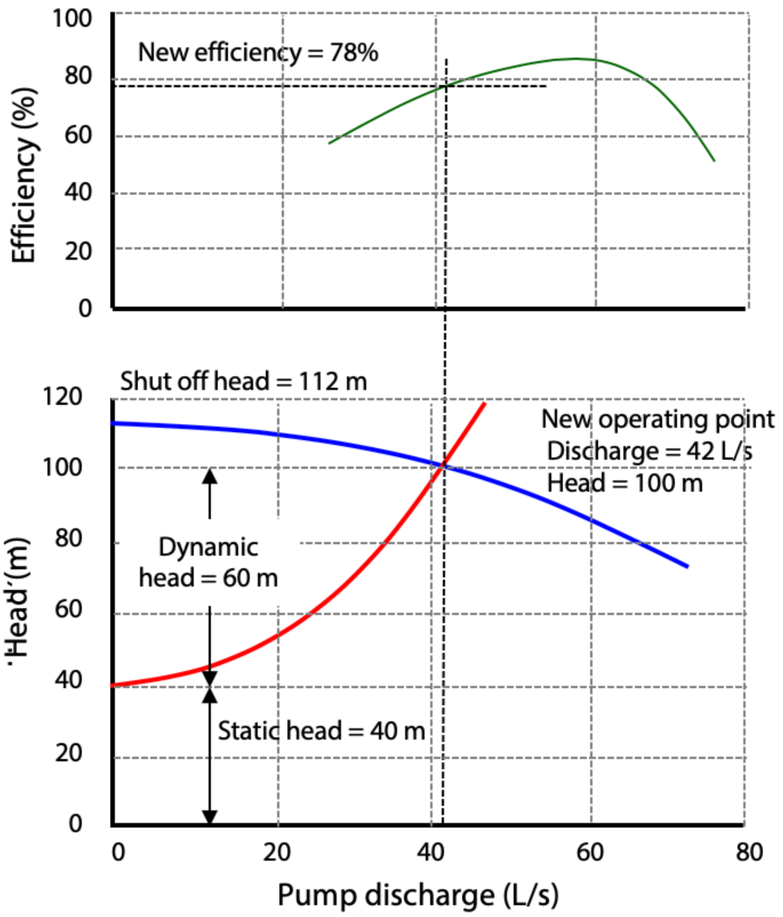


Figure S9.2 New system head curve

9.3 PUMP EFFICIENCY

On Figure P9.3, indicate the pump impeller diameter (in) that will give the highest efficiency at a flow of 150 gal/min.

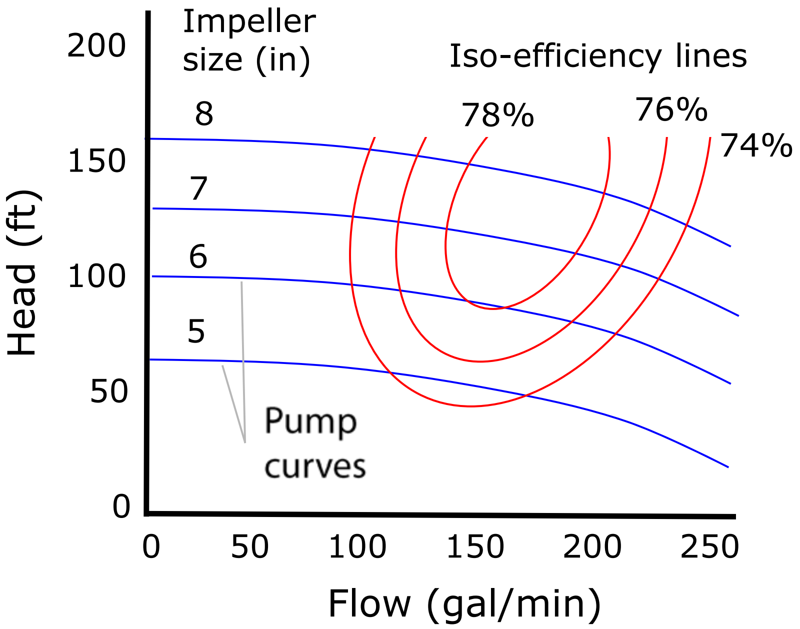


Figure P9.3 Pump efficiency

Solution

Impeller size = 7 inches

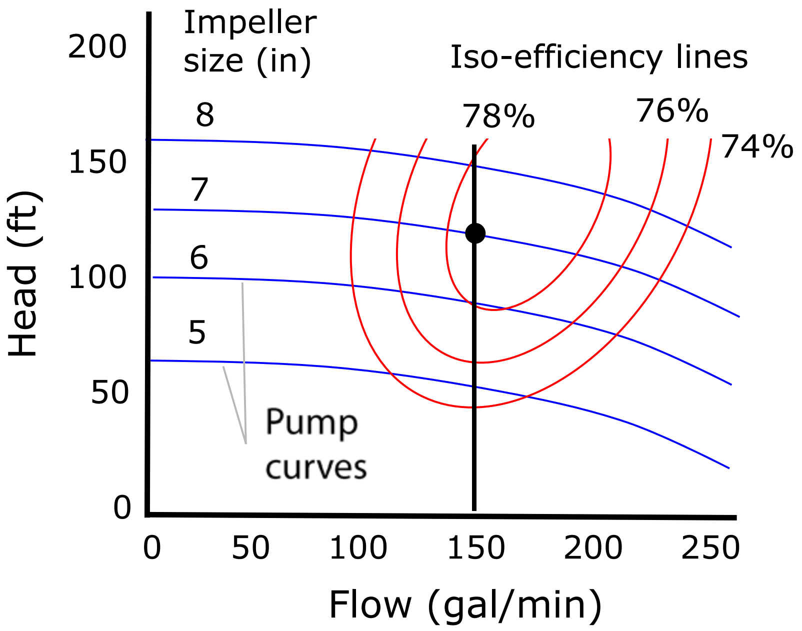


Figure S9.3

9.4 THROTTLED PUMP CHARACTERISTIC CURVE

In a typical month a pumping system (Figure P9.4) operates 600 hours, half of this time at the design point (the best efficiency point) and half of the time in throttled conditions at about half the discharge. (a) What is the average pumping efficiency? (b) Estimate the energy used, in kWh, per typical month.

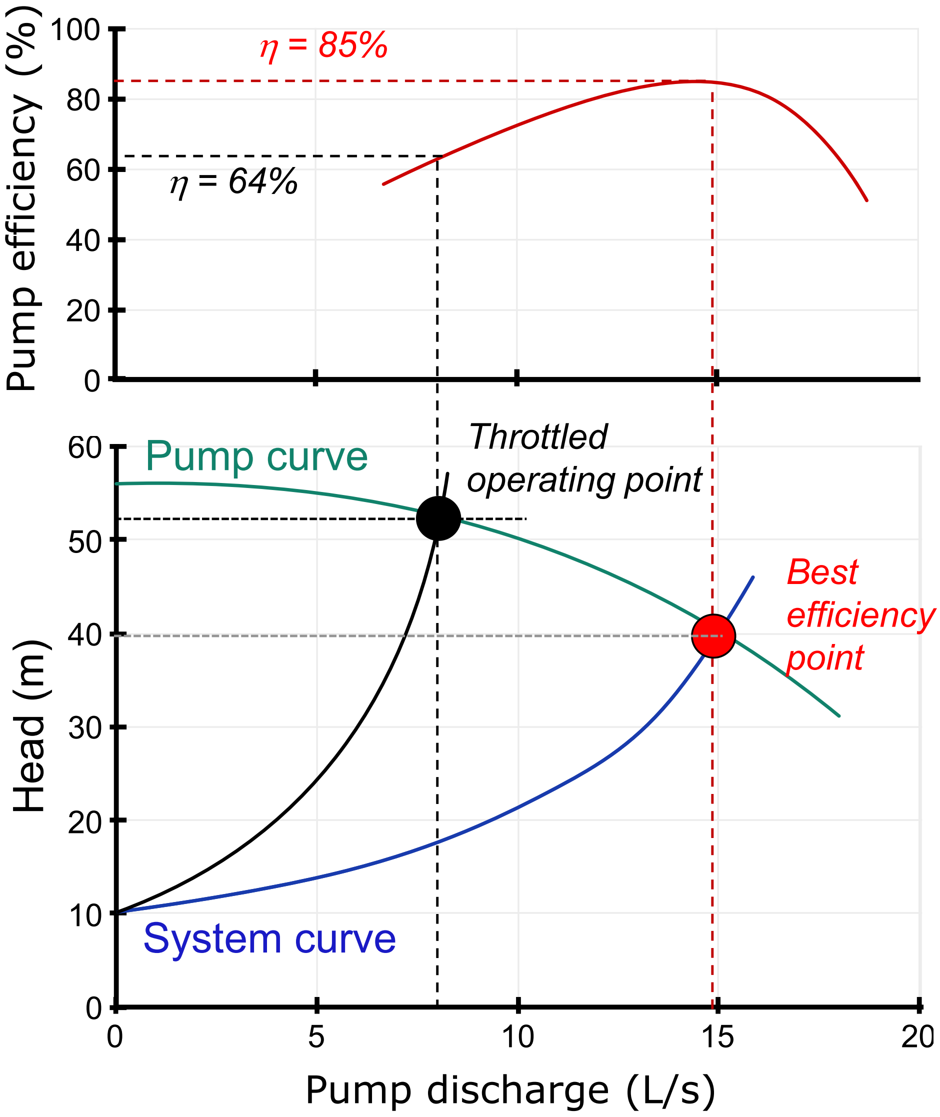


Figure P9.4 Throttled pump characteristic curve

Solution

a) Average pumping efficiency

Efficiency at 15 L/s = 85%

Efficiency at 8 L/s = 64%

Average efficiency = 74.5%

b) Energy use per month

Power(kW) delivered to the water by the pump $P_o = g\rho HQ/1000$

where P_o = power delivered by the pump (kW)

ρ = density of water (kg/m^3)

g = acceleration of gravity (9.81 m/s^2)

H = total head loss (m)

Q = flow rate (m^3/s)

The power that must be supplied by the drive motor to the pump is P_s, where

$$P_s = P_o/\eta_p$$

The power input that must be supplied to the motor is P_i, where

$$P_i = P_s/\eta_m = P_o/\eta_p\eta_m$$

where P_s = power delivered to the pump (kW)
η_p = pump efficiency
P_i = input power to the pump motor (kW)
η_m = efficiency of the motor

1) Design conditions (unthrottled): Q = 15 L/s = 0.015 m^3/s and H = 40 m
   P_o = (9.81 m/s^2) (1000 kg/m^3)(40 m)(0.015 m^3/s)/(1000 W/kW) = 5.886 kW
   Account for efficiency = 85%
   P_i = 5.886 kW/0.85 = 6.925 kW
   Hours of operation at this condition = 300 h
   Energy used = (6.925 kW)(300 h) = 2,077 kWh

2) Throttled condition: Q = 8 L/s = 0.008 m^3/s and H = 52 m
   P_o = (9.81 m/s^2) (1000 kg/m^3)(52 m) (0.008 m^3/s)/(1000 W/kW) = 4.081 kW
   Account for efficiency = 64%
   P_i = 4.081 kW/0.64 = 6.376 kW
   Hours of operation at this condition = 300 h
   Energy used = (6.376 kW)(300 h) = 1,913 kWh

Total monthly energy = 2,077 kW + 1,913 kW = 3990 kWh

9.5 HEAD LOSS IN A STRAIGHT PIPE

Calculate the friction loss in a straight pipe of length L = 2,000 m and diameter D = 0.8 m when the velocity is v = 1.2 m/s. The friction factor is f = 0.07.

Solution

$$h_f = f\frac{L}{D}\frac{v^2}{2g} = 0.07\left(\frac{2{,}000\text{ m}}{0.8\text{ m}}\right)\left[\frac{(1.2\text{ m/s})^2}{2(9.81\text{ m/s}^2)}\right] = 12.84\text{ m}$$

9.6 HEAD LOSS IN A PIPE WITH THREE ELBOWS

Figure P9.6 is a plan view (looking down) of a hypothetical pipe that is 50 m long and has three elbows. The fluid velocity is 3 m/s. The pipe friction factor is 0.02. (a) Calculate the head loss. (b) What fraction of the total head loss is due to *minor* losses? (c) Does your calculation change if this is a plan view (looking down) or an elevation view (looking from the side)?

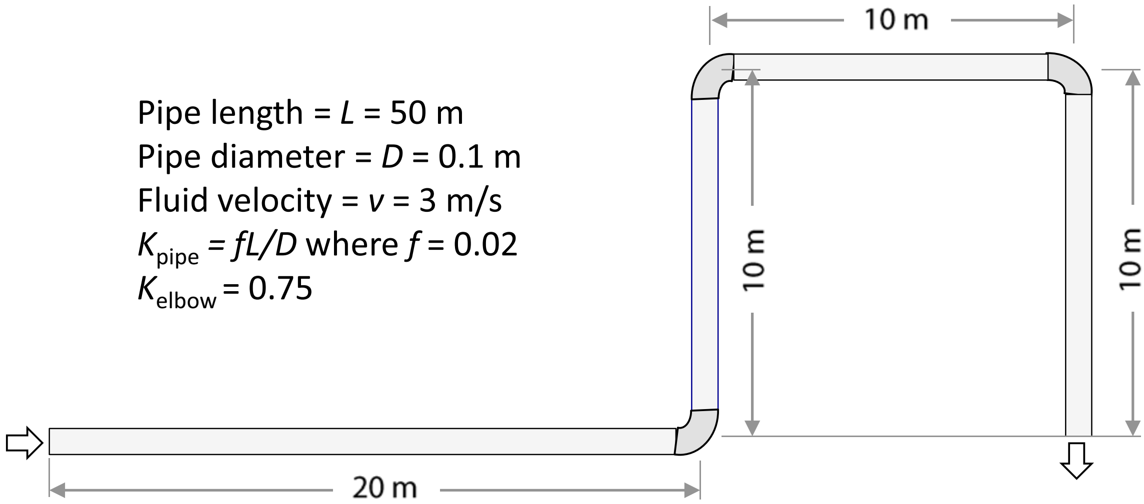

Pipe length = L = 50 m
Pipe diameter = D = 0.1 m
Fluid velocity = v = 3 m/s
$K_{\text{pipe}} = fL/D$ where f = 0.02
K_{elbow} = 0.75

Figure P9.6 Simple pipe section with L = 50 m, 3 elbows, f = 0.02, and v = 3 m/s

Solution

a) Head loss

Inlet and outlet are at the same elevation there is no static head.

Diameter of pipe and the elbows is D = 0.1 m
Velocity of water flowing in the system is v = 3 m/s
Pipe friction factor = 0.02
Total length of pipe = 50 m
Gravitational constant, g = 9.81 m/s^3.

The headloss of any element can be calculated using

$$h = K\frac{v^2}{2g}$$

Velocity head

$$\frac{v^2}{2g} = \frac{(3\ \text{m/s})^2}{2(9.81\ \text{m/s}^2)} = 0.4587\ \text{m}$$

The head loss due to pipe friction is

$$h_{\text{pipe}} = f\frac{L}{D}\frac{v^2}{2g} = 0.02\left(\frac{50\ \text{m}}{0.1\ \text{m}}\right)(0.4587\ \text{m}) = 4.587\ \text{m}$$

Head loss for one elbow = 0.75(0.4587 m) = 0.344 m
Head loss for 3 elbows = 3(0.75)(0.4587 m) = 1.032 m

Total head loss = 4.587 m + 1.032 m = 5.619 m

b) Minor loss percentage
Minor losses = (1.032 m)/(5.610 m) = 0.184 = 18.4%

c) Does plan vs. elevation view make a difference? No. The entrance and discharge elevations are the same in either case.

9.7 HEAD LOSS WITH A GATE VALVE

A pipe system has 80 m of 0.3 m diameter pipe with two 90° elbows and a gate valve. The average flow is 0.1 m^3/s, but this can range from is 0.05 m^3/s to is 0.2 m^3/s. The pipe friction factor is $f = 0.08$. (a) Calculate and plot the system head curve for a half-open open gate valve ($K = 2.1$) and a static head of 6 m. (b) Does it matter where the gate valve is installed?

Solution

Head loss for all elements can be calculated using

$$h = K\frac{v^2}{2g}$$

K values from the Engineering Toolbox

Standard flanged 90° elbow: $K = 0.3$

Gate valve: Open: $K = 0.15$ Half- open: $K = 2.1$

Sample calculations for $Q = 0.1\ \text{m}^3/\text{s}$

Area of 0.3 m pipe = $A = 0.0707\ \text{m}^2$

Velocity = $v = Q/A = (0.1\ \text{m}^3/\text{s})/(0.0707\ \text{m}^2) = 1.415\ \text{m/s}$

$v^2/2g = (1.415\ \text{m/s})^2/((2)(9.81\ \text{m/s}^2)) = 0.102\ \text{m}$

Pipe friction losses:

$$h_{\text{pipe}} = f\frac{L}{D}\frac{v^2}{2g} = 0.08\left(\frac{80\ \text{m}}{0.3\ \text{m}}\right)(0.102\ \text{m}) = (21.33)(0.102\ \text{m}) = 2.176\ \text{m}$$

Two 90° Elbows: $K = 2(0.3) = 0.6$ $h_{\text{Elbows}} = 0.6(0.102\ \text{m}) = 0.061\ \text{m}$

Gate valve: 50% open $K = 2.1$ $h_{\text{50\% Gate valve}} = 2.1(0.102\ \text{m}) = 0.214\ \text{m}$

For $Q = 0.1\ \text{m}^3/\text{s}$

Friction loss in pipe and fittings = $h = 2.176 + 0.061 + 0.214 = 2.451\ \text{m}$

Total head loss = $H = 6\ \text{m} + 2.451\ \text{m} = 8.451\ \text{m}$

Calculations for flows from 0.05 to 0.2 m/s are given in Table S9.7

Q (m^3/s)	Velocity (m/s)	$v^2/2g$ (m)	Head Losses (m)				
			Pipe	Two 90° elbows	Gate valve	Dynamic head loss	Total head loss
0.05	0.707	0.026	0.544	0.015	0.054	0.613	6.613
0.06	0.849	0.037	0.783	0.022	0.077	0.883	6.883
0.07	0.990	0.050	1.066	0.030	0.105	1.201	7.201
0.08	1.132	0.065	1.393	0.039	0.137	1.569	7.569
0.09	1.273	0.083	1.763	0.050	0.174	1.986	7.986
0.10	1.415	0.102	2.176	0.061	0.214	2.452	8.452
0.11	1.556	0.123	2.633	0.074	0.259	2.966	8.966
0.12	1.698	0.147	3.134	0.088	0.308	3.530	9.530
0.13	1.839	0.172	3.678	0.103	0.362	4.143	10.143
0.14	1.981	0.200	4.265	0.120	0.420	4.805	10.805
0.15	2.122	0.230	4.896	0.138	0.482	5.516	11.516
0.16	2.264	0.261	5.571	0.157	0.548	6.276	12.276
0.17	2.405	0.295	6.289	0.177	0.619	7.085	13.085
0.18	2.546	0.331	7.051	0.198	0.694	7.943	13.943
0.19	2.688	0.368	7.856	0.221	0.773	8.850	14.850
0.20	2.829	0.408	8.705	0.245	0.857	9.806	15.806

Table S9.7

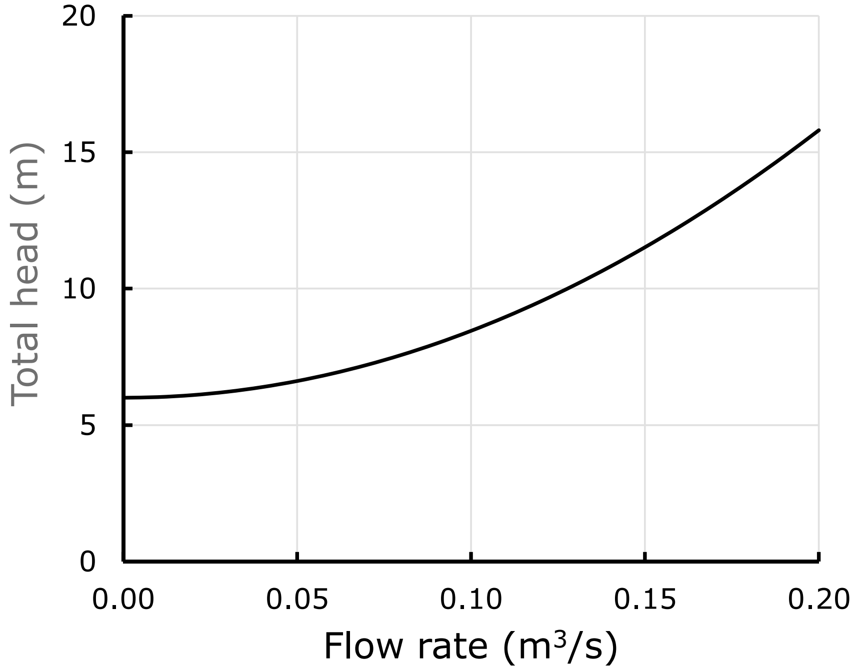


Figure S9.7 System head curve

b) There is no important difference due to the gate valve location in the pipe. This is because the pipe friction loss is large in comparison, and the static head amplifies the difference.

9.8 STATIC HEAD PLUS DYNAMIC HEAD

Figure P9.8 is an elevation view of a pipe system. The pump (not shown) must lift the water 100 m and overcome the friction losses in the pipe, the elbows, and the valve. What is the total operating head?

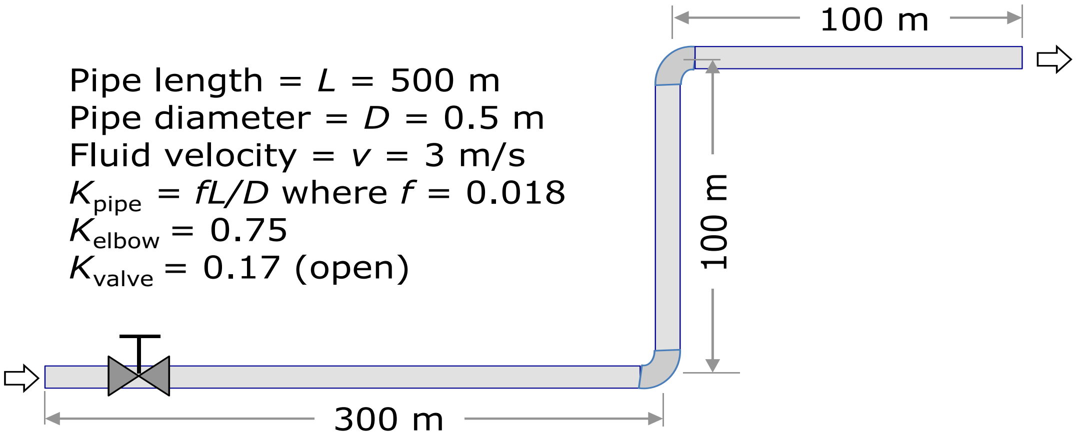


Figure P9.8 Pipe system

Solution

Velocity head

$v^2/2\text{g} = (3 \text{ m/s})^2/(2(9.81 \text{ m/s2})) = 0.459 \text{ m}$

Head loss due to pipe friction

$$h_{pipe} = f\frac{L}{D}\frac{v^2}{2g} = 0.018\left(\frac{500 \text{ m}}{0.5 \text{ m}}\right)(0.459 \text{ m}) = 8.26 \text{ m}$$

Head losses in elbows and valve

= [(2 elbows)(0.75 m/elbow) + (0.17 m/valve)]($v^2/2g$)

= (1.67)(0.459 m) = 0.766 m

Total head = 100 m + 8.26 m + 0.77 m = 109.0

Note: In this design, the *minor losses* (valves, elbows, etc.) really are minor.

9.9 SYSTEM CURVE AND PUMP EFFICIENCY

Figure P9.9 shows a pump that must deliver water from a lower reservoir to a higher reservoir, with an elevation difference of 10 ft. The pipe diameter is D = 0.5 ft and the equivalent length of the pipe and fittings is L = 200 ft with f = 0.015. (a) Calculate the system curve and plot it on the pump characteristic curve. (b) What is the operating point? (c) Is this the best operating point?

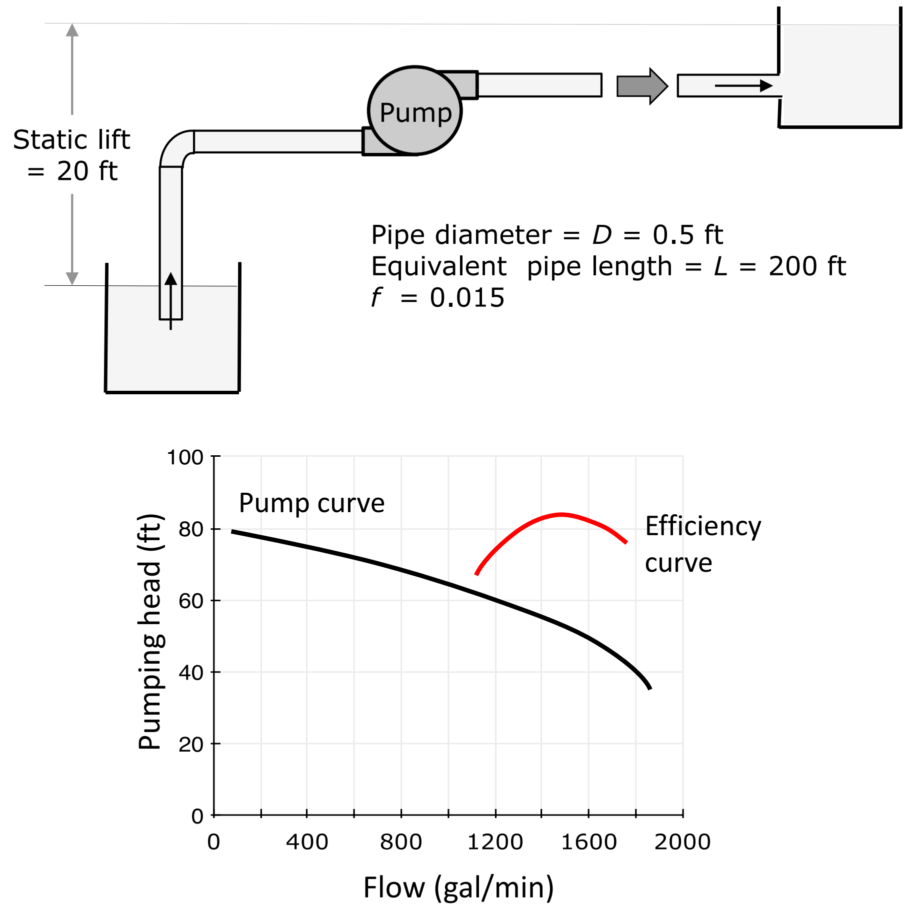


Figure P9.9 System curve and pump efficiency

Solution

The static head is the 10 lift.

Diameter = D = 0.5 ft

Length = L = 200 ft

Friction factor = f = 0.015

Sample calculation for Q = 800 gal/min

$$Q = 800 \text{ gal/min} = 107 \text{ ft}^3\text{/min} = 1.78 \text{ ft}^3\text{/s}$$

$$A = 3.1416(0.5 \text{ ft})^2/4 = 0.196 \text{ ft}^2$$

$$v = Q/A = (1.78 \text{ ft}^3\text{/s})/(0.196 \text{ ft}^2) = 9.08 \text{ ft/s}$$

$$v/2g = (9.08 \text{ ft/s})^2/((2)(32.2 \text{ ft/s}^2)) = 1.28 \text{ ft}$$

$$h_{\text{pipe}} = f\frac{L}{D}\frac{v^2}{2g} = 0.015\left(\frac{200 \text{ ft}}{0.5 \text{ ft}}\right)(1.28 \text{ ft}) = 7.68 \text{ ft}$$

Total head = h_{pipe} + static head = 7.68 ft + 10 ft = 17.68 ft

The pump and system head curves are in Figure S9.9. The operating point is approx. 1680 gal/min and 45 ft of total head. This is not the most efficient operating point.

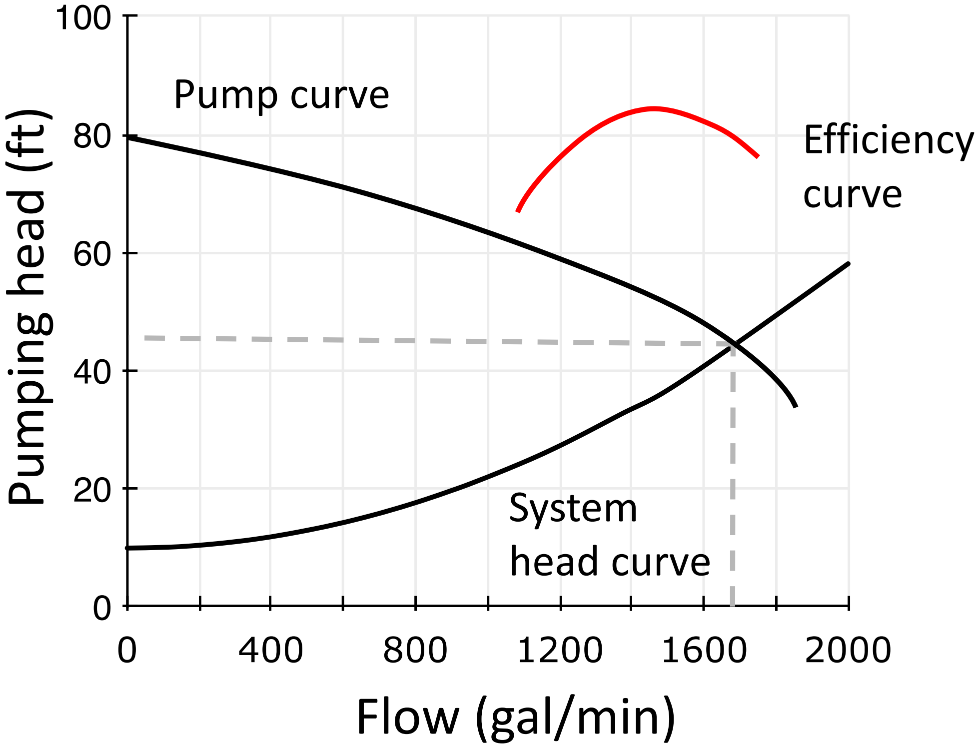


Figure S9.9 System head curve and pump curve

Flow (gpm)	Flow (cfs)	Velocity (ft/s)	$v^2/2g$	Head Loss in pipe (ft)	Total head (ft)
0	0	0	0	0	10
100	0.223	1.135	0.020	0.12	10.12
200	0.446	2.270	0.080	0.48	10.48
300	0.668	3.404	0.180	1.08	11.08
400	0.891	4.539	0.320	1.92	11.92
500	1.114	5.674	0.500	3.00	13.00
600	1.337	6.809	0.720	4.32	14.32
700	1.560	7.944	0.980	5.88	15.88
800	1.783	9.078	1.280	7.68	17.68
900	2.005	10.213	1.620	9.72	19.72
1000	2.228	11.348	2.000	12.00	22.00
1200	2.674	13.618	2.879	17.28	27.28
1400	3.119	15.887	3.919	23.52	33.52
1600	3.565	18.157	5.119	30.71	40.71
1800	4.011	20.426	6.479	38.87	48.87
2000	4.456	22.696	7.999	47.99	57.99

Table S9.9 System head curve calculations

9.10 PUMPING SYSTEM

Calculate the total head for the transport of water from reservoir 1, at elevation 10 m, to reservoir 2, at elevation 28 m, as shown in Figure P9.10. The L = 400 m of pipe has diameter = 0.2 m. The friction factor is f = 0.022. The elbows, valves, and other features of the pipe system combine to have a head loss equivalent to the losses in 400 m of pipe. Calculate the pump operating head for a flow of 0.1 m^3/s.

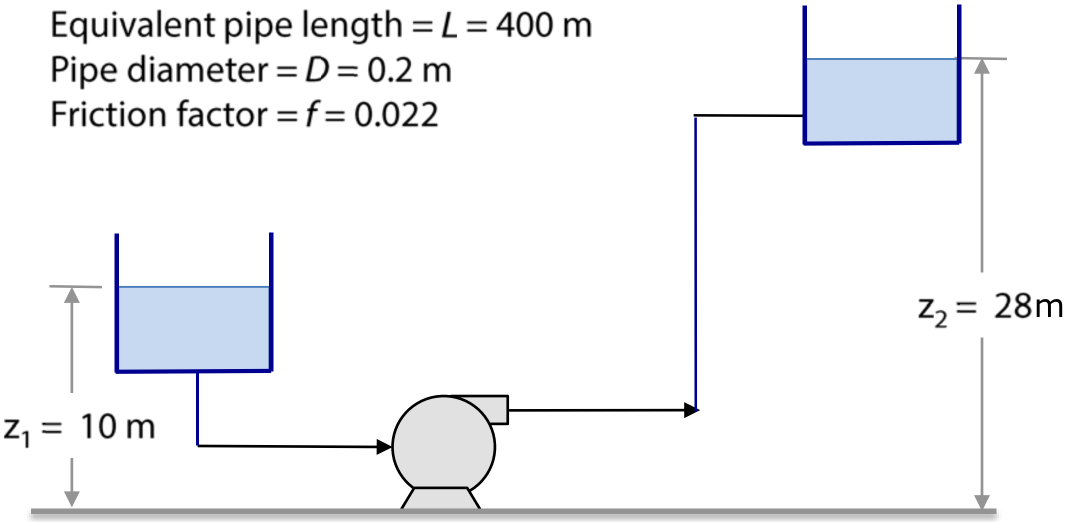


Figure P9.10 Pumping between two reservoirs

Solution

Static head = 28 m – 10 m = 18 m

Pipe area = 3.1416(0.2 m)^2/4 = 0.0314 m^2

v = Q/A = (0.1 m^3/s)/(0.0314 m^2) = 3.18 m/s

Velocity head

$v^2/2g$ = (3.18 m/s)^2/((2)(9.81 m/s^2)) = 0.516 m

Pipe friction losses

$$h_{\text{pipe}} = f\frac{L}{D}\frac{v^2}{2g} = 0.022\left(\frac{400\text{ m}}{0.2\text{ m}}\right)(0.516\text{ m}) = 22.70\text{ m}$$

Losses from elbows, valves and other features = pipe friction losses = 22.70 m

Total head = h_{pipe} + Other losses + Static head

= 22.70 m + 22.70 m + 18 m = 63.4 m

9.11 PIPE LOOP I

A total flow of 2 m^2/s is to be delivered from A to B via two pipes, as shown in Figure P9.11. How the flow divides itself between the two pipes depends upon their relative hydraulic resistance. Calculate the flow in the two pipes.

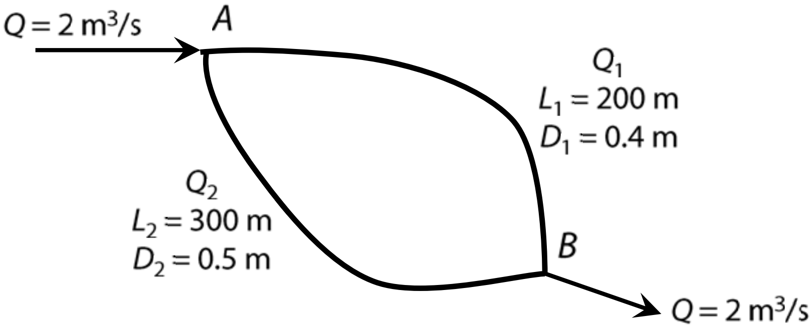


Figure P9.11 Pipe loop I

Solution

The pressure difference (head loss) between A and B must be the same for pipe 1 and pipe 2, otherwise there would be two different pressures at point B. The pressure difference between the two points is due to friction loss in the pipe.

$$\Delta p_{AB} = p_A - p_B = f_1 \frac{L_1}{D_1}\frac{v_1^2}{2g} = f_2 \frac{L_2}{D_2}\frac{v_2^2}{2g}$$

The two pipes are of the same material and roughness so $f_1 = f_2$.
Noting that $v = Q/A = Q/(\pi D^2/4)$ gives

$$\frac{L_1}{D_1}\left(\frac{Q_1}{\pi D_1^2/4}\right)^2 = \frac{L_2}{D_2}\left(\frac{Q_2}{\pi D_2^2/4}\right)^2 \quad \Rightarrow \quad L_1\frac{Q_1^2}{D_1^5} = L_2\frac{Q_2^2}{D_2^5}$$

$$Q_1 = Q_2\left(\frac{D_1}{D_2}\right)^{2.5}\sqrt{\frac{L_2}{L_1}} = Q_2\left(\frac{0.4\text{ m}}{0.5\text{ m}}\right)^{2.5}\sqrt{\frac{300\text{ m}}{200\text{ m}}} = 0.7011\,Q_2$$

$0.7011\ Q_2 + Q_2 = 2\ \text{m}^3/\text{s}$

$Q_2 = 1.18\ \text{m}^3/\text{s}$

$Q_1 = 2\ \text{m}^3/\text{s} - 1.18\ \text{m}^3/\text{s} = 0.82\ \text{m}^3/\text{s}$

9.12 PIPE LOOP II

A network with three pipes and two loops has a flow = 10 m³/s and is described in Table P9.12 and Figure P9.12. The head loss in each pipe is $h = f(L/D)(v^2/2g)$. Calculate flow in each pipe.

Pipe	f	Length (m)	Diameter (m)
1	0.01	1,600	0.4
2	0.02	800	0.2
3	0.02	900	0.25

Table P9.12 Pipe characteristics for loop system II

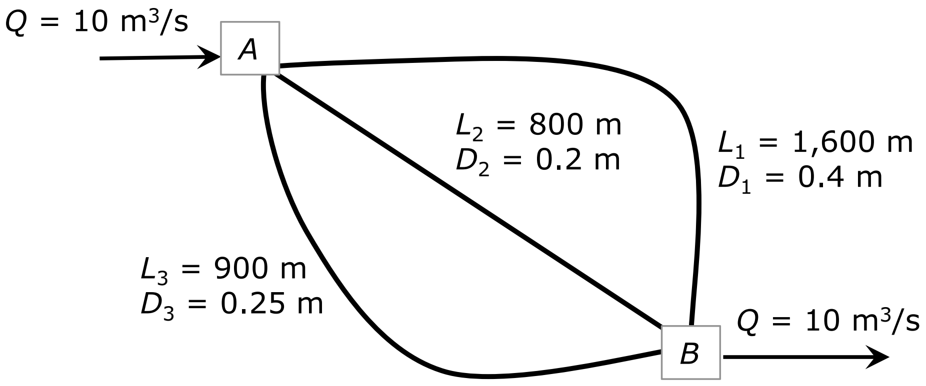


Figure P9.12 Pipe loop II

Solution

Write the headloss equation in terms of flow rather than velocity

$v = Q/A = Q/(\pi D^2/4)$

$$h = f\frac{L}{D}\frac{v^2}{2g} = f\frac{L}{D}\frac{(Q/(\pi D^2/4))^2}{2g} = f\frac{L}{D}\left(\frac{16Q^2}{\pi^2 D^4 2g}\right) = Kf\left(\frac{L}{D^5}\right)Q^2$$

$K = 8/\pi^2 g$ is a constant proportionality factor and can be omitted from the calculations. The resistance factors (fL/D^5) and head loss equations are in Table S9.12.

Pipe	f	L (m)	D (m)	fL/D^5	Head Loss
1	0.01	1,600	0.4	1,562	$h_1 = 1{,}562Q_1^2$
2	0.02	800	0.2	50,000	$h_2 = 50{,}000Q_2^2$
3	0.02	900	0.25	18,432	$h_3 = 18{,}432Q_3^2$

Table S9.12

The headloss from A to B is equal whichever path is taken.

$$h_1 = h_2 = h_3$$
$$1{,}562\ Q_1^2 = 50{,}000\ Q_2^2$$
$$1{,}562\ Q_1^2 = 18{,}432\ Q_3^2$$
$$Q_2 = 0.177\ Q_1$$
$$Q_3 = 0.291\ Q_1$$

Also $Q_1 + Q_2 + Q_3 = 10\ \text{m}^3/\text{s}$

$$Q_1 + 0.177\ Q_1 + 0.291\ Q_1 = 10\ \text{m}^3/\text{s}$$
$$1.468\ Q_1 = 10\ \text{m}^3/\text{s}$$

giving $Q_1 = 6.81\ \text{m}^3/\text{s}$ $Q_2 = 1.21\ \text{m}^3/\text{s}$ $Q_3 = 1.98\ \text{m}^3/\text{s}$

9.13 PUMPING BETWEEN TWO RESERVOIRS

An electric motor drives a centrifugal pump to deliver 1.2 m^3/s of water between two tanks with an elevation difference of 40 m as shown in Figure P9.13. The pipe connecting the tanks is 220 m long with a diameter of 500 mm and a pipe friction factor $f = 0.018$. Neglect minor losses. (a) Calculate the friction loss (m) in the pipe. (b) Calculate the total head for the system.

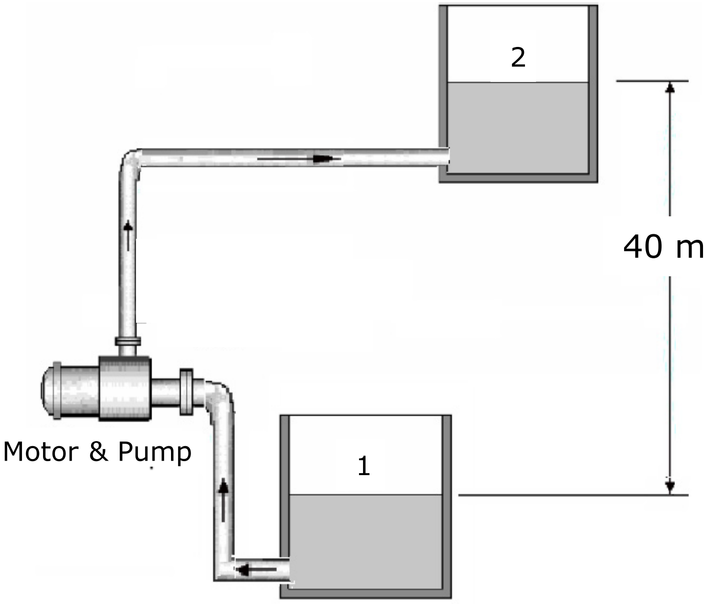


Figure P9.13 Pumping between two reservoirs

]

Solution

Pipe area = 3.1416(0.5 m)^2/4 = 0.196 m^2
Water velocity = v = (1.2 m^3/s)/(0.196 m^2) = 6.12 m/s
Velocity head = $v^2/2g$ = (6.12 m/s)^2/((2)(9.81 m^2/s)) = 1.91 m
Friction loss in the pipe

$$h_{\text{pipe}} = f\frac{L}{D}\frac{v^2}{2g} = 0.018\left(\frac{220\text{ m}}{0.5\text{ m}}\right)(1.91\text{ m}) = 15.13\text{ m}$$

Total head = friction loss + static head = 15.13 m + 40 m = 55.13 m

9.14 HEATING SYSTEM

The heating system shown in the diagram has a water heater, two radiators, a valve and a pump. If the head losses are: water heater = 3 m, radiator = 4 m, valve = 2 m, pipe 1 = 2m, pipe 2 = pipe 3 = pipe 4 = pipe 5 = 1 m. The head loss in the pipe section with the pump and valve can be ignored. Ignore losses in elbows and tees. (a) If the pump discharge is 10 m^3/h, what is the flow through each of the radiators? Will the flows be equal? If not, which do you think will be larger? If you want the flow through each radiator to be equal, so each delivers the same amount of heat energy to its surroundings, how should the network be modified?

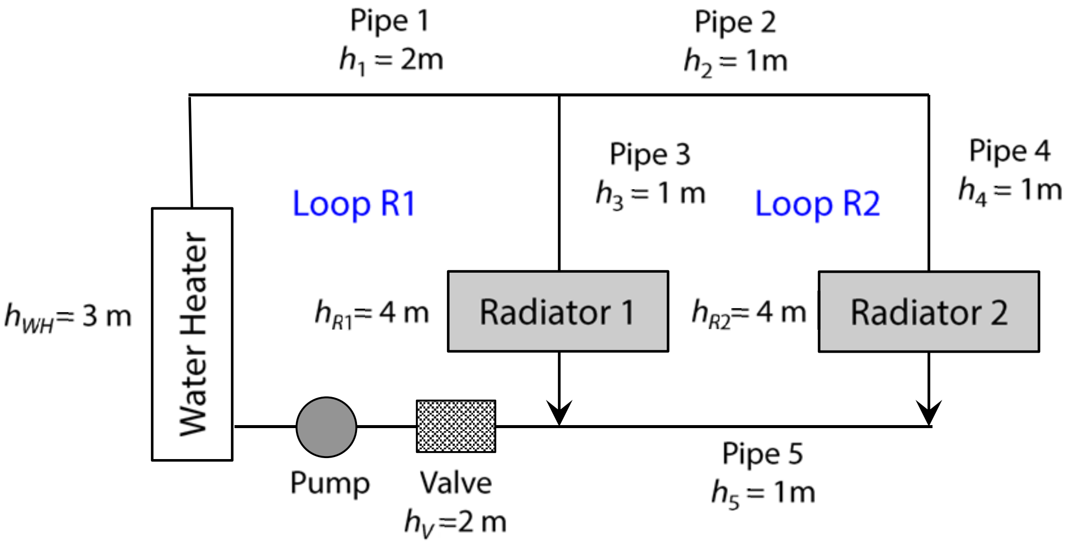


Figure P9.14 Heating system

Solution

This is an open-ended question that is meant to provoke discussion. No solution is provided.

10 ENERGY FOR BLOWERS & COMPRESSORS

Some useful pressure conversions

1 kg/cm^2 = 98,083 Pa = 0.981 bar = 0.968 atmosphere = 736 mm Hg

= 10,000 mm H_2O = 10 m H_2O

1 atm = 2,116 psf = 14.7 psi = 29.92 in Hg = 407 in H_2O = 33.9 ft H_2O = 10.33 m H_2O

10.1 BLOWER OPERATING CURVE

Figure P10.1 is the performance map for a variable speed centrifugal blower.

a) Identify the constant speed lines, and the constant efficiency curves.
b) Define and explain the *turndown, shutdown, and choke.*

c) Can this blower operate at a turndown of 85% of the design speed? What is the discharge pressure if the design flow rate is maintained? What is the flow rate if the discharge pressure is maintained?

d) At what inlet flow rate and discharge pressure does surge occur at 100% of design speed?

e) At what discharge pressure and flow rate will choke be obtained if the compressor operates at 100% of design speed.

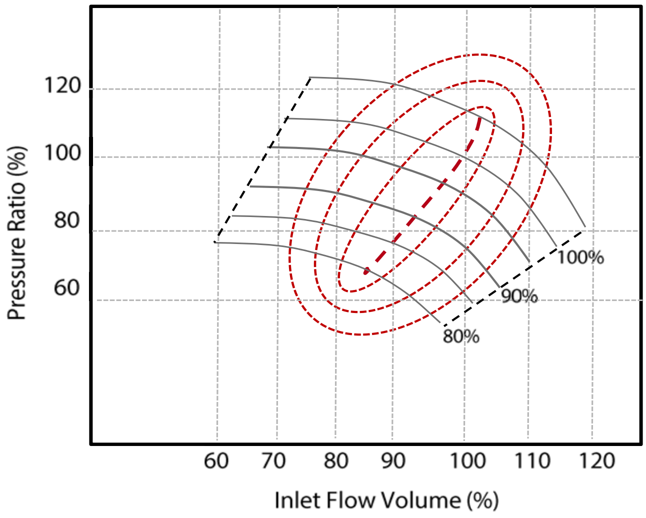


Figure P10.1 Centrifugal compressor performance map

Solution

a) Constant speed lines and efficiency curves are indicated in Figure S10.1. Also shown are surge, choke, trace of optimum efficiency and design point

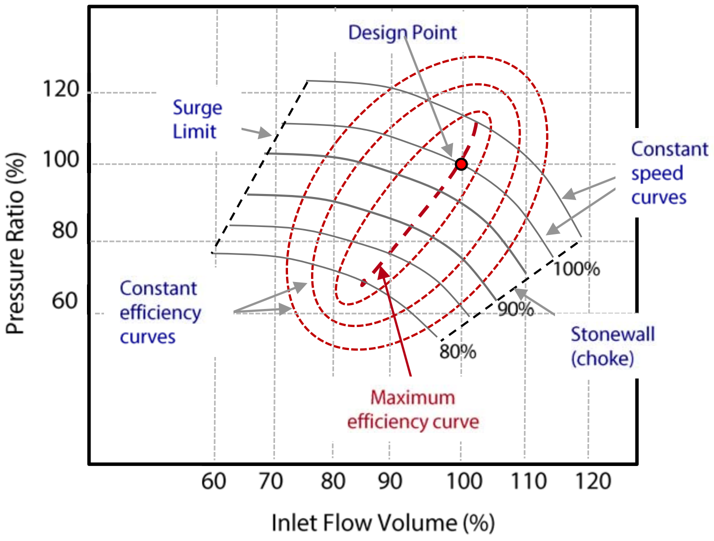


Figure S10.1 Centrifugal compressor performance map

b) The *turndown limit*, or simply *turndown* is the lowest speed for a compressor. Turndown can also be given as a percentage of the rated flow. Values range from 45-60% but 50% is a good value for many blowers.
Surge is the point at which the compressor cannot add enough energy to overcome the system resistance or backpressure. Surge is the operating point where maximum discharge pressure and minimum flow capacity is reached. Surge causes a flow reversal. The *surge limit* is the curve that passes through the lowest points of the speed lines.
Choke is a limit that occurs when the discharge increases as the discharge pressure decreases. The flow velocity increases to the sonic speed (Mach 1) somewhere within the compressor stage. The compressor cannot operate beyond this limit.
Use the constant speed curve for 100%.

c) Yes, but at the design flow the discharge pressure will be lower (about 60% of design). For 85% turndown the discharge pressure cannot be maintained at the design pressure, at most it will be about 85% of the design pressure.

d) At 100% of design speed, surge occurs at about 70% of design flow and 110% of design pressure.

e) At 100% of design speed, choke occurs at about 115% of design flow and 75% of design pressure.

10.2 WASTEWATER AERATION

A wastewater treatment plant serves 30,000 persons and has an estimated BOD load of 0.1 kg BOD/person, or 3,000 kg/day. The oxygen required to treat this wastewater, as a quick estimate, is 2 kg O_2/kg BOD = 6,000 kg O_2/day, or 250 kg/h. The oxygen transfer efficiency in actual field conditions is 19%. Estimate the airflow required.

Solution

The oxygen content of 1 Nm^3 of air = 0.296 kg O_2.
Dissolved oxygen (DO) supplied by one Nm^3 delivered to the aeration tank
= (0.19)(0.296 kg O_2/Nm^3) = 0.0562 kg O_2/Nm^3
Oxygen demand (given) = 250 kg/h = 6,000 kg/d
Volume of air required at the aeration tank
(6,000 kg O_2/d)/(0.0562 kg O_2/Nm^3) = 106,800 Nm^3/d =74.1 Nm^3/min

10.3 ESTIMATING THE REQUIRED AIR FLOW

An eight million gallon per day (mgd) activated sludge process needs an oxygen supply of 6,000 lb/d. The oxygen content of 1 scfm of air is 0.0173 lb O_2/min = 24.91 lb O_2/d. The selected fine bubble diffusers will dissolve 32% of this oxygen operating in clean water at 20°C, 1 atm, and 0 mg/L dissolved oxygen (DO) concentration. This is the standard oxygen transfer efficiency (SOTE, i.e. SOTE = 32%). Actual operating conditions allow only sixty percent of the SOTE to be achieved. Calculate the required air flow rate.

Solution

The SOTE can be converted to the standard oxygen transfer rate (SOTR) by

$$\text{SOTR} = \text{SOTE}\,(O_2 \text{ content of air})(\text{Air flow rate})$$

$$\text{SOTR} = 0.32(0.0173 \text{ lb } O_2/\text{scf})(Q_{air}) = (0.00554 \text{ lb } O_2/\text{scf})(Q_{air})$$

$$\text{AOTR} = 0.60\,(\text{SOTR}) = 6{,}000 \text{ lb } O_2/\text{d}$$

$$\text{AOTR} = 0.60(0.00554 \text{ lb } O_2/\text{scf})(Q_{air}) = (0.00332 \text{ lb } O_2/\text{scf})(Q_{air})$$

The required airflow rate is

$$Q_{\text{air}} = \frac{6{,}000 \text{ lb } O_2/\text{d}}{0.00332 \text{ lb } O_2/\text{scf}} = 1{,}807{,}229 \text{ scfd} = 1{,}255 \text{ scfm}$$

10.4 PRESSURE DROP IN FINE BUBBLE DIFFUSER SYSTEM (U.S. UNITS)

Figure P10.4 shows a blower-aeration system. The barometric pressure at the blower air filter inlet is 14.7 psia. The loss in the blower air filter and inlet manifold is 0.2 psi. There is a pressure loss of 1.4 psi in the distribution piping between the blower and the diffusers, and 1 psi in the diffusers. The water depth is 15 ft. Calculate the diffuser discharge pressure, with an added allowance for clogging and a safety factor.

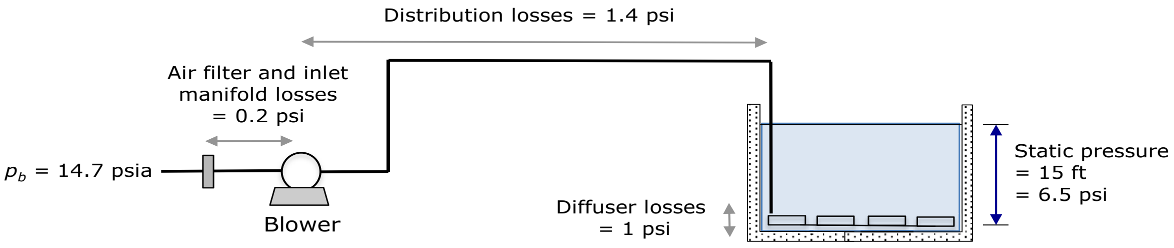


Figure P10.4 Pressure drop in diffuser system

Solution

The static pressure of 15 ft of water = (15 ft)(62.4 lb/ft^3)/(144 in^2/ft^2) = 6.5 psi

Pressure at blower intake = p_i = 14.7 psia – 0.2 psi = 14.5 psi

Pressure at diffuser discharge

$$p_{\text{discharge}} = 14.5 \text{ psi} + 1.4 \text{ psi} + 1.0 \text{ psi} + 6.5 \text{ psi} = 23.4 \text{ psi}$$

Add 0.5 psi for safety and clogging = 23.9 psi

10.5 PRESSURE DROP IN FINE BUBBLE DIFFUSER SYSTEM (SI UNITS)

Figure P10.5 shows a blower-aeration system. The barometric pressure at the blower air filter inlet is 1 atm. The loss in the filter and the blower inlet manifold is 0.015 atm. There is a pressure loss of 0.06 atm in the air distribution piping and a loss of 0.03 atm in the aeration tank downpipe and the fine bubble diffusers. The static pressure is 5.50 m of water. Calculate the diffuser discharge pressure.

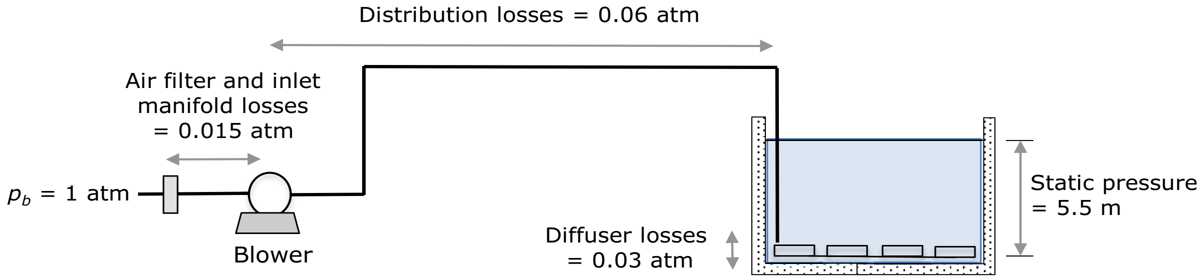


Figure P10.5 Pressure drop in diffuser system

Solution

The static pressure of 5 m of water

= 5 m(1 atm/10.33 m) 0.484 atm

Pressure at blower intake = p_i = 1 atm – 0.015 atm = 0.985 atm

Pressure at diffuser discharge

$p_{\text{discharge}}$ = 0.985 atm + 0.06 atm + 0.03 atm + 0.484 atm = 1.559 atm

Add 0.05 atm for safety and clogging = 1.609

10.6 BLOWER OUTLET TEMPERATURE

A blower operates at a design atmospheric (barometric) pressure p_b = 14.6 psia with a pressure drop Δp = 0.25 psig through the inlet filter and inlet manifold. The outlet air pressure is 8.2 psig. The inlet temperature T_{In} = 50°F = 510°R. Calculate the outlet temperature of the air.

Solution

Blower inlet pressure = p_{In} = 14.6 psia – 0.25 psig = 14.35 psia

Outlet pressure at discharge = 8.2 psig

Blower outlet pressure = p_{Out} = 14.35 + 8.2 = 22.55 psia

The outlet temperature T_{Out} is

$$T_{\text{Out}} = T_{\text{In}}\left(\frac{p_{\text{Out}}}{p_{\text{In}}}\right)^{0.286} = (510°\text{R})\left(\frac{22.55}{14.35}\right)^{0.286} = 578°\text{R}$$

T_{Out} = 578°R = 118°F

10.7 BLOWER POWER (U.S. UNITS)

The air requirement is 40,000 scfm and the air density is 0.0779 lb/ft³. The inlet conditions are p_1 = 14.2 psia and T_1 = 50°F = 510°R. The outlet pressure is p_2 = 22.4 psig. The specific heat for air is 0.24 Btu/lb°F (0.24 Btu/lb°R). Calculate the blower power.

Solution

$$P = \rho_{\text{air}} Q_{\text{air}} c_{P,\ \text{air}} T_1 \left[\left(\frac{p_2}{p_1} \right)^{0.286} - 1 \right]$$

$$= \left(40{,}000 \frac{\text{ft}^3}{\text{min}} \right) \left(0.0779 \frac{\text{lb}}{\text{ft}^3} \right) \left(0.24 \frac{\text{Btu}}{\text{lb°R}} \right) (510\text{°R}) \left[\left(\frac{22.4\text{psia}}{14.2\text{psia}} \right)^{0.286} - 1 \right]$$

$$= 53{,}105 \text{ Btu/min} = 3{,}186{,}000 \text{ Btu/h}$$

P = (3,186,000 Btu/h)(1 hp/2,544 Btu/h) = 1252 hp

P = (3,186,000 Btu/h)(2.931x10^{-4} kW/Btu/h) = 934 kW

P = (3,186,000 Btu/h)(1 kJ/0.9478 Btu) = 3,361,000 kJ/h = 3361 MJ/h

10.8 BLOWER POWER (SI UNITS)

Calculate the blower power required for an inlet airflow rate of 100 m^3/s for these conditions:

Blower inlet pressure = p_1 = 0.985 atm
Blower outlet pressure = p_2 = 1.52 atm
Blower inlet temperature = T_1 = 10°C = 283 K

Solution

Density of dry air at atm and 0°C = 1.2754 kg/m^3
Heat capacity = $c_{P,\text{air}}$ = 1.006 kJ/kg K

$$P = \rho_{\text{air}} Q_{\text{air}} c_{P,\text{ air}} T_1 \left[\left(\frac{p_2}{p_1} \right)^{0.286} - 1 \right]$$

$$= \left(100 \frac{\text{m}^3}{\text{s}}\right)\left(1.2754 \frac{\text{kg}}{\text{m}^3}\right)\left(1.006 \frac{\text{kJ}}{\text{kg-K}}\right)(283\text{ K})\left[\left(\frac{1.52\text{ atm}}{0.985\text{ atm}}\right)^{0.286} - 1\right]$$

$$= 4{,}797\text{ kJ/s} = 4{,}797\text{ kW}$$

10.9 DIURNAL AIR FLOW VARIATION

The organic load on an activated sludge process changes continually, typically being a minimum in the early morning, with a peak mid-day and evening. Table P10.9 shows that the air flow rates to the process are highest during the daytime hours. The blower inlet pressure and temperature are p_1 = 14.4 psia and T_1 = 75°F. Also air density = 0.075 lb/ft^3 and air specific heat = 0.24 Btu/lb°R. (a) Calculate the blower power in Btu/min and horsepower (hp). (b) Calculate the energy used in hp-h and kWh.

Time Interval	Airflow Q (scfm)	Discharge pressure (psig)	% of day
0000 - 0600	12,500	8.2	25.0
0600 - 0800	22,500	8.4	8.33
0800 - 1300	25,000	8.5	20.8
1300 - 1800	32,500	8.6	20.8
1800 - 2400	17,500	8.4	25.0

Table P10.9 Blower operation for a typical day

Solution

Given

p_1 = 14.4 psia

T_1 = 460°R + 75°F = 535°R

Discharge pressure (psia) = p_2 =14.4 psia + p_2 (psig)

X_a = adiabatic factor = $[(p_2/p_1)^{0.286} - 1]$

Sample calculation for time interval 0000-0600:

p_2 = 14.4psia + 8.2 psig = 22.6 psia

X_a = [(22.6 psia/14.4 psia)$^{0.286}$ – 1] = 0.13758

Power = $Q_{air}\ \rho_{air}\ c_P\ T_1\ X_a$

= (12,500 scfm)(0.075 lb/ft^3)(0.24 Btu/lb°R)(535°R)(0.13758)

= 16,561 Btu/min = 993,672 Btu/h

Power (hp) = (993,672 Btu/h)/((2,544 Btu/h)/hp) = 391 hp

Prorated Power (hp) = [fraction of time][Power (hp)] = (0.25)(391 hp) = 98 hp

Interval	Q_{air} (scfm)	p_2 (psia)	Adiabatic Factor X_a	Power (Btu/min)	(hp)	% of time	Prorated (hp)
0000-0600	12,500	22.6	0.13758	16,562	391	25.0	98
0600-0800	22,500	22.8	0.14045	29,811	703	8.33	59
0800-1300	25,000	22.9	0.14188	33,123	781	20.8	162
1300-1800	32,500	23.0	0.14331	43,060	1016	20.8	211
1800-2400	17,500	22.8	0.14045	23,186	547	25.0	137
						Total =	667

Table S10.9 - Blower operation for a typical day

Total daily power

= 667 hp

= (667 hp)((2544Btu/h)/hp)/(60min/h) = 28,300 Btu/min

Energy use

= (667 hp)(24 h) = 16,000 hp-h

= (16,000 hp-h)(0.7457 kWh/hp-h) = 11,900 kWh

11 ECONOMICS OF ENERGY MANAGEMENT

Some Useful Equations

Power in horsepower	$P_o = \rho g H Q/550$	$P_o = 32.2\rho H Q/550$
Power in kW	(1 kW = 0.7457 hp)	$P_o = 0.0437\ \rho H Q$
Power in kW	$P_o = \rho g H Q/1000$	$P_o = 9.81\rho Q/1000$

where P_o = power delivered by the pump (kW, hp)
ρ = density of water (kg/m^3, lb/ft^3)
g = acceleration of gravity (9.81 m/s^2, 32.2 ft/s^2)
H = total head loss (m, ft)
Q = flow rate (m^3/s, ft^3/s)

11.1 ENERGY FOR DRINKING WATER AND WASTEWATER UTILITIES

In 2015, the U.S. electric power sector emitted an estimated 1,925 million metric tons of carbon dioxide (CO_2), or about 37% of the total U.S. energy-related CO_2 emissions of 5,271 million metric tons. An estimated 3% of national energy consumption is used for drinking water and wastewater services. Assuming the average mix of energy sources in the country, how many million tons of CO_2 did the water and wastewater treatment industry add to the atmosphere?

Source	Million metric tons	Share of total
Coal	1,364	71%
Natural gas	530	28%
Petroleum	24	1%
Other[3]	7	<1%
Total	1,925	

Table P11.1 Electric power sector CO_2 emissions in the U.S in 2015

Solution

If 3% of this total (1,925 million metric tons) is assigned to water and wastewater utilities, the CO_2 emitted is

$$(0.03)(1{,}925 \text{ million metric tons}) = 57.75 \text{ million metric tons} = 57{,}750{,}000{,}000 \text{ kg}$$

11.2 ENERGY FOR WASTEWATER TREATMENT

In Austin, Texas, 60% of municipal electric energy is for water and wastewater treatment, 10% is for street lights and traffic signals, and 30% is for other city uses. The fraction of total cost going for energy is 34% for the water utility and 28% for the wastewater system. This compares to 35% and 48% of the cost, respectively, going for labor. Looking for opportunities to reduce energy costs is very worthwhile. Energy audits at 200 water and wastewater plants suggest that 10-20% energy savings are available through process changes and another 10-20% through equipment modifications. How will implementing these savings change the distribution of municipal energy use?

Solution

Basis = 100 units of energy use
Assume average savings of 15% by process changes and 15% by equipment modifications
Total savings on water and wastewater energy use = 30%
For an energy demand of 60 units, savings = 0.3(60 units) = 18 units

Energy Demand	Total (%)	Present (units)	Savings (%)	Future (units)	Future (%)
Water & wastewater	60	60	18	42	51
Street lights & signals	10	10	0	10	12
Other	30	30	0	30	37
Total	100	100	18	82	100

Table S11.2

Savings of 18% of present energy use (reduction from 100 units to 82 units)

Share for water & wastewater = 100(51/82) = 51%, down from 60%.

Similar savings are probable in the other sectors, for example by more efficient lighting and heating.

11.3 WASTEWATER TREATMENT PLANT ENERGY I

The National Council of Clean Water Agencies (2005) reported a survey of 47 wastewater treatment plants that used a combined 2.1 billion kWh of electricity. The breakdown was 38% for in-plant pumping, 26% for aeration, 25% for effluent pumping, and 11% for other uses. Suppose the pumping efficiency can be improved by 15% and aeration efficiency can be improved by 20%. How much electricity can be saved?

Solution

Demand	% of Total	Current Use (10^6 kWh)	Savings (10^6 kWh)	After Savings (10^6 kWh)
In-plant pumping	38	798	120	678
Aeration	26	546	109	437
Effluent pumping	25	525	79	446
Other	11	231	0	231
Total	100	2,100	308	1,792

Table S11.3

Electricity savings = 308×10^6 kwh

11.4 WASTEWATER TREATMENT PLANT ENERGY II

Table P11.4 divides the energy used in a 7.5 million gallon per day activated sludge wastewater treatment plant into 12 accounting categories of electricity use, with activated sludge being by far the largest consumer. The energy use averages 2,700 kWh per million gallons (kWh/MG). This is above average for a plant of this size. Possible savings include 140 kWh/MG by installing fine pore air diffusers, 50 kWh/MG for dissolved oxygen control systems, 50 kWh/MG for blower control systems, and 100 kWh/MG for energy efficiency blowers. There is also a possible 10% reduction for more efficiency pumps and motors. This would apply to raw wastewater pumping, primary clarifier, and secondary clarifier. A 20% overall reduction might be achieved by better utilization of sludge digester gas. Calculate the energy use for the existing plant and for the plant if the energy conservative measures were implemented.

Category	Treatment Process	Electricity Use (kWh/MG)
1	Raw wastewater pumping	108
2	Grit removal	5
3	Primary clarifier	297
4	Activated sludge	1,535
5	Secondary clarifiers	81
6	Sludge thickeners	27
7	Effluent filters	27
8	Utility water	68
9	Sludge dewatering	203
10	Heating	216
11	Lighting	81
12	Disinfection	52
Total		2700

Table P11.4 Accounting categories for energy use in an activated sludge wastewater treatment plant

Solution

Savings from aeration system redesign (diffusers, DO and blower controls, and blowers)
= (140 kWh/MG + 50 kWh/MG + 50 kWh/MG + 100 kWh/MG) = 340 kWh/MG
= 340 kWh/MG (7.5 mgd) = 2,550 kWh/d

Savings from higher efficiency pumping (raw wastewater, primary and secondary clarifiers)
= 0.1(108 kWh/MG + 297 kWh/MG + 81 kWh/MG) = 0.1(486 kWh/MG)
= 11 kWh/MG + 30 kWh/MG + 8 kWh/MG = 49 kWh/MG
= (49 kWh/MG)(7.5mgd) = 367.5 kWh/d

Savings from better utilization of digester gas = (0.2)(2,311 kWh/MG) = 462 kWh/MG
= (462 kWh/MG)(7.5 mgd) = 3,465 kWh/d

Total savings = 2,700 kWh/MG – 1,849 kWh/MG = 851 kWh/MG
= (851 kWh/MG)(7.5 mgd) = 6,383 kWh/d = 2,330,400 kWh/y
Total savings at $0.12/kWh = (2,330,400 kWh/y)($0.12/kWh) = $280,000/y

Treatment Process	Present Use		Savings	Use with Modifications	
	(kWh/MG)	%	(kWh/MG)	Upgrades (kWh/MG)	Biogas Use (kWh/MG)
Raw wastewater pumping	108	4	11	97	78
Grit removal	5	0.2	0	5	4
Primary clarifier	297	11	30	267	214
Activated sludge	1,535	57	340	1,195	956
Secondary clarifiers	81	3	8	73	58
Sludge thickeners	27	1	0	27	22
Effluent filters	27	1	0	27	22
Utility water	68	3	0	68	54
Sludge dewatering	203	7	0	203	162
Heating	216	8	0	216	173
Lighting	81	3	0	81	65
Disinfection	52	2	0	52	42
	2,700	100	389	2,311	1,849

Table S11.4

11.5 COMPRESSED AIR

Compressed air costs real money, usually a substantial amount of money. Compressed air is often taken for granted as a necessary cost, and is often abused and wasted. Its cost flows into the nebulous pot called, "overhead." Because of this, it tends to get squandered and misused.

A plant has two 50 hp and one 25 hp compressors. Calculate the average cost of compressed air, assuming \$0.14/kWh. Each compressor operates 8,760 hours per year and has an efficiency of 90 percent.

Solution

Total horsepower = 2(50 hp) + 25 hp = 125 hp
Power in kWh = (125 hp)(0.7457 kW/hp) = 93.21 kW
Annual Cost = [(93.21 kW)/(0.9)](\$0.14/kWh)(8,760 h/y) = \$127,000/y

11.6 COST OF COMPRESSED AIR

Compressed air is one of the most expensive sources of energy in a plant. The overall efficiency of a typical compressed air system can be as low as 10-15%. For example, to operate a 1 hp air motor at 100 psig, approximately 7-8 hp of electrical power must be supplied to the air compressor.

An air compressor at factory uses 160 kW of power (215 bhp) and operates 6800 h/y. It is fully loaded 85% of the time (motor efficiency = 95%) and under loaded the rest of the time (25% full-load and motor efficiency = 90%). The aggregate electric rate is \$0.10/kWh. Calculate the cost of compressed air using

Solution

Fully loaded for (6,800 h/y)(0.85) = 5780 h/y; 95% efficiency

$$\text{Cost (\$/y)} = \frac{(160\text{ kW})(5{,}780\text{ h/y})(\$0.10/\text{kWh})}{0.95} = \$97{,}347/\text{y}$$

Partially loaded for (6,800 h/y)(0.15) = 1020 h; efficiency = 90%

$$\text{Cost (\$/y)} = \frac{(160\text{ kW})(1{,}020\text{ h/y})(\$0.10/\text{kWh})}{0.90} = \$18{,}133/\text{y}$$

Total annual energy cost = \$115,480 per year

11.7 ECONOMY OF SCALE – HEAT EXCHANGERS

A new heat exchanger with area = 100 m^2 costs $92,000. What is the cost for a similar unit with area = 50 m^2. The economy-of-scale exponent is M = 0.44.

Solution

$$C_2 = C_1\left(\frac{Q_1}{Q_2}\right)^M = \$92{,}000\left(\frac{50\ \text{m}^2}{100\ \text{m}^2}\right)^{0.44} = \$92{,}000(0.737) = \$67{,}800$$

11.8 JOINT TREATMENT

A group of industries have started to discuss building a single large treatment plant that will be shared instead of building individual treatment facilities. How does economy-of-scale affect their decision? Does it matter how many industries are involved? Does the relative size of the cooperating industries matter?

Solution

This is an open-ended question for class or group discussion. No solution is provided.

11.9 POLLUTON PREVENTION SAVES

The purchase price of a process (installed) is a function of the process capacity. When the capacity is 1, the cost is \$10,000. When the capacity is 10, the cost is \$50,000. The cost-capacity equation is

$$C = \$10{,}000Q^{0.7}$$

Suppose that an industry plans to build a process of 20 capacity units, but before any equipment is purchased or any construction has started the pollution control engineer discovers a way to reduce the needed capacity by 25%. How much money has this pollution prevention intervention saved the company?

Solution

The cost for 20 units of capacity is

$$C = \$10{,}000(20)^{0.7} = \$10{,}000(8.1418) = \$81{,}408$$

With a 25% reduction the required capacity is 15 units. The cost is

$$C = \$10{,}000(15)^{0.7} = \$10{,}000(6.6568) = \$66{,}568$$

The savings is \$14,840. There will be additional savings from lower maintenance and operation costs.

11.10 AUDIT OF PUMPING ENERGY

Centrifugal pumps are one of our most efficient pieces of equipment and, when properly maintained, they will have a long life. An energy audit of a water pumping installation provides the information listed in Table P11.10 for four pumps. The oldest, and the largest, was installed in 1992 and the newest in 2002. Rated Horsepower or Nameplate horsepower is the measure of the motor's mechanical output rating. The measured efficiency is the line-to-water value. (a) Calculate the actual power consumption, the energy use per year, and the cost per year if electricity costs \$0.18 kWh. (b) Comment on opportunities to upgrade the pumping complex and reduce the cost of operation.

Pump	Installed	Rated Power		Efficiency (line to water)	Operation (h/y)
1	1992	200 hp	149 kW	0.75	2,000
2	1994	150 hp	112 kW	0.93	4,000
3	1995	80 hp	60 kW	0.85	4,000
4	2002	40 hp	30 kW	0.93	5,000

Table P11.10 Energy audit for four pumps

Solution

a) Power use and energy costs
Sample calculation for pump1

kWh/y = (Rated power, kW)(hours/year operation)/efficiency
= (149kW)(2,000 h/y)/(0.75) = 397,333 kWh/y
Cost = ($0.18/kWh)(397,333 kWh/y) = $71,520/y

Pump	Rated Power		Efficiency	Operation (h/y)	Power consumption (kWh/y)	Annual cost ($)
1	200 hp	149 kW	0.75	2,000	397,333	71,520
2	150 hp	112 kW	0.93	4,000	481,720	86,710
3	80 hp	60 kW	0.85	4,000	282,353	50,824
4	40 hp	30 kW	0.93	5,000	161,290	29,032

Table S11.10 Energy audit for four pumps

11.11 ELECTRIC BILL

The monthly electric bill asks payment for delivery of 10,400 kWh at $0.14 per kWh. In addition the peak demand was 56.2 kW and the peak demand charge is $16.65 per kW. There is also a base charge of $65 per month per customer. Calculate the total payment due.

Solution

Usage charge = (10,400 kWh)($0.14/kWh) = $1,456
Peak demand charge = (56.2 kW)($16.65/kW) = $936
Base charge = $65
Total charges = $2,457

Peak demand charge is 38% of the total.

11.12 PEAK ELECTRICAL DEMAND CHARGES

The data in Table P11.12 are the highest demands for power during a hypothetical billing period. The peak demand charge is calculated using the single largest peak demand for power during the billing period (usually the average over a 15 minute period). The normal peak demand at a pollution control facility is 5,900 kW, but this has been exceeded several times in this billing period due to special operating demands. Assume the peak demand charge is $19.40/kW.

a) Calculate the peak demand charge for a typical month.
b) How much has the peak demand increased because of the excursions above 5,900 kW.
c) Assume that peak power demand excursions of this magnitude occur every month. How much could be saved per year if the some of the peak demand could be shifted to one of the low periods of demand?

Date	Time	Demand (kW)	kW Above 590 kW
May 10	10:00 am	6320	420
May 24	10:30 am	6220	320
May 14	11:00 am	6140	240
May 5	1:30 pm	6090	190
May 20	2:30 pm	6050	150
May 15	10:30 am	6020	120
May 15	10:00 am	6010	110
May 8	2:00 pm	6000	100
May 9	2:00 pm	5990	90
May 13	1:30 pm	595	50
May 5	2:00 pm	592	20

Table P11.12 Highest electrical energy demands for a hypothetical billing period in May

Solution

a) Peak demand for a typical month is 5,900 kW.
Peak demand charge = (5,900 kW)($19.40/kW) = $114,460
b) The highest peak demand has increased by 6,320 kW - 5,900 kW = 420 kW
c) Limiting peak demand to 5900 kW would reduce the peak demand by 420 kW
At $19.40/kW the savings is s $8,148 per month, or $97,776 per year.
To affect this reduction requires a total sheddable load of at least 420 kW

11.13 DEMAND CHARGES

An electric utility's demand charge is $7.40/kW and the electric energy rate is $0.15/kWh. Suppose you use a 1000W appliance during your power company's 15-minute peak demand interval.

a) What is the demand charge?
b) What is the energy charge?
c) What is the total cost, in $ and $/kWh, of operating the appliance during the 15-minute peak demand period?

Solution

a) The demand charge depends on *when* the appliance is used. It does not depend on *how long* the appliance was used.

Demand charge = ($7.40/kW)(1000 W)(kW/1000 W) = $7.40

b) The usage charge depends on *how long* the appliance is used. It is the same whenever the appliance is used.

Energy charge for using a 1000W appliance during any 15-minute period of the month is:

Electricity used = (1000 W)(0.25 h)/(1000 W/kW) = 0.250 kWh
Cost = ($0.15/kWh)(0.250 kWh) = $0.0375

It costs just as much to operate a 1000-watt appliance during the 15-minute peak demand interval as it does to operate the 1000-watt appliance for ($7.40/$0.0375) = 197 15 min periods at any other time during the month.

c) Total cost for operating during the peak load period = Usage charge + Peak Charge

Total cost = $7.40 + 0.0375 = $7.4375
Net cost per kilowatt hour = $7.4375/0.25 h = $29.75/kWh

Tutorial Note on the Present Value Calculation

Saving money is a great incentive to reduce energy use. One of the most important applications of this is the electrical cost for operating pumps and blowers, which are very large. This is also one of the easiest situations to understand. Therefore, we include several problems that include economic calculations.

The future value, $F_{n,i}$, of an amount P_0, compounded for n years at interest rate i is

$$F_{n,i} = PV(1+i)^n$$

The converse gives the present value (PV)

$$PV = \frac{F}{(1+i)^n}$$

Appendix 8 has tables of factors for converting (1) an initial amount (e.g. capital cost or loan) into a series of equal annual payments, or the inverse (2) converting a series of equal annual amounts to a present value.

11.14 PAYBACK TIME FOR SPRAY PAINTING

An engineer wants to install new piping from a paint mix room to the spray booths to reduce the line cleaning waste. An investment of $10,000 will eliminate 5,000 gal/y of semi-solid waste. Each gallon of waste represents $3.00 of wasted raw material. Waste disposal, including transportation and in-plant labor, costs $0.45/gal. Estimate the payback time.

Solution

The total annual savings are

Waste disposal savings = (5,000 gal/y)($0.45/gal) = $2,250/y
Raw material savings = (5,000 gal/y)($3.00/gal) = $15,000/y
Total savings = $17,250/y
Payback time = $10,000/($17,250/y) = 0.6 y = 7 months

11.15 PAYBACK PERIOD I

The initial investment for a still to recycle waste solvent is $9,000, and it will provide a net annual operations savings of $4,600. What is the payback period?

Solution

The payback period, assuming equal annual savings, is the net annual savings is divided by the initial project investment cost. For this project the payback period is

Payback Period = $9,000/($4,600/y) = 2.0 y

11.16 PAYBACK PERIOD II

A shop manager learns that installation of a solvent recovery still will cost $7,700, but provide a net annual operational savings of $4,634. What is the payback period for the solvent recovery project?

Solution

The payback period, assuming equal annual savings, is the net annual savings is divided by the initial project investment cost. For this project the payback period is

Payback time = ($7,700)/($4,634/y) = 1.7 y

11.17 SAVINGS AT SHEBOYGAN WI

The wastewater treatment plant in Sheboygan implemented the energy saving projects listed in Table P11.17. What is the payback time for each energy saving measure?

Energy Saving Measure	Installed Cost	Annual savings	
	($)	(kWh)	($)(a)
Replaced two 200 HP influent pump station motors with premium efficient motors and variable speed drives	$170,000	157,000	$18,840
Replaced two 125 HP process motors with premium efficient motors and VFDs	$150,000	79,140	9,500
Blower replacement	$773,000	358,000	42,960
Dissolved oxygen control	$128,000	459,000	55,080
Total	$1,221,000	1,053,140	$126,380

(a) Electricity at $0.12/kWh
Data source: Water Research Foundation 2013, *Electricity Use and Management in the Municipal Water Supply and Wastewater Industries*, Denver, CO

Table P11.17 Energy efficiency results at Sheboygan, WI

Solution

The payback period, assuming equal annual savings, is the net annual savings is divided by the initial project investment cost.

Sample calculation
For the two 200 HP motor replacements the payback period is
Payback time = ($170,000)/($18,840/y) = 9.0 y

Energy Saving Measure	Installed Cost	Annual savings		Payback Time
	($)	(kWh)	($)	(y)
Replaced two 200 HP influent pump station motors with premium efficient motors and variable speed drives	170,000	157,000	18,840	9.0
Replaced two 2125 HP process motors with premium efficient motors and VFDs	150,000	79,140	9,500	15.8
Blower replacement	773,000	358,000	42,960	18.0
Dissolved oxygen control	128,000	459,000	55,080	2.3
Total	1,221,000	1,053,140	126,380	9.7

Table S11.17 Payback time for energy efficiency results at Sheboygan, Wi

11.18 FUTURE VALUE OF MONEY

An amount, $25,000 invested today at 5% interest is worth how much in 10 years?

Solution

The future value of an amount *P*, compounded for *n* years at interest rate *i* is

$$F_{10,\,5\%} = PV(1+i)^n = \$25{,}000(1.05)^{10} = \$25{,}000(1.6289) = \$40{,}722.$$

11.19 PRESENT VALUE OF MONEY

You own a note that promises payment of \$25,000 in 10 years. You have a chance to sell this note for \$18,000 cash, paid today. The current interest rate is 5% per year. What is the rational economic decision, assuming you do not need the money today for an emergency? Should you sell the note or keep it until maturity?

Solution

The present value (*PV*) of \$25,000 at $i = 5\%$ for $n = 10$ years is

$$PV_{10,\ 5\%} = \frac{F}{(1+i)^{10}} = \frac{\$25{,}000}{(1+0.05)^{10}} = \$25{,}000\,/\,1.6289 = \$15{,}348$$

Put another way, \$15,348 today invested at 5% for ten years will yield \$25,000.

Sell the note and take the \$18,000 because it is more than the present value of the note.
Invest the \$18,000 at 5% for 10 years and you will have

$$\$18{,}000(1.05)^{10} = \$18{,}000(1.6289) = \$29{,}320.$$

You earn an extra \$4,320.

11.20 AERATED LAGOON ENERGY SAVINGS

A wastewater treatment plant treats a maximum daily dry weather flow of 2.1 mgd with two 1,000,000 gallon oxidation ditches followed by secondary clarifiers. An oxidation ditch (Figure P11.20) is a variation of the activated sludge process. The aeration tank is a circular or oval concrete channel (or *ditch*). Aeration is provided by mixers that revolve on a horizontal shaft. The mixers also act as ‘pumps’ to move the wastewater around the channel. Each oxidation ditch operated four 30-hp aerators 24 hours per day, seven days a week, for a total of 240 hp constantly being used of aeration.

Figure P11.20 Oxidation ditch with a mechanical aerator

An on-line dissolved oxygen control system was installed to maintain a constant DO of 1.5mg/L to 2.0 mg/L. Instead of four aerators running constantly, the process can, at times, operate with only two aerators in each ditch, with additional aerators cycling on and off as needed.

The on-line DO control system produces savings of 48 kW and 420,000 kWh/y and reduces the annual cost of electricity by $31,700.

Calculate

a) The 10-year present value of the savings on electricity for i = 6%.
b) The simple payback period, for a total project cost of $125,000.
c) The treatment plant's payback period, taking in to account a State of California Process Optimization Program (CalPOP) that paid sixty percent of the project cost.

Solution

a) This can be done in a table (spreadsheet) by calculating the Present Value of the savings for each year and summing the ten values. The PV factor for each year n is

$$1/(1+i)^n = 1/(1+0.06)^n$$

These calculations are in Table S11.20. The total PV = $233,315.

The alternate calculation is to multiply the annual cost savings by the sum of the PV factors for the 10 years. *PVF* = 7.36009. This can be calculated, as done in Table S11.21, or it can be looked up in financial tables in Appendix 8.

PV of total annual savings = 7.36009($31,700) = $233,315

Year	PV Factor	Savings ($/y)	PV ($/y)
1	0.94340	31,700.0	29,906
2	0.89000	31,700.0	28,213
3	0.83962	31,700.0	26,616
4	0.79209	31,700.0	25,109
5	0.74726	31,700.0	23,688
6	0.70496	31,700.0	22,347
7	0.66506	31,700.0	21,082
8	0.62741	31,700.0	19,889
9	0.59190	31,700.0	18,763
10	0.55839	31,700.0	17,701
Totals	7.36009		$233,315

Table S11.20

b) Simple payback period = Capital Cost/Annual savings

= \$125,000/(\$31,700/y) = 4 y

c) CalPOP pays (0.6)(\$125,000) = \$75,000

Wastewater utility pays = \$50,000

Payback time for utility = \$50,000/(\$31,700/y) = 1.6 y

11.21 LOAN REPAYMENT

A loan of \$25,000 carries terms of 5% interest with full repayment in 10 years. You plan to repay this in (a) equal annual payments or (b) equal monthly payments. Which plan has the lowest cost?

Solution

Repayment over time as a series of payments is called amortization.

You have just been given \$25,000. That is the present value of your commitment.

PV = \$25,000

The future value is the \$25,000 plus all of the interest you pay over the next 10 years.

a) For 10 equal annual payments of amount A, this is easy to write out in full.

$$PV_{10,\ 5\%}=A\left(\frac{1}{1+0.05}+\frac{1}{(1+0.05)^2}+\frac{1}{(1+0.05)^3}+\ \cdots\ +\frac{1}{(1+0.05)^{10}}\right)$$

$$= A(0.9524+0.9070+0.8638+0.8227+0.7835+0.7462+0.7107+0.6768+0.6446+0.6139)$$

$$= 7.7217\ A$$

A = \$25,000/7.7217 = \$3,238/y

Total loan payments = (10 years)(\$3,238/year) = \$32,380

This is \$25,000 principal + \$7,380 interest

b) For equal monthly payments of amount M, use

i = 5%/12 = 0.0417% per month

n = 10(12) =120 payments

$$PV_{120,\ 0.0417\%}= M\left(\frac{1}{1.00417}+\frac{1}{(1.00417)^2}+\frac{1}{(1.00417)^3}+\ \cdots\ +\frac{1}{(1.00417)^{120}}\right)$$

$$= 94.2827\ M$$

M = \$25,000/94.2827 = \$256.16/month

The value of the summation can be found in tables for financial calculations, or it can be calculated using a spreadsheet. Also, there are convenient online calculators for amortization and loan repayments.

The monthly payment will be $265.16.
Total annual loan payments = (12)($265.16) = $3,181.92
Total loan payments = $31,819.20
Total interest paid = $31,819.20 - $25,000 = $6,820.

Monthly payments have the lower cost because the money is repaid slightly faster. More of the payment goes to the principal and less toward the interest.

11.22 COMPARING TWO PUMPS

The costs for two pumps, Table P11.22, includes shipping to the point of use and installation. Annual O&M cost includes electricity, labor, minor repairs, etc. Both pumps have a lifetime of 10 years. Use a discount rate of 8% per year to determine which pump is more economical.

Cost Factor	Pump A	Pump B
Purchase price ($)	40,000	50,000
Annual O&M cost ($/y)	6,000	5,000
Pump lifetime (years)	10	10

Table P11.22 Economic summary for comparison of two pumps

Solution

The Total Present Values (10 year lifetime, *i* = 8%) are purchase cost + PV of O&M cost.
Pump A = $40,000 + $40,260 = $80,260
Pump B = $50,000 + $33,550 = $83,550

The present value calculations are in Table S11.22a. The analysis is summarized in Table S11.22b.

Year	PV Factor	O&M A ($/y)	PV A ($/y)	O&M B ($/y)	PV B ($/y)
1	0.92593	6,000	5,556	5,000	4,630
2	0.85734	6,000	5,144	5,000	4,287
3	0.79383	6,000	4,763	5,000	3,969
4	0.73503	6,000	4,410	5,000	3,675
5	0.68058	6,000	4,083	5,000	3,403
6	0.63017	6,000	3,781	5,000	3,151
7	0.58349	6,000	3,501	5,000	2,917
8	0.54027	6,000	3,242	5,000	2,701
9	0.50025	6,000	3,001	5,000	2,501
10	0.46319	6,000	2,779	5,000	2,316
Totals	6.71008		$40,260		$33,550

Table S11.22a Present value calculations for two pumps

Cost Factor	Pump A	Pump B
Purchase price ($)	40,000	50,000
Annual O&M cost ($/y)	6,000	5,000
Pump lifetime (y)	10	10
Simple lifetime cost ($/y)	100,000	100,000
Present Value O&M cost ($)	40,260	33,550
Total Present Value ($)	80,260	83,550

Table S11.22b Economic summary for comparison of two pumps

Pump A is the more economical choice.

11.23 AIR COMPRESSOR LIFE CYCLE COST

An air compressor costs $110,000. Oil is changed every six months at a cost of $250. An annual minor overhaul is $4,000, a major overhaul every 5 years is $32,000. The estimated compressor life is 20 years. The company's discount rate is 8%. (a) Calculate the present value of cost for oil changes and overhauls. (b) Calculate the equal annual costs for the $110,000 initial investment. (c) Calculate the equal annual payments for the present value of the oil changes and overhauls.

Solution

Treat cost of oil change as $500/y.
Minor overhaul is needed every year. Cost is paid at the end of the year.
Major overhaul needed in years 5, 10, and 15. Compressor life ends in year 20 so no overhaul is needed.

Because the costs are not the same each year the easiest solution is with a spreadsheet calculation of the year-by-year costs and present values. This is done in Table S11.23.
Total PV = $90,870

This is divided into

Total PV oil = $$4,909

Total PV minor overhauls = $39,273

Total PV major overhauls = $46,689

Year	Annual PV Factor	Oil ($)	Minor overhaul ($)	Major overhaul ($)	Total ($)	Annual PV ($)
1	0.9259	500	4,000		4,500	4,167
2	0.8573	500	4,000		4,500	3,858
3	0.7938	500	4,000		4,500	3,572
4	0.7350	500	4,000		4,500	3,308
5	0.6806	500	4,000	32,000	36,500	24,841
6	0.6302	500	4,000		4,500	2,836
7	0.5835	500	4,000		4,500	2,626
8	0.5403	500	4,000		4,500	2,431
9	0.5002	500	4,000		4,500	2,251
10	0.4632	500	4,000	32,000	36,500	16,907
11	0.4289	500	4,000		4,500	1,930
12	0.3971	500	4,000		4,500	1,787
13	0.3677	500	4,000		4,500	1,655
14	0.3405	500	4,000		4,500	1,532
15	0.3152	500	4,000	32,000	36,500	11,506
16	0.2919	500	4,000		4,500	1,314
17	0.2703	500	4,000		4,500	1,216
18	0.2502	500	4,000		4,500	1,126
19	0.2317	500	4,000		4,500	1,043
20	0.2145	500	4,000		4,500	965
Totals	9.8181					$90,870

Table S11.23

b) The amortized capital cost, *A*, can be calculated using the inverse of the present value factor,

PVF = 9.8181.

A = \$110,000/9.8181 = \$11,204/y

c) The equal annual O&M costs that are equivalent to the total present value can be calculated in the same way.

Present value maintenance costs = \$90,870

PVF = 9.8181

A = \$90,870/9.8181 = \$9,255/y

Comment: The annual cost for oil changes and overhauls is 83% of the annualized cost of the compressor.

11.24 COST OF LIFTING WATER

Improvements are considered to reduce the cost for a pumping system that presently costs $12,500/year per meter of total operating head. The pump has a wire-to-wire efficiency of 55% so one opportunity could be to increase this efficiency. Changes to pipe and valves might be helpful. Hardware details will not be considered until it is determined what capital costs of investment in improvements is equivalent to saving 1 m of head over 20 years at 6.5% interest. What is the potential savings?

Solution

The question is "What is the *PV* of $12,500 per year over 20 years at a discount rate of 6.5%?

From tables (Appendix 8), or calculations, PVF = 11.02
PV = (11.02)($12,500) = $137,750

This is a great potential savings. Get to work on the hardware and hydraulics.

11.25 WATER FILTRATION

Three filter installations are nearly equivalent for water treatment (Table P11.25). Identify the lowest cost alternative based on annual cost. Assume an interest rate = 8% and project life = 20 years.

	Rapid sand filters	Upflow filters	Microstrainers
Capital cost	$1,775,000	$1,870,000	$1,740,000
Electricity/year	$80,000	$87,900	$59,000

Table P11.25 Cost of three filtration systems.

Solution

No calculations are needed. Microstrainers dominate both capital cost and electricity cost per year, so it must have the lowest present value.

The PVF = 9.818
PV Rapid sand filters = $1,775,000 + 9.818($80,000) = $2,560,000
PV Upflow filters = $1,870,000 + 9.818($87,900) = $2,733,000
PV Microstrainers = $1,740,000 + 9.818($59,000) = $2,319,000

11.26 TEMPORARY WATER MAIN

A temporary water main is required for three years to supply water to a construction camp at a large dam. Which of the following designs (Table P11.26) should be used if the interest rate is 8% and if all equipment can be sold at the end of the 3-year project for 30% of the initial price.

Pipe diameter (in)	6	8	10
Initial cost of pipe and pumps	\$500,000	\$600,000	\$770,000
Annual pumping cost	\$75,000	\$55,000	\$40,000

Table P11.26 Water main costs

Solution

Sample calculation for 6-inch pipe

For 3-year project life and 8% discount rate

$PVF_{3,8\%} = 2.5771$

PV Annual pumping costs = 2.5771(\$75000) = \$193,300

Total *PV* of costs = \$500,000 + 193,300 = \$693,300

Salvage is income

Salvage value is discounted from year 3 to year 1.

Salvage value = (0.3)\$500,000 = \$150,000 at year 3

PV salvage value = \$150,000/$(1 + 0.08)^3$ = \$150,000/(1.2597) = \$119,100

Total PV = Capital Cost + PV Pumping Costs – PV Salvage value

Total PV = \$500,000 + \$193,300 - \$119,100 = \$574,200

Cost or Present Value	Pipe diameter (in)		
	6	8	10
Initial cost of pipe and pumps ($)	500,000	600,000	770,000
Annual pumping cost ($/y)	75,000	55,000	40,000
PV annual pumping cost ($)	193,300	141,700	103,100
Total PV of costs ($)	693,300	741,700	873,100
Salvage price at 3 years ($)	150,000	180,000	231,000
PV salvage ($)	119,100	142,900	183,400
Total *PV* ($)	574,200	598,800	689,700

Table S11.26 Total present value

11.27 ACTIVATED SLUDGE AIR SUPPLY

Equipment to control the air supply in an activated sludge process costs \$900,000 in a basic configuration or \$1,300,000 in an upgraded configuration. If electricity costs \$0.09/kWh, how much energy savings will justify the complex system. State all assumptions.

Solution

Assume a project lifetime of 15 years
Assume a discount rate of 6%
PVF = 9.7123

Electricity savings require a *PV* equal to the difference in process capital costs
= \$1,300,000 – \$900,000 = \$400,000

PV of electricity savings = \$400,000 = *A* (9.7123)
where *A* = annual savings
A = \$41,200/y

Energy required to be saved at \$0.09/kWh
= (\$41,200/y)/(\$0.09/kWh) = 458,000 kWh/y = 1245 kWh/d

11.28 PUMPING BETWEEN TWO RESERVOIRS (SI UNITS)

A pump operates at a total head of 115 m, which consists of a static lift of 40 m and friction losses in the pipe network of 75 m. The flow is $Q = 0.5\ \mathrm{m^3/s}$. The pump efficiency is $\eta_p = 0.85$, motor efficiency is $\eta_m = 0.91$.

a) Calculate the theoretical pumping power (power delivered by the pump to the water).
b) Calculate the electrical power input to the drive motor of the pump.
c) Calculate the daily and annual cost of electricity, at \$0.16 kWh, if the pump is operated 10 hours per day for 250 days of the year.
d) An on-site generator can be installed for \$750,000 and cleaned biogas can be purchased for \$0.05 per kWh. The generator has a useful life of 10 years. The company's internal discount rate is 15%. Is this a good investment?

Solution

a) Power delivered by the pump to the water

Total head = 40 m + 75 m = 115 m

$$P_0 = \frac{9.81\rho QH}{1000} = \frac{(9.81\text{ m/s}^2)(1000\text{ kg/m}^3)(0.5\text{ m}^3\text{/s})(115\text{ m})}{1000\text{ W/kW}} = 564\text{ kW}$$

b) Electrical power input to the drive motor

$$P_I = \frac{P_0}{\eta_p\eta_m} = \frac{564\text{ kW}}{(0.85)(0.91)} = 729\text{ kW}$$

c) Daily and annual cost of electricity

Pump operates 10 h/d and 250 d/y

Daily electricity use = (729 kW)(10 h/d) = 7,290 kWh/d

Daily cost = ($0.16/kWh)(7,290 kWh/d) = $1,166/d

Annual electricity use = (7,290 kWh/d)(250 d/y) = 1,822,500 kWh/y

Annual cost = ($0.16/kWh)(1,822,500 kWh/y) = $291,600/y

d) Annualized (amortized) cost for the generator purchase

$$PV = \$750{,}000 = \frac{A}{1+0.15} + \frac{A}{(1+0.15)^2} + \frac{A}{(1+0.15)^2} + \ldots + \frac{A}{(1+0.15)^{10}}$$

$$\$750{,}000 = A\,(0.8696 + 0.7561 + 0.6575 + 0.5718 + \ldots + 0.2843 + 0.2472)$$

$$\$750{,}000 = 5.0188\,A$$

$$A = (\$750{,}000)/5.0188 = \$148{,}440/\text{y}$$

The annualized (amortized) cost of the generator is less than the annual cost of purchased electricity so this is a good investment. Also the price of cleaned biogas is less than the cost of electricity.

12 APPENDIX 1 - ABRIDGED TABLE OF ATOMIC NUMBERS AND ATOMIC MASSES

Element	Symbol	Atomic Number	Atomic Mass	Element	Symbol	Atomic Number	Atomic Mass
Aluminum	Al	13	27.0	Mercury	Hg	80	200.6
Antimony	Sb	51	121.8	Molybdenum	Mo	42	95.9
Argon	Ar	18	40.0	Neon	Ne	10	20.2
Arsenic	As	33	74.9	Nickel	Ni	28	58.7
Barium	Ba	56	137.3	Nitrogen	N	7	14.0
Beryllium	Be	4	9.0	Oxygen	O	8	16.0
Bismuth	Bi	83	209.0	Phosphorus	P	15	31.0
Boron	B	5	10.8	Platinum	Pt	78	195.1
Bromine	Br	35	79.9	Plutonium	Pu	94	(244)
Cadmium	Cd	48	112.4	Polonium	Po	84	(209)
Calcium	Ca	20	40.1	Potassium	K	19	39.1
Carbon	C	6	12.0	Radium	Ra	88	226.0
Chlorine	Cl	17	35.5	Radon	Rn	86	(222)
Chromium	Cr	24	52.0	Selenium	Se	34	79.0
Cobalt	Co	27	58.9	Silicon	Si	14	28.1
Copper	Cu	29	63.5	Silver	Ag	47	107.9
Fluorine	F	9	19.0	Sodium	Na	11	23.0
Gallium	Ga	31	69.7	Strontium	Sr	38	87.6
Gold	Au	79	197.0	Sulfur	S	16	32.1
Helium	He	2	4.0	Tin	Sn	50	118.7
Hydrogen	H	1	1.0	Titanium	Ti	22	47.9
Iodine	I	53	126.9	Tungsten	W	74	183.8
Iron	Fe	26	55.8	Uranium	U	92	238.0
Krypton	Kr	36	83.8	Vanadium	V	23	50.9
Lead	Pb	82	207.2	Xenon	Xe	54	131.3
Lithium	Li	3	6.9	Zinc	Zn	30	65.4
Magnesium	Mg	12	24.3	Zirconium	Zr	40	91.2
Manganese	Mn	25	54.9				

Table A1.1 Atomic masses for selected elements (Rounded to one decimal place.)

13 APPENDIX 2 - CONVERSION FACTORS

Linear Measure Equivalents

meter	foot	centimeter	inch
1	3.2808	100	39.37
0.2048	1	30.48	12.0
100	0.03281	1	0.3937
0.0254	0.0833	2.54	1

Area Equivalents

hectare	sq. meter	acre	sq. foot
1	10,000	2.471	107,639.1
0.0001	1	0.000247	10.764
0.4047	4,046.9	1	43,560
9.29×10^{-6}	0.0929	0.000,023	1

Volume Equivalents (U.S. units)

cubic foot	U. S. gallon	acre-foot	barrel (U.S. petroleum)
1	7.48	---	0.1781
0.1337	1	0.000,0031	
43,560	325,851	1	
65.615	42.0	---	1

Volume Equivalents (Metric & U.S.)

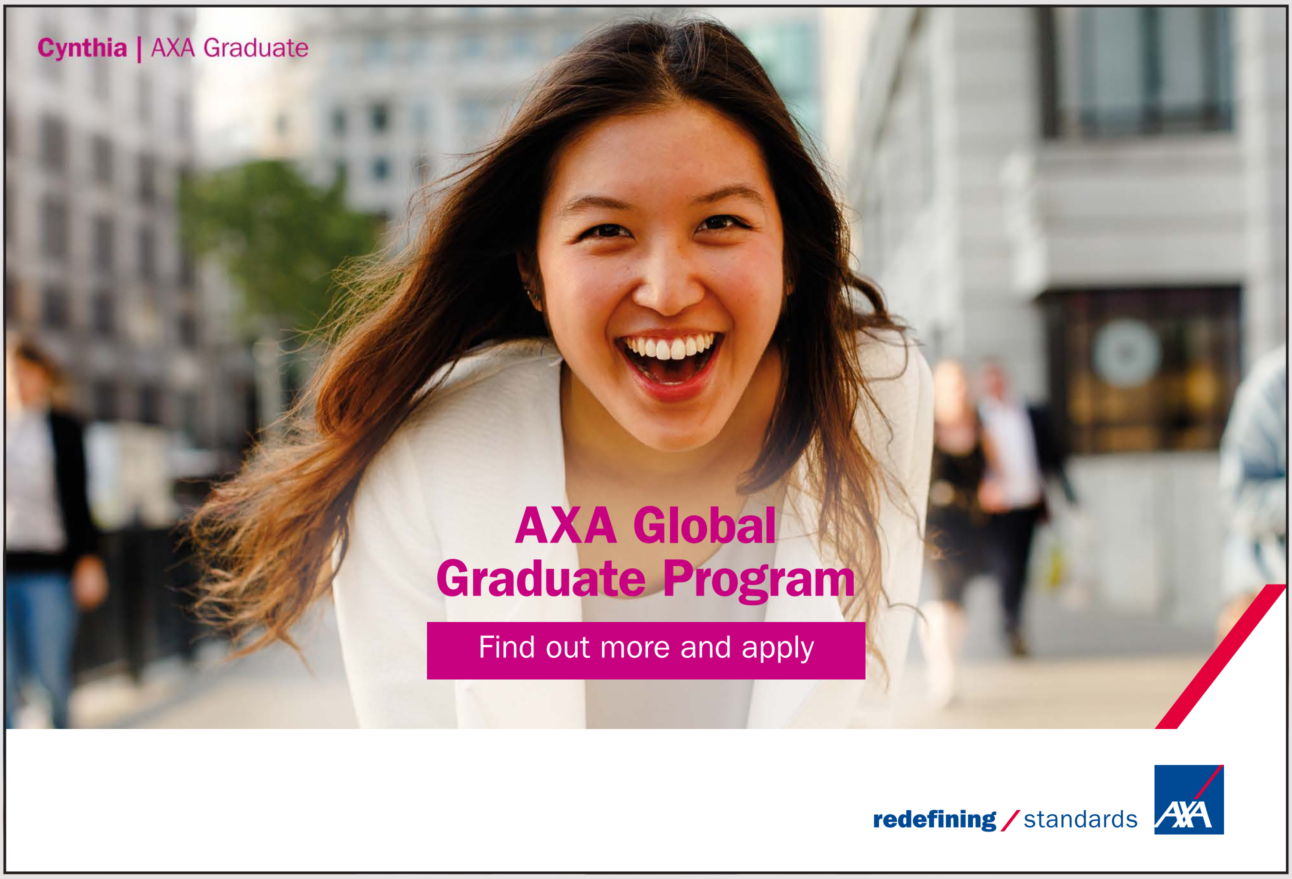
liter	cubic meter	U.S. gallon	cubic foot
1	0.001	0.2642	0.0353
1,000	1	264.172	35.315
3.785	0.00378	1	0.1337
28.317	0.02832	7.48	1

Power Equivalents

horsepower	kilowatt	ft-lb/s	Btu/s
1	0.7457	550	0.7068
1.341	1	737.56	0.9478
0.001,818	0.001,356	1	0.001285
1.415	1.055	778.16	1

Heat, Energy, or Work Equivalents

Joule (kg-m)	ft-lb	kWh	hp-h	Liter-atm	Btu
1	7.233	2.724 x 10^{-6}	3.653 x 10^{-6}	0.0968	0.009,296
0.1383	1	3,766 x 10^{-7}	5.050 x 10^{-7}	0.0134	0.000,324
367,100	2,655,000	1	1.341	35,534	3412.8
273,750	1,980,000	0.7455	1	26,494	2,545
10.33	74.73	2.815 x 10^{-5}	3.774 x 10^{-5}	1	0.0242
426.7	3,086	0.001,162	0.001,558	41.29	1



14 APPENDIX 3 - DENSITIES AND SPECIFIC WEIGHTS

U. S. Units			SI Units		
Temperature (°F)	Density ρ (lb/ft^3)	Specific Weight γ (lb/ft^3)	Temperature (°C)	Density ρ (kg/m^3)	Specific Weight γ (N/m^3)
-40	0.09464	0.09464	-40	1.514	14.85
-20	0.09032	0.09032	-20	1.395	13.68
0	0.08639	0.08639	0	1.293	12.67
10	0.08456	0.08456	5	1.269	12.45
20	0.08279	0.08279	10	1.247	12.23
30	0.08111	0.08111	15	1.225	12.01
32	0.08063	0.08063	20	1.204	11.81
40	0.07950	0.07950	25	1.184	11.61
50	0.07792	0.07792	30	1.165	11.43
60	0.07641	0.07641	40	1.127	11.05
70	0.07499	0.07499	50	1.109	10.88
80	0.07361	0.07361	60	1.060	10.40
90	0.07226	0.07226	70	1.029	10.09
100	0.07097	0.07097	80	0.9996	9.803
120	0.06852	0.06852	90	0.9721	9.533
140	0.06624	0.06624	100	0.9461	9.278
160	0.06408	0.06408	200	0.7461	7.317
180	0.06208	0.06208	300	0.6159	6.040
200	0.06021	0.06021	400	0.5243	5.142
300	0.05229	0.05229	500	0.4565	4.477
400	0.04621	0.04621	1000	0.2772	2.719
500	0.04138	0.04138			
750	0.03284	0.03284			
1,000	0.02721	0.02721			
1,500	0.02025	0.02025			

The correct U.S. unit for density is slugs/ft^3; the more convenient and unit is lb/ft^3
Specific weight = (density)(acceleration of gravity)

Table A3.1 Density and specific weight of air (at 1 atm)

Gas	Formula	Molar Mass (g/mol)	Density	
			(kg/m³)	(lb/ft³)
Acetylene	C_2H_2	26.02	1.1708	0.0732
Air			1.2928	0.0808
Ammonia	NH_4	17.03	0.7708	0.0482
Butane	C_4H_{10}	58.08	2.5985	0.1623
Carbon dioxide	CO_2	44.00	1.9768	0.1235
Carbon monoxide	CO	28.00	1.2501	0.0781
Chlorine	Cl_2	70.91	3.2204	0.2011
Cyanogen	C_2N_2	52.02	2.3348	0.1459
Ethane	C_2H_6	30.05	2.8700	0.1793
Ethylene	C_2H_4	28.03	1.2644	0.0783
Fluorine	F_2	38.00	1.6354	0.1022
Hydrogen	H_2	2.016	0.0898	0.0056
Hydrogen chloride	HCl	36.47	1.6394	0.1024
Hydrogen sulfide	H_2S	34.08	1.5992	0.0961
Methane	CH_4	16.03	0.7167	0.0448
Methyl chloride	CH_3Cl	50.48	2.3044	0.1440
Natural gas		19.50	0.7-0.9	0.044-0.056
Nitrogen	N_2	28.02	1.2507	0.0782
Oxygen	O_2	32.00	1.4289	0.0892
Propane	C_3H_6	44.09	1.8820	0.1175
Sulfur dioxide	SO_2	64.06	2.9268	0.1828
Water vapor (steam)	H_2O	18.02	0.8040	0.0480

Table A3.2 Density of selected gases at standard conditions (0°C and 1 atm)

Material	Sp. gr.	Material	Sp. gr.
Metals		**Various liquids**	
Aluminum	2.55-2.8	Alcohol, ethyl (100%)	0.79
Bronze	7.4-8.9	Alcohol, methyl (100%)	0.80
Iron, gray cast	7.03-7.10	Acid, nitric (91%)	1.50
hematite ore	5.2	Acid, sulfuric (87%)	1.80
magnetite ore	4.9-5.2	Chloroform	1.50
Lead	11.34	Oils, vegetable	0.91-0.94
galena ore	7.3-7.6	**Concrete masonry**	
Steel, cold-drawn	7.83	cement, stone, sand	2.2-2.4
Various solids		slag. etc.	1.9-2.3
Cereals, corn (bulk)	0.73	cinder, etc.	1.5-1.7
Cotton, flax, hemp	1.47-1.50	**Earth, etc., excavated**	
Glass, common	2.4-2.8	Clay, dry	1.00
Glass, plate	2.45-2.72	damp plastic	1.76
Glass, flint	3.2-4.7	Earth, dry loose	1.20
Leather	0.86-1.02	dry, packed	1.5 95
Paper	0.70-1.15	moist, loose	1.30
Rubber, goods	1.0-2.0	moist, packed	1.60
Salt, granulated (piled)	0.77	**Bituminous substances**	
Sulfur	1.93-2.07	Asphalt	1.11-1.5
Timber		Refined kerosene	0.78-0.82
Fir, Douglas	0.48-0.55	Gasoline	0.70-0.75
Maple, white	0.53	Tar, bituminous	1.2
Oak, white	0.77	**Coal and coke, piled**	
Redwood, California	0.42	anthracite	0.75-0.93
Teak, African	0.99	bituminous	0.64-0.87
Stone, quarried & piled		charcoal	0.166-0.23
Limestone, marble, quartz	1.50	coke	0.37-0.51
Sandstone	1.30		

Table A3.3 Approximate specific gravities of miscellaneous solids and liquids.

15 APPENDIX 4 – HEATING VALUES

The heating value is the amount of heat produced by combustion of a unit quantity of a fuel. We differentiate between gross and net heating values:

The *gross or high heating value* is the amount of heat produced by the complete combustion of a unit quantity of fuel. The gross heating value is obtained when all products of the combustion are cooled down to the temperature before the combustion the water vapor formed during combustion is condensed

The *net or lower heating value* is obtained by subtracting the latent heat of vaporization of the water vapor formed by the combustion from the gross or higher heating value.

Common Units for heating values:

1 Btu/ft^3 = 8.9 kcal/m^3 = 3.73×10^4 J/m^3
1 Btu/lb = 2,326.1 J/kg = 0.55556 kcal/kg
1 J/kg = 0.00043 Btu/lb = 2.39×10^{-4} kcal/kg
1 kcal/kg = 1.80 Btu/lb = 4,187 J/kg

Gas	Higher Heating Value (HHV)		Lower Heating Value (LHV)	
	(Btu/ft³)	(Btu/lb)	(Btu/ft³)	(Btu/lb)
Acetylene (ethyne)	1,498	21,569	1,447	20,837
Benzene	3,741	18,150	3,590	17,418
Blast Furnace gas	92	1,178	92	1,178
Butane	3,225	21,640	2,977	19,976
Butylene (butene)	3,077	20,780	2,876	19,420
Carbon to CO_2		14,150		14,150
Carbon monoxide	323	4,368	323	4,368
Coke Oven Gas	574	17,048	514	15,266
Digester Gas (Biogas)	690	11,316	621	10,184
Ethane	1,783	22,198	1,630	20,295
Ethylene	1,631	21,884	1,530	20,525
Hexane	4,667	20,526	4,315	18,976
Hydrogen	325	61,084	275	51,628
Hydrogen Sulfide	672	7,479		
Landfill Gas	476			
Methane	1,011	23,811	910	21,433
Natural gas (typical)	950-1,150	19,500-22,500	850-1,050	17,500-22,000
Propane	2,572	21,564	2,371	19,834
Propylene (Propene)	2,332	20,990	2,181	19,630
Toluene	4,408	18,129	4,206	17,301
Sasol	500	14,550	443	13,016
Water Gas (bituminous)	261	4,881	239	4,469
Xylene	5,155	18,410		

Table A4.1 Gross (High) and Net (Low) Heating Values of Some Gases (U.S. Units)

Gas	Higher Heating Value (HHV)		Lower Heating Value (LHV)	
	(MJ/m³)	(MJ/kg)	(MJ/m³)	(MJ/kg)
Acetylene (ethyne)	55.88	50.17	53.97	48.47
Benzene	139.54	42.22	133.91	40.52
Blast Furnace gas	3.43	2.74	3.43	2.74
Butane	120.29	50.34	111.04	46.47
Butylene (butene)	114.77	48.34	107.27	45.17
Carbon to CO_2		32.91		32.91
Carbon monoxide	12.05	10.16	12.05	10.16
Coke Oven Gas	21.41	39.66	19.17	35.51
Digester Gas (Biogas)	25.74	26.32	23.16	23.69
Ethane	66.51	51.63	60.80	47.21
Ethylene	60.84	50.90	57.07	47.74
Hexane	174.08	47.75	160.95	44.14
Hydrogen	12.12	142.09	10.26	120.09
Hydrogen Sulfide	25.07	17.40		
Landfill Gas	17.75			
Methane	37.71	55.39	33.94	49.86
Natural gas (typical)	35.44 - 42.90	45.56 - 52.34	31.71 - 39.20	40.71 - 51.17
Propane	95.94	50.16	88.44	46.14
Propylene (Propene)	86.98	48.82	81.35	45.66
Toluene	164.42	42.17	156.88	40.24
Sasol	18.65	33.84	16.52	30.28
Water Gas (bituminous)	9.74	11.35	8.91	10.40
Xylene	192.28	42.82		

Table A4.2 Gross (High) and Net (Low) Heating Values of Some Gases (SI Units)

Chemical Substance	Btu/lb	kJ/kg	Chemical	Btu/lb	kJ/kg
Gases			**Liquids**		
Ammonia (anhydrous)	8,000	18,608	Acetaldehyde	11,390	26,493
Cyanogen	8,930	20,771	Acetic acid	6,265	14,572
Formaldehyde	8,180	19,027	Acetone	13,260	30,843
Isobutane	19,610	45,613	Benzene	17,260	40,147
Methane	21,500	50,009	Butyl alcohol	15,530	36,123
Methyl chloride	5,850	13,607	Chlorobenzene	12,000	27,912
Propylene	19,700	45,822	Creosote (coal tar)	12,500	29,075
Vinyl chloride	8,140	18,934	Cresol	14,700	34,192
Solids			Diesel fuel	18,400	42,798
			Ethyl acetate	11,000	25,586
Anthracene	17,300	40,240	Ethylbenzene	17,600	40,938
Benzoic acid	11,370	26,447	Ethylene glycol	8,175	19,015
Citric acid (anhydrous)	4,390	10,211	Ethylene glycol diacetate	15,000	34,890
Hexachlorobenzene	3,220	7,490	Glycerine (glycerol)	7,760	18,050
Menthol	17,380	40,426	Heptane	19,380	45,078
Naphthalene	17,300	40,240	Hexane	19,230	44,729
Nitrobenzene	7,400	17,212	Kerosene	15,500	36,053
Nitrophenol	8,900	20,701	Methyl acetate	9,260	21,539
p-Nitrotoluene	11,665	27,133	Methyl alcohol	9,755	22,690
Palmitic acid	16,470	38,309	Methyl ethyl ketone	14,600	33,960
Phenanthrene	17,020	39,589	Methyl mercaptan	11,050	25,702
Phenol	14,000	32,564	Motor oil	18,500	43,031
Phthalic acid	8,350	19,422	Naphtha	18,000	41,868
Polypropylene	19,600	45,590	Nicotine	11,510	26,772
Stearic acid	17,060	39,682	Nitrobenzene	10,810	25,144

Chemical Substance	Btu/lb	kJ/kg	Chemical	Btu/lb	kJ/kg
Solids			**Liquids**		
Strychnine	14,460	33,634	o-Nitrotoluene	11,290	26,261
Sucrose	7,090	16,491	Octanol	17,440	40,565
Tannic acid	9,810	22,818	Oil, crude	18,250	42,450
Trichloroacetic acid	1,020	2,373	Oil, vegetable	16,000	37,216
Trinitrobenzene	5,600	13,026	Pentane	19,340	44,985
Trinitrotoluene	6,500	15,119	Polypropylene glycol	14,200	33,029
Urethane	8,025	18,666	Propyl alcohol	14,460	33,634
Wax (Paraffin)	18,000	41,868	Styrene	18,100	42,101
			Tallow	18,000	41,868
			Tetraethyl lead	7,870	18,306
			Toluene	17,420	40,519
			Triethylaluminum	18,360	42,705
			Vinyl acetate	9,750	22,679
			Xylene	17,500	40,705

Table A4.3 Heat of combustion of selected chemical compounds.

16 APPENDIX 5 – ENTHALPY OF WATER AND STEAM

T (°F)	Vapor Pressure (atm)	Enthalpy (Btu/lb)			*T* (°C)	Vapor Pressure (kPa)	Enthalpy (kJ/kg)		
		Sat. Liquid	ΔH_v	Sat. Vapor			Sat. Liquid	ΔH_v	Sat. Vapor
32	0.0060	0	1075.1	1075.1	0	0.62	0	2500.9	2500.9
40	0.0083	8.05	1070.5	1078.6	5	0.87	21.02	2489.1	2510.1
50	0.0121	18.07	1064.8	1082.9	10	1.23	42.02	2477.2	2519.2
60	0.0174	28.07	1059.1	1087.2	15	1.71	62.98	2465.4	2528.4
70	0.0247	38.05	1053.4	1091.5	20	2.34	83.92	2453.6	2537.5
80	0.0345	48.02	1047.8	1095.8	25	3.17	104.84	2441.7	2546.5
90	0.0475	58.00	1042.1	1100.1	30	4.25	125.75	2429.9	2555.6
100	0.0646	67.97	1036.4	1104.4	35	5.63	146.64	2418.0	2564.6
110	0.0867	77.94	1030.9	1108.8	40	7.38	167.54	2406.0	2573.5
120	0.115	87.91	1025.3	1113.2	45	9.59	188.44	2394.1	2582.5
130	0.151	97.89	1019.5	1117.4	50	12.35	209.34	2382.0	2591.3
140	0.196	107.88	1013.7	1121.6	55	15.67	230.24	2369.9	2600.1
150	0.253	117.87	1007.8	1125.7	60	19.95	251.15	2357.7	2608.8
160	0.332	127.87	1002.0	1129.9	65	25.04	272.08	2346.4	2618.5
170	0.408	137.89	996.1	1134.0	70	31.20	293.02	2333.1	2626.1
180	0.511	147.91	990.2	1138.1	75	38.60	313.97	2320.6	2634.6
190	0.635	157.95	984.1	1142.1	80	47.41	334.95	2308.1	2643.0
200	0.784	167.99	977.8	1145.8	85	57.87	355.95	2295.4	2651.3
210	0.961	178.06	971.5	1149.6	90	70.18	376.97	2282.5	2659.5
212	1.000	180.07	970.3	1150.4	95	84.61	398.02	2269.6	2667.6
220	1.170	188.14	965.2	1153.3	100	101.33	419.10	2256.5	2675.6
230	1.414	198.22	958.7	1156.9	110	143.38	461.36	2229.7	2691.1
240	1.699	208.34	952.1	1160.4	120	198.67	503.78	2202.1	2705.9
250	2.029	218.48	945.3	1163.8	130	270.26	546.39	2173.7	2720.1
260	2.411	228.65	938.6	1167.3	140	361.50	589.20	2144.2	2733.4
270	2.848	238.84	931.8	1170.6	150	476.10	632.25	2113.7	2745.9
280	3.348	249.06	924.6	1173.7	160	618.14	675.57	2081.8	2757.4
290	3.916	259.31	917.4	1176.7	170	792.05	719.21	2048.7	2767.9
300	4.560	269.60	910.1	1179.7	180	1002.60	763.19	2014.0	2777.2

Table A5.1 Enthalpy and latent heat of vaporization, ΔH_v, of saturated water and steam. (Complete steam tables can be found in Perry's Chemical Engineer's Handbook, 8th ed. (2006), CRC Press, Boca Rotan.

17 APPENDIX 6 – ENTHALPY OF AIR

Temp.		Saturation Pressure (N/m^2)	Moisture at Saturation (kg H_2O/ kg dry air)	Specific Volume		Specific Enthalpy	
°C	°F			Dry Air (m^3/kg)	Saturated Mixture (m^3/kg dry air)	Dry Air (kJ/kg)	Saturated Mixture (kJ/kg dry air)
-40	-40	12.84	0.000079	0.660	0.660	-40.2	-40.0
-30	-22	38	0.00023	0.688	0.688	-30.2	-29.6
-25	-13	63.25	0.00039	0.702	0.703	-25.2	-24.2
-20	-4	103.2	0.00064	0.716	0.717	-20.1	-18.5
-15	5	165.2	0.0010	0.731	0.732	-15.1	-12.6
-10	14	259.2	0.0016	0.745	0.747	-10.1	-6.1
-5	23	401.5	0.0025	0.759	0.762	-5.0	1.2

Temp.		Saturation Pressure (N/m²)	Moisture at Saturation (kg H_2O/ kg dry air)	Specific Volume		Specific Enthalpy	
°C	°F			Dry Air (m³/kg)	Saturated Mixture (m³/kg dry air)	Dry Air (kJ/kg)	Saturated Mixture (kJ/kg dry air)
0	32	610.8	0.0038	0.773	0.778	0	9.5
5	41	871.9	0.0054	0.788	0.794	5.0	18.6
10	50	1227	0.0077	0.802	0.812	10.1	29.5
15	59	1704	0.011	0.816	0.830	15.1	42.9
20	68	2337	0.015	0.830	0.850	20.1	58.2
25	77	3167	0.020	0.844	0.872	25.2	76.1
30	86	4243	0.027	0.859	0.896	30.2	99.2
35	95	5623	0.037	0.873	0.924	35.2	130.1
40	104	7378	0.049	0.887	0.957	40.2	166.4
45	113	9585	0.065	0.901	0.995	45.3	213.2
50	122	12339	0.087	0.915	1.042	50.3	275.9
55	131	14745	0.12	0.929	1.1	55.3	367.6
60	140	19925	0.15	0.944	1.175	60.4	452.1
65	149	25014	0.21	0.958	1.272	65.4	615.7
70	158	31167	0.28	0.972	1.404	70.4	806.8
75	167	38554	0.38	0.986	1.592	75.5	1078
80	176	47365	0.55	1	1.879	80.5	1537
85	185	57809	0.84	1.015	2.363	85.5	2317
90	194	70112		1.03	3.340		3876

Table A6.1 Enthalpy of Air

18 APPENDIX 7 - LOWER AND UPPER EXPLOSIVE LIMITS

Gas	LEL (% vol)	UEL (% vol)	Gas	LEL (% vol)	UEL (% vol)
Acetaldehyde	4	60	Hexane	1.1	7.5
Acetic acid	4	19.9	Hydrogen	4	75
Acetone	2.6	12.8	Hydrogen sulfide	4.3	46
Acetylene	2.5	81	Isobutyl alcohol	2	11
Acrylonitrile	3	17	Isopropanol	2	12
Ammonia	15	28	Kerosene Jet A-1	0.7	5
Benzene	1.35	6.65	Methane	4.4	16.4
1,3-Butadiene	2	12	Methanol	6.7	36
n-Butane	1.86	8.41	Methyl Chloride	10.7	17.4
Butyl alcohol, Butanol	1	11	Methyl Ethyl Ketone	1.8	10
Butylene	1.98	9.65	Mineral spirits	0.7	6.5
Carbon Disulfide	1.3	50	Naphthalene	0.9	5.9
Carbon Monoxide	12	75	n-Heptane	1	6
Cyanogen	6	42.6	n-Hexane	1.25	7
Cyclobutane	1.8	11.1	n-Pentene	1.65	7.7
Cyclohexane	1.3	8	Nitrobenzene	2	9
1,1-Dichloroethane	6	11	n-Octane	1	7
Diethyl Ether	1.9	36	n-Pentane	1.4	7.8
Diesel fuel	0.6	7.5	Propane	2.1	10.1
Ethane	3	12.4	Propylene	2	11.1
Ethylene	2.75	28.6	Propylene oxide	2.3	36
Ethyl Alcohol, Ethanol	3.3	19	Styrene	1.1	6.1
Ethylbenzene	1	7.1	Toluene	1.27	6.75
Ethyl Chloride	3.8	15.4	Trichloroethylene	13	90
Etylene glycol	3	22	Turpentine	0.8	-
Fuel Oil No.1	0.7	5	Vinyl acetate	2.6	13.4
Gasoline	1.4	7.6	Vinyl chloride	3.6	33
Glycerol	3	19	p-Xylene	1	6
Heptane	1	6.7			

Table A7.1 Lower Explosive Limit (LEL) and Upper Explosive Limit (UEL) for selected volatile compounds (% volume in air). Source: www.engineerstools box.com

19 APPENDIX 8 – FINANCIAL TABLES

Convert a Series of Uniform Annual Costs to a Present Value

Convert a uniform annual cost, A to a Present Value, PV, using

$$PV_{n,i} = \frac{A}{(1+i)^1} + \frac{A}{(1+i)^2} + \frac{A}{(1+i)^3} + \ldots + \frac{A}{(1+i)^{n-1}} + \frac{A}{(1+i)^n} = A\sum_{j=1}^{n} \frac{1}{(1+i)^j}$$

The summation of the $1/(1+i)^n$ terms is the Present Value Factor

$$\text{Present Value Factor} = PVF_{n,\,i} = F_{AP,\,n,\,i} = \sum_{j=1}^{n} \frac{1}{(1+i)^j} = \frac{(1+i)^n - 1}{i(1+i)^n}$$

$$PV = (A)\ F_{AP,\ n,\ i} = (A)\ PVF$$

Year	Interest Rate (% per Year)							
	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
1	0.97087	0.96154	0.95238	0.94340	0.93458	0.92593	0.91743	0.90909
2	1.91347	1.88609	1.85941	1.83339	1.80802	1.78326	1.75911	1.73554
3	2.82861	2.77509	2.72325	2.67301	2.62432	2.57710	2.53129	2.48685
4	3.71710	3.62990	3.54595	3.46511	3.38721	3.31213	3.23972	3.16987
5	4.57971	4.45182	4.32948	4.21236	4.10020	3.99271	3.88965	3.79079
6	5.41719	5.24214	5.07569	4.91732	4.76654	4.62288	4.48592	4.35526
7	6.23028	6.00205	5.78637	5.58238	5.38929	5.20637	5.03295	4.86842
8	7.01969	6.73274	6.46321	6.20979	5.97130	5.74664	5.53482	5.33493
9	7.78611	7.43533	7.10782	6.80169	6.51523	6.24689	5.99525	5.75902
10	8.53020	8.11090	7.72173	7.36009	7.02358	6.71008	6.41766	6.14457
11	9.25262	8.76048	8.30641	7.88687	7.49867	7.13896	6.80519	6.49506
12	9.95400	9.38507	8.86325	8.38384	7.94269	7.53608	7.16073	6.81369
13	10.63496	9.98565	9.39357	8.85268	8.35765	7.90378	7.48690	7.10336
14	11.29607	10.56312	9.89864	9.29498	8.74547	8.24424	7.78615	7.36669
15	11.93794	11.11839	10.37966	9.71225	9.10791	8.55948	8.06069	7.60608
16	12.56110	11.65230	10.83777	10.10590	9.44665	8.85137	8.31256	7.82371
17	13.16612	12.16567	11.27407	10.47726	9.76322	9.12164	8.54363	8.02155
18	13.75351	12.65930	11.68959	10.82760	10.05909	9.37189	8.75563	8.20141
19	14.32380	13.13394	12.08532	11.15812	10.33560	9.60360	8.95011	8.36492
20	14.87747	13.59033	12.46221	11.46992	10.59401	9.81815	9.12855	8.51356
21	15.41502	14.02916	12.82115	11.76408	10.83553	10.01680	9.29224	8.64869
22	15.93692	14.45112	13.16300	12.04158	11.06124	10.20074	9.44243	8.77154
23	16.44361	14.85684	13.48857	12.30338	11.27219	10.37106	9.58021	8.88322
24	16.93554	15.24696	13.79864	12.55036	11.46933	10.52876	9.70661	8.98474
25	17.41315	15.62208	14.09394	12.78336	11.65358	10.67478	9.82258	9.07704
26	17.87684	15.98277	14.37519	13.00317	11.82578	10.80998	9.92897	9.16095
27	18.32703	16.32959	14.64303	13.21053	11.98671	10.93516	10.02658	9.23722
28	18.76411	16.66306	14.89813	13.40616	12.13711	11.05108	10.11613	9.30657
29	19.18845	16.98371	15.14107	13.59072	12.27767	11.15841	10.19828	9.36961
30	19.60044	17.29203	15.37245	13.76483	12.40904	11.25778	10.27365	9.42691

Table A8.1 Factors (PVF) to convert a series of uniform annual costs, *A*, to a present value, *PV*.

Convert a Present Value to a Series of Uniform Annual Costs

The factor to convert a present value, which is often the capital cost, to a series of uniform annual costs is called the Capital Recovery Factor. It is the inverse of the factors in Table A8.1

$$PV_{n,i} = \frac{A}{(1+i)^1} + \frac{A}{(1+i)^2} + \frac{A}{(1+i)^3} + \dots + \frac{A}{(1+i)^{n-1}} + \frac{A}{(1+i)^n} = A\sum_{j=1}^{n}\frac{1}{(1+i)^j} = A\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]$$

Solving for A gives $A = PV\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = PV \times CRF$

$$\text{Capital Recovery Factor} = CRF_{n,\,i} = F_{PA,\,n,\,i} = \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$A = (PV)\ F_{PA,\,n,\,i} = (PV)\ CRF$$

Year	Interest Rate (% per Year)							
	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10
1	1.03000	1.04000	1.05000	1.06000	1.07000	1.08000	1.09000	1.10000
2	0.52261	0.53020	0.53780	0.54544	0.55309	0.56077	0.56847	0.57619
3	0.35353	0.36035	0.36721	0.37411	0.38105	0.38803	0.39505	0.40211
4	0.26903	0.27549	0.28201	0.28859	0.29523	0.30192	0.30867	0.31547
5	0.21835	0.22463	0.23097	0.23740	0.24389	0.25046	0.25709	0.26380
6	0.18460	0.19076	0.19702	0.20336	0.20980	0.21632	0.22292	0.22961
7	0.16051	0.16661	0.17282	0.17914	0.18555	0.19207	0.19869	0.20541
8	0.14246	0.14853	0.15472	0.16104	0.16747	0.17401	0.18067	0.18744
9	0.12843	0.13449	0.14069	0.14702	0.15349	0.16008	0.16680	0.17364
10	0.11723	0.12329	0.12950	0.13587	0.14238	0.14903	0.15582	0.16275
11	0.10808	0.11415	0.12039	0.12679	0.13336	0.14008	0.14695	0.15396
12	0.10046	0.10655	0.11283	0.11928	0.12590	0.13270	0.13965	0.14676
13	0.09403	0.10014	0.10646	0.11296	0.11965	0.12652	0.13357	0.14078
14	0.08853	0.09467	0.10102	0.10758	0.11434	0.12130	0.12843	0.13575
15	0.08377	0.08994	0.09634	0.10296	0.10979	0.11683	0.12406	0.13147
16	0.07961	0.08582	0.09227	0.09895	0.10586	0.11298	0.12030	0.12782
17	0.07595	0.08220	0.08870	0.09544	0.10243	0.10963	0.11705	0.12466
18	0.07271	0.07899	0.08555	0.09236	0.09941	0.10670	0.11421	0.12193
19	0.06981	0.07614	0.08275	0.08962	0.09675	0.10413	0.11173	0.11955
20	0.06722	0.07358	0.08024	0.08718	0.09439	0.10185	0.10955	0.11746
21	0.06487	0.07128	0.07800	0.08500	0.09229	0.09983	0.10762	0.11562
22	0.06275	0.06920	0.07597	0.08305	0.09041	0.09803	0.10590	0.11401
23	0.06081	0.06731	0.07414	0.08128	0.08871	0.09642	0.10438	0.11257
24	0.05905	0.06559	0.07247	0.07968	0.08719	0.09498	0.10302	0.11130
25	0.05743	0.06401	0.07095	0.07823	0.08581	0.09368	0.10181	0.11017
26	0.05594	0.06257	0.06956	0.07690	0.08456	0.09251	0.10072	0.10916
27	0.05456	0.06124	0.06829	0.07570	0.08343	0.09145	0.09973	0.10826
28	0.05329	0.06001	0.06712	0.07459	0.08239	0.09049	0.09885	0.10745
29	0.05211	0.05888	0.06605	0.07358	0.08145	0.08962	0.09806	0.10673
30	0.05102	0.05783	0.06505	0.07265	0.08059	0.08883	0.09734	0.10608

Table A8.2 Factors (CRF) to convert a present value, *PV*, to a series of uniform annual costs, *A*.