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Main Category:	General Engineering
Sub Category:	Thermodynamics
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Course Content:	44 pgs
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ENG-114 EXAM PREVIEW

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Exam Preview:

1. Specific gravity (S.G.) is a measure of the relative density of a substance as compared to the density of water at a standard temperature. Physicists use 39.2°F (4°C) as the standard, but engineers ordinarily use ___ °F.
   a. 50
   b. 60
   c. 65
   d. 68

2. Humidity is the amount of moisture (water vapor) in the air. It can be expressed as absolute humidity or relative humidity. Absolute humidity is the mass of water vapor divided by _____.
   a. 100%
   b. SG of air
   c. Total mass of air
   d. A unit volume of air

3. Heat is described as energy in transit. This transfer occurs on a molecular level as a result of temperature differences.
   a. True
   b. False

4. _____ is the heat added or removed that causes a temperature change.
   a. Latent heat
   b. Sensible heat
   c. Relative heat
   d. Absolute heat

5. A thermodynamic process is the succession of states that a system passes through. Adiabatic process is a series of processes that results in the system returning to its original state.
   a. True
   b. False
6. According to the reference material, the Celsius scale has 100 units between the freezing and boiling point of water at standard atmospheric pressure, whereas the Fahrenheit scale has ___ units between these points.
   a. 152
   b. 160
   c. 180
   d. 212
7. According to the reference material, if a quantity of matter in a given state is divided into two equal parts, each part will have the same value of extensive property as the original and half the value of the intensive property.
   a. True
   b. False
8. A process in which the entropy of the system remains unchanged is a ____ process.
   a. Reversible
   b. Irreversible
   c. Adiabatic
   d. Isentropic
9. A reversible process for a system is defined as a process that, once having taken place, can be reversed, and in so doing leaves no change in either the system or surroundings. In reality, there are no truly reversible processes; however, for analysis purposes, one uses reversible to make the analysis simpler, and to determine maximum theoretical efficiencies.
   a. True
   b. False
10. When pressure is measured relative to a perfect vacuum, it is called absolute pressure (psia). Using the reference material, what is the correct value for 14.7psia = ___ inches of water?
    a. 29.9
    b. 290.9
    c. 372
    d. 408

OVERVIEW

The *Department of Energy Fundamentals Handbook* entitled *Thermodynamics, Heat Transfer, and Fluid Flow* was prepared as an information resource for personnel who are responsible for the operation of the Department's nuclear facilities. A basic understanding of the thermal sciences is necessary for DOE nuclear facility operators, maintenance personnel, and the technical staff to safely operate and maintain the facility and facility support systems. The information in the handbook is presented to provide a foundation for applying engineering concepts to the job. This knowledge will help personnel more fully understand the impact that their actions may have on the safe and reliable operation of facility components and systems.

The *Thermodynamics, Heat Transfer, and Fluid Flow* handbook consists of three modules that are contained in three volumes. The following is a brief description of the information presented in each module of the handbook.

Volume 1 of 3

Module 1 - Thermodynamics

This module explains the properties of fluids and how those properties are affected by various processes. The module also explains how energy balances can be performed on facility systems or components and how efficiency can be calculated.

Volume 2 of 3

Module 2 - Heat Transfer

This module describes conduction, convection, and radiation heat transfer. The module also explains how specific parameters can affect the rate of heat transfer.

Volume 3 of 3

Module 3 - Fluid Flow

This module describes the relationship between the different types of energy in a fluid stream through the use of Bernoulli's equation. The module also discusses the causes of head loss in fluid systems and what factors affect head loss.

Department of Energy
Fundamentals Handbook

THERMODYNAMICS, HEAT TRANSFER, AND FLUID FLOW
Module 1
Thermodynamics

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

TABLE OF CONTENTS (Cont.)

LIST OF FIGURES

LIST OF FIGURES (Cont.)

LIST OF FIGURES (Cont.)

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- VanWylen, G. J. and Sonntag, R. E., Fundamentals of Classical Thermodynamics SI Version, 2nd Edition, John Wiley and Sons, New York, ISBN 0-471-04188-2.
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TERMINAL OBJECTIVE

1.0 Given operating conditions of a system, **EVALUATE** the thermodynamic state of the system.

ENABLING OBJECTIVES

1.1 **DEFINE** the following properties:
   a. Specific volume
   b. Density
   c. Specific gravity
   d. Humidity

1.2 **DESCRIBE** the following classifications of thermodynamic properties:
   a. Intensive properties
   b. Extensive properties

1.3 **DEFINE** the thermodynamic properties temperature and pressure.

1.4 **DESCRIBE** the Fahrenheit, Celsius, Kelvin, and Rankine temperature scales including:
   a. Absolute zero temperature
   b. The freezing point of water at atmospheric pressure
   c. The boiling point of water at atmospheric pressure

1.5 **CONVERT** temperatures between the Fahrenheit, Celsius, Kelvin, and Rankine scales.

1.6 **DESCRIBE** the relationship between absolute pressure, gauge pressure, and vacuum.

1.7 **CONVERT** pressures between the following units:
   a. Pounds per square inch
   b. Inches of water
   c. Inches of mercury
   d. Millimeters of mercury
   e. Microns of mercury

1.8 **DEFINE** the following:
   a. Heat
   b. Latent heat
   c. Sensible heat
   d. Unit used to measure heat

ENABLING OBJECTIVES (Cont.)

1.9 **DEFINE** the following thermodynamic properties:
  a. Specific enthalpy
  b. Entropy

1.10 **DESCRIBE** the following types of thermodynamic systems:
  a. Isolated system
  b. Closed system
  c. Open system

1.11 **DEFINE** the following terms concerning thermodynamic systems:
  a. Thermodynamic surroundings
  b. Thermodynamic equilibrium
  c. Control volume
  d. Steady-state

1.12 **DESCRIBE** the following terms concerning thermodynamic processes:
  a. Thermodynamic process
  b. Cyclic process
  c. Reversible process
  d. Irreversible process
  e. Adiabatic process
  f. Isentropic process
  g. Throttling process
  h. Polytropic process

1.13 **DISTINGUISH** between intensive and extensive properties.

1.14 **DEFINE** the following terms:
  a. Saturation
  b. Subcooled liquid
  c. Superheated vapor
  d. Critical Point
  e. Triple Point
  f. Vapor pressure curve
  g. Quality
  h. Moisture content

1.15 **DESCRIBE** the processes of sublimation, vaporization, condensation, and fusion.

ENABLING OBJECTIVES (Cont.)

1.16 Given a Mollier diagram and sufficient information to indicate the state of the fluid, **DETERMINE** any unknown properties for the fluid.

1.17 Given a set of steam tables and sufficient information to indicate the state of the fluid, **DETERMINE** any unknown properties for the fluid.

1.18 **DETERMINE** the change in the enthalpy of a fluid as it passes through a system component, given the state of the fluid at the inlet and outlet of the component and either steam tables or a Mollier diagram.

1.19 **STATE** the First Law of Thermodynamics.

1.20 Using the First Law of Thermodynamics, **ANALYZE** an open system including all energy transfer processes crossing the boundaries.

1.21 Using the First Law of Thermodynamics, **ANALYZE** cyclic processes for a thermodynamic system.

1.22 Given a defined system, **PERFORM** energy balances on all major components in the system.

1.23 Given a heat exchanger, **PERFORM** an energy balance across the two sides of the heat exchanger.

1.24 **IDENTIFY** the path(s) on a T-s diagram that represents the thermodynamic processes occurring in a fluid system.

1.25 **STATE** the Second Law of Thermodynamics.

1.26 Using the Second Law of Thermodynamics, **DETERMINE** the maximum possible efficiency of a system.

1.27 Given a thermodynamic system, **CONDUCT** an analysis using the Second Law of Thermodynamics.

1.28 Given a thermodynamic system, **DESCRIBE** the method used to determine:
    a. The maximum efficiency of the system
    b. The efficiency of the components within the system

ENABLING OBJECTIVES (Cont.)

1.29 **DIFFERENTIATE** between the path for an ideal process and that for a real process on a T-s or h-s diagram.

1.30 Given a T-s or h-s diagram for a system **EVALUATE**:
  a. System efficiencies
  b. Component efficiencies

1.31 **DESCRIBE** how individual factors affect system or component efficiency.

1.32 Apply the ideal gas laws to **SOLVE** for the unknown pressure, temperature, or volume.

1.33 **DESCRIBE** when a fluid may be considered to be incompressible.

1.34 **CALCULATE** the work done in constant pressure and constant volume processes.

1.35 **DESCRIBE** the effects of pressure changes on confined fluids.

1.36 **DESCRIBE** the effects of temperature changes on confined fluids.

THERMODYNAMIC PROPERTIES

Thermodynamic properties describe measurable characteristics of a substance. A knowledge of these properties is essential to the understanding of thermodynamics.

EO 1.1 DEFINE the following properties:
  a. Specific volume
  b. Density
  c. Specific gravity
  d. Humidity

EO 1.2 DESCRIBE the following classifications of thermodynamic properties:
  a. Intensive properties
  b. Extensive properties

Mass and Weight

The *mass* (m) of a body is the measure of the amount of material present in that body. The *weight* (wt) of a body is the force exerted by that body when its mass is accelerated in a gravitational field. Mass and weight are related as shown in Equation 1-1.

$$\text{wt} = \frac{mg}{g_c} \tag{1-1}$$

where:

wt = weight (lbf)
m = mass (lbm)
g = acceleration of gravity = 32.17 ft/sec^2
g_c = gravitational constant = 32.17 lbm-ft/lbf-sec^2

Note that g_c has the same numerical value as the acceleration of gravity at sea level, but is not the acceleration of gravity. Rather, it is a dimensional constant employed to facilitate the use of Newton's Second Law of Motion with the English system of units.

The weight of a body is a force produced when the mass of the body is accelerated by a gravitational acceleration. The mass of a certain body will remain constant even if the gravitational acceleration acting upon that body changes.

According to Newton's Second Law of Motion, force (F) = ma, where a is acceleration. For example, on earth an object has a certain mass and a certain weight. When the same object is placed in outer space, away from the earth's gravitational field, its mass is the same, but it is now in a "weightless" condition (that is, gravitational acceleration and, thus, force equal zero).

The English system uses the pound-force (lbf) as the unit of weight. Knowing that acceleration has the units of ft/sec^2 and using Newton's second law, we can determine that the units of mass are lbf-sec^2/ft. For simplification, 1 lbf-sec^2/ft is called a slug. The basic unit of mass in the English system is the slug. However, the slug is an almost meaningless unit for the average individual. The unit of mass generally used is the pound-mass (lbm). In order to allow lbm to be used as a unit of mass, we must divide Newton's second law by the gravitational constant (g_c).

$$\left(32.17\ \frac{\text{lbm} - \text{ft}}{\text{lbf} - \text{sec}^2}\right) = g_c$$

Newton's second law can be expressed by Equation 1-2.

$$F = \frac{ma}{g_c} \tag{1-2}$$

Use of the gravitational constant, g_c, adapts Newton's second law such that 1 lbf = 1 lbm at the surface of the earth. It is important to note that this relationship is only true at the surface of the earth, where the acceleration due to gravity is 32.17 ft/sec^2. However, because all of our discussions will be based upon experiences and observations on earth, we will use the lbm as the unit of mass.

NOTE: In Equation 1-2, acceleration "a" is often written as "g" because, in this case, the acceleration is the gravitational acceleration due to the earth's gravitational field ($g = 32.17$ ft/sec^2).

Example:

Using Equation 1-2, prove that 1 lbf = l lbm on earth.

Solution:

$$F = \frac{mg}{g_c}$$

$$1\ \text{lbf} = \frac{(1\ \text{lbm})\ (32.17\ \text{ft/sec}^2)}{32.17\ \dfrac{(\text{lbm} - \text{ft})}{(\text{lbf} - \text{sec}^2)}}$$

$$1\ \text{lbf} = 1\ \text{lbf}\ (\text{an equality})$$

Specific Volume

The *specific volume* (ν) of a substance is the total volume (V) of that substance divided by the total mass (m) of that substance (volume per unit mass). It has units of cubic feet per pound-mass (ft^3/lbm).

$$\nu = \frac{V}{m} \tag{1-3}$$

where:

ν = specific volume (ft^3/lbm)

V = volume (ft^3)

m = mass (lbm)

Density

The *density* (ρ) of a substance is the total mass (m) of that substance divided by the total volume (V) occupied by that substance (mass per unit volume). It has units of pound-mass per cubic feet (lbm/ft^3). The density (ρ) of a substance is the reciprocal of its specific volume (ν).

$$\rho = \frac{m}{V} = \frac{1}{\nu} \tag{1-4}$$

where:

ρ = density (lbm/ft^3)

m = mass (lbm)

V = volume (ft^3)

ν = specific volume (ft^3/lbm)

Specific Gravity

Specific gravity (S.G.) is a measure of the relative density of a substance as compared to the density of water at a standard temperature. Physicists use 39.2°F (4°C) as the standard, but engineers ordinarily use 60°F. In the International System of Units (SI Units), the density of water is 1.00 g/cm^3 at the standard temperature. Therefore, the specific gravity (which is dimensionless) for a liquid has the same numerical value as its density in units of g/cm^3. Since the density of a fluid varies with temperature, specific gravities must be determined and specified at particular temperatures.

Humidity

Humidity is the amount of moisture (water vapor) in the air. It can be expressed as absolute humidity or relative humidity. *Absolute humidity* is the mass of water vapor divided by a unit volume of air (grams of water/cm^3 of air). *Relative humidity* is the amount of water vapor present in the air divided by the maximum amount that the air could contain at that temperature. Relative humidity is expressed as a percentage. The relative humidity is 100% if the air is saturated with water vapor and 0% if no water vapor is present in the air at all.

Intensive and Extensive Properties

Thermodynamic properties can be divided into two general classes, intensive and extensive properties. An *intensive property* is independent of the amount of mass. The value of an *extensive property* varies directly with the mass. Thus, if a quantity of matter in a given state is divided into two equal parts, each part will have the same value of intensive property as the original and half the value of the extensive property. Temperature, pressure, specific volume, and density are examples of intensive properties. Mass and total volume are examples of extensive properties.

Summary

The important information from this chapter is summarized below.

Thermodynamic Properties Summary

The following properties were defined:

- Specific volume (ν) is the total volume (V) of a substance divided by the total mass (m) of that substance.
- Density (ρ) is the total mass (m) of a substance divided by the total volume (V) occupied by that substance.
- Specific gravity (S.G.) is a measure of the relative density of a substance as compared to the density of water at a standard temperature.
- Humidity is the amount of moisture (water vapor) in the air. It can be measured in absolute or relative units.

The following classifications of thermodynamic properties were described:

- Intensive properties are those that are independent of the amount of mass.
- Extensive properties are those that vary directly with the mass.

TEMPERATURE AND PRESSURE MEASUREMENTS

Several types of temperature and pressure measurements are used during discussions of thermodynamics. Operators must recognize the different types and their interrelationships in order to understand thermodynamics.

EO 1.3 DEFINE the thermodynamic properties temperature and pressure.

EO 1.4 DESCRIBE the Fahrenheit, Celsius, Kelvin, and Rankine temperature scales including:
  a. Absolute zero temperature
  b. The freezing point of water at atmospheric pressure
  c. The boiling point of water at atmospheric pressure

EO 1.5 CONVERT temperatures between the Fahrenheit, Celsius, Kelvin, and Rankine scales.

EO 1.6 DESCRIBE the relationship between absolute pressure, gauge pressure, and vacuum.

EO 1.7 CONVERT pressures between the following units:
  a. Pounds per square inch
  b. Inches of water
  c. Inches of mercury
  d. Millimeters of mercury
  e. Microns of mercury

Temperature

Temperature is a measure of the molecular activity of a substance. The greater the movement of molecules, the higher the temperature. It is a relative measure of how "hot" or "cold" a substance is and can be used to predict the direction of heat transfer.

Temperature Scales

The two temperature scales normally employed for measurement purposes are the Fahrenheit (F) and Celsius (C) scales. These scales are based on a specification of the number of increments between the freezing point and boiling point of water at standard atmospheric pressure. The Celsius scale has 100 units between these points, and the Fahrenheit scale has 180 units. The zero points on the scales are arbitrary.

The freezing point of water was selected as the zero point of the Celsius scale. The coldest temperature achievable with a mixture of ice and salt water was selected as the zero point of the Fahrenheit scale. The temperature at which water boils was set at 100 on the Celsius scale and 212 on the Fahrenheit scale. The relationship between the scales is represented by the following equations.

$$°F = 32.0 + (9/5)°C \quad (1\text{-}5)$$

$$°C = (°F - 32.0)(5/9) \quad (1\text{-}6)$$

It is necessary to define an absolute temperature scale having only positive values. The absolute temperature scale that corresponds to the Celsius scale is called the Kelvin (K) scale, and the absolute scale that corresponds to the Fahrenheit scale is called the Rankine (R) scale. The zero points on both absolute scales represent the same physical state. This state is where there is no molecular motion of individual atoms. The relationships between the absolute and relative temperature scales are shown in the following equations.

$$°R = °F + 460 \quad (1\text{-}7)$$

$$°K = °C + 273 \quad (1\text{-}8)$$

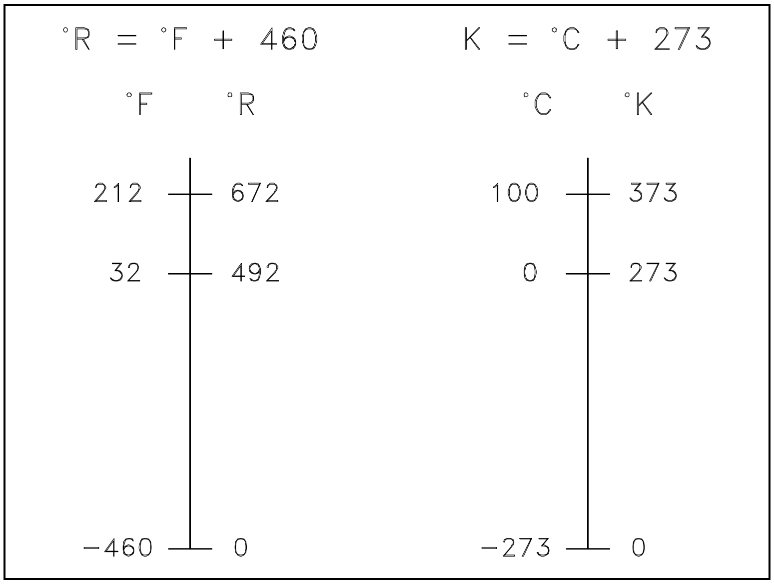

Figure 1 Comparison of Temperature Scales

The conversion of one temperature scale to another is sometimes required at nuclear facilities, and the operator should be acquainted with the process. The following two examples will be helpful.

Example 1: Temperature Scale Conversion

What is the Rankine equivalent of 80°C?

Solution:

$$
\begin{aligned}
°F &= (9/5)\ °C + 32 \\
&= (9/5)(80) + 32 \\
&= 176\ °F \\
°R &= °F + 460 \\
&= 176 + 460 \\
&= 636\ °R
\end{aligned}
$$

Example 2: Temperature Scale Conversion

What is the Kelvin equivalent of 80°F?

Solution:

$$
\begin{aligned}
°C &= (5/9)\ (°F - 32) \\
&= (5/9)\ (80 - 32) \\
&= 26.7°C \\
°K &= °C + 273 \\
&= 26.7 + 273 \\
&= 299.7\ °K
\end{aligned}
$$

Pressure

Pressure is a measure of the force exerted per unit area on the boundaries of a substance (or system). It is caused by the collisions of the molecules of the substance with the boundaries of the system. As molecules hit the walls, they exert forces that try to push the walls outward. The forces resulting from all of these collisions cause the pressure exerted by a system on its surroundings. Pressure is frequently measured in units of lbf/in^2 (psi).

Pressure Scales

When pressure is measured relative to a perfect vacuum, it is called absolute pressure (psia); when measured relative to atmospheric pressure (14.7 psi), it is called gauge pressure (psig). The latter pressure scale was developed because almost all pressure gauges register zero when open to the atmosphere. Therefore, pressure gauges measure the difference between the pressure of the fluid to which they are connected and that of the surrounding air.

If the pressure is below that of the atmosphere, it is designated as a vacuum. A perfect vacuum would correspond to absolute zero pressure. All values of absolute pressure are positive, because a negative value would indicate tension, which is considered impossible in any fluid. Gauge pressures are positive if they are above atmospheric pressure and negative if they are below atmospheric pressure. Figure 2 shows the relationships between absolute, gauge, vacuum, and atmospheric pressures, as do Equations 1-9 and 1-10.

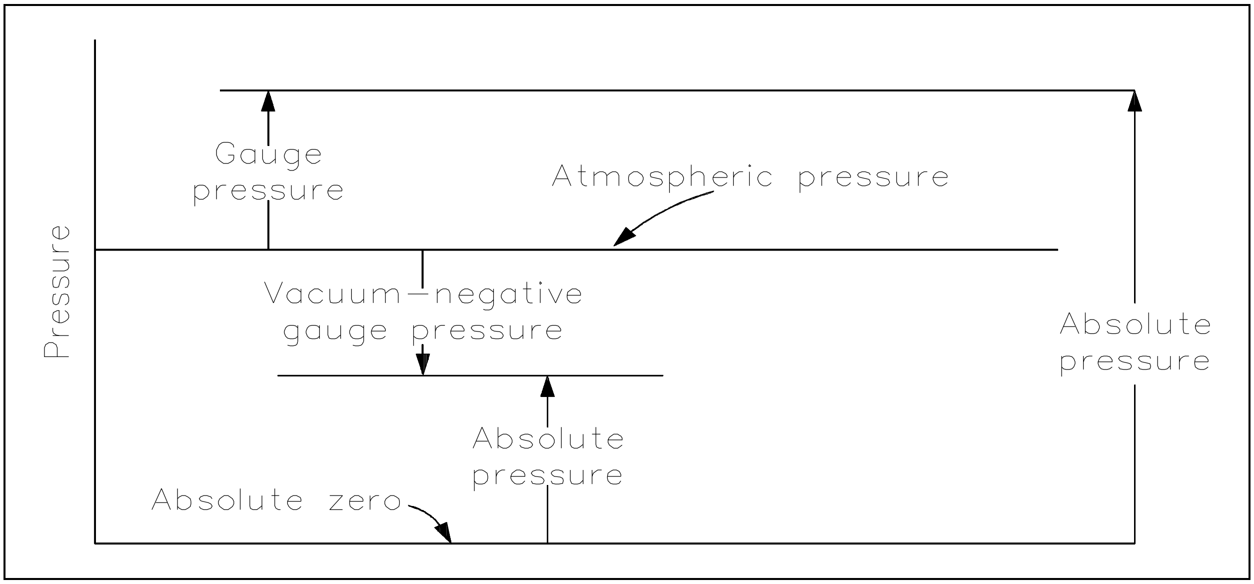

Figure 2 Pressure Relationships

$$P_{abs} = P_{atm} + P_{gauge} \tag{1-9}$$

$$P_{abs} = P_{atm} - P_{vac} \tag{1-10}$$

P_{atm} is atmospheric pressure, which is also called the barometric pressure. P_{gauge} is the gauge pressure, and P_{vac} is vacuum. Once again, the following examples relating the various pressures will be helpful in understanding the idea of gauge versus absolute pressures.

Example 1: Pressure Relationships

> How deep can a diver descend in ocean water (density = 64 lbm/ft^3) without damaging his watch, which will withstand an absolute pressure of 80 psia? (P = density • height)

Solution:

Assume: $P_{atm} = 14.7$ psia

$$P_{abs} = P_{atm} + P_{gauge}$$

$$80 \text{ psia} = 14.7 + P_{gauge}$$

$$P_{gauge} = (80 - 14.7) = 65.3 \text{ psig}$$

$$P_{gauge} = \text{density} \bullet \text{height} = \rho H$$

$$(65.3)(144 \text{ in}^2/\text{ft}^2) = (64 \text{ lbm/ft}^3)H$$

$$H = (65.3)(144)/(64)$$

$$H = 146.9 \text{ ft}$$

Example 2: Pressure Relationships

> What is the absolute pressure at the bottom of a swimming pool 6 feet deep that is filled with fresh water? $P_{atm} = 14.7$ psia

Solution:

$$
\begin{aligned}
P_{abs} &= P_{atm} + P_{gauge} \\
&= 14.7 + \rho H \\
&= 14.7 + [(62.4\ \text{lbm/ft}^3)(6\ \text{ft})/(144\ \text{in.}^2/\text{ft}^2)] \\
&= 14.7 + 2.6 \\
P_{abs} &= 17.3\ \text{psia}
\end{aligned}
$$

In addition to pounds per square inch, pressure can be measured with reference to the force that exists in a column of fluid at a certain height. The most common of these are inches of water, inches of mercury, millimeters of mercury, and microns of mercury. Conversion factors are listed below.

14.7 psia = 408 inches of water

14.7 psia = 29.9 inches of mercury

1 inch of mercury = 25.4 millimeters of mercury

1 millimeter of mercury = 10^3 microns of mercury

Summary

The important information from this chapter is summarized below.

Temperature and Pressure Scales Summary

The following properties were defined as follows.

- Temperature is a measure of the molecular activity of a substance.
- Pressure is a measure of the force per unit area exerted on the boundaries of a substance (or system).

The relationship between the Fahrenheit, Celsius, Kelvin, and Rankine temperature scales was described.

- Absolute zero = -460 °F or -273 °C
- Freezing point of water = 32 °F or 0 °C
- Boiling point of water = 212 °F or 100 °C

Conversions between the different scales can be made using the following formulas.

- °F = 32 + (9/5)°C
- °C = (°F - 32)(5/9)
- °R = °F + 460
- °K = °C + 273

Relationships between absolute pressure, gauge pressure, and vacuum can be shown using the following formulas.

- $P_{abs} = P_{atm} + P_{gauge}$
- $P_{abs} = P_{atm} - P_{vac}$

Temperature and Pressure Scales Summary (Cont.)

Converting between the different pressure units can be done using the following conversions.

- 14.7 psia = 408 inches of water
- 14.7 psia = 29.9 inches of mercury
- 1 inch of mercury = 25.4 millimeters of mercury
- 1 millimeter of mercury = 10^3 microns of mercury

ENERGY, WORK, AND HEAT

Heat and work are the two ways in which energy can be transferred across the boundary of a system. One of the most important discoveries in thermodynamics was that work could be converted into an equivalent amount of heat and that heat could be converted into work.

EO 1.8 DEFINE the following:
- **a. Heat**
- **b. Latent heat**
- **c. Sensible heat**
- **d. Units used to measure heat**

EO 1.9 DEFINE the following thermodynamic properties:
- **a. Specific enthalpy**
- **b. Entropy**

Energy

Energy is defined as the capacity of a system to perform work or produce heat.

Potential Energy

Potential energy (PE) is defined as the energy of position. Using English system units, it is defined by Equation 1-11.

$$PE = \frac{mgz}{g_c} \tag{1-11}$$

where:

PE = potential energy (ft-lbf)

m = mass (lbm)

z = height above some reference level (ft)

g = acceleration due to gravity (ft/sec^2)

g_c = gravitational constant = 32.17 ft-lbm/lbf-sec^2

In most practical engineering calculations, the acceleration due to gravity (g) is numerically equal to the gravitational constant (g_c); thus, the potential energy (PE) in foot-pounds-force is numerically equal to the product of the mass (m) in pounds-mass times the height (z) in feet above some reference level.

Example:

> Determine the potential energy of 50 lbm of water in a storage tank 100 ft above the ground.

Solution:

> Using Equation 1-11

$$PE = \frac{mgz}{g_c}$$

$$PE = \frac{(50\ \text{lbm})\ (32.17\ \text{ft/sec}^2)\ (100\ \text{ft})}{32.17\ \text{ft}-\text{lbm/lbf}-\text{sec}^2}$$

$$PE = 5000\ \text{ft}-\text{lbf}$$

Kinetic Energy

Kinetic energy (KE) is the energy of motion. Using English system units, it is defined by Equation 1-12.

$$KE = \frac{mv^2}{2g_c} \qquad (1\text{-}12)$$

where:

KE = kinetic energy (ft-lbf)

m = mass (lbm)

v = velocity (ft/sec)

g_c = gravitational constant = 32.17 ft-lbm/lbf-sec^2

Example:

Determine the kinetic energy of 7 lbm of steam flowing through a pipe at a velocity of 100 ft/sec.

Solution:

Using Equation 1-12.

$$KE = \frac{mv^2}{2g_c}$$

$$KE = \frac{(7\ \text{lbm})\ (100\ \text{ft/sec})^2}{2(32.17\ \text{ft-lbm/lbf-sec}^2)}$$

$$KE = \frac{(7\ \text{lbm})\ (10{,}000\ \text{ft}^2/\text{sec}^2)}{(64.34\ \text{ft-lbm/lbf-sec}^2)}$$

$$KE = 1088\ \text{ft-lbf}$$

Specific Internal Energy

Potential energy and kinetic energy are macroscopic forms of energy. They can be visualized in terms of the position and the velocity of objects. In addition to these macroscopic forms of energy, a substance possesses several microscopic forms of energy. Microscopic forms of energy include those due to the rotation, vibration, translation, and interactions among the molecules of a substance. None of these forms of energy can be measured or evaluated directly, but techniques have been developed to evaluate the change in the total sum of all these microscopic forms of energy. These microscopic forms of energy are collectively called *internal energy*, customarily represented by the symbol U. In engineering applications, the unit of internal energy is the *British thermal unit* (Btu), which is also the unit of heat.

The specific internal energy (u) of a substance is its internal energy per unit mass. It equals the total internal energy (U) divided by the total mass (m).

$$u = \frac{U}{m} \tag{1-13}$$

where:

u = specific internal energy (Btu/lbm)

U = internal energy (Btu)

m = mass (lbm)

Example:

Determine the specific internal energy of 12 lbm of steam if the total internal energy is 23,000 Btu.

Solution:

Using Equation 1-13.

$$u = \frac{U}{m}$$

$$u = \frac{23{,}000 \text{ Btu}}{12 \text{ lbm}}$$

$$u = 1916.67 \text{ Btu/lbm}$$

Specific P-V Energy

In addition to the internal energy (U), another form of energy exists that is important in understanding energy transfer systems. This form of energy is called P-V energy because it arises from the pressure (P) and the volume (V) of a fluid. It is numerically equal to PV, the product of pressure and volume. Because energy is defined as the capacity of a system to perform work, a system where pressure and volume are permitted to expand performs work on its surroundings. Therefore, a fluid under pressure has the capacity to perform work. In engineering applications, the units of P-V energy, also called flow energy, are the units of pressure times volume (pounds-force per square foot times cubic feet), which equals foot-pounds force (ft-lbf).

The specific P-V energy of a substance is the P-V energy per unit mass. It equals the total P-V divided by the total mass m, or the product of the pressure P and the specific volume ν, and is written as Pν.

$$P\nu = \frac{PV}{m} \tag{1-14}$$

where:

P = pressure (lbf/ft^2)

V = volume (ft^3)

ν = specific volume (ft^3/lbm) $= \frac{V}{m}$

m = mass (lbm)

Example:

Determine the specific P-V energy of 15 lbm of steam at 1000 psi in an 18 ft^3 tank.

Solution:

Using Equation 1-14

$$P\nu = \frac{PV}{m}$$

$$P\nu = \frac{(1000\ \text{lbf/in.}^2)\ (144\ \text{in.}^2/\text{ft}^2)\ (18\ \text{ft}^3)}{15\ \text{lbm}}$$

$$P\nu = 172{,}800\ \text{ft}-\text{lbf/lbm}$$

Specific Enthalpy

Specific enthalpy (h) is defined as $h = u + P\nu$, where u is the specific internal energy (Btu/lbm) of the system being studied, P is the pressure of the system (lbf/ft^2), and ν is the specific volume (ft^3/lbm) of the system. Enthalpy is usually used in connection with an "open" system problem in thermodynamics. Enthalpy is a property of a substance, like pressure, temperature, and volume, but it cannot be measured directly. Normally, the enthalpy of a substance is given with respect to some reference value. For example, the specific enthalpy of water or steam is given using the reference that the specific enthalpy of water is zero at .01°C and normal atmospheric pressure. The fact that the absolute value of specific enthalpy is unknown is not a problem, however, because it is the change in specific enthalpy (Δh) and not the absolute value that is important in practical problems. Steam tables include values of enthalpy as part of the information tabulated.

Work

Kinetic energy, potential energy, internal energy, and P-V energy are forms of energy that are properties of a system. *Work* is a form of energy, but it is energy in transit. Work is not a property of a system. Work is a process done by or on a system, but a system contains no work. This distinction between the forms of energy that are properties of a system and the forms of energy that are transferred to and from a system is important to the understanding of energy transfer systems.

Work is defined for mechanical systems as the action of a force on an object through a distance. It equals the product of the force (F) times the displacement (d).

$$W = Fd \tag{1-15}$$

where:

W = work (ft-lbf)

F = force (lbf)

d = displacement (ft)

Example:

Determine the amount of work done if a force of 150 lbf is applied to an object until it has moved a distance of 30 feet.

Solution:

Using Equation 1-15

$$W = Fd$$

$$W = (150 \text{ lbf})(30 \text{ ft})$$

$$W = 4500 \text{ ft-lbf}$$

In dealing with work in relation to energy transfer systems, it is important to distinguish between work done by the system on its surroundings and work done on the system by its surroundings. Work is done by the system when it is used to turn a turbine and thereby generate electricity in a turbine-generator. Work is done on the system when a pump is used to move the working fluid from one location to another. A positive value for work indicates that work is done by the system on its surroundings; a negative value indicates that work is done on the system by its surroundings.

Heat

Heat, like work, is energy in transit. The transfer of energy as heat, however, occurs at the molecular level as a result of a temperature difference. The symbol Q is used to denote heat. In engineering applications, the unit of heat is the British thermal unit (Btu). Specifically, this is called the 60 degree Btu because it is measured by a one degree temperature change from 59.5 to 60.5°F.

As with work, the amount of heat transferred depends upon the path and not simply on the initial and final conditions of the system. Also, as with work, it is important to distinguish between heat added to a system from its surroundings and heat removed from a system to its surroundings. A positive value for heat indicates that heat is added to the system by its surroundings. This is in contrast to work that is positive when energy is transferred from the system and negative when transferred to the system. The symbol q is sometimes used to indicate the heat added to or removed from a system per unit mass. It equals the total heat (Q) added or removed divided by the mass (m). The term "specific heat" is not used for q since specific heat is used for another parameter. The quantity represented by q is referred to simply as the heat transferred per unit mass.

$$q = \frac{Q}{m} \tag{1-16}$$

where:

q = heat transferred per unit mass (Btu/lbm)

Q = heat transferred (Btu)

m = mass (lbm)

Example:

Determine the heat transferred per unit mass if 1500 Btu's are transferred to 40 lbm of water.

Solution:

Using Equation 1-16

$$q = \frac{Q}{m}$$

$$q = \frac{1500\ \text{Btu}}{40\ \text{lbm}}$$

$$q = 37.5\ \text{Btu/lbm}$$

The best way to quantify the definition of heat is to consider the relationship between the amount of heat added to or removed from a system and the change in the temperature of the system. Everyone is familiar with the physical phenomena that when a substance is heated, its temperature increases, and when it is cooled, its temperature decreases. The heat added to or removed from a substance to produce a change in its temperature is called *sensible heat*. The units of heat are often defined in terms of the changes in temperature it produces.

Another type of heat is called *latent heat*. Latent heat is the amount of heat added to or removed from a substance to produce a change in phase. When latent heat is added, no temperature change occurs. There are two types of latent heat. The first is the *latent heat of fusion*. This is the amount of heat added or removed to change phase between solid and liquid. The second type of latent heat is the *latent heat of vaporization*. This is the amount of heat added or removed to change phase between liquid and vapor. The latent heat of vaporization is sometimes called the latent heat of condensation.

Different substances are affected to different magnitudes by the addition of heat. When a given amount of heat is added to different substances, their temperatures increase by different amounts. The ratio of the heat (Q) added to or removed from a substance to the change in temperature (ΔT) produced is called the *heat capacity* (C_p) of the substance. The heat capacity of a substance per unit mass is called the *specific heat* (c_p) of the substance. The subscript p indicates that the heat capacity and specific heat apply when the heat is added or removed at constant pressure.

$$C_p = \frac{Q}{\Delta T}$$

$$c_p = \frac{Q}{m\Delta T} \tag{1-17}$$

$$c_p = \frac{q}{\Delta T}$$

where:

C_p = heat capacity at constant pressure (Btu/°F)

c_p = specific heat at constant pressure (Btu/lbm-°F)

Q = heat transferred (Btu)

q = heat transferred per unit mass (Btu/lbm)

m = mass (lbm)

ΔT = temperature change (°F)

One lbm of water is raised 1°F and one Btu of heat is added. This implies that the specific heat (c_p) of water is one Btu/lbm-°F. The c_p of water is equal to one Btu/lbm-°F only at 39.1°F.

By rearranging Equation 1-17 we obtain $Q = mc_p\Delta T$, which is used to calculate latent heat. By substituting mass flow rate in lbm/hr, $\dot{m}$, for m, we obtain $\dot{Q} = \dot{m}c_p\Delta T$. This equation is used to calculate heat transfer in Btu/hr and will be useful in later chapters.

Example:

> How much heat is required to raise the temperature of 5 lbm of water from 50°F to 150°F? (Assume the specific heat (c_p) for water is constant at 1.0 Btu/lbm-°F.)

Solution:

$$c_p = \frac{Q}{m\Delta T}$$

$$Q = c_p m\Delta T$$

$$Q = (1.0\ \text{Btu/lbm-°F})(5\ \text{lbm})(150°\text{F} - 50°\text{F})$$

$$Q = (1.0\ \text{Btu/lbm-°F})(5\ \text{lbm})(100°\text{F})$$

$$Q = 500\ \text{Btu}$$

From the previous discussions on heat and work, it is evident that there are many similarities between them. Heat and work are both transient phenomena. Systems never possess heat or work, but either or both may occur when a system undergoes a change of energy state. Both heat and work are boundary phenomena in that both are observed at the boundary of the system. Both represent energy crossing the system boundary.

Entropy

Entropy (S) is a property of a substance, as are pressure, temperature, volume, and enthalpy. Because entropy is a property, changes in it can be determined by knowing the initial and final conditions of a substance. Entropy quantifies the energy of a substance that is no longer available to perform useful work. Because entropy tells so much about the usefulness of an amount of heat transferred in performing work, the steam tables include values of specific entropy (s = S/m) as part of the information tabulated. Entropy is sometimes referred to as a measure of the inability to do work for a given heat transferred. Entropy is represented by the letter S and can be defined as ΔS in the following relationships.

$$\Delta S = \frac{\Delta Q}{T_{abs}} \tag{1-18}$$

$$\Delta s = \frac{\Delta q}{T_{abs}} \tag{1-19}$$

where:

ΔS = the change in entropy of a system during some process (Btu/°R)

ΔQ = the amount of heat transferred to or from the system during the process (Btu)

T_{abs} = the absolute temperature at which the heat was transferred (°R)

Δs = the change in specific entropy of a system during some process (Btu/lbm -°R)

Δq = the amount of heat transferred to or from the system during the process (Btu/lbm)

Like enthalpy, entropy cannot be measured directly. Also, like enthalpy, the entropy of a substance is given with respect to some reference value. For example, the specific entropy of water or steam is given using the reference that the specific entropy of water is zero at 32°F. The fact that the absolute value of specific entropy is unknown is not a problem because it is the change in specific entropy (Δs) and not the absolute value that is important in practical problems.

Energy and Power Equivalences

The various forms of energy involved in energy transfer systems (such as potential energy, kinetic energy, internal energy, P-V energy, work and heat) may be measured in numerous basic units. In general, three types of units are used to measure energy: (1) mechanical units, such as the foot-pound-force (ft-lbf); (2) thermal units, such as the British thermal unit (Btu); and (3) electrical units, such as the watt-second (W-sec). In the mks and cgs systems, the mechanical units of energy are the joule (j) and the erg, the thermal units are the kilocalorie (kcal) and the calorie (cal), and the electrical units are the watt-second (W-sec) and the erg. Although the units of the various forms of energy are different, they are equivalent.

Some of the most important experiments in science were those conducted by J. P. Joule in 1843, who showed quantitatively that there was a direct correspondence between mechanical and thermal energy. These experiments showed that one kilocalorie equals 4,186 joules. These same experiments, when performed using English system units, show that one British thermal unit (Btu) equals 778.3 ft-lbf. These experiments established the equivalence of mechanical and thermal energy. Other experiments established the equivalence of electrical energy with both mechanical and thermal energy. For engineering applications, these equivalences are expressed by the following relationships.

$$1 \text{ ft-lbf} = 1.286 \times 10^{-3} \text{ Btu} = 3.766 \times 10^{-7} \text{ kW-hr}$$

$$1 \text{ Btu} = 778.3 \text{ ft-lbf} = 2.928 \times 10^{-4} \text{ kW-hr}$$

$$1 \text{ kW-hr} = 3.413 \times 10^{3} \text{ Btu} = 2.655 \times 10^{6} \text{ ft-lbf}$$

There is one additional unit of energy encountered in engineering applications. It is the horsepower-hour (hp-hr). It is a mechanical unit of energy defined by the following relationship:

$$1 \text{ hp-hr} = 1.980 \times 10^{6} \text{ ft-lbf}$$

These relationships can be used to convert between the various English system units for the various forms of energy.

Most computations involving the energy of the working fluid in an energy transfer system are performed in Btu's. Forms of mechanical energy (such as potential energy, kinetic energy, and mechanical work) and other forms of energy (such as P-V energy) are usually given in foot-pounds-force. These are converted to Btu's by using 1 Btu = 778.3 ft-lbf.

This conversion factor is often used. In fact, a constant called the mechanical equivalent of heat, usually denoted by the symbol J and sometimes referred to as *Joule's constant*, is defined as:

$$J = 778 \ \frac{\text{ft-lbf}}{\text{Btu}}.$$

Power is defined as the time rate of doing work. It is equivalent to the rate of the energy transfer. Power has units of energy per unit time. As with energy, power may be measured in numerous basic units, but the units are equivalent. In the English system, the mechanical units of power are foot-pounds-force per second or per hour (ft-lbf/sec or ft-lbf/hr) and horsepower (hp). The thermal units of power are British thermal units per hour (Btu/hr), and the electrical units of power are watts (W) or kilowatts (kW). For engineering applications, the equivalence of these units is expressed by the following relationships.

$$1 \text{ ft-lbf/sec} = 4.6263 \text{ Btu/hr} = 1.356 \times 10^{-3} \text{ kW}$$

$$1 \text{ Btu/hr} = 0.2162 \text{ ft-lbf/sec} = 2.931 \times 10^{-4} \text{ kW}$$

$$1 \text{ kW} = 3.413 \times 10^{3} \text{ Btu/hr} = 737.6 \text{ ft-lbf/sec}$$

Horsepower is related to foot-pounds-force per second (ft-lbf/sec) by the following relationship:

$$1 \text{ hp} = 550.0 \text{ ft-lbf/sec}$$

These relationships can be used to convert the English system units for power.

Summary

The important information from this chapter is summarized below.

Energy, Work, and Heat Summary

- Heat is described as energy in transit. This transfer occurs on a molecular level as a result of temperature differences. The unit of heat is the British thermal unit (Btu).

  Latent heat = the amount of heat added or removed to produce only a phase change.

  Sensible heat = the heat added or removed that causes a temperature change.

- The following properties were defined:

  Specific enthalpy (h) is defined as $h = u + P\nu$, where u is the specific internal energy (Btu/lbm) of the system being studied, P is the pressure of the system (lbf/ft^2), and ν is the specific volume (ft^3/lbm) of the system.

  Entropy is sometimes referred to as a measure of the inability to do work for a given heat transferred.

THERMODYNAMIC SYSTEMS AND PROCESSES

Defining an appropriate system can greatly simplify a thermodynamic analysis. A thermodynamic system is any three-dimensional region of space that is bounded by one or more surfaces. The bounding surfaces may be real or imaginary and may be at rest or in motion. The boundary may change its size or shape. The region of physical space that lies outside the selected boundaries of the system is called the surroundings or the environment.

EO 1.10 DESCRIBE the following types of thermodynamic systems:

- **a. Isolated system**
- **b. Closed system**
- **c. Open system**

EO 1.11 DEFINE the following terms concerning thermodynamic systems:

- **a. Thermodynamic surroundings**
- **b. Thermodynamic equilibrium**
- **c. Control volume**
- **d. Steady-state**

EO 1.12 DESCRIBE the following terms concerning thermodynamic processes:

- **a. Thermodynamic process**
- **b. Cyclic process**
- **c. Reversible process**
- **d. Irreversible process**
- **e. Adiabatic process**
- **f. Isentropic process**
- **g. Throttling process**
- **h. Polytropic process**

Thermodynamic Systems and Surroundings

Thermodynamics involves the study of various systems. A *system* in thermodynamics is nothing more than the collection of matter that is being studied. A system could be the water within one side of a heat exchanger, the fluid inside a length of pipe, or the entire lubricating oil system for a diesel engine. Determining the boundary to solve a thermodynamic problem for a system will depend on what information is known about the system and what question is asked about the system.

Everything external to the system is called the *thermodynamic surroundings*, and the system is separated from the surroundings by the *system boundaries*. These boundaries may either be fixed or movable. In many cases, a thermodynamic analysis must be made of a device, such as a heat exchanger, that involves a flow of mass into and/or out of the device. The procedure that is followed in such an analysis is to specify a control surface, such as the heat exchanger tube walls. Mass, as well as heat and work (and momentum), may flow across the control surface.

Types of Thermodynamic Systems

Systems in thermodynamics are classified as isolated, closed, or open based on the possible transfer of mass and energy across the system boundaries. An *isolated system* is one that is not influenced in any way by the surroundings. This means that no energy in the form of heat or work may cross the boundary of the system. In addition, no mass may cross the boundary of the system.

A thermodynamic system is defined as a quantity of matter of fixed mass and identity upon which attention is focused for study. A *closed system* has no transfer of mass with its surroundings, but may have a transfer of energy (either heat or work) with its surroundings.

An *open system* is one that may have a transfer of both mass and energy with its surroundings.

Thermodynamic Equilibrium

When a system is in equilibrium with regard to all possible changes in state, the system is in *thermodynamic equilibrium*. For example, if the gas that comprises a system is in thermal equilibrium, the temperature will be the same throughout the entire system.

Control Volume

A *control volume* is a fixed region in space chosen for the thermodynamic study of mass and energy balances for flowing systems. The boundary of the control volume may be a real or imaginary envelope. The *control surface* is the boundary of the control volume.

Steady State

Steady state is that circumstance in which there is no accumulation of mass or energy within the control volume, and the properties at any point within the system are independent of time.

Thermodynamic Process

Whenever one or more of the properties of a system change, a change in the state of the system occurs. The path of the succession of states through which the system passes is called the *thermodynamic process*. One example of a thermodynamic process is increasing the temperature of a fluid while maintaining a constant pressure. Another example is increasing the pressure of a confined gas while maintaining a constant temperature. Thermodynamic processes will be discussed in more detail in later chapters.

Cyclic Process

When a system in a given initial state goes through a number of different changes in state (going through various processes) and finally returns to its initial values, the system has undergone a *cyclic process or cycle*. Therefore, at the conclusion of a cycle, all the properties have the same value they had at the beginning. Steam (water) that circulates through a closed cooling loop undergoes a cycle.

Reversible Process

A *reversible process* for a system is defined as a process that, once having taken place, can be reversed, and in so doing leaves no change in either the system or surroundings. In other words the system and surroundings are returned to their original condition before the process took place. In reality, there are no truly reversible processes; however, for analysis purposes, one uses reversible to make the analysis simpler, and to determine maximum theoretical efficiencies. Therefore, the reversible process is an appropriate starting point on which to base engineering study and calculation.

Although the reversible process can be approximated, it can never be matched by real processes. One way to make real processes approximate reversible process is to carry out the process in a series of small or infinitesimal steps. For example, heat transfer may be considered reversible if it occurs due to a small temperature difference between the system and its surroundings. For example, transferring heat across a temperature difference of 0.00001 °F "appears" to be more reversible than for transferring heat across a temperature difference of 100 °F. Therefore, by cooling or heating the system in a number of infinitesamally small steps, we can approximate a reversible process. Although not practical for real processes, this method is beneficial for thermodynamic studies since the rate at which processes occur is not important.

Irreversible Process

An *irreversible process* is a process that cannot return both the system and the surroundings to their original conditions. That is, the system and the surroundings would not return to their original conditions if the process was reversed. For example, an automobile engine does not give back the fuel it took to drive up a hill as it coasts back down the hill.

There are many factors that make a process irreversible. Four of the most common causes of irreversibility are friction, unrestrained expansion of a fluid, heat transfer through a finite temperature difference, and mixing of two different substances. These factors are present in real, irreversible processes and prevent these processes from being reversible.

Adiabatic Process

An *adiabatic process* is one in which there is no heat transfer into or out of the system. The system can be considered to be perfectly insulated.

Isentropic Process

An *isentropic process* is one in which the entropy of the fluid remains constant. This will be true if the process the system goes through is reversible and adiabatic. An isentropic process can also be called a constant entropy process.

Polytropic Process

When a gas undergoes a reversible process in which there is heat transfer, the process frequently takes place in such a manner that a plot of the Log P (pressure) vs. Log V (volume) is a straight line. Or stated in equation form PV^n = a constant. This type of process is called a *polytropic process*. An example of a polytropic process is the expansion of the combustion gasses in the cylinder of a water-cooled reciprocating engine.

Throttling Process

A *throttling process* is defined as a process in which there is no change in enthalpy from state one to state two, $h_1 = h_2$; no work is done, $W = 0$; and the process is adiabatic, $Q = 0$. To better understand the theory of the ideal throttling process let's compare what we can observe with the above theoretical assumptions.

An example of a throttling process is an ideal gas flowing through a valve in midposition. From experience we can observe that: $P_{in} > P_{out}$, $vel_{in} < vel_{out}$ (where P = pressure and vel = velocity). These observations confirm the theory that $h_{in} = h_{out}$. Remember $h = u + Pv$ (v = specific volume), so if pressure decreases then specific volume must increase if enthalpy is to remain constant (assuming u is constant). Because mass flow is constant, the change in specific volume is observed as an increase in gas velocity, and this is verified by our observations.

The theory also states W = 0. Our observations again confirm this to be true as clearly no "work" has been done by the throttling process. Finally, the theory states that an ideal throttling process is adiabatic. This cannot clearly be proven by observation since a "real" throttling process is not ideal and will have some heat transfer.

Summary

The important information from this chapter is summarized below.

Thermodynamic Systems and Processes Summary

- A thermodynamic system is a collection of matter and space with its boundaries defined in such a way that the energy transfer across the boundaries can be best understood.
- Surroundings are everything not in the system being studied.
- Systems are classified into one of three groups:

  Isolated system - neither mass nor energy can cross the boundaries
  Closed system - only energy can cross the boundaries
  Open system - both mass and energy can cross the boundaries

- A control volume is a fixed region of space that is studied as a thermodynamic system.
- Steady state refers to a condition where the properties at any given point within the system are constant over time. Neither mass nor energy are accumulating within the system.
- A thermodynamic process is the succession of states that a system passes through. Processes can be described by any of the following terms:

  Cyclic process - a series of processes that results in the system returning to its original state
  Reversible process - a process that can be reversed resulting in no change in the system or surroundings
  Irreversible process - a process that, if reversed, would result in a change to the system or surroundings
  Adiabatic process - a process in which there is no heat transfer across the system boundaries
  Isentropic process - a process in which the entropy of the system remains unchanged
  Polytropic process - the plot of Log P vs. Log V is a straight line, PV^n = constant
  Throttling process - a process in which enthalpy is constant $h_1 = h_2$, work = 0, and which is adiabatic, Q=0.