



Engineering Thermodynamics-I



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PREFACE

The Module is prepared for Hawassa University and organized into seven chapters that cover properties of pure substance, First law of thermodynamics, Second law of thermodynamics and Entropy.

Following an introductory **chapter one** that presents fundamental concepts of thermodynamics, **Chapter 2** presents the general work and heat, Energy of a System Energy transport by heat and work Expansion and Compression work.

Chapter 3 Pure Substances, Properties of Pure Substances, Fixing the State of a Simple, Pure Substance, Phase Diagrams and Thermodynamics Property Tables , while **Chapter 4**, The First Law of Thermodynamics, The First Law of a Closed System, The First Law for a Control Volume, Some Steady Flow Engineering Devices. The last three chapters in this section **Chapter 5** the Second law of Thermodynamics, Equivalence of Kelvin-Planck and Clausius Statements, Reversible Process and Irreversibility and Causes of Irreversibility. The second section **Chapter 6** Entropy, The Clausius Inequality, Entropy change for an irreversible process While **Chapter 7** available energy, availability and irreversibility, Available and Unavailable Energy Reversible Work in A Non-flow Process, Reversible Work in A Steady-state Control Volume, Availability, Availability Change Involving Heat Exchange with Reservoirs and Irreversibility



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CHAPTER ONE

BASIC CONCEPTS AND DEFINITIONS

Thermodynamics is the science that deals with heat and work and those properties of substance that bear a relation to heat and work. Thermodynamics is the study of the patterns of energy change. Most of this course will be concerned with understanding the patterns of energy change. The name ‘thermodynamics’ is derived from the Greek words therme, meaning ‘heat’ and dynamis meaning power. Thus, thermodynamics is basically the study of heat and power.

1.1 Application Area of Thermodynamics

Energy transfer is present in almost all the engineering activities. Hence, the principles of thermodynamics are playing vital role in designing all the engineering equipments such as internal combustion engines, rockets, jet engines, nuclear power plants, refrigerators etc.

1.2 Statistical and Classical Thermodynamics

Statistical thermodynamics is microscopic approach in which, the matter is assumed to be made of numerous individual molecules. Classical thermodynamics is macroscopic approach. The state or condition of the system can be completely described by measured values of pressure, temperature and volume which are called macroscopic or time-averaged variables.

Table 1.1 Macroscopic and microscopic approach comparative way

Macroscopic approach	Microscopic approach
<ol style="list-style-type: none">1. In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level. In other words this approach to thermodynamics is concerned with gross or overall behaviour. This is known as classical thermodynamics.2. The analysis of macroscopic system requires simple mathematical formulae.3. The values of the properties of the system	<ol style="list-style-type: none">1. The approach considers that the system is made up of a very large number of discrete particles known as molecules. These molecules have different velocities and energies. The values of these energies are constantly changing with time. This approach to thermodynamics, which is concerned directly with the structure of the matter, is known as statistical thermodynamics.

<p>are their average values. For example, consider a sample of a gas in a closed container. The pressure of the gas is the average value of the pressure exerted by millions of individual molecules. Similarly the temperature of this gas is the average value of transnational kinetic energies of millions of individual molecules. These properties like pressure and temperature can be measured very easily. The changes in properties can be felt by our senses.</p> <p>4. In order to describe a system only a few properties are needed.</p>	<ol style="list-style-type: none">2. The behaviour of the system is found by using statistical methods, as the number of molecules is very large. so advanced statistical and mathematical methods are needed to explain the changes in the system.3. The properties like velocity, momentum, impulse, kinetic energy, and instruments cannot easily measure force of impact etc. that describe the molecule. Our senses cannot feel them.4. Large numbers of variables are needed to describe a system. So the approach is complicated.
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1.3 Thermodynamic Systems and Surroundings

In our study of thermodynamics, we will choose a small part of the universe to which we will apply the laws of thermodynamics. We call this subset a SYSTEM. The rest of the universe outside the system close enough to the system to have some perceptible effect on the system is called the surroundings. The surfaces which separate the system from the surroundings are called the boundaries as shown in fig1.1 below (e.g.: walls of the kettle, the housing of the engine).).

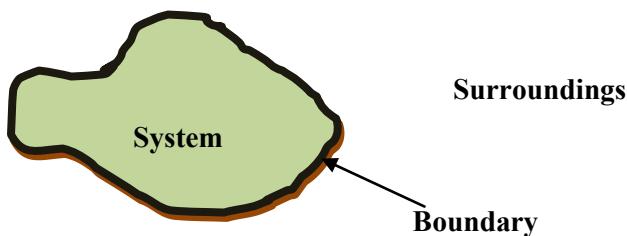


Fig.1.1 Thermodynamic System, boundary, surroundings

1.3.1 Types of Thermodynamic Systems

There are three types of thermodynamic systems:

- a) Closed System

- b) Open System and
- c) Isolated System

In **closed system**, attention is focused on a fixed mass. Energy in the form of heat and work (*The terms heat and work will be defined in the chapter 2.*) can cross the boundary of the system. But there is no mass flow across the boundary. Hence, the possibility of change in volume is always there in the closed systems. Example: Car battery, Tea kettle and Water in a tank

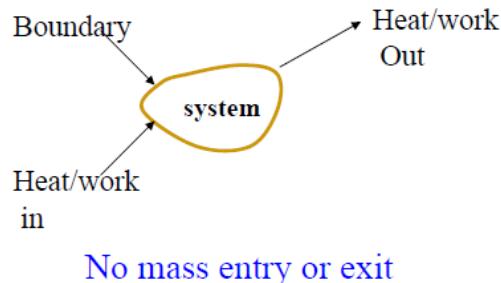


Fig.1.2 Closed system

In **open system**, the system which can exchange both the mass and energy (Heat and work) with its surrounding. Here, the behaviour of a fixed region in space called control volume is investigated and hence, there is no change in volume. The surface of the control volume is known as control surface. Example: Water Pump, Boilers, turbines and heat exchangers.

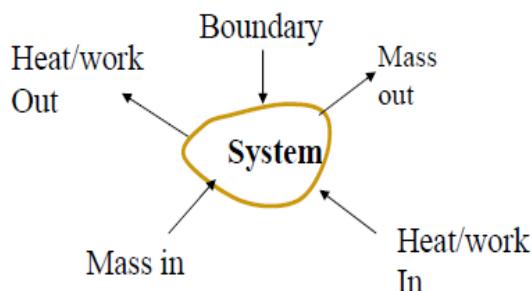


Fig.1.3 Open system

A system that exchanges neither energy nor matter with its surroundings is known as an isolated system. No such system physically exists. Universe is the only example, which is perfectly isolated system.

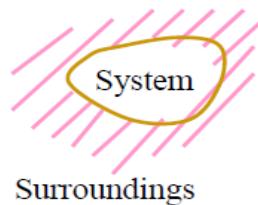


Fig.1.2 Isolated system

1.4 Thermodynamic Properties

In all thermodynamic problems energy transfer to or from the system is observed. To receive, store and deliver energy a working substance is present within the system. The characteristics which can be used to describe the condition of the system are known as properties. Thermodynamic properties are classified into two categories: intensive and extensive. Intensive properties are independent of quantity of matter or mass whereas extensive properties are dependent on mass. Consider a vessel containing air. If a membrane is assumed to be introduced into the vessel and it is divided into two equal parts. The properties remaining unchanged such as pressure and temperature are intensive properties. Volume of air will be reduced to half of its initial value. Hence, it is an extensive property.

1.5 Thermodynamic State and Equilibrium

When a system does not undergo any change, all the properties has fixed values. This condition is known as a thermodynamic state. The word equilibrium means balance. A system is said to be in an equilibrium state if its properties will not change without some perceivable effect in the surroundings. The factors that cause a change without any interactions with its surroundings are:

- A. Pressure difference
- B. Temperature difference
- C. Chemical reaction

If a system is balanced in all respects, it is in a state of thermodynamic equilibrium. Balanced in all respects means:

- There should not be any temperature difference within the system, so that the system is thermally balanced.

- No pressure difference exists between any two points within the system (Neglecting gravitational effects) and between the system and surroundings, so that it is mechanically balanced.
- No chemical reaction is taking place, so that it is chemically balanced.
- If two phases are involved, mass of each phase remains constant so that phase equilibrium is achieved.

Hence, for a system in a state of thermodynamic equilibrium, there is no change in any macroscopic property.

1.6 Processes and Cycles

When a system is taken from one equilibrium state to another, the change is known as process. The series of intermediate states through which a system passes during a process is called the path of the process. If all these intermediate states are equilibrium states, the process is known as quasi equilibrium or quasi-static process. Consider a certain quantity of gas taken in a frictionless piston cylinder arrangement as shown in Fig 1.5. The system is in thermodynamic equilibrium so that there is no unbalanced force acting on piston.

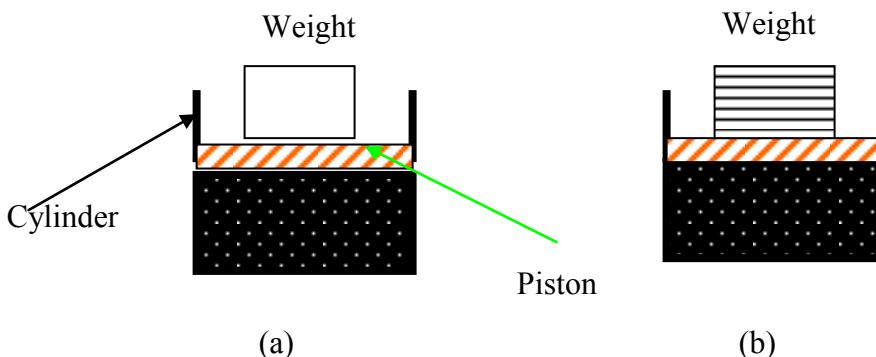


Fig.1.5 Illustration for thermodynamic equilibrium

The moment the weight is removed from the piston, mechanical equilibrium does not exist and as a result the piston is moved upward until mechanical equilibrium is restored again. Therefore the actual process occurs only when equilibrium does not exist. As shown in Fig.1.5.a, if the entire weight on the piston is removed at once, the deviation from the equilibrium is high and the expansion is rapid. For such a process the intermediate states are not equilibrium states and hence the process would be non-quasi-equilibrium.

A process is said to be reversible if both the system and its surroundings can be restored to their respective initial states by reversing the direction of the process.

- **Reversible:** if the process happens slow enough to be reversed.
- **Irreversible:** if the process cannot be reversed (like most processes).
- **Isobaric:** process done at constant pressure
- **Isochoric:** process done at constant volume
- **Isothermal:** process done at constant temperature
- **Adiabatic:** process where $q=0$
- **Cyclic:** process where initial state = final state

1.7 Point and Path Functions

Thermodynamic functions are classified into two categories namely point and path functions. Point functions are those for which the change depends on only the end states and not on the path followed. Hence point functions are inexact differentials. Path functions are those for which the change depends not only on the end states but also on the path followed. Hence path functions are exact differentials. It can be observed that the change in any property during a process depends only on end states. Therefore all the properties are point functions. To demonstrate path and point functions, let us consider two stations A and B on a hill as shown in Fig.1.6. While moving from station A to station B, let the distance traveled and increase in height from the mean sea level be observed. Distance traveled in path 1 is different from that in path 2. Hence it may be regarded as path function. But the change in height is same in both path 1 and path 2; therefore it is a point function.

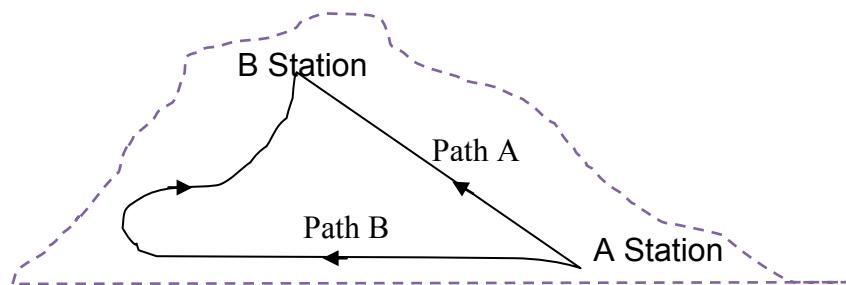


Fig.1.6 Illustration of point and path functions

1.8 State Postulate and Property Diagrams

As mentioned earlier, properties are meant for describing the state of a system. To fix a state, all the properties need not be specified. If any two independent intensive properties are specified, rest of the properties automatically assumes certain values. This is known as state postulate.

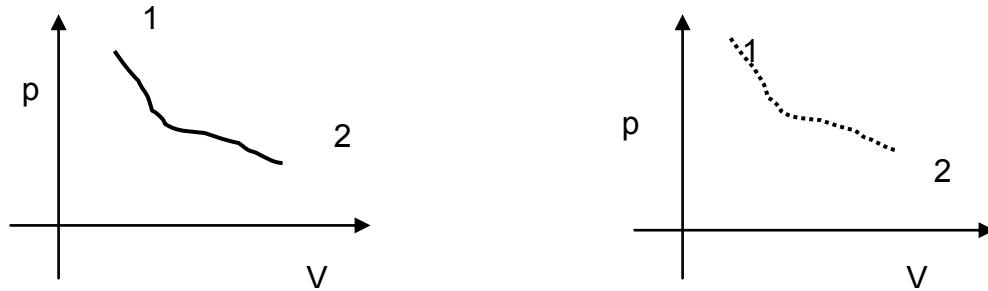


Fig.1.7 property diagram of equilibrium and non equilibrium processes

Consider pressure and specific volume (*Volume per unit mass*) is the two independent, intensive properties, describing the state of a compressible system. On a p-V diagram the state will assume a point as represented in the Fig.1.7 (a). Let the system be taken to another state such that all the intermediate states are equilibrium states. The curve connecting the initial state and final state, passing through all the intermediate states is indicating the path of the process. In non-quasi-equilibrium process as the intermediate status can not be defined, the path is denoted by dashed line as given in Fig.1.7 (b)

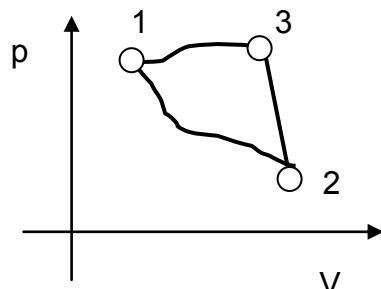
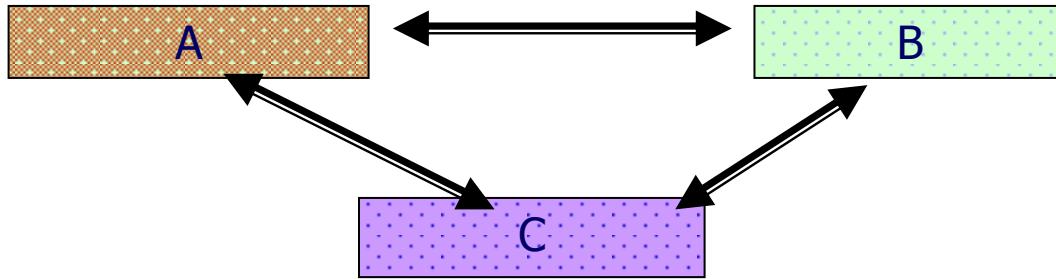


Figure 1.8: A system undergoing a cycle consisting of three quasi-equilibrium processes.

1.9 Temperature and Zeroth Law

Maxwell defined the temperature of a system as *its Thermal state considered with reference to its ability to communicate heat to other bodies*. When a hot body is brought into contact with a cold body, the hot body becomes cooler and the cold body becomes hotter. After sufficient time, the temperature of both the bodies will be equal. At that point, the two bodies are said to have

reached thermal equilibrium. Consider three bodies A, B and C. If the bodies A and B are in thermal equilibrium with C when brought into contact separately, they are also in thermal equilibrium with each other. This concept is known as zeroth law of thermodynamics.



The zeroth law was first formulated and labeled by R.H. Fowler in 1931.

1.10 Dimension and units

Any physical quantity can be characterized by dimensions. The magnitudes assigned to the dimensions are called units. Some basic dimensions such as mass m, length L, time t, and temperature T are selected as primary or fundamental dimensions, while others such as velocity V, energy E, and volume V are expressed in terms of the primary dimensions and are called secondary dimensions, or derived dimensions.

In SI, the units of mass, length, and time are the kilogram (kg), meter (m), and second (s), respectively. The respective units in the English system are the pound-mass (lbm), foot (ft), and second (s). The pound symbol lb is actually the abbreviation of libra, which was the ancient Roman unit of weight. The English retained this symbol even after the end of the Roman occupation of Britain in 410. The mass and length units in the two systems are related to each other by In the English system, force is usually considered to be one of the primary dimensions and is assigned a non derived unit. This is a source of confusion and error that necessitates the use of a dimensional constant (gc) in many formulas.

In SI, the force unit is the newton (N), and it is defined as the force required accelerating a mass of 1 kg at a rate of 1 m/s². In the English system, the force unit is the **pound-force** (lbf) and is defined as the force required accelerating a mass of 32.174 lbm (1 slug) at a rate of 1 ft/s².

1.11 Homogeneous and Heterogeneous Systems

Matter can exist in any one of the three phases' namely solid, liquid and gas. A system consisting of a single phase is known as homogeneous systems. For example, Mixture of air and water vapour, water plus nitric acid and octane plus heptanes. If the matter exists in more than one phase, the system is known as heterogeneous system. For example, Water plus steam, Ice plus water and water plus oil.

1.12 Pure Substances

Substances of fixed chemical composition throughout are known as pure substances. That is, pure substances have homogenous and invariable chemical composition irrespective of the phase or phases in which they exist.

Example

- a. Atmosphere air b. Water c. Nitrogen
- d. Water-steam mixture e. Product of combustion.

Though, mixture of water and steam is considered a pure substance, air and liquid air cannot be, since, the chemical composition of liquid air differs from that of gaseous air.

1.13 The Ideal Gas

Based on the experimental work carried out by Boyle, Charles and Gay-Lussac, pressure, temperature and specific volume of many gases at low pressure and moderate temperature are related by the following equation.

$$pv = RT \quad (1.1)$$

Where, $R = R_u/M$

This equation is known as equation of state of an ideal gas. The term R is known as characteristic gas constant, M molecular mass and R_u universal gas constant. In SI unit $R_u = 8.314 \text{ kJ/kgmol.K}$.

1.14 Concept of continuum

In microscopic approach the substance is assumed to be continuously distributed, and made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes, this is known as continuum hypothesis. The continuum idealization allows us to treat properties as



point functions and to assume the properties vary continually in space with no jump discontinuities. Since the matter is treated as continuous, the density at a point can be defined as

$$\rho = \lim_{v' \rightarrow v} \left(\frac{m}{v'} \right) \quad (1.2)$$

Where v' is the smallest volume for which a definite value of the ratio exists. Below the limiting value of v' , the fluctuation in average density will be high and a definite value for the ratio becomes impossible, with the *mean free path** of the molecules approaching the order of magnitude of the dimension of the vessel.

* *mean free path is the distance traveled between two consecutive collisions of a molecule.*

Exercises

1. Identify the type of the systems given below.
 - a) Reciprocating air compressor
 - b) Steam turbine in a steam power plant
 - c) Pressure cooker
 - d) Radiator of an automobile engine
 - e) A can of soft drink cooled inside the refrigerator
2. In _____ system control volume approach is employed.
3. Define a quasi-equilibrium process.
4. Define intensive and Extensive properties. Give examples.
5. What is the state postulate?
6. What is zeroth law of thermodynamics?
7. When does the concept of continuum become invalid?
8. In which type of system neither mass nor energy is allowed to cross the boundary.
9. What is meant by thermodynamic equilibrium?
10. What is meant by a control surface?
11. What is meant by microscopic and macroscopic approach?
12. Universal gas constant = Characteristic Gas constant \times Molecular weight (T/F)
13. What is an open system? Give examples.
14. Define a closed system. Give examples.

CHAPTER TWO

WORK AND HEAT

Energy can be transferred to or from a system in three forms: heat, work, and mass flow. Energy interactions are recognized at the system boundary as they cross it, and they represent the energy gained or lost by a system during a process. The only two forms of energy interactions associated with a fixed mass or closed system are heat transfer and work. In this chapter various forms of work and modes of heat transfers are discussed.

2.1 Work as Defined in Mechanics

Work is done when the point of application of a force moves in the direction of the force. The amount of work is equal to the product of the force and the distance through which the point of application moves in the direction of the force. i.e., work is identified only when a force moves its point of application through an observable distance.

2.2 The Thermodynamic Definition of Work

Positive work is done by a system, during a given process, when sole effect external to the system could be reduced to the lifting of a mass. Consider a gas expanding in a piston cylinder arrangement as given in Figure 2.1. Here no mass is actually lifted against gravity. But if the existing surroundings are fitted with an arrangement as given in the Figure 2.2, there is a possibility of lifting the mass. Hence work is said to be done by the system.

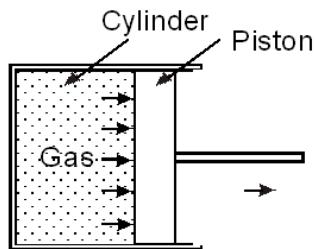


Figure 2.1 Expansion without actual lifting of mass

While exploring the possibility of lifting a mass the effects that are external to the system alone must be taken into account. For example, a lift with a person and a suitcase is considered as a

system. If the person lifts the suitcase, it should not be taken into account, because this event occurs within the system.

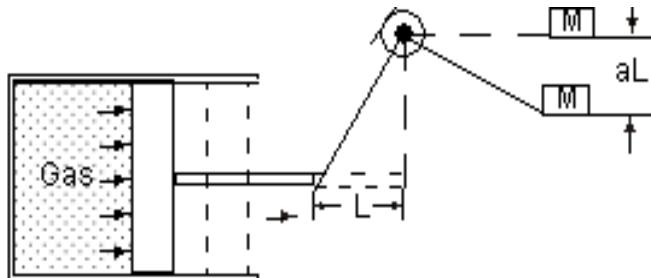


Figure 2.2 Expansion with actual lifting of mass

2.3 Units of Work and Power

In the international system (SI), the unit of force is Newton (N) and that of distance is meter (m). Hence the unit of work is Nm which is also given a special name Joule. In most of the applications large quantity of work is involved. Therefore kJ is commonly used.

Rate of doing work is known as power. Hence its unit is Nm/S or J/S which is again given a special name Watts (W).

2.4 Sign Convention of Work

Heat and work are directional quantities, and thus the complete description of a heat or work interaction requires the specification of both the magnitude and direction.

- Work done by the system on the surroundings is considered as positive work.
- Work done on the system by the surroundings is taken as negative work.

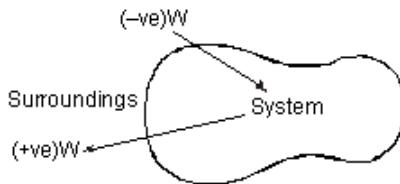


Figure 2.3 Sign Convention of work

2.5 Displacement Work

Consider a piston cylinder arrangement as given in the Figure 2.4. If the pressure of the fluid is greater than that of the surroundings, there will be an unbalanced force on the face of the piston. Hence, the piston will move towards right.

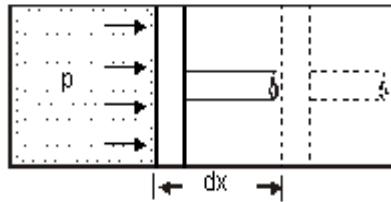


Figure 2.4 Displacement work

$$\begin{aligned} \text{Force acting on the piston} &= \text{Pressure} \times \text{Area} \\ &= pA \end{aligned}$$

$$\begin{aligned} \therefore \text{Work done} &= \text{Force} \times \text{distance} \\ &= pA \times dx \\ &= pdV \end{aligned}$$

(2.1)

Where, dV – change in volume

This work is known as displacement work or pdV work corresponding to the elemental displacement dx . To obtain the total work done in a process, this elemental work must be added from the initial state to the final state.

2.6 Evaluation of Displacement Work

2.6.1 Constant Pressure Process

Figure 2.5 shows a piston cylinder arrangement containing a fluid. Let the fluid expands such that the pressure of the fluid remains constant throughout the process. Figure 2.6 shows the process in a p - V diagram.

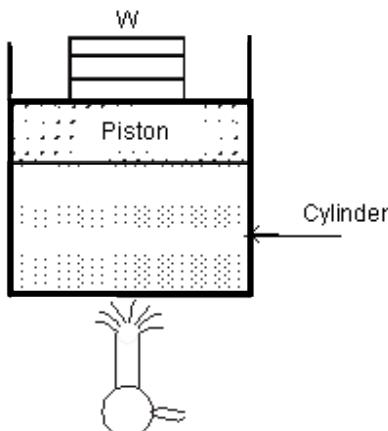


Figure 2.5

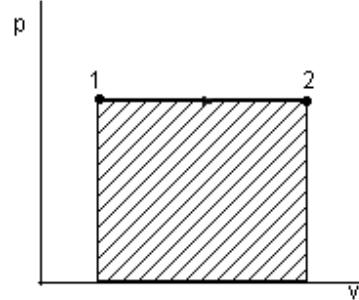


Figure 2.6

The mathematical expression for displacement work can be obtained as follows:

$$= p(V_2 - V_1) \quad (2.2)$$

This expression shows that the area under a curve in a p-V diagram gives work done in the process.

2.6.2 Constant volume process

Consider a gas contained in a rigid vessel being heated. Since there is no change in volume, no displacement works.

2.6.3 Hyperbolic process

Let the product of pressure and volume remains constant at all the intermediate states of a process. In the p-V diagram it will be a hyperbola as given in Figure 2.7.

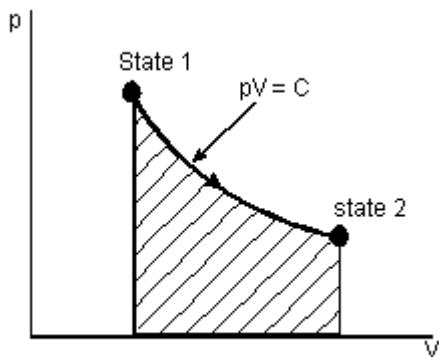


Figure 2.7

$$\begin{aligned}
 W_{21} &= \int_1^2 p dV \\
 &= \int_1^2 C dV \text{ where } C=pV \\
 &= C \int_1^2 \frac{1}{V} dV \\
 &= C \ln(V_2/V_1) \\
 &= p_1 V_1 \ln(V_2/V_1) \text{ (or) } p_2 V_2 \ln(V_2/V_1)
 \end{aligned} \quad (2.3)$$

For Ideal gases when temperature remains constant, pV will be constant i.e., isothermal processes are hyperbolic processes for an ideal gas.

2.6.4 Polytropic Process

Any process can be represented by the general form $pV^n = \text{constant}$. Based on the value of n , the process differs as given below; for other values of n , the process is known as polytropic process. Figure 2.8 shows the polytropic process of various possible polytropic index ‘ n ’ on p-V coordinates.

Work done due to differential volume change: $dW = PdV$

Expression for displacements work for a polytropic process can be obtained as follows:

$$\begin{aligned} W_2 &= \int_1^2 pdV \\ &= \int_1^2 \frac{C}{V^n} dV \quad \text{Where, } C = pV^n \end{aligned}$$

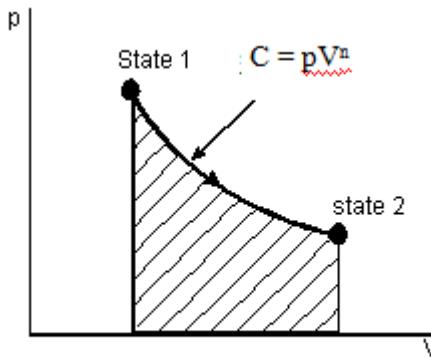


Figure 2.8

$$\begin{aligned} &= C \int_1^2 V^{-n} dV \\ &= C \left[\frac{V^{-n+1}}{-n+1} \right]_1^2 \\ &= \left[\frac{CV_2^{-n+1} - CV_1^{-n+1}}{-n+1} \right]_1^2 \\ &= \left[\frac{p_2 V_2^n V_2^{-n+1} - p_1 V_1^n V_1^{-n+1}}{-n+1} \right] \quad \text{since, } C = p_1 V_1^n = p_2 V_2^n \\ &= \left[\frac{p_2 V_2 - p_1 V_1}{-n+1} \right] \end{aligned} \tag{2.4}$$



Work done due to differential pressure change: $dw=vdP$ (open system or control volume)

$$_1W_2 = \int_1^2 Vdp, \text{ where } PV^n=C$$

$$_1W_2 = C \int_1^2 \frac{1}{p^{1/n}} dp, \text{ integrate similar with above procedure}$$

$$_1W_2 = n \frac{P_1V_1 - P_2V_2}{n-1} \quad (2.5)$$

2.7 Work is a Path Function

Consider a working substance initially occupying 0.2 m^3 at 1 bar as represented by state 1 in the Figure 2.9. Let the system changes its state such that the final volume is 0.05m^3 and pressure 2 bar. The change of state may occur along the paths 1A2, 1B2 or 1C2. As mentioned earlier, area under the curve representing the process in a p-V diagram gives the work done in the process. Comparing the area under the paths 1A2, 1B2 and 1C2, it is clear that the work done in these paths are different. Hence it can be concluded that the amount of work done is not only a function of the end states of a process, but also the path followed between the states. Therefore work is a path function.

2.8 Additivity of Work Over Processes

If a system is taken through two or more number of processes, the total work done is the sum of work done in the individual processes.

Let a system executes three processes as shown in Figure 2.10. The total work done,

$$_1W_4 = _1W_2 + _2W_3 + _3W_4 \quad (2.6)$$

2.9 Heat

Heat is defined as the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference. If a system, at a given temperature is brought in contact with another system (or surroundings) at a lower temperature, it can be observed that heat is transferred from the system at the higher temperature to the system at lower temperature. This heat transfer occurs solely because of the temperature difference between the

two systems. Another important aspect of the definition of heat is that a body never contains heat. Rather, heat can be identified only as it crosses the boundary. Similar to work, heat is also a form of energy transfer occurring at the boundary of the system and is a path function.

2.10 Sign Convention of Heat

- Heat given into a system is positive
- Heat coming out of the system is negative

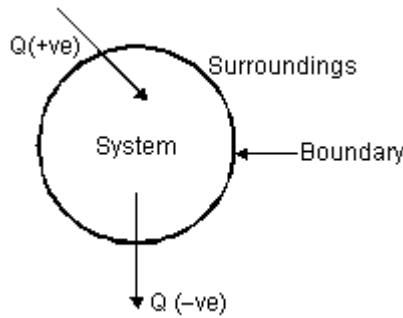


Fig. 2.9 Sign convention of heat

2.11 Modes of Heat Exchange

Conduction, convection and radiation are the three possible modes of heat transfer between systems, and between system and its surroundings. Conduction occurs without bulk movement of molecules. Energy transfer in conduction is due to lattice vibration and free electron movement. It is the predominant mode of heat transfer in solids.

Convection occurs with bulk movement of molecules and therefore, occurs in gases and liquids. If the bulk movement or flow is due to an external device, it is known as forced convection. In the absence of an external device the flow is due to the difference in density caused by the temperature difference. This mode is known as natural convection.

Bodies separated by a distance may exchange heat in the form of electromagnetic waves without the participation of the intervening medium. It is known as radiation. It is generally a surface phenomenon. Sometimes as in the case of gas mixtures containing carbon dioxide and water vapour it is a volume phenomenon.

2.12 Sensible and Latent Heat

It is known that a substance can exist in three phases namely solid, liquid and gas. When a substance is heated or cooled temperature of the substance increases or decreases respectively unless there is any phase change. Quantity of heat added or removed to change the temperature by unit degree is known as specific heat. For solids and liquids same quantity of heat is required to cause unit degree rise for both constant pressure heating as well as constant volume heating as they are incompressible. But for gases there is appreciable difference in the quantity of heat required to cause unit difference in temperature between constant volume and constant pressure processes. Accordingly, they are known as specific heat at constant volume (C_V) and specific heat at constant pressure (C_p). Thus to increase the temperature of m kg of the given substance by ΔT degree, amount of heat required is given by

$$Q = mC_V\Delta T \text{ at Constant Volume} \quad (2.7)$$

$$Q_1 = mC_p\Delta T \text{ at Constant Pressure} \quad (2.8)$$

If a certain single component system is undergoing phase change at constant pressure, temperature of the system remains constant during heating or cooling. Quantity of heat removed or added to cause the change of phase of unit mass of the substance is known as latent heat. For example latent heat of fusion of water is the amount of heat to be removed to solidify 1 kg of water into 1 kg of ice at a given temperature.

Let us consider a process of converting 1 kg of ice at -30°C to steam at 250°C at atmospheric pressure. We know that ice melts at 0°C and water evaporates at 100°C at atmospheric pressure.

For a constant rate of heating, if temperature at different instants are plotted we will get a graph as shown in Figure 2.10.

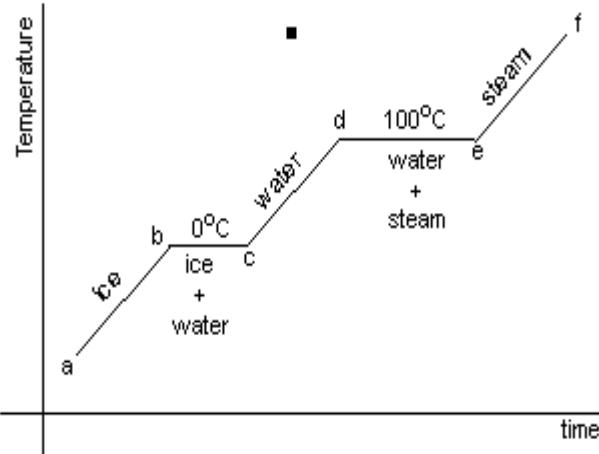


Figure 2.10 Illustration for sensible and latent heat

The total heat required can be obtained as follows:

$$Q = Q_{ab} + Q_{bc} + Q_{cd} + Q_{de} + Q_{ef} \quad (2.9)$$

$$Q_{ab} = mC_{ice} (t_b - t_c) \quad (2.10)$$

Q_{bc} = Latent heat of melting of ice at 0°C

$$Q_{cd} = mC_{water} (t_d - t_c) \quad (2.11)$$

Q_{de} = Latent heat of evaporation of water at 100°C

$$Q_{ef} = mC_{PSteam} (t_f - t_e) \quad (2.12)$$

Where C_{ice} = Specific heat of ice

C_{water} = Specific heat of water

C_{PSteam} = Specific heat of steam at constant pressure

2.13 Reversible Adiabatic Process

A reversible process during which, the system and the surroundings do not exchange any heat across the boundary is known as reversible adiabatic process. For such a process, pressure and volume variation is governed by the law:

$$pV^{\gamma}=\text{constant} \quad (2.13)$$

Where,

C_p is the specific heat at constant pressure

C_V is the specific heat at constant volume

Detailed discussion on these specific heats is presented in the next chapter. A wall which does not permit the heat flow across it is known as adiabatic wall, whereas the wall that permits the heat is known as diathermic wall. In an adiabatic process the only possible energy interaction across the boundary of the system is work transfer to or from the system.

Displacement work involved in a reversible adiabatic process can be expressed as

$$W = \left[\frac{p_2 V_2 - p_1 V_1}{-\gamma + 1} \right] \quad (2.14)$$

2.14 Comparison between work and heat

- Both heat and work are boundary phenomena, that is, they occur only at the boundary.
- The interaction due to the temperature difference is heat and all other interactions are to be taken as work.
- Both work and heat are path functions, that is, they are inexact differentials.

Table 2.1: Energy analysis for non-flow processes summary

S.No. PROCESS S	P-V-T RELATION	WORK DONE	dU	dQ	dH
1. $V = C$ Isochoric process	$P_1/T_1 = P_2/T_2$	0	$= mC_V(T_2 - T_1)$	$= mC_V(T_2 - T_1)$	$= mC_p(T_2 - T_1)$
During Expansion and heating WD and Q is +ive while during Compression and cooling WD and Q is -ive					
2. $P = C$ Isobaric process	$V_1/T_1 = V_2/T_2$	$= P(V_2 - V_1)$ $= mR(T_2 - T_1)$	$= mC_V(T_2 - T_1)$	$= mC_p(T_2 - T_1)$	$= mC_p(T_2 - T_1)$
3. $T = C$ Isothermal proc.	$P_1 V_1 = P_2 V_2$	$= P_1 V_1 \ln P_1/P_2$ $= P_1 V_1 \ln V_2/V_1$ $= mRT_1 \ln V_2/V_1$	0	$Q = W$	0
4. $PV^\gamma = C$ Adiabatic pro.	$P_1 V_1^\gamma = P_2 V_2^\gamma = C$ $T_1/T_2 = (V_2/V_1)^{\gamma-1}$ $= (P_1/P_2)^{\gamma-1}$ $V_1/V_2 = (P_2/P_1)^{1/\gamma}$	$= mR(T_2 - T_1)^{\gamma-1}$ $= (P_1 V_1 - P_2 V_2)/\gamma-1$	$= -dW$ $= mC_p(T_2 - T_1)$	0	$= mC_p(T_2 - T_1)$

Solved problems:

Example 2.1:

A mass of 1.2 kg of air at 150 kPa and 12°C is contained in a gas tight, frictionless piston-cylinder device. The air is now compressed to a final pressure of 600 kPa. During the process, heat is transferred from the air such that the temperature inside the cylinder remains constant. Calculate the work done during this process. Assume a quasi-static process and the ideal gas law is valid.

Solution:

For air we have the molecular mass, $M = 28.97 \text{ kg/kmol}$, from table A-1

$$R = \mathfrak{R}/M = (8.314 \text{ kJ/kmol}\cdot\text{K})/(28.97 \text{ kg/kmol}) = 0.2870 \text{ kJ/kg K}$$

For a constant temperature process we found:

Also we write the ideal gas law as:

$$P \cdot V / m \cdot R \cdot T = 1$$

Then:

$$P_1 \cdot V_1 / m \cdot R \cdot T_1 = P_2 \cdot V_2 / m \cdot R \cdot T_2$$

But m , R and T are constants. It follows that

$$P_1 \cdot V_1 = P_2 \cdot V_2$$

$$V_2/V_1 = P_1/P_2$$

$$\begin{aligned} W &= m \cdot R \cdot T \cdot \ln(P_1/P_2) \\ &= 1.2 \text{ kg} \cdot (0.2870 \text{ kJ/kg K}) \cdot [(12+273) \text{ K}] \ln(150/600) \\ &= -136.1 \text{ kJ} \end{aligned}$$

Example 2.2:

5m³ of air at 2bar, 270°C is compressed up to 6bar pressure following $PV^{1.3} = \text{constant}$. It is subsequently expanded adiabatically to 2 bar. Considering the two processes to be reversible, determine the net work done, also plot the processes on T – S diagrams.

Sol: $V_1 = 5 \text{ m}^3$, $P_1 = P_3 = 2 \text{ bar}$, $P_2 = 6 \text{ bar}$, and $n = 1.3$

$$V_2 = V_1 (P_1/P_2)^{1/1.3} = 5(2/6)^{1/1.3} = 2.147 \text{ m}^3$$

Hence work done during process 1 – 2 is W_{1-2}

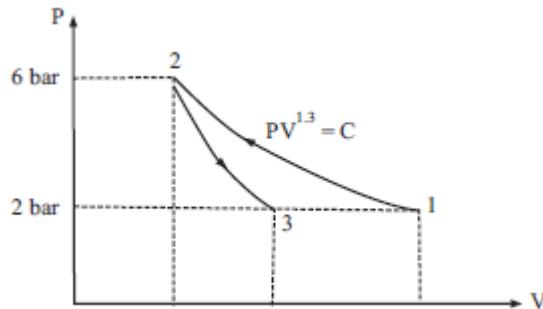
$$= (P_2 V_2 - P_1 V_1) / (1 - n)$$

$$= (6 \times 105 \times 2.47 - 2 \times 105 \times 5) / (1-1.3) = -9.618 \times 105 \text{ J}$$

Similarly to obtain work done during processes 2 – 3, we apply

$$W_{2-3} = (P_3V_3 - P_2V_2) / (1 - g); \text{ where } g = 1.4$$

$$\text{And } V_3 = V_2(P_2/P_3)1/g = 2.147(6/2)1/1.4 = 4.705 \text{ m}^3$$



$$\text{Thus } W_{2-3} = (2 \times 105 \times 4.705 - 2 \times 105 \times 2.147) / (1 - 1.4) = 8.677 \times 105 \text{ J}$$

Net work done

$$W_{\text{net}} = W_{1-2} + W_{2-3} = -9.618 \times 105 + 8.677 \times 105 = -0.9405 \times 105 \text{ J}$$

$$\mathbf{W_{\text{net}} = -94.05 \text{ KJ}}$$

Example 2.3:

A gas is contained in a piston cylinder arrangement as given in the Figure 2.28. Initial volume of the gas is 0.5 m^3 . It is compressed from 1 bar to 10 bar such that the temperature remains constant. Find the final volume and work done.

Given: $V_1=0.5 \text{ m}^3$, $P_1=1 \text{ bar}$, $p_2= 10 \text{ bar}$, $T=C$

Required: V_2 and W

Solution:

a) Final volume

$$\begin{aligned} P_1V_1 &= P_2V_2 \text{ and a} \\ V_2 &= P_1V_1 / P_2 \\ &= 0.5 \text{ m}^3 \times 1 \text{ bar} / 10 \text{ bar} \\ &= 0.05 \text{ m}^3 \end{aligned}$$

b) Work done

$$\begin{aligned} W &= P_1V_1 \ln(V_2/V_1) \\ &= 100 \text{ kPa} \times 0.5 \text{ m}^3 \times \ln(0.05 \text{ m}^3 / 0.5 \text{ m}^3) \\ &= -115.13 \text{ KJ} \end{aligned}$$



Example 2.4:

1 Kg of air undergoes expansion from 800 kPa, 300 K to 120 kPa in such a way that $p(v + 0.2) = \text{Constant}$, where p is the pressure in kPa and v is the specific volume in m³/Kg. Find the work done in the process.

Given: P₂=120 kpa, P₁=800kpa, T₁=300K, P (V+0.2)=C

Required: W₁₋₂=?

Solution: W₁₋₂= $\int P dv$

$$W_{1-2} = \int \frac{C}{V+0.2} dv, \text{ let } x=V+0.2 \text{ and } dx=dv$$

$$W_{1-2} = \int \frac{C}{X} dx$$

$$W_{1-2} = C \ln(X_2/X_1)$$

For iso thermal process P_i(V_i+0.2)=C

$$P_1(V_1+0.2) = P_2(V_2+0.2)$$

$$\frac{V_2 + 0.2}{V_1 + 0.2} = \frac{P_1}{P_2} = 6.667$$

Using idea gas equation Pv=RT

$$\begin{aligned} v_1 &= RT/P_1 = 286.9 \times 300 \text{ K}/800\text{Kpa} \\ &= 0.107 \text{ m}^3/\text{kg} \end{aligned}$$

$$W_{1-2} = p_1(v_1+0.2) \ln(6.667) = 466.88 \text{ kJ}$$



Exercises

1. Name the forms of energy transfer across the boundary of a thermodynamic system.
2. State the thermodynamics definition of work.
3. Displacement work is not applicable to _____ systems.
4. The polytropic index n of process can be represented by
 - a) $n = 2$
 - b) $n = 1$
 - c) $n = 1.6$ choose the right answer.
5. What are points and path functions? Give examples.
6. What is meant by displacement work?
7. What is meant by an indicator diagram?
8. Define mean effective pressure.
9. What are the modes of heat transfer?
10. A certain fluid expands in a quasi-static process from 0.1 m^3 to 0.8 m^3 at a constant pressure of 1000 kPa . Find the work done.
[700 kJ]
11. Zeroth law of thermodynamics is the basis of _____
 - a) Temperature measurement
 - b) Pressure measurement
 - c) Heat measurement
 - d) Internal energy
 - e) EnthalpyChoose the correct answer
12. Mass remains constant for a closed system (T / F)
13. What are the similarities between work and heat?
14. Calculate the work required to lift a 25 kg body from an elevation of 200 m above mean sea level to an elevation of 300 m in 2 minutes.
[24.525 kJ]
15. What is the work done in compressing a spring of stiffness 500 N/cm by 2 cm ?
[1 kJ]
16. An electric water with a resistance of 50 Ohms heater is connected across a power supply of 240 Volt for a period of 1 hour .
 - a) Determine the work done by the power source on the heater.
 - b) How many units of electricity are consumed?
[5184 kJ; 1.44 k Whr]

17. Air expands from 0.1 m^3 to 0.23 m^3 at a constant temperature of 50°C . Calculate the work done per kg of air. $R_{\text{air}} = 0.287 \text{ kJ/kgK}$.

[77.2 kJ]

18. Oxygen contained in a cylinder fitted with a piston expands in a quasistatic process according to the law $pV^{1.5} = \text{constant}$. The initial pressure, temperature and volume are 5 bar, 300 K and 0.05 m^3 . After expansion, the pressure is 2 bar.

Find the following :

- Final volume
- Final temperature
- Work done

[**0.0921 m³ ; 221 K ; 13.16 kJ**]

19. Air is compressed adiabatically from 0.92 m^3 to 0.29 m^3 in a piston cylinder arrangement. Taking its initial pressure and temperature as 103 kPa and 300 K respectively, find the work done. Also find the final temperature.

[**-139.04 kJ ; 476 K**]

20. A spherical balloon has a diameter of 25 cm and contains air at a pressure of 150 kPa. The diameter of the balloon increases to 30 cm because of heating, and during this process, the pressure is proportional to the diameter. Calculate the work done on the gas assuming reversible work interaction.

[**0.989 kJ**]

21. A bicycle pump has a total stroke of 25 cm and is used to pump air into a tyre against a pressure of 3.5 bar. Calculate the length stroke necessary before air enters the tyre when the piston is pushed in

- rapidly
- slowly

Assume atmospheric pressure is 1 bar.

[**17.0 cm ; 17.9 cm**]

22. A mass of air occupying 0.5 m^3 at 2 bar and 200°C is compressed reversibly and adiabatically to 5 bar and then it undergoes isobaric expansion so that it gives out 45 kJ of work. If the system is to be brought back to its initial state what should be the polytropic

index ? calculate the network interaction of this cycle. Sketch the cycle on a p-V diagram. Also compute the power developed if the number of cycles executed per minute is 300.

[2.57; 17.8 kJ ; 88.9 kW]

23. It is required to lift five people on an elevator through a height of 100 m. The work required is found to be 341.2 kJ and the gravitational acceleration is 9.75 m/s^2 . Determine the average mass per person.

[69.95 kg]

24. What is the work required to accelerate a vehicle of mass 500 kg from rest to a velocity of 60 kmph.

[69.44 kJ]

25. The indicator card of an 8 cm bore, 10 cm stroke water pump is in the shape of a rectangle of dimension $2 \times 10 \text{ cm}$. The indicator spring constant is 22 MPa/m.
- Find the mean effective pressure.
 - If the cycle is repeated once in every second, what is the power required by the pump?

[440 kPa ; 0.22 kW]

26. A quantity of a substance in a closed vessel is undergoing a reversible process in such a way that the pressure is proportional to the square root of volume from 1 m^3 to 2m^3 . The initial pressure is 100 KPa. Compute the work done.

[2.33 kJ]

27. A cylinder of 8 cm internal diameter is fitted with a piston loaded by a coil spring of stiffness 140 N/cm of compression. The cylinder contains 0.0005m^3 of air at 15°C and 3 bar. Find the work done when the piston moves by 4 cm as the gas expands.

[7.11 J]

28. Carbon dioxide is taken in a piston cylinder arrangement such that it occupies a volume of 1m^3 at 1 bar and 27°C . It has to be compressed to 0.2 m^3 such that the temperature remains constant during compression. Compute the workdone and final pressure.

[-160.94 kJ; 500 kPa]



29. 5 kg of oxygen initially at 10 bar, 370 K is undergoing expansion to 1 bar. If the final temperature is 300K, Determine the following:

- a) Initial volume
- b) Final volume
- c) Polytropic index
- d) Work done

Take the molecular weight of oxygen as 32.

[**0.48m³; 3.897m³; 1.1; 903 kJ**]

30. A rigid container of volume 0.4 m^3 is filled with oxygen until the pressure reaches 1200 kPa. It is then cooled so that the pressure reduces to 900 kPa. How much work is performed? Draw a p-V diagram for the process.

[**0 kJ**]

31. A paddle wheel supplies work to a system at the rate of 80 W. During a period of 1 minute the system expands from 0.03 m^3 to 0.08 m^3 against a constant pressure of 500 kPa. Find the net work interaction during this period of 1 minute.

Ans : [20.2 kJ]

CHAPTER THREE

PROPERTIES OF PURE SUBSTANCES

If any two independent intensive properties of a simple compressible system are defined, other properties automatically assume definite values. These properties can be expressed in terms of charts, tables or equations. This chapter covers the charts and tables of properties of steam.

3.1 Pure Substances

Substances of fixed chemical composition are known as pure substances

Example: Water, Helium, Nitrogen, Oxygen etc.

Substances exist in any one of the three phases' namely solid, liquid and gas. For example, H_2O may exist in the form ice (solid), Water (Liquid) or Steam (Gaseous). In all these phases it will have the same chemical composition. A Mixture of two or more phases of a pure substance should also be regarded as pure substance. If Water and Steam Co-exist in a container, the chemical composition of both the Vapour and liquid phases will be identical. Hence this heterogeneous system is also a pure substance.

3.2 Phases of Pure Substance

- A phase is identified as having a distinct molecular arrangement.
- This molecular arrangement is homogeneous throughout the system.
- The phase separated from the other phases by easily identifiable boundary surfaces.

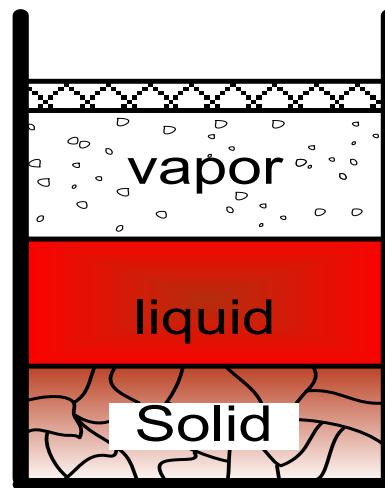


Figure 3.1 phase of pure substance

3.3 Phase Transformation

Consider a unit mass of ice heated steadily at a constant pressure of 1 atm. Let the initial temperature be -30°C . Due to heating, temperature increases upto 0°C (Figure 3.1). At 0°C ice starts melting and until entire mass of ice becomes water, temperature is remaining constant. Heat added during this phase change is known as latent heat of fusion.

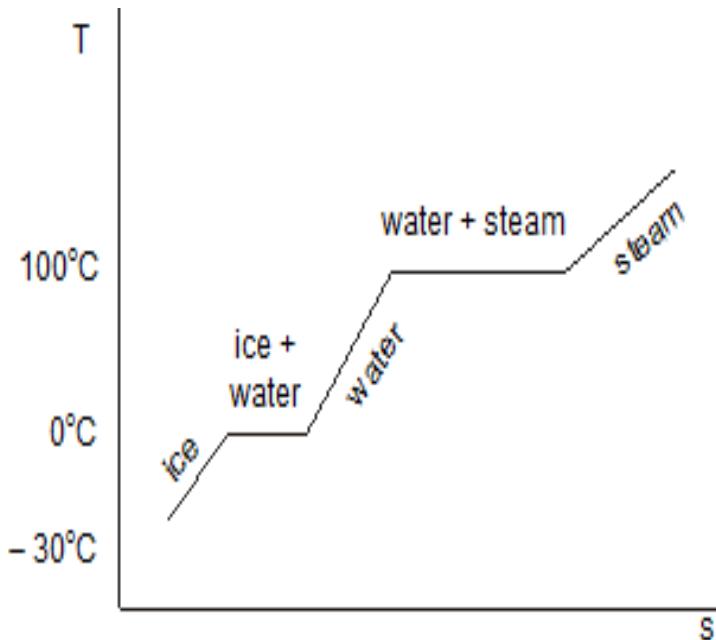


Figure 3.2 phase transformation

Further heating increases the temperature of water. This continues until 100°C . At 100°C Evaporation of water into steam is taking place. Temperature once again remains constant at 100°C until complete conversion of water into steam occurs. Heat added during this phase change is known as latent heat of evaporation. Temperature of steam continues to increase afterwards.

3.3.1 p-T Diagram of a Pure Substance

Instead of 1atm. pressure, if water is heated at 5 bar, evaporation will be taking place at 15.186°C . In the similar manner, each pressure has its own saturation temperature for a given substance. In a p-T diagram the locus of saturation temperatures against the corresponding pressures forms a curve known as vaporisation curve. It separates liquid and vapour phases in p-T diagram. Similarly solid & liquid phases are separated by fusion curve in p-T diagram.

Below a limiting value of pressure known as Triple point, direct conversion of solid into vapour is taking place. This is known as sublimation. Sublimation curve separate solid and vapour phases in p-T diagram. Sublimation curve, vapourisation curve and fusion curve are represented on a p-T Coordinates in Figure 3.3. Sublimation and vapourisation curves are having positives slopes for all substances. Fusion curve for most of the substances is having positive slope but for water it is negative. From p-T diagram it can be inferred that the given substance exists in liquid phase when the temperature is below the saturation temperature corresponding to the given pressure and in vapour phase if the given temperature is greater than the saturation temperature. When the given temperature is equal to the saturation temperature it may be liquid, vapour (or) a mixture of both.

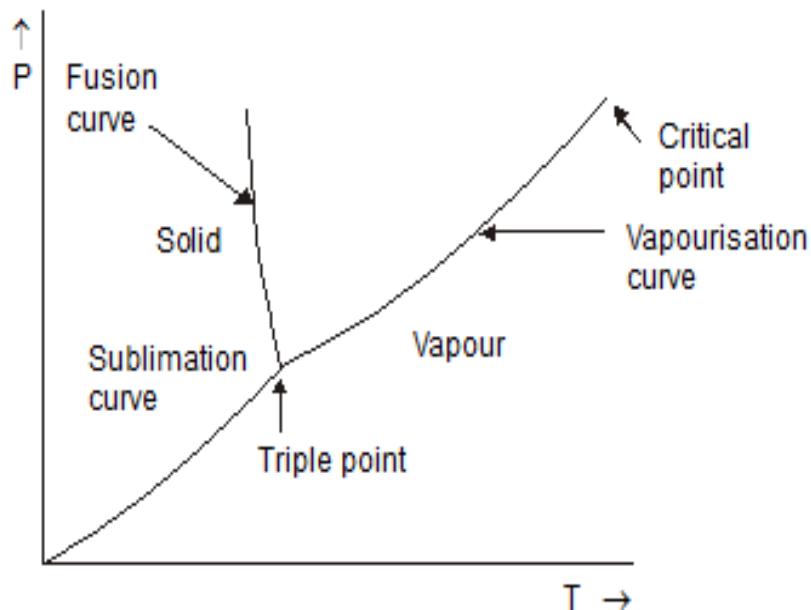


Figure 3.3 p -T Diagram of a Pure Substance

3.3.2 T-v Diagram of a Pure Substance

For simplicity let us consider only the liquid and vapour phases, which are commonly encountered in most of the engineering applications. Let a system of unit mass of water be heated at constant pressure. 1-2-3-4 in Figure 3.3 Shows the T-v Variations at constant pressure.

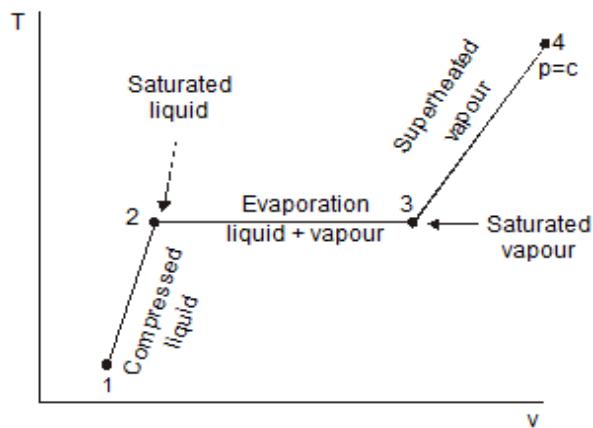


Figure 3.4 T -V Diagram of a Pure Substance

From 1 to 2, heat addition increases the temperature with a very small increase in volume. State of water between 1 and 2 is known as subcooled liquid or compressed liquid because for a given pressure it is at a temperature lower than the saturation temperature (or) for a given temperature it is at a pressure higher than saturation pressure. The state of water at 2 is known saturated liquid. Temperature at this state is equal to the saturation temperature. Any further addition of heat causes evaporation of water.

From 2 to 3, evaporation is taking place. During this phase change, temperature remains constant and increase in volume is high. At state 3, entire mass is in the form of vapour known dry saturated vapour.

From 3 to 4, heating causes increase in both temperature and volume. State of steam in this region is called super-heated state.

As mentioned earlier, at higher pressure evaporation occurs at higher temperature and at lower pressure evaporation occurs at lower temperature. Latent heat of evaporation decreases with increase in pressure. For a particular pressure it becomes zero so that the change from liquid to vapour phase occurs suddenly without a distinct intermediate state. This pressure is known as critical pressure. This state on a property diagram is known as critical point. By connecting the saturated liquid state at different pressures a line called saturated liquid line is obtained. In the same way, by connecting the saturated vapour states, saturated vapour line is obtained. It can be observed that the saturated liquid and vapour line meet at critical point. Figure 3.4 shows all these lines and various regions on a T-v diagram.

The region between saturated liquid line and saturated vapour line is known as wet region, consisting of both liquid and vapour. The percentage of composition or quality of this wet steam is expressed in terms of dryness fraction which is defined as the ratio of mass of vapour to the mass of the mixture. Specific volume of *wet steam* is expressed as

$$\begin{aligned}
 v &= xv_g + (1 - x)v_f \\
 &= v_f + x(v_g - v_f) \\
 &= v_f + xv_{fg}
 \end{aligned} \tag{3.1}$$

Where v_f - specific volume of the saturate liquid @ the given Pressure or Temperature

v_g - specific volume of sat. vapour @ the given Pressure or Temperature

x - dryness fraction.

Since $v_f \ll v_g$

$$V = v_f + xv_g \tag{3.2}$$

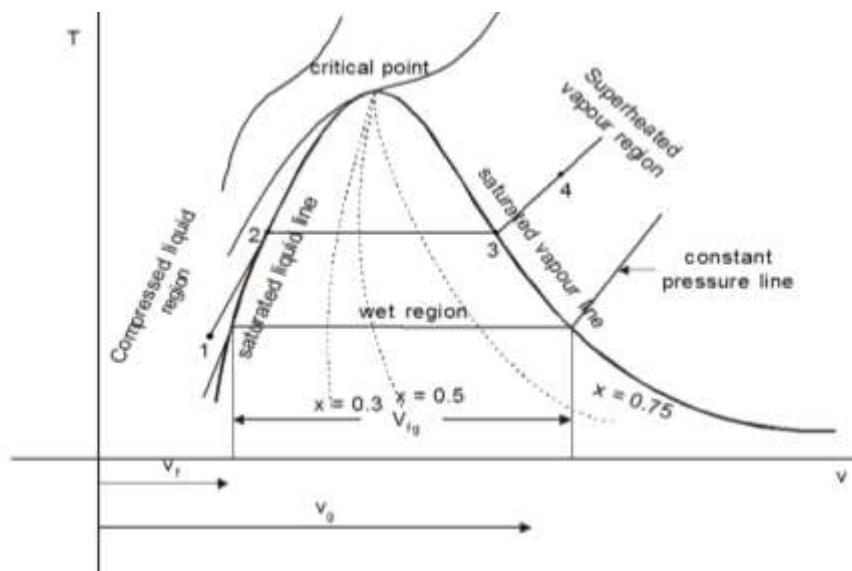


Figure 3.5: Shows all these lines and various regions on a T-v diagram

In the compressed liquid region, specific volume may be regarded as a function of temperature alone since the liquid is incompressible.

$$v = v_f @ \text{the given temperature.}$$

In the superheated region, v is function of both temperature and pressure.

3.3.3 T-s Diagram for a Pure Substance

Similar to T-v diagram, T-s diagram can also be drawn for a pure substance. Figure 7.5 shows various regions on a T-s diagram. The salient features of this diagram are:

- There are three distinct regions : to the left of the saturated liquid line is the liquid region, between saturated liquid and saturated vapour line is wet region, and to the right of saturated vapour line is superheated region
- Constant pressure lines coincide with the constant temperature lines in the wet region. These lines becomes curved in the superheated region
- Slope of the saturated liquid line is less compared to that in T-v diagram.

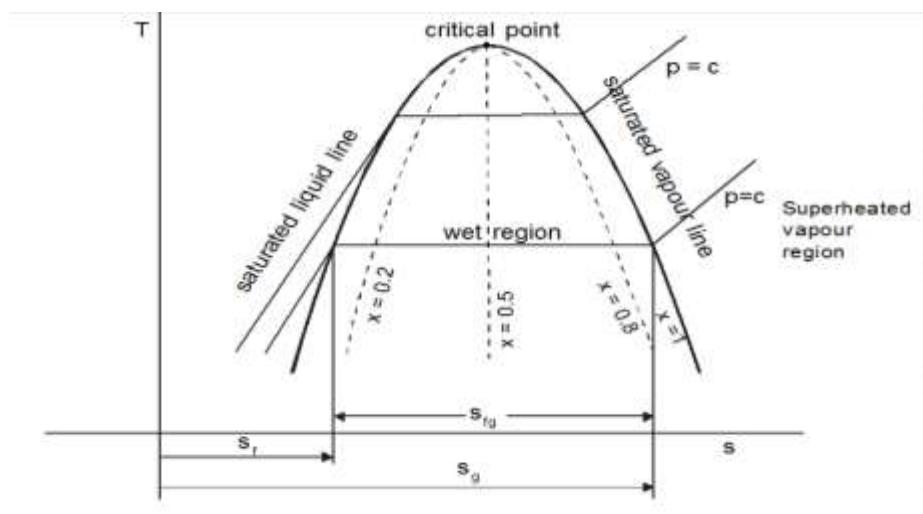


Figure 3.6: T -S Diagram of a Pure Substance

Entropy of a fluid at saturated liquid state $s = s_f$ @ the given p or T

For saturated vapour state

$$s = s_g \text{ @ the given } p, T$$

For Wet state

$$s = s_f + x s_{fg} \quad (3.3)$$

Where, s_f and s_{fg} are functions of p or T .

For superheated state

$$s = s(p, t)$$

For subcooled liquid

$$s = s_f + c_{pl} \ln \frac{T}{T_s} \quad (3.4)$$

Where, $s_f \rightarrow$ sat. liquid entropy @ the given pressure

c_{pl} → Liquid specific heat at the given temperature

T_s → Sat. temp. corresponding to the given pressure

T → Given Temperature.

3.3.4 h-s Diagram for a Pure Substance

Within the wet region both isobars and isotherms are the same, but beyond saturated vapour line they deviate. Also it can be noted that the constant pressure lines diverge from each other towards the super heated vapour region. In the super heated vapour region, slope of isotherms become almost zero. The slope of constant pressure curves at any point is a measure of temperature, by noting that.

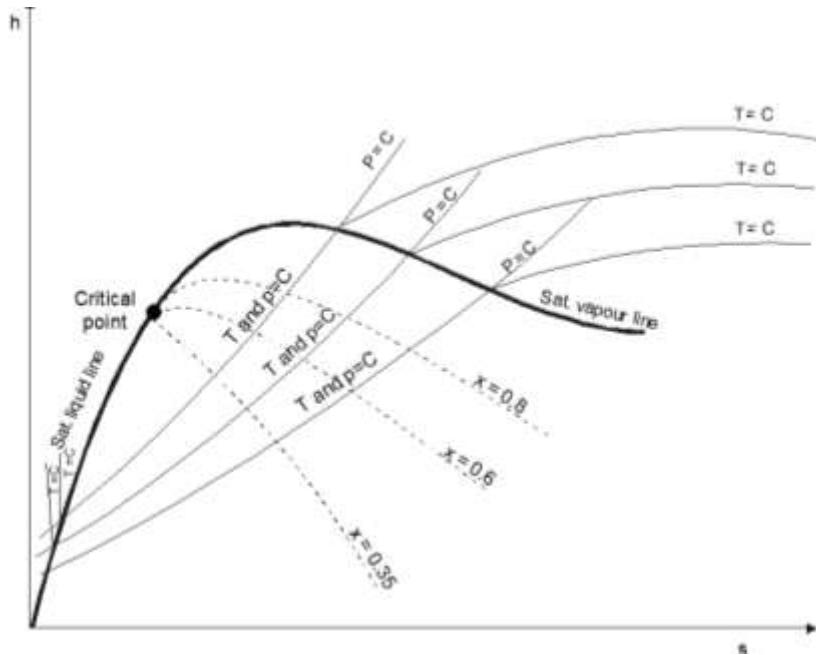


Figure 3.7: h - s Diagram of a Pure Substance

3.3.5 P-v Diagram Of A Pure Substance

Figure .9 shows the pv diagram of a pure substance. The saturated liquid and saturated-vapour curves meet at the critical point. The region to the left of the saturated-liquid line is compressed liquid, and the region to the right of the saturated-vapour line is superheated vapour. In between the two lines is the two-phase liquid-vapour region. Several isotherms are shown in the figure.

The critical isotherm has an inflection point and a zero slope at the critical point. Isotherms below the critical point experience two discontinuities in slope as they cross the saturated-liquid and saturated-vapour lines. In between these two lines, the slope of the isotherms is zero, and a state in this region can be entirely saturated liquid, entirely saturated vapour, or a combination of the two.

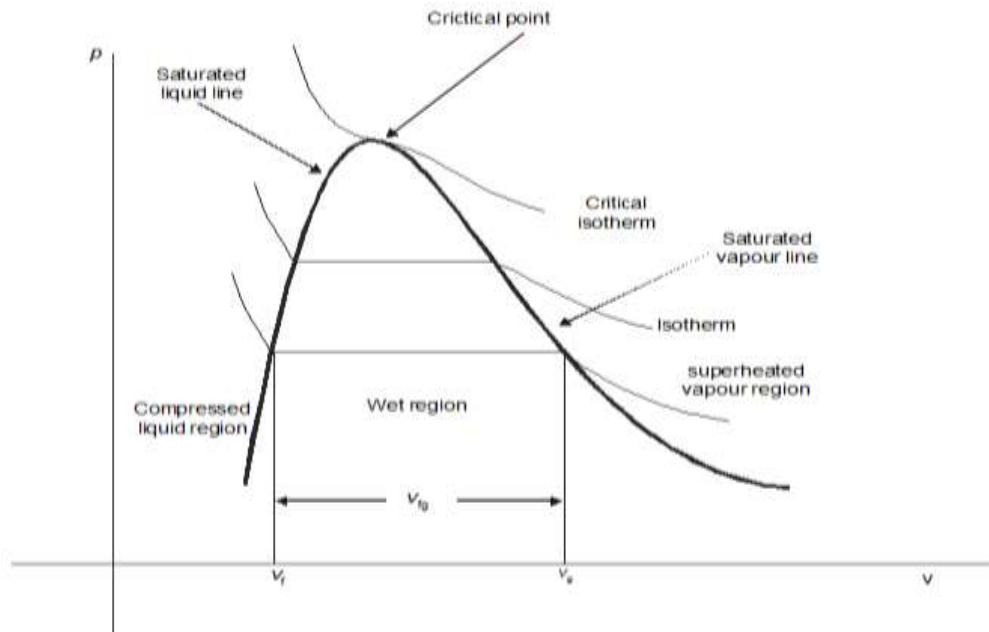


Figure 3.8 p - V Diagram of a Pure Substance

3.3.6 Extending p-v Diagram for a Pure Substance to Solid Phase

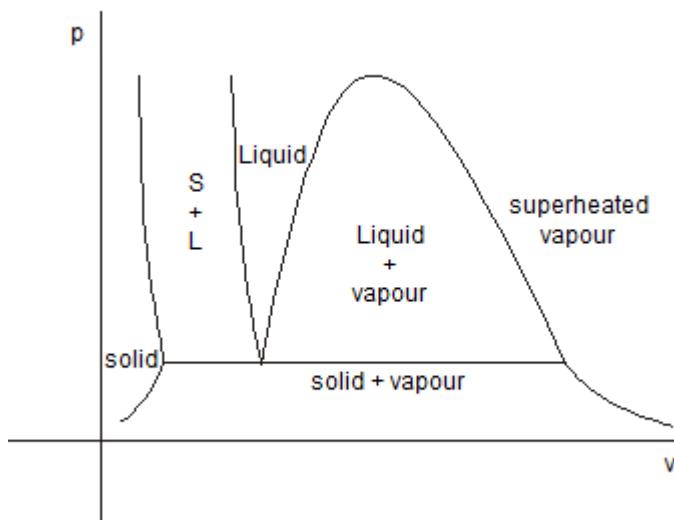


Figure 3.9a: Extending p-v Diagram for a Pure Substance to Solid Phase

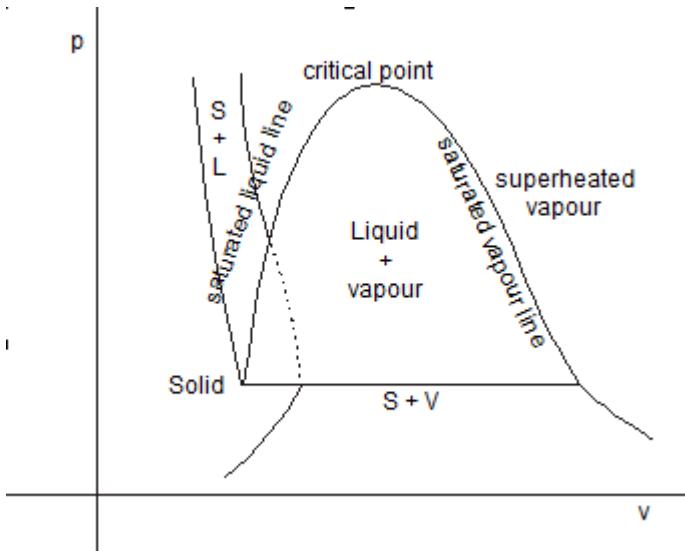


Figure 3.9b: Extending p-v Diagram for a Pure Substance to Solid Phase

Figure 3.9a shows various regions of pure substances on a p-v coordinates. Volume continuously increases from solid to super-heated vapour region. But for water volume decreases on melting and afterwards increases as shown Figure 7.8b.

3.3.7 p-V-T Surface

p-V-T behaviour of a pure substance can be expressed in a single three dimensional p-v-t surface as shown in the Figure 3.10(a). For water as its volume decreases on melting unlike other substances its p-v-t surface will be different from that of others as given in Figure 3.10(b).

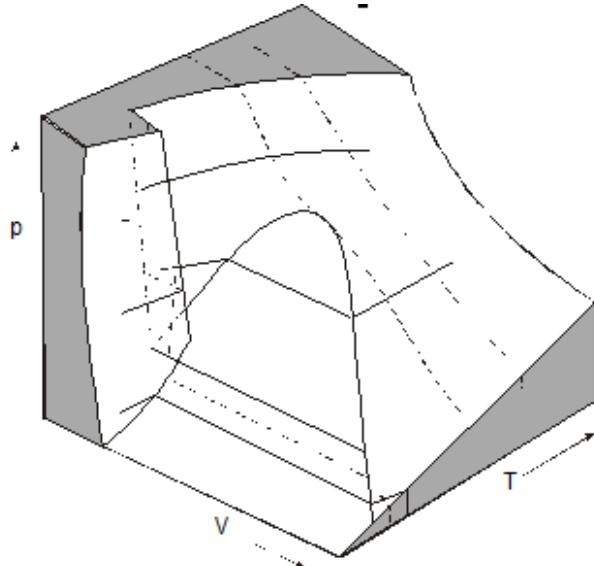


Figure 3.10 (a) P-V-T Surface for a substance that expands on freezing

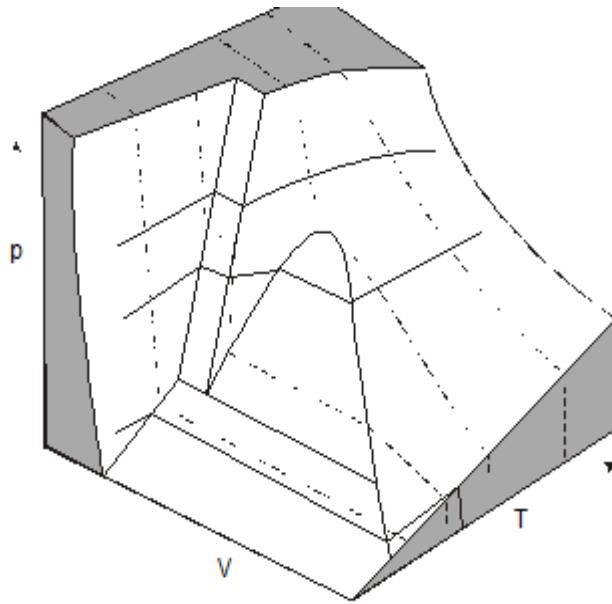


Figure 3.10 (b) P-V-T Surface for a substance that contracts on freezing

3.4 Thermodynamics Tables

As defined earlier to define the thermodynamic state of a given substance, any two independent intensive properties are sufficient. Once the state is fixed, all other properties can be computed. Tables giving the property values of saturated liquid and saturated vapour with respect temperature and pressure are available along with the properties of superheated steam. These tables can be made use of in the calculation of properties at any state. [See Appendix A1 & A2]

For refrigeration application, fluids like Ammonia and R134a are used. Properties of these fluids are also available in the form of tables. For refrigeration application, fluids like Ammonia and R134a are used. Properties of these fluids are also available in the form of tables.

3.4.1 Property Tables

In addition to the temperature, pressure, and volume data, Tables A-4 through A-8 contain the data for the specific internal energy u the specific enthalpy h and the specific entropy s . The enthalpy is a convenient grouping of the internal energy, pressure, and volume and is given by

$$H = U + PV \quad (3.8)$$

The enthalpy per unit mass is

$$h = u + Pv \quad (3.9)$$

We will find that the enthalpy h is quite useful in calculating the energy of mass streams flowing

into and out of control volumes. The enthalpy is also useful in the energy balance during a constant pressure process for a substance contained in a closed piston-cylinder device. The enthalpy has units of energy per unit mass, kJ/kg. The entropy s is a property defined by the second law of thermodynamics and is related to the heat transfer to a system divided by the system temperature; thus, the entropy has units of energy divided by temperature. The concept of entropy is explained in Chapters 6 and 7.

3.4.2 Saturated Water Tables

Since temperature and pressure are dependent properties using the phase change, two tables are given for the saturation region. Table A-4 has temperature as the independent property; Table A-5 has pressure as the independent property. These two tables contain the same information and often only one table is given.

For the complete Table A-4, the last entry is the critical point at 373.95 °C.

TABLE A-4

Saturated water-Temperature table

Temp, $T^{\circ}\text{C}$	Sat. Press., $P_{\text{sat}} \text{ kPa}$	Specific volume, m^3/kg		Internal energy, kJ/kg		Enthalpy, kJ/kg		Entropy, $\text{kJ/kg}\text{K}$	
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_g	Sat. liquid, h_f	Evap., h_g	Sat. vapor, s_f	Evap., s_g
0.01	0.6117	0.001000	206.00	0.00	2374.9	2374.9	0.00	2500.9	2500.9
5	0.8725	0.001000	147.03	21.02	2360.8	2381.8	21.02	2489.1	2510.1
10	1.228	0.001000	106.32	42.02	2346.6	2388.7	42.02	2477.2	2519.2
15	1.706	0.001001	77.885	62.98	2332.5	2395.5	62.98	2465.4	2528.3
20	2.339	0.001002	57.762	83.91	2318.4	2402.3	83.91	2453.5	2537.4
25	3.170	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5
30	4.247	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6
								0.3672	8.1895
								0.4368	8.0152
									8.4520

TABLE A-5
Saturated water-Pressure table

Press. P kPa	Sat. Temp. T_s °C	Specific volume, m³/kg			Internal energy, kJ/kg		Enthalpy, kJ/kg			Entropy, kJ/kg·K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.6117	0.01	0.001000	206.00	0.00	2374.9	2374.9	0.00	2500.9	2500.9	0.0000	9.1556	9.1556
1.0	6.97	0.001000	129.19	29.30	2355.2	2384.5	29.30	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.69	2338.1	2392.8	54.69	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.43	2325.5	2398.9	73.43	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.42	2315.4	2403.8	88.42	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765

For the complete Table A-5, the last entry is the critical point at 22.064 MPa.

Saturation pressure is the pressure at which the liquid and vapor phases are in equilibrium at a given temperature.

Saturation temperature is the temperature at which the liquid and vapor phases are in equilibrium at a given pressure.

The subscript **fg** used in Tables A-4 and A-5 refers to the difference between the saturated vapor value and the saturated liquid value region. That is,

$$u_{fg} = u_g - u_f$$

$$h_{fg} = h_g - h_f$$

$$s_{fg} = s_g - s_f$$

The quantity h_{fg} is called the enthalpy of vaporization (or latent heat of vaporization). It represents the amount of energy needed to vaporize a unit of mass of saturated liquid at a given temperature or pressure. It decreases as the temperature or pressure increases, and becomes zero at the critical point.

3.4.3 Quality and Saturated Liquid-Vapor Mixture

Now, let's review the constant pressure heat addition process for water shown in Figure 2-3

(page 26). Since state 3 is a mixture of saturated liquid and saturated vapor, how do we locate it on the T-v diagram? To establish the location of state 3 a new parameter called the quality x is defined as:

$$x = \frac{\text{mass of saturated vapor}}{\text{total mass}} = \frac{m_g}{m_f + m_g}$$

The quality is zero for the saturated liquid and one for the saturated vapor ($0 \leq x \leq 1$). The average specific volume at any state 3 is given in terms of the quality as follows. Consider a mixture of saturated liquid and saturated vapor. The liquid has a mass m_f and occupies a volume V_f . The vapor has a mass m_g and occupies a volume V_g .

We note

$$V = V_f + V_g$$

$$m = m_f + m_g$$

$$V = mv, \quad V_f = m_f v_f, \quad V_g = m_g v_g$$

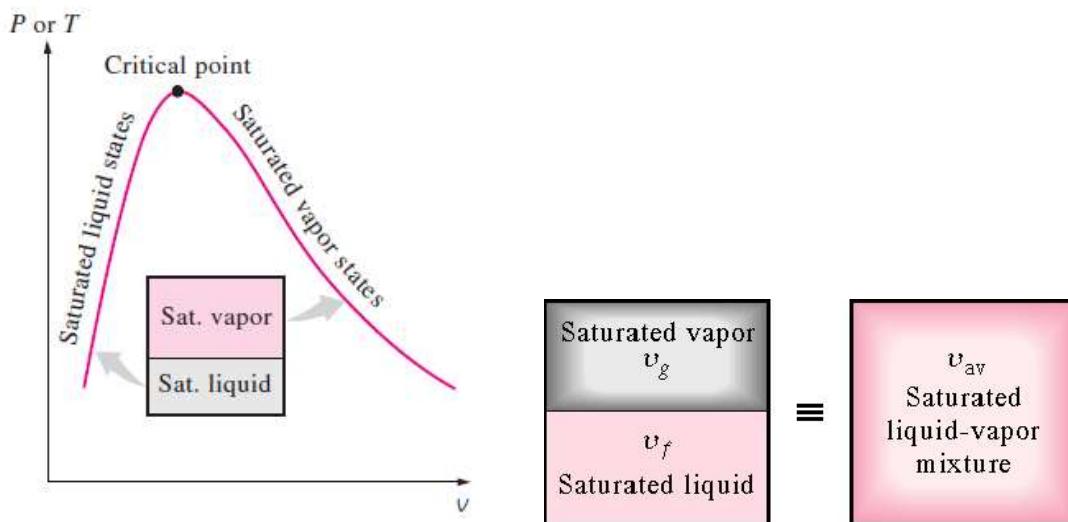


Figure 3.11: The relative amounts of liquid and vapor phases in a saturated mixture are specified by the *quality* x .

$$mv = m_f v_f + m_g v_g$$

$$v = \frac{m_f v_f}{m} + \frac{m_g v_g}{m}$$

Using the definition of the quality x



$$x = \frac{m_g}{m} = \frac{m_g}{m_f + m_g}$$

Then

$$\frac{m_f}{m} = \frac{m - m_g}{m} = 1 - x$$

Note, quantity $1 - x$ is often given the name moisture. The specific volume of the saturated mixture becomes

$$v = (1 - x) v_f + x v_g$$

The form that we use most often is

$$v = v_f + x (v_g - v_f)$$

It is noted that the value of any extensive property per unit mass in the saturation region is calculated from an equation having a form similar to that of the above equation. Let Y be any extensive property and let y be the corresponding intensive property, Y/m , then

$$y = \frac{y}{m} = y_f + x(y_g - y_f)$$

$$y = y_f + x y_{fg}$$

$$\text{where } y_{fg} = y_g - y_f$$

The term y_{fg} is the difference between the saturated vapor and the saturated liquid values of the property y ; y may be replaced by any of the variables v , u , h , or s .

We often use the above equation to determine the quality x of a saturated liquid-vapor state.

The following application is called

the Lever Rule:

$$x = \frac{y - y_f}{y_{fg}}$$

The Lever Rule is illustrated in the following figures.

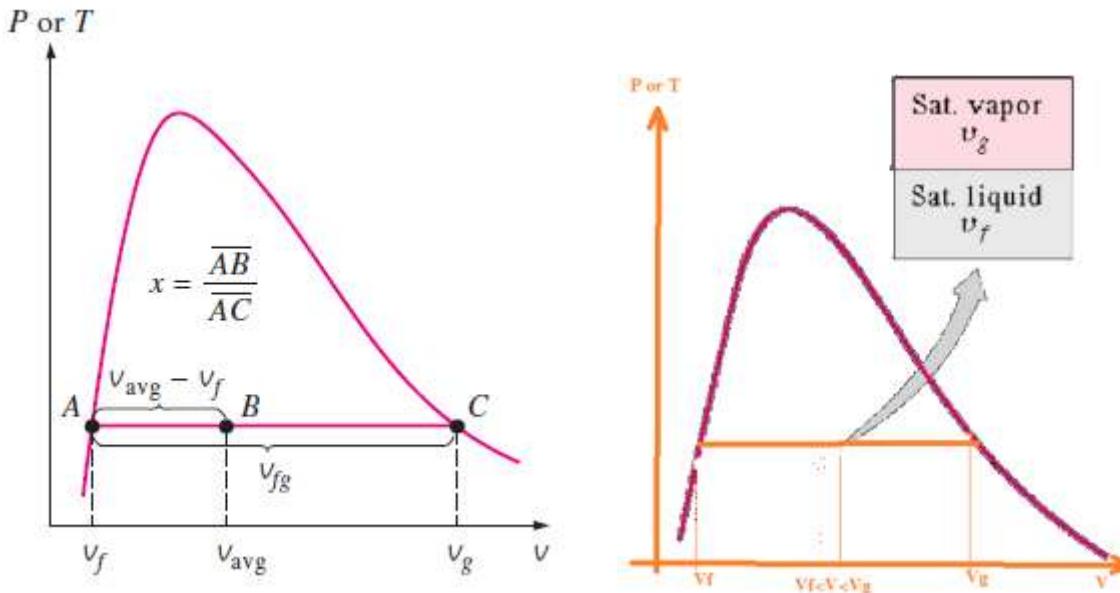


Figure 3.12 Lever Rule is illustration

3.4.4 Superheated Water Table

A substance is said to be superheated if the given temperature is greater than the saturation temperature for the given pressure. State 5 in Figure 3-3 (page 26) is a superheated state.

In the superheated water Table A-6, T and P are the independent properties. The value of temperature to the right of the pressure is the saturation temperature for the pressure. The first entry in the table is the saturated vapor state at the pressure.

TABLE A-6 Superheated water

T °C	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg-K
<i>P = 0.01 MPa (45.81°C)</i>				
Sat.	14.670	2437.2	2583.9	8.1488
50	14.867	2443.3	2592.0	8.1741
100	17.196	2515.5	2687.5	8.4489
150	19.513	2587.9	2783.0	8.6893
200	21.826	2661.4	2879.6	8.9049
250	24.136	2736.1	2977.5	9.1015
300	26.446	2812.3	3076.7	9.2827

T °C	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg-K
<i>P = 0.05 MPa (81.32°C)</i>				
Sat.	3.2403	2483.2	2645.2	7.5931
100	3.4187	2511.5	2682.4	7.6953
150	3.8897	2585.7	2780.2	7.9413
200	4.3562	2660.0	2877.8	8.1592
250	4.8206	2735.1	2976.2	8.3568
300	5.2841	2811.6	3075.8	8.5387

3.4.5 Compressed Liquid Water Table

A substance is said to be a compressed liquid when the pressure is greater than the saturation pressure for the temperature. It is now noted that state 1 in Figure 2-3 (page 26) is called a compressed liquid state because the saturation pressure for the temperature T_1 is less than P_1 . Data for water compressed liquid states are found in the compressed liquid tables, Table A-7. Table A-7 is arranged like Table A-6, except the saturation states are the saturated liquid states. Note that the data in Table A-7 begins at 5 MPa or 50 times atmospheric pressure.

TABLE A-7 Compressed liquid water

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s $\text{kJ/kg}\cdot\text{K}$
$P = 5 \text{ MPa} (263.94^\circ\text{C})$				
Sat.	0.0012862	1148.1	1154.5	2.9207
0	0.0009977	0.04	5.03	0.0001
20	0.0009996	83.61	88.61	0.2954
40	0.0010057	166.92	171.95	0.5705
60	0.0010149	250.29	255.36	0.8287

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s $\text{kJ/kg}\cdot\text{K}$
$P = 10 \text{ MPa} (311.00^\circ\text{C})$				
Sat.	0.0014522	1393.3	1407.9	3.3603
0	0.0009952	0.12	10.07	0.0003
20	0.0009973	83.31	93.28	0.2943
40	0.0010035	166.33	176.37	0.5685
60	0.0010127	249.43	259.55	0.8260

At pressures below 5 MPa for water, the data are approximately equal to the saturated liquid data at the given Temperature. We approximate intensive parameter y , that is v , u , h , and s data as

$$y \cong y_{f@T}$$

The enthalpy is more sensitive to variations in pressure; therefore, at high pressures the enthalpy can be approximated by

$$h \cong h_{f@T} + v_f (P - P_{sat})$$

For our work, the compressed liquid enthalpy may be approximated by

$$h \cong h_{f@T}$$

3.4.6 Saturated Ice-Water Vapor Table

When the temperature of a substance is below the triple point temperature, the saturated solid and liquid phases exist in equilibrium. Here we define the quality as the ratio of the mass that is

vapor to the total mass of solid and vapor in the saturated solid-vapor mixture. The process of changing directly from the solid phase to the vapor phase is called sublimation. Data for saturated ice and water vapor are given in Table A-8. In Table A-8, the term **Subl.** refers to the difference between the saturated vapor value and the saturated solid value.

TABLE A-8
Saturated ice-water vapor

Temp., <i>T</i> °C	Sat. Press., <i>P_{sat}</i> kPa	Specific volume, m ³ /kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg-K		
		Sat. ice, <i>v_i</i>	Sat. vapor, <i>v_g</i>	Sat. ice, <i>u_i</i>	Subl., <i>u_{ig}</i>	Sat. vapor, <i>u_g</i>	Sat. ice, <i>h_i</i>	Subl., <i>h_{ig}</i>	Sat. vapor, <i>h_g</i>	Sat. ice, <i>s_i</i>	Subl., <i>s_{ig}</i>	Sat. vapor, <i>s_g</i>
0.01	0.6117	0.0010909	206.0	-333.40		2374.5	-333.40		2500.5	-1.220		9.154
0	0.6112	0.0010909	206.2	-333.43	2707.9	2374.5	-333.43	2833.9	2500.5	-1.220	10.375	9.154
-2	0.5177	0.0010905	241.6	-337.63	2709.4	2371.8	-337.63	2834.5	2496.8	-1.236	10.453	9.218
-4	0.4375	0.0010902	283.8	-341.80	2710.8	2369.0	-341.80	2835.0	2493.2	-1.251	10.533	9.282
-6	0.3687	0.0010898	334.3	-345.94	2712.2	2366.2	-345.93	2835.4	2489.5	-1.267	10.613	9.347
-8	0.3100	0.0010895	394.7	-350.04	2713.5	2363.5	-350.04	2835.8	2485.8	-1.282	10.695	9.413
-10	0.2599	0.0010892	467.2	-354.12	2714.8	2360.7	-354.12	2836.2	2482.1	-1.298	10.778	9.480
-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-
-36	0.0200	0.0010850	5460.1	-404.40	2729.0	2324.6	-404.40	2838.4	2434.0	-1.499	11.969	10.470
-38	0.0161	0.0010847	6750.5	-408.07	2729.9	2321.8	-408.07	2838.4	2430.3	-1.514	12.071	10.557
-40	0.0128	0.0010844	8376.7	-411.70	2730.7	2319.0	-411.70	2838.3	2426.6	-1.530	12.174	10.644

The specific volume, internal energy, enthalpy, and entropy for a mixture of saturated ice and saturated vapor are calculated similarly to that of saturated liquid-vapor mixtures.

$$y_{ig} = y_g - y_i$$

$$y = y_i + x \cdot y_{ig}$$

where the quality *x* of a saturated ice-vapor state is

$$x = \frac{m_g}{m_i + m_g}$$

3.4.7 How to Choose the Right Table

The correct table to use to find the thermodynamic properties of a real substance can always be determined by comparing the known state properties to the properties in the saturation region.



Given the temperature or pressure and one other property from the group v , u , h , and s , the following procedure is used. For example if the pressure and specific volume are specified, three questions are asked: For the given pressure,

$$\text{is } v < v_f ?$$

$$\text{is } v_f < v < v_g ?$$

$$\text{is } v > v_g ?$$

The answer to one of these questions must be yes. If the answer to the first question is yes, the state is in the compressed liquid region, and the compressed liquid tables are used to find the properties of the state. If the answer to the second question is yes, the state is in the saturation region, and either the saturation temperature table or the saturation pressure table is used to find the properties. Then the quality is calculated and is used to calculate the other properties, u , h , and s . If the answer to the third question is yes, the state is in the superheated region and the superheated tables are used to find the other properties.

Some tables may not always give the internal energy. When it is not listed, the internal energy is calculated from the definition of the enthalpy as

$$u = h - Pv$$

3.5 Equations of state

The tables with which we have been working provide an accurate relationship between temperature, pressure and other important thermodynamic properties. If we restrict consideration to only the vapor state, then we may often find a simple algebraic relationship between temperature, pressure and specific volume; such a **relationship** is called **an equation of state**.

For gases at low pressure it has been observed that pressure, P , is directly proportional to temperature, T , (this is known as Charles' law) and inversely proportional to specific volume, v (Boyle's law).

$$P = R \cdot \frac{T}{v}$$

Here, R is known as the gas constant.



It is further found that there is a relationship between the various gas constants and the molecular weight of the particular gas. Specifically, it is found that the product of the gas constant and the gas molecular weight yields the same constant for all gases. This product is known as the **Universal Gas Constant**.

Therefore, the gas constant for a specific (R) gas is equal to:

$$R = \frac{R_u}{M}$$

The Universal gas constant is considered a fundamental constant, similar to the gravitational constant. $R_u = 8.314 \text{ kJ/kmol K}$

Alternate forms of the ideal gas law:

$$P \cdot v = R \cdot T$$

$$P \cdot V = m \cdot R \cdot T$$

$$P = \rho \cdot R \cdot T$$

$$P \cdot V = N \cdot R_u \cdot T$$

Remember that: mass (m) = Number of moles (N) \times Molecular Mass (M)

Following the ideal gas law, for a process form (1) to (2), we can write:

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

3.5.1 Compressibility Factor: A measure of deviation from ideal-gas behavior.

It was stated previously that the ideal gas law is valid for low pressure. The question is, “what is low”? One way to approach this question is through the compressibility factor, defined as follows:

$$Z = \frac{P \cdot v}{R \cdot T}$$

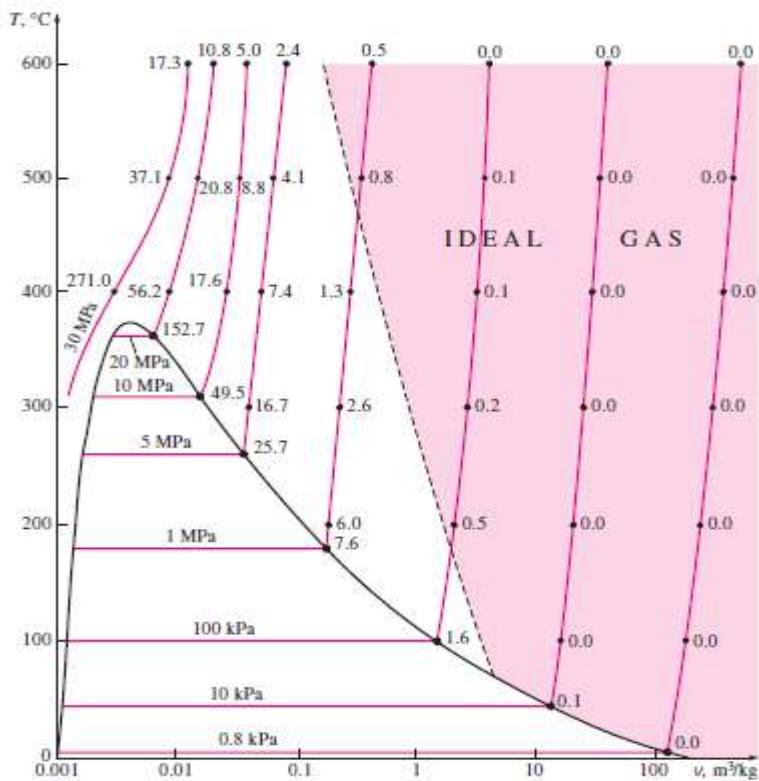


Figure 3.13 Percentage of error ($(|V_{\text{table}} - V_{\text{ideal}}|/V_{\text{table}}) \times 100$) involved in assuming steam to be an ideal gas, and the region where steam can be treated as an ideal gas with less than 1 percent error.

For an ideal gas, $Z = 1$. As the compressibility factor deviates from 1, the gas may be considered to be increasingly non-ideal.

In attempting to make a general characterization of many gases, it has proven useful to try to put the phase diagrams for many gases together. In order to “normalize” the graphs, we introduce a normalized pressure and temperature:

$$P_r = \frac{P}{P_{\text{critical}}} \quad T_r = \frac{T}{T_{\text{critical}}}$$

The critical temperature and pressure of several gases are tabulated in tables. The ratio of the vapor pressure to the critical pressure for the same gas and the temperature to the critical temperature for the same gas is termed the reduced pressure and reduced temperature, respectively.

The figure below represents the compressibility factor, Z , as a function of the reduced pressure, P_R , for various reduced temperatures, T_R .

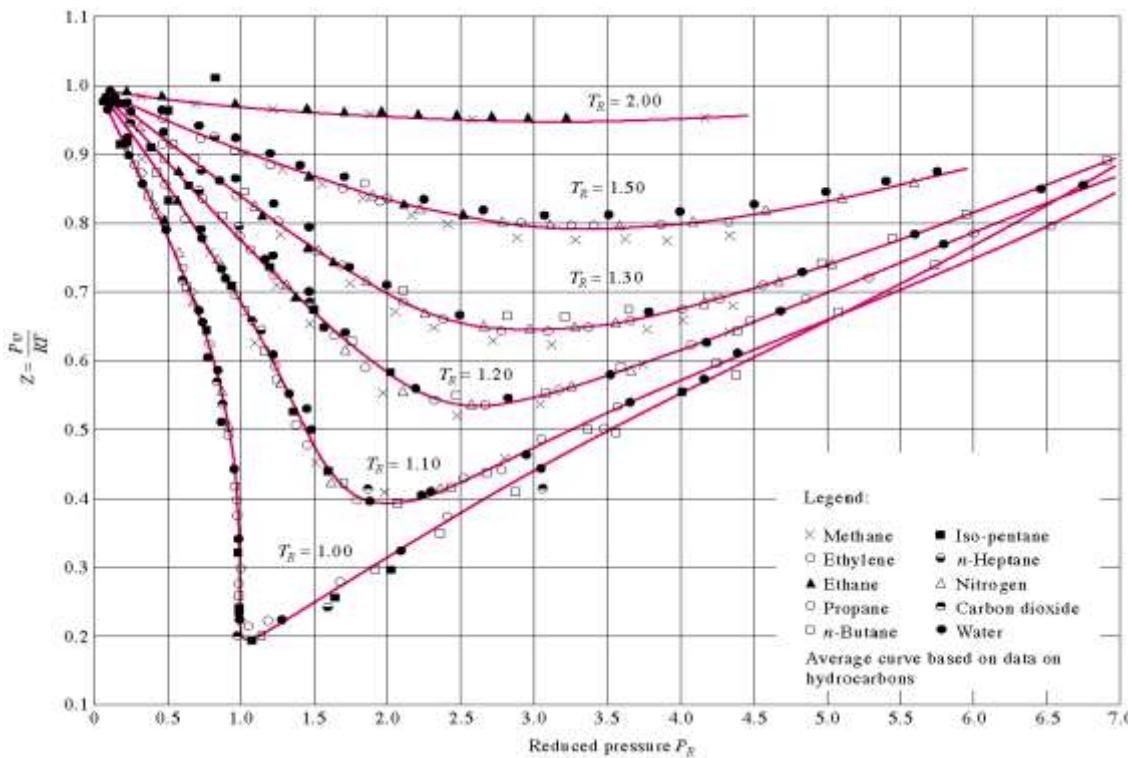


Figure 3.14: Compressibility factor as a function of reduced pressure and reduced temperature.

The worst correlation for the ideal gas law is near the critical point, i.e. $P_R = 1$ and $T_R = 1$.

These charts show the conditions for which $Z = 1$ and the gas behaves as an ideal gas:

Important →

1- $P_R < 10$ and $T_R > 2$
2- $P_R \ll 1$

Note 1: When P_R is small, we must make sure that the state is not in the **compressed liquid region** for the given temperature. A compressed liquid state is certainly not an ideal gas state.

Note 2: The fact that gases behave as ideal gases when the reduced temperature is greater than 2, $T_R > 2$, is the most commonly encountered. Consider the boiling point of several gases, taken from Tables A-1 and A-1E, shown below:

Substance	Critical Temperature
Argon	151K
Helium	5.3K
Hydrogen	33.3K
Nitrogen	126.2K
Oxygen	154.8K

We think of each of these substances as gases because the maximum temperatures at which they are liquids are very low, far below temperatures normally encountered in nature. For that reason, it is common in nature that the $T_c > T_R$ for these substances and they can be treated as ideal gases.

The Tables for fluid properties provided in the appendix of the textbook will always provide the most accurate means of determining fluid properties. However, for fluids for which tables are not available it may prove sufficiently accurate to use the ideal gas law as corrected by the compressibility factor. It is the general applicability of the compressibility factor to all gases at all temperatures and pressures that makes the concept such a powerful tool.

3.5.2 Other Equations of State

A simple, accurate equation of state has long been desired in engineering practice. The wide spread use of computer programs in engineering has increased the need for such an equation. Obviously, virtually any algebraic equation, either implicit or explicit, would be easier to program and solve than trying to work with something so cumbersome as the vapor tables. When the program must deal with a variety of fluids, the impetus is increased even more.

3.5.2.1 Van der Waals equation

Van der Waals examined the ideal gas equation and concluded that it failed near the critical point because it failed to fully account for the attraction forces between molecules and molecular volume. Molecular repulsive forces in gases are generally quite small. Since these forces drop rapidly as the molecules move apart, it is only at very high pressure, when molecules are unusually close together, that such forces are significant. Similarly, gaseous molecules are often widely spaced and do not physically occupy a large fraction of the space in which they exist. At very high pressures, these molecules are forced together and their volume may become significant. Van der Waals proposed the model:

$$\left(P + \frac{a}{v^2} \right) (v - b) = R \cdot T$$

where the constant **a** accounts for the repulsion between molecules and increases the forces between them. The constant **b** accounts for the volume physically occupied by molecules and decreases the effective open volume. Numerical values of a & b can be calculated as follows:

$$a = \frac{27 \cdot R^2 \cdot T_{critical}^2}{64 \cdot P_{critical}} \quad b = \frac{R \cdot T_{critical}}{8 \cdot P_{critical}}$$

3.5.2.2 Beattie-Bridgeman equation

The Beattie Bridgemen Equation of State represents another attempt, patterned after the approach used by Van der Waals, to improve the accuracy of the ideal gas law by accounting for repulsion forces and the volume of the gaseous molecules. While the algebraic form is also slightly different, the major difference is that the constants, corresponding to a & b, are obtained experimentally for the particular gas. While accuracy is improved the model can only be applied to gases for which data is available.

$$P = \frac{R_U T}{\bar{v}^2} \left(1 - \frac{c}{\bar{v} T^3} \right) (\bar{v} + B) - \frac{A}{\bar{v}^2}$$

Where

$$A = A_0 \left(1 - \frac{a}{\bar{v}} \right) \text{ and } B = B_0 \left(1 - \frac{b}{\bar{v}} \right)$$

The constants are given in specific tables for various substances.

3.5.2.3 Benedict-Webb-Rubin equation

This represents a more recent attempt to improve on the Van der Waals equation by introducing a more complicated model with additional experimental constants. Again, it is successful in improving accuracy but continues to be limited by available data.

3.5.2.4 Virial equation

This represents an alternate means of improving the Van der Waals equation of state, this time using an infinite series to represent the dependence of temperature and specific volume on pressure.



$$P = \frac{RT}{v} + \frac{B(T)}{v^2} + \frac{C(T)}{v^3} + \dots$$

SOLVED PROBLEMS:

Example 3-1: Saturated Liquid and Saturated Vapor

A rigid tank contains 50 kg of saturated liquid water at 90°C. Determine the pressure in the tank and the volume of the tank. (Table A-4)

(Answers: 70.14 kPa, 0.0518 m³)

Example 2-3: Saturated Liquid and Saturated Vapor

A mass of 200 g of saturated liquid water is completely vaporized at a constant pressure of 75 kPa. Determine (a) the volume change and (b) the amount of energy added to the water.

(Answers: 0.4439 m³, 455.72 kJ)

Example 2-4: Saturated Liquid-vapor mixture (continued)

A rigid tank contains 10 kg of water at 90°C. If 8 kg of water is in the liquid form and the rest is in the vapor form, determine (a) the pressure in the tank and (b) the volume of the tank.

(Answers: 70.14 kPa, 4.73 m³)

Example 2-5: Saturated Liquid-vapor mixture (continued)

An 80-L vessel contains 4 kg of refrigerant 134a at a pressure of 160 kPa. Determine a) the temperature of the refrigerant, b) the quality, c) the enthalpy of the refrigerant, and d) the volume occupied by the vapor phase.

(Answers: -15.62°C, 0.158, 62.7 kJ/kg, 0.0777 m³)

Example 2-6: Superheated Vapor

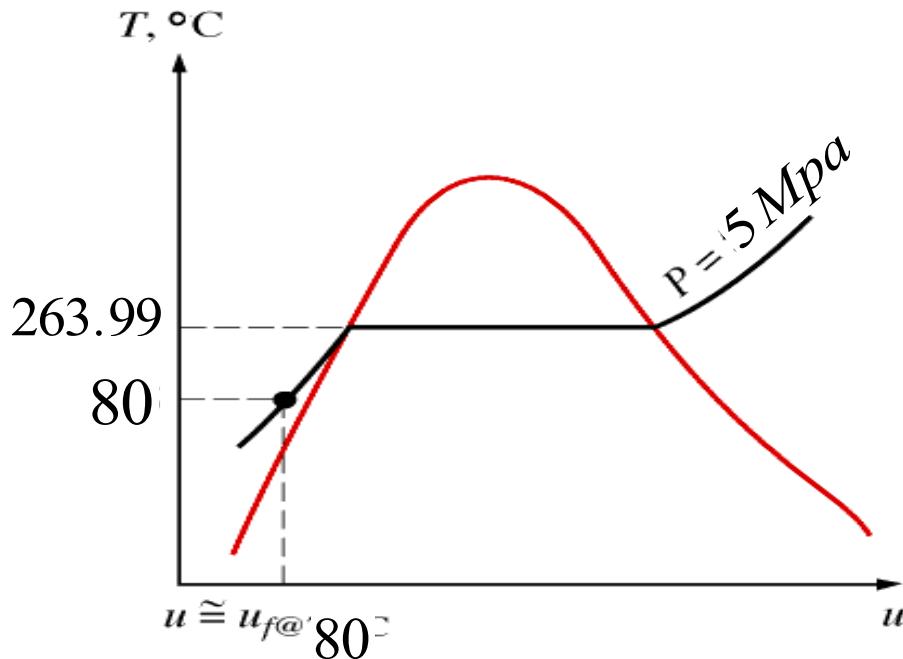
Determine the temperature of water at a state of P = 0.5 MPa and h = 2890 kJ/kg.

(Answers: 216.4 °C)

Example 2-7: Example on Compressed Liquid

Determine the internal energy of compressed liquid water at 80°C and 5 MPa using (a) data from the compressed liquid table and (b) saturated liquid data. What is the error involved in the second

case? (Answers: 333.72 kJ/kg, 334.86 kJ/kg, 0.34%)



Exercise

1. Is iced water a pure substance? Why?
2. What is the difference between saturated liquid and compressed liquid?
3. What is the difference between saturated vapor and superheated vapor?
4. Is there any difference between the intensive properties of saturated vapor at a given temperature and the vapor of a saturated mixture at the same temperature?
5. Is there any difference between the intensive properties of saturated liquid at a given temperature and the liquid of a saturated mixture at the same temperature?
6. Is it true that water boils at higher temperatures at higher pressures? Explain.
7. If the pressure of a substance is increased during a boiling process, will the temperature also increase or will it remain constant? Why?
8. Why are the temperature and pressure dependent properties in the saturated mixture region?
9. What is the difference between the critical point and the triple point?
10. A 400-L rigid tank contains 5 kg of air at 25°C. Determine the reading on the pressure gage if the atmospheric pressure is 97 kPa.

-
11. Does the amount of heat absorbed as 1 kg of saturated liquid water boils at 100°C have to be equal to the amount of heat released as 1 kg of saturated water vapor condenses at 100°C?
 12. What is the physical significance of h_{fg} ? Can it be obtained from a knowledge of h_f and h_g ? How?
 13. In the absence of compressed liquid tables, how is the specific volume of a compressed liquid at a given P and T determined?
 14. Use of Steam Table to Determine Properties
 15. Determine the missing properties and the phase descriptions in the following table for water.

$T, ^\circ\text{C}$	P, kPa	$U, \text{kJ/kg}$	x	Phase description
(a)	200		0.6	
(b)	125	1600		
(c)		1000	2950	
(d)	75	500		
(e)		850	0.0	

15. The temperature in a pressure cooker during cooking at sea level is measured to be 250°F. Determine the absolute pressure inside the cooker in psia and in atm. Would you modify your answer if the place were at a higher elevation?



FIGURE P15

16. The atmospheric pressure at a location is usually specified at standard conditions, but it changes with the weather conditions. As the weather forecasters frequently state, the atmospheric pressure drops during stormy weather and it rises during clear and sunny days. If the pressure difference between the two extreme conditions is given to be 0.3 in of mercury, determine how much the boiling temperatures of water will vary as the weather changes from one extreme to the other.

17. A person cooks a meal in a 30-cm-diameter pot that is covered with a well-fitting lid and lets the food cool to the room temperature of 20°C. The total mass of the food and the pot is 8 kg. Now the person tries to open the pan by lifting the lid up. Assuming no air has leaked into the pan during cooling, determine if the lid will open or the pan will move up together with the lid.

18. Water is to be boiled at sea level in a 30-cm-diameter stainless steel pan placed on top of a 3-kW electric burner. If



FIGURE P18

19. Repeat Prob. 18 for a location at an elevation of 1500 m where the atmospheric pressure is 84.5 kPa and thus the boiling temperature of water is 95°C.

20. Water is boiled at 1 atm pressure in a 25-cm-internal-diameter stainless steel pan on an electric range. If it is observed that the water level in the pan drops by 10 cm in 45 min, determine the rate of heat transfer to the pan.

21. Repeat Prob. 20 for a location at 2000-m elevation where the standard atmospheric pressure is 79.5 kPa.

22. Saturated steam coming off the turbine of a steam power plant at 30°C condenses on the outside of a 3-cm-outer-diameter, 35-m-long tube at a rate of 45 kg/h. Determine the rate of heat transfer from the steam to the cooling water flowing through the pipe.

23. The average atmospheric pressure in Denver (elevation = 1610 m) is 83.4 kPa. Determine the temperature at which water in an uncovered pan boils in Denver.

Answer: 94.6°C

24. Water in a 5-cm-deep pan is observed to boil at 98°C. At what temperature will the water in a 40-cm-deep pan boil? Assume both pans are full of water.

25. A cooking pan whose inner diameter is 20 cm is filled with water and covered with a 4-kg lid. If the local atmospheric pressure is 101 kPa, determine the temperature at which the water starts boiling when it is heated.

Answer: 100.2°C

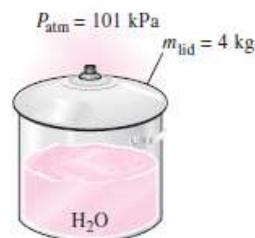


FIGURE P25

26. Reconsider Prob. 25. Using EES (or other) software, investigate the effect of the mass of the lid on the boiling temperature of water in the pan. Let the mass vary from 1 kg to 10 kg. Plot the boiling temperature against the mass of the lid, and discuss the results.

27. Water is being heated in a vertical piston–cylinder device. The piston has a mass of 20 kg and a cross-sectional area of 100 cm². If the local atmospheric pressure is 100 kPa, determine the temperature at which the water starts boiling.

CHAPTER FOUR

THE FIRST LAW OF THERMODYNAMICS

Energy interactions between a system and its surroundings across the boundary in the form of heat and work have been discussed separately in the previous chapter two. We have considered various forms of energy such as heat Q , work W , and total energy E individually, and no attempt is made to relate them to each other during a process. First law of thermodynamics often called as law of conservation of energy, relating work, heat, and energy content of the system will be discussed in detail in this chapter.

4.1 First Law of Thermodynamics

In its more general form, the first law may be stated as follows

“When energy is either transferred or transformed, the final total energy present in all forms must precisely equal the original total energy”.

This statement, which is largely based on the experiments of Joule in the first half of the nineteenth century, cannot be drawn from any other known physical principle and is recognized as a fundamental principle.

4.2 First Law of Thermodynamics for a Closed System

Undergoing a Process

The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process. That is,

$$\left[\begin{array}{l} \text{Energy entered} \\ \text{into the system} \end{array} \right] + \left[\begin{array}{l} \text{Energy left} \\ \text{the system} \end{array} \right] = \left[\begin{array}{l} \text{Change in the energy} \\ \text{content of the system} \end{array} \right] \quad (4.1)$$

For a system of constant mass, energy can enter or leave the system only in two forms namely work and heat. Let a closed system of initial energy E_1 receives Q units of net heat and gives out W units of work during a process. If E_2 is energy content at the end of the process as given in Figure 4.1, applying first law we get

$$Q - W = (E_2 - E_1) \quad (4.2)$$

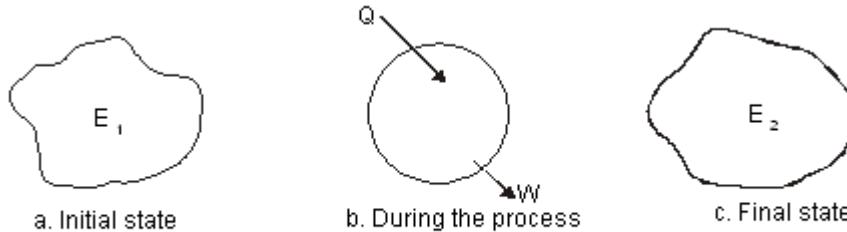


Figure 4.1 First Law for a closed system

Energy is a fundamental concept of thermodynamics and one of the most significant aspects of engineering analysis. Energy can be stored within systems in various macroscopic forms: kinetic energy, gravitational potential energy, and internal energy. Energy can also be transformed from one form to another and transferred between systems. For closed systems, energy can be transferred by work and heat transfer. The total amount of energy is conserved in all transformations and transfers.

$$\begin{aligned} E &= \text{Internal Energy} + \text{Kinetic energy} + \text{Potential energy} \\ &= U + \frac{1}{2} \frac{mC^2}{g_c} + mgz \end{aligned}$$

The term internal energy usually denoted by the letter U is the energy due to such factors as electron spin and vibrations, molecular motion and chemical bond. Kinetic energy term is due to the system movement with a velocity C. For stationary systems this term will be zero. The term g_c (gravitational constant) is a constant of value 1 in SI unit. It will be dropped here after since SI unit is followed throughout the book. Potential energy term is due to the location of the system in the gravitational field. It remains constant for a stationary system. The unit of energy in SI is kJ.

4.3 The Thermodynamic Property Enthalpy

Consider a stationary system of fixed mass undergoing a quasi-equilibrium constant pressure process

Applying first law

$$Q_{12} - P_1 V_2 = E_2 - E_1$$

$$\begin{aligned} \text{Where, } E_2 - E_1 &= (U_2 - U_1) + m(C_2^2 - C_1^2) + mg(Z_2 - Z_1) \\ &= (U_2 - U_1), \text{ since it is a stationary system.} \end{aligned}$$

$$\begin{aligned} \text{Also, } {}_1W_2 &= p(V_2 - V_1) \\ &= p_2V_2 - p_1V_1, \text{ Where } P_0 = P_1 = P_2 \\ \therefore Q_{12} &= (p_2V_2 - p_1V_1) + (U_2 - U_1) \\ &= (U_2 + p_2V_2) - (U_1 + p_1V_1) \end{aligned}$$

The terms within brackets are all properties depending on the end states. This combination of properties may be regarded as a single property known as enthalpy. It is usually denoted by the letter H.

$$\text{ie } H = U + pV \quad (4.3a)$$

$$(\text{or}) h = u + pv \quad (4.3b)$$

Where, h is specific enthalpy in kJ/kg

u is specific internal energy in kJ/kg and

v is specific volume in m³/kg

4.4 Flow Energy

Flow energy is defined as the energy required to push a mass into or out of the control volume against a pressure. Consider a mass of volume V entering into a control volume as given in the Figure 4.2 against a pressure p.

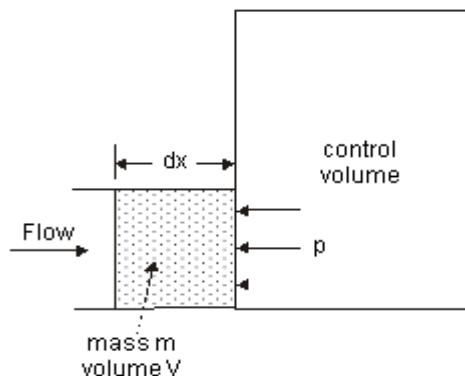


Figure 4.2 Flow energy

The Flow energy = Work done in moving the mass

$$\begin{aligned} &= \text{Force} \times \text{distance} \\ &= pA \times dx = p \times (Adx) \\ &= pV \end{aligned} \quad (4.4)$$

Therefore, Enthalpy = Internal energy + Flow energy

Work done by a system is considered positive: $W > 0$. Work done on a system is considered negative: $W < 0$. The time rate of doing work, or power, is symbolized by and adheres to the same sign convention. And heat transfer to a system is positive and heat transfer from a system is negative

4.5 First Law of Thermodynamics for a Control Volume

Mass simultaneously entering and leaving the system is a very common phenomenon in most of the engineering applications. Control volume concept is applied to these devices by assuming suitable control surfaces. To analyze these control volume problems, conservation of mass and energy concepts are to be simultaneously considered.

Energy may cross the control surface not only in the form of heat and work but also by total energy associated with the mass crossing the boundaries. Hence apart from kinetic, potential and internal energies, flow energy should also be taken into account.

Conservation of mass

$$\left[\begin{array}{l} \text{Total mass} \\ \text{entering the} \\ \text{control volume} \end{array} \right] + \left[\begin{array}{l} \text{Total mass} \\ \text{leaving the} \\ \text{control volume} \end{array} \right] = \left[\begin{array}{l} \text{Net change in the} \\ \text{mass content of the} \\ \text{control volume} \end{array} \right]$$

Conservation of energy

$$\left[\begin{array}{l} \text{Net energy crossing the} \\ \text{boundary in the} \\ \text{form of heat} \\ \text{and work} \end{array} \right] + \left[\begin{array}{l} \text{Total energy} \\ \text{associated with the} \\ \text{mass entering} \\ \text{the control volume} \end{array} \right] - \left[\begin{array}{l} \text{Total energy} \\ \text{associated with the} \\ \text{mass leaving} \\ \text{the control volume} \end{array} \right] = \left[\begin{array}{l} \text{Net change} \\ \text{in the energy} \\ \text{content of the} \\ \text{control volume} \end{array} \right] \quad 4.5)$$

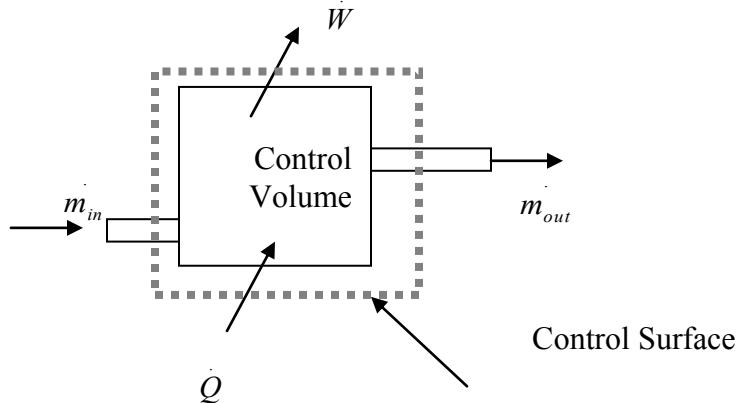


Figure 4.3: First Law of Thermodynamics Applied to a control Volume

As a rate equation, it becomes

$$[\dot{Q} - \dot{W}] + \sum_{in} m_{in} \left[h + \frac{C^2}{2} + Zg \right] - \sum_{out} m_{out} \left[h + \frac{C^2}{2} + Zg \right] = [\Delta E_{CV}] \quad (4.6)$$

4.6 The Steady-state Flow Process

When a flow process is satisfying the following conditions, it is known as a steady flow process.

1. The mass and energy content of the control volume remains constant with time.
2. The state and energy of the fluid at inlet, at the exit and at every point within the control volume are time independent.
3. The rate of energy transfer in the form of work and heat across the control surface is constant with time.

Therefore for a steady flow process

$$\sum m_{in} = \sum m_{out} \quad (4.7)$$

also

$$[\Delta E_{CV}] = 0 \quad (4.8)$$

$$[\dot{Q} - \dot{W}] + \sum_{in} m_{in} \left[h + \frac{C^2}{2} + Zg \right] - \sum_{out} m_{out} \left[h + \frac{C^2}{2} + Zg \right] = 0 \quad (4.9)$$

For problem of single inlet stream and single outlet stream

$$[\dot{Q} - \dot{W}] = \dot{m} \left[(h_2 - h_1) + \left(\frac{C_2^2 - C_1^2}{2} \right) + (Z_2 - Z_1)g \right] \quad (4.10)$$

This equation is commonly known as steady flow energy equation (SFEET).

4.7 Application of SFEE

SFEE governs the working of a large number of components used in many engineering practices. In this section a brief analysis of such components working under steady flow conditions are given and the respective governing equations are obtained.

4.7.1 Turbines

Turbines are devices used in hydraulic, steam and gas turbine power plants. As the fluid passes through the turbine, work is done on the blades of the turbine which are attached to a shaft. Due to the work given to the blades, the turbine shaft rotates producing work.

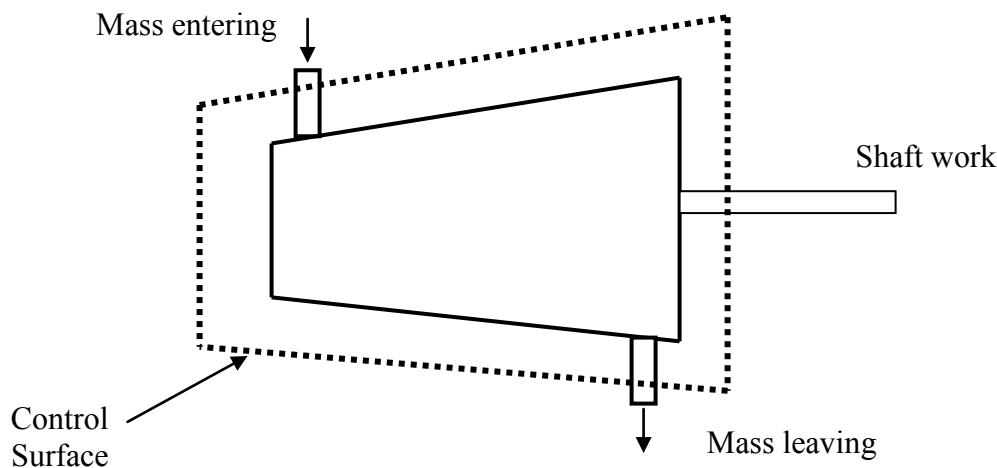


Figure 4.4 Schematic Representation of a Turbine

General Assumptions

1. Changes in kinetic energy of the fluid are negligible
2. Changes in potential energy of the fluid are negligible.

$$[\dot{Q} - \dot{W}] = \dot{m}[(h_2 - h_1)] \quad (4.11)$$

4.7.2 Compressors

Compressors (fans and blowers) are work consuming devices, where a low-pressure fluid is compressed by utilizing mechanical work. Blades attached to the shaft of the turbine impart kinetic energy to the fluid which is later converted into pressure energy.

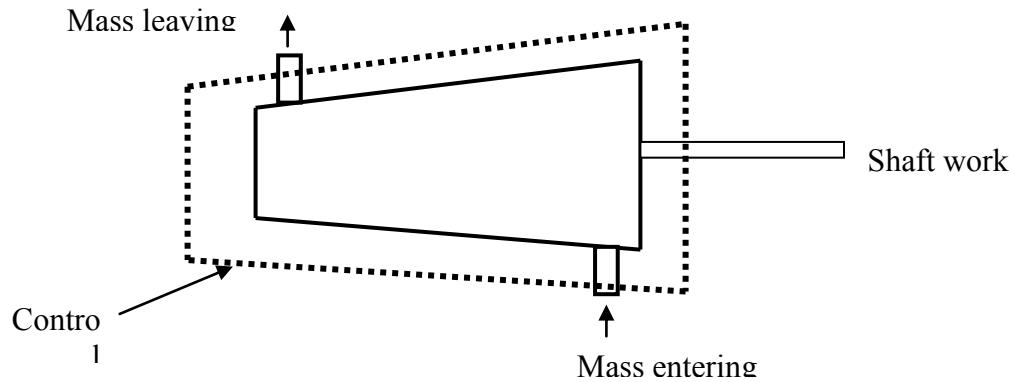


Figure 4.5 Schematic Representation of a Compressor

General Assumptions

1. Changes in the kinetic energy of the fluid are negligible
2. Changes in the potential energy of the fluid are negligible

Governing Equation

Applying the above equations SFEE becomes

$$[\dot{Q} - \dot{W}] = \dot{m}[(h_2 - h_1)] \quad (4.12)$$

4.7.3 Pumps

Similar to compressors pumps are also work consuming devices. But pumps handle incompressible fluids, whereas compressors deal with compressible fluids.

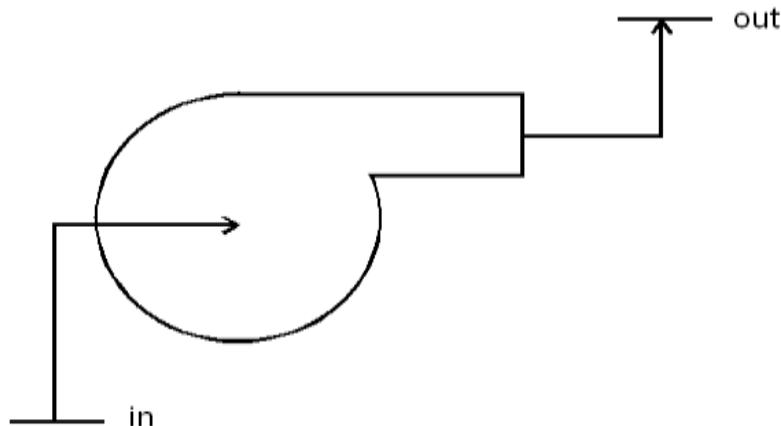


Figure 4.6 Schematic Diagram of a pump

General Assumptions

1. No heat energy is gained or lost by the fluids;
2. Changes in kinetic energy of the fluid are negligible.

Governing Equation

$$[-\dot{W}] = \dot{m}[(h_2 - h_1) + (Z_2 - Z_1)g] \quad (4.13)$$

As the fluid passes through a pump, enthalpy of the fluid increases (internal energy of the fluid remains constant) due to the increase in pv (flow energy). Increase in potential energy of fluid is the most important change found in almost all pump applications.

4.7.4 Nozzles

Nozzles are devices which increase the velocity of a fluid at the expense of pressure. A typical nozzle used for fluid flow at subsonic* speeds is shown in Figure 4.7.

General Assumptions

1. In nozzles fluids flow at a speed which is high enough to neglect heat lost or gained as it crosses the entire length of the nozzle. Therefore, flow through nozzles can be regarded as adiabatic. That is $\dot{Q} = 0$.
2. There is no shaft or any other form of work transfer to the fluid or from the fluid; that is $\dot{W} = 0$.
3. Changes in the potential energy of the fluid are negligible.

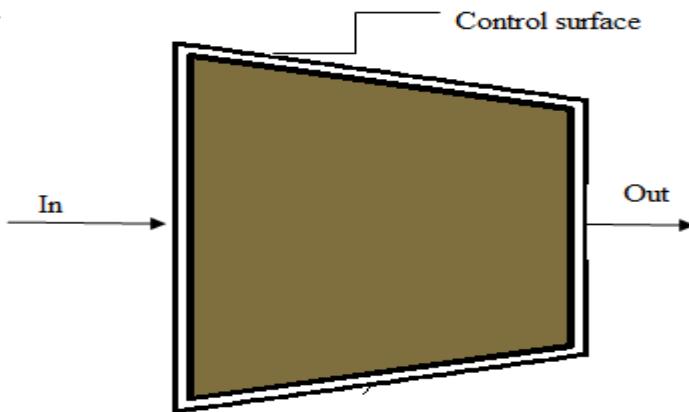


Figure 4.7 Schematic Representation of a Nozzle

Governing Equation

$$\left[(h_2 - h_1) + \left(\frac{C_2^2 - C_1^2}{2} \right) \right] = 0 \quad (4.14)$$

$$\left(\frac{C_2^2 - C_1^2}{2} \right) = (h_1 - h_2)$$

4.7.5 Diffusers

Diffusers are (reverse of nozzles) devices which increase the pressure of a fluid stream by reducing its kinetic energy.

General Assumptions

Similar to nozzles, the following assumptions hold good for diffusers.

1. Heat lost or gained as it crosses the entire length of the nozzle. Therefore, flow through nozzles can be regarded as adiabatic. That is $\dot{Q} = 0$
2. There is no shaft or any other form of work transfer to the fluid or from the fluid; that is $= 0$.
3. Changes in the potential energy of the fluid are negligible

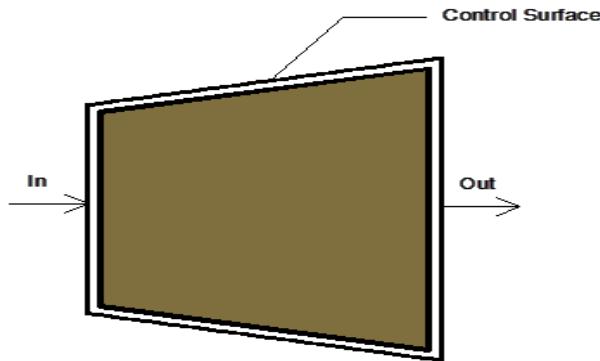


Figure 4.8 Schematic Representation of a Diffuser

Governing Equation

$$\left[(h_2 - h_1) + \left(\frac{C_2^2 - C_1^2}{2} \right) \right] = 0$$

$$(h_2 - h_1) = \left(\frac{C_1^2 - C_2^2}{2} \right) \quad (4.15)$$

4.7.6 Heat Exchangers

Devices in which heat is transferred from a hot fluid stream to a cold fluid stream are known as heat exchangers.

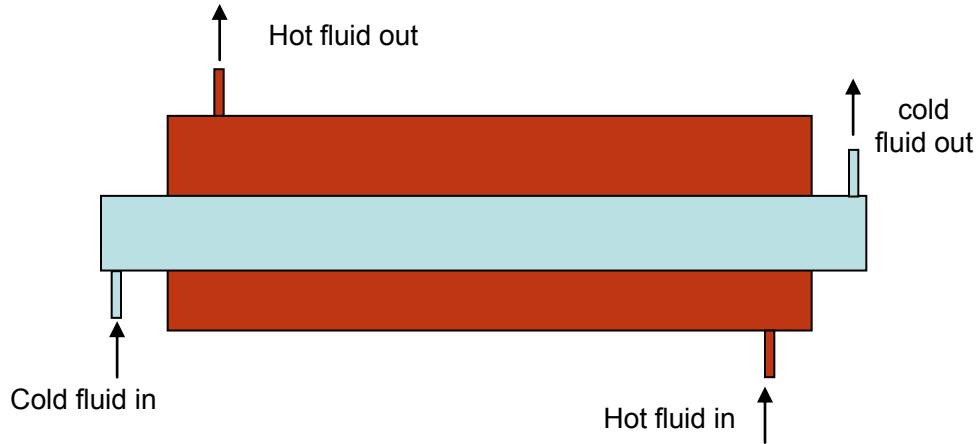


Figure 4.9 Schematic Representation of a Heat exchanger

General Assumptions

1. Heat lost by the hot fluid is equal to the heat gained by the cold fluid.
2. No work transfer across the control volume.
3. Changes in kinetic and potential energies of both the streams are negligible.

Governing Equation

For both hot and cold streams

$$[\dot{Q}] = \dot{m}[(h_2 - h_1)]$$

As per the assumption,

$$-\dot{Q}_{hot} = \dot{Q}_{cold}$$

The negative sign in the LHS is to represent that heat is going out of the system.

$$\dot{m}_h(h_1 - h_2) = \dot{m}_c(h_2 - h_1) \quad (4.16)$$

4.7.7 Throttling

A throttling process occurs when a fluid flowing in a line suddenly encounters a restriction in the flow passage. It may be

- a plate with a small hole as shown in Figure 4.10 (a)

- a valve partially closed as shown in Figure 4.10 (b)
- a capillary tube which is normally found in a refrigerator as shown in Figure 4.10 (c)
- a porous plug as shown in Figure 4.10 (d)

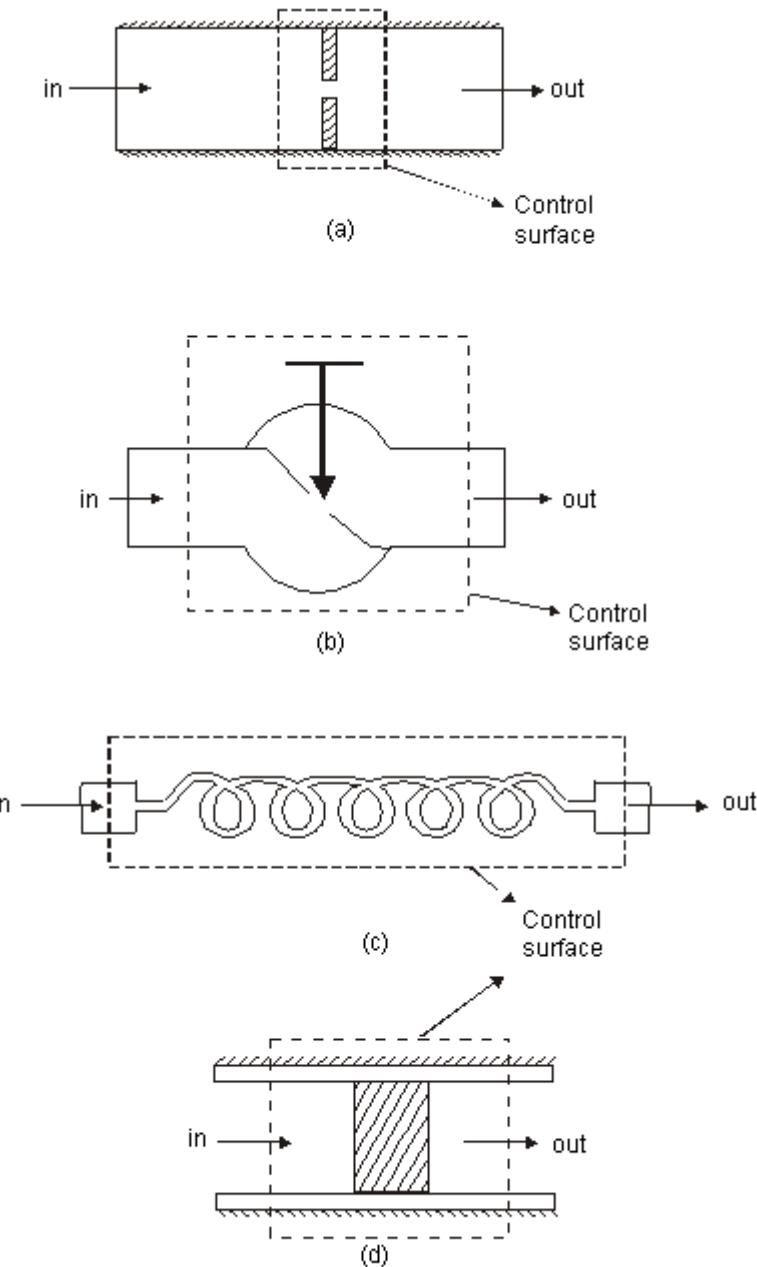


Figure 4.10 Examples of throttling processes

General assumptions

1. No heat energy is gained or lost by the fluid; ie., $\dot{Q} = 0$

2. There is typically some increase in velocity in a throttle, but both inlet and exit kinetic energies are usually small enough to be neglected.
3. There is no means for doing work; ie., $= 0$.
4. Changes in potential energy of the fluid is negligible.

Governing Equation

$$h_2 = h_1 \quad (4.17)$$

Therefore, throttling is an **isenthalpic process**.

4.8 First Law for a Cyclic Process

In a cyclic process the system is taken through a series of processes and finally returned to its original state. The end state of a cyclic process is identical with the state of the system at the beginning of the cycle. This is possible if the energy level at the beginning and end of the cyclic process are also the same. In other words, the net energy change in a cyclic process is zero.

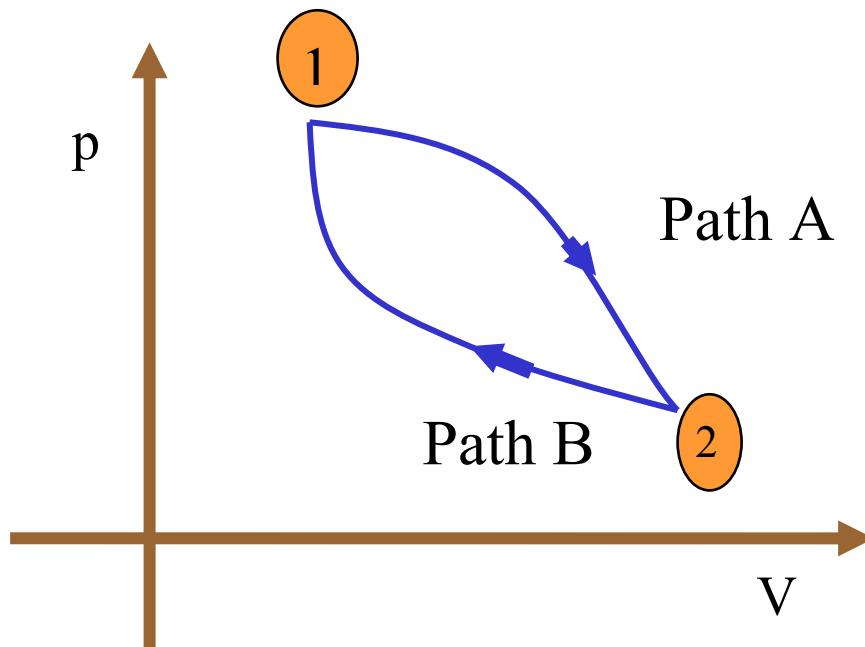


Figure 4.11 First Law for a Cyclic Process

Consider a system undergoing a cycle consisting of two processes A & B as shown in Figure 4.11 Net energy change

$$\Delta E_A + \Delta E_B = 0 \quad (4.18)$$

$$(Q_A - W_A) + (Q_B - W_B) = 0 \quad (4.19)$$

i.e

$$Q_A - Q_B = W_A - W_B \quad (4.20)$$

(or)

$$\oint dQ = \oint dW \quad (4.21)$$

Hence for a cyclic process algebraic sum of heat transfers is equal to the algebraic sum of work transfer.

This was first proved by Joule, based on the experiments he conducted between 1843 and 1858, that were the first quantitative analysis of thermodynamic systems.

4.9 Energy is a property of a system

Consider a system undergoing a process from state 1 to state 2 along path A as shown in Figure 4.12. Let the system be taken back to the initial state 1 along two possible paths B and C. Process A, combined separately with process B and C forms two possible cycles.

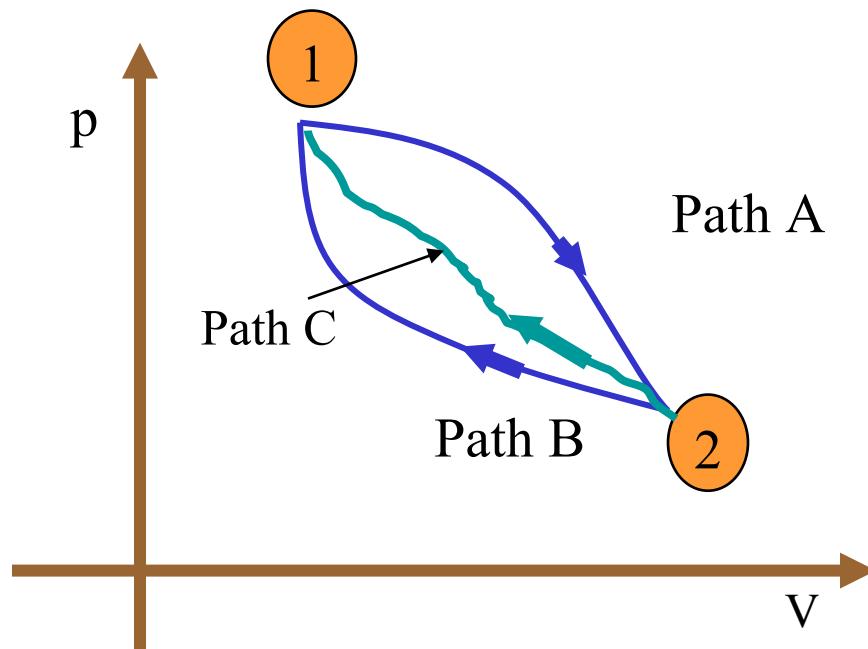


Figure 4.12 Illustration to show that energy is property

Cycle 1A2B1

$$\begin{aligned} Q_A + Q_B &= [W_A + W_B] \\ Q_A - W_A &= -[Q_B - W_B] \\ \Delta E_A &= -\Delta E_B \end{aligned} \quad (4.22)$$

Cycle 1A2C1

$$\begin{aligned} Q_A + Q_C &= [W_A + W_C] \\ Q_A - W_A &= -[Q_C - W_C] \\ \Delta E_A &= -\Delta E_C \end{aligned} \quad (4.23)$$

From Equation (4.22) and (4.23) it can be concluded that energy change in path B and path C are equal and hence energy is a point function depending only on the end states. It has been already shown that all the properties are point functions and hence energy is also a property of the system.

4.10 Specific Heat at Constant Volume and at Constant Pressure

Specific heat at constant volume of a substance is the amount of heat added to rise the temperature of unit mass of the given substance by 1 degree at constant volume. From first law for a stationary closed system undergoing a process

$$dQ = pdV + dU \text{ or } dq = pdv + du$$

For a constant volume process

$$dQ = dU \text{ or } dq = du$$

And

$$du = C_VdT \quad (4.24)$$

Similarly specific heat at constant pressure is the quantity of heat added to rise the temperature of unit mass of the given substance by 1 degree at constant pressure

$$\begin{aligned} \text{where } dQ &= pdV + dU \\ &= pdV + d(H - PV) \\ dQ &= pdV + dH - Vdp - pdV \\ dQ &= dH - Vdp \end{aligned}$$

For a constant pressure process $dp = 0$

Hence $dQ = dH$ or $dq = dh$

$$dh = C_pdT \quad 4.25)$$

Note:

- For solids and liquids, constant volume and constant pressure processes are identical and hence, there will be only one specific heat.

- The difference in specific heats $C_p - C_v = R$
- The ratio of sp. heat $\gamma = C_p/C_v$
- Since h and u are properties of a system, $dh = C_p dT$ and $du = C_v dT$, for all processes.

4.11 Work Interaction in a Reversible Steady Flow Process

In a steady flow process the work interaction per unit mass between an open system and the surroundings can be expressed in differential form as

$$\begin{aligned} dq - dw &= dh + CdC + gdz \\ dw &= dq - (dh + CdC + gdz) \end{aligned}$$

Also, $dq = du + pdv$ (or) $dh = vdp$

Therefore, $\begin{aligned} dw &= dh - vdp - (dh + CdC + gdz) \\ &= - vdp - (CdC + gdz) \end{aligned}$

$$W = - \int_1^2 vdp - \left(\frac{C_2^2 - C_1^2}{2} \right) - g(z_2 - z_1) \quad (4.26)$$

For a stationary system

$$W = - \int_1^2 vdp \quad (4.27)$$

4.12 First law for an open system under unsteady flow conditions

Many processes of engineering interest involve unsteady flow, where energy and mass content of the control volume increase or decrease.

Examples for such conditions are:

- 1) Filling closed tanks with a gas or liquid.
 - 2) Discharge from closed vessels.
 - 3) Fluid flow in reciprocating equipments during an individual cycle.
- To develop a mathematical model for the analysis of such systems the following assumptions are made.
- 1) The control volume remains constant relative to the coordinate frame.

-
- 2) The state of the mass within the control volume may change with time, but at any instant of time the state is uniform throughout the entire control volume.
 - 3) The state of the mass crossing each of the areas of flow on the control surface is constant with time although the mass flow rates may be time varying.

Unlike in steady flow system, duration of observation Δt plays an important role in transient analysis. Let mass of the working fluid within the control volume before and after the observation be m_1 and m_2 respectively. Applying mass balance we get,

$$(m_2 - m_1)_{CV} = \sum m_i - \sum m_0 \quad (4.28)$$

Where $\sum m_i$ is the mass entered the control volume during the interval Δt seconds.

$\sum m_0$ is the mass left the control volume during the interval Δt seconds.

By applying energy balance we get,

$$[Q_{cv} - W_{cv}] + \sum_{in} m_{in} \left[h + \frac{C^2}{2} + Zg \right] - \sum_{out} m_{out} \left[h + \frac{C^2}{2} + Zg \right] = \Delta E_{cv} \quad (4.29)$$

Where, E_{CV} is the change in energy content of the control volume in Δt seconds.

Q_{CV} is the heat energy entered into the control volume in Δt seconds.

W_{CV} is the work energy left the control volume in Δt seconds.

h_i & h_0 are specific enthalpy of the inlet and outlet streams respectively.

are the kinetic energy of the inlet and outlet streams respectively.

Z_{ig} & Z_{0g} are the potential energy of inlet and outlet streams respectively.

4.13 Perpetual Motion Machine - I

An engine which could provide work transfer continuously without heat transfer is known as perpetual motion machine of first kind. It is impossible to have such an engine as it violates first law of thermodynamics.

A device that violates the first law of thermodynamics (by *creating* energy) is called a **perpetual-motion machine of the first kind** (PMM1), and a device that violates the second law of thermodynamics is called a **perpetual-motion machine of the second kind** (PMM2).

4.14 Application of first law of thermodynamics

(a) Ideal Rankine Cycle

Application of the First law of thermodynamics to the control volume (pump, steam generator, turbine and condenser), gives

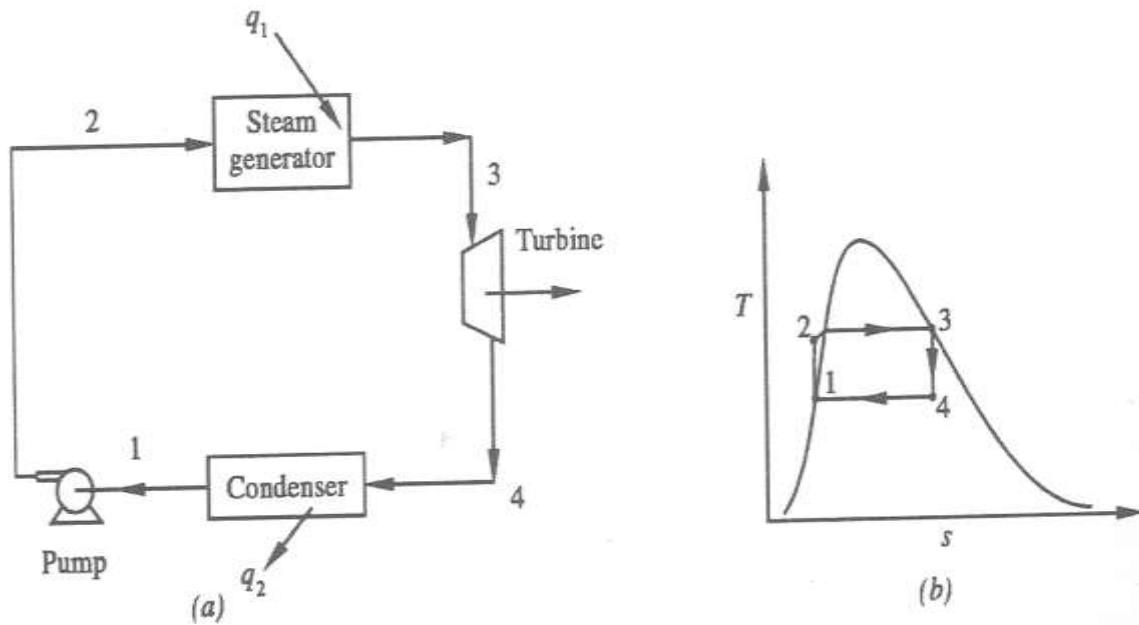


Fig. 4.13 (a) Schematic representation of an ideal Rankine cycle (b) T-s diagram of an ideal

Work done on pump, per kg of water, $W_p = h_2 - h_1$

Energy added in steam generator, $q_1 = h_3 - h_2$

Work delivered by turbine, $W_T = h_3 - h_4$

Energy rejected in the condenser, $q_2 = h_4 - h_1$

The thermal efficiency of the Rankine cycle is given by,

$$\eta = \frac{\text{Net work done}}{\text{energy absorbed}}$$

$$\eta = \frac{q_1 - q_2}{q_1} = \frac{(h_3 - h_2) - (h_4 - h_1)}{h_3 - h_2} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

(b) Practical rankine cycle

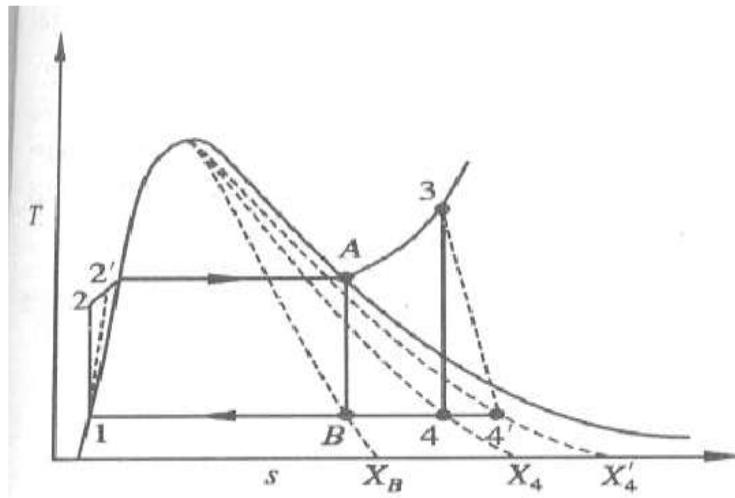


Fig. 4.14 (a) Schematic representation of an practical Rankine cycle

Pump and Turbine do not operate isentropically in practice.

The practical Rankine cycle is shown as 1-2'-3-4'-1.

In the actual turbine, the work delivered is less than the isentropic turbine. Similarly, the work consumed by an actual pump is greater than the work consumed by an isentropic pump.

That is,

$$h_3 - h_4' < h_3 - h_4$$

$$h_2' - h_1 > h_2 - h_1$$

Thermal efficiency of a practical Rankine cycle,

$$\eta = \frac{(h_3 - h_4') - (h_2' - h_1)}{h_3 - h_2}$$

The performance of an actual turbine or pump is usually expressed in terms of isentropic efficiency.

Isentropic efficiency of turbine (η_T) is defined as the ratio of 'Work delivered by actual turbine' to 'Work delivered by an isentropic turbine'.

$$\eta_T = \frac{h_3 - h_4'}{h_3 - h_4}$$

Isentropic efficiency of pump (η_P) is defined as the ratio of 'Work required by isentropic pump' to 'Work required by actual pump'

$$\eta_P = \frac{h_2 - h_1}{h_2' - h_1}$$

(c) Methods to increase the efficiency of the Rankine cycle

Basic idea: Increase the average temperature at which heat is transferred to the working fluid in the boiler, or decrease the average temperature at which heat is rejected from the working fluid in the condenser.

I. Lowering the condenser Pressure:-

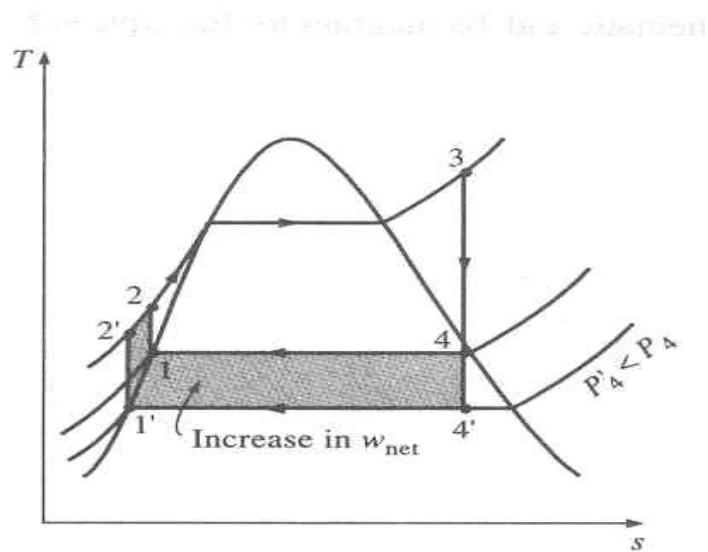


Fig. 4.15 (a) Schematic representation of an practical Rankine cycle by lowering the condenser pressure

Lowering the operating pressure of the condenser lowers the temperature at which heat is rejected. The overall effect of lowering the condenser pressure is an increase in the thermal efficiency of the cycle.

II. Superheating the steam to high temperatures:-

The average temperature at which heat is added to the steam can be increased without increasing the boiler pressure by superheating the steam to high temperatures.

Superheating the steam to higher temperatures has another very desirable effect: It decreases the moisture content of the steam at the turbine exit.

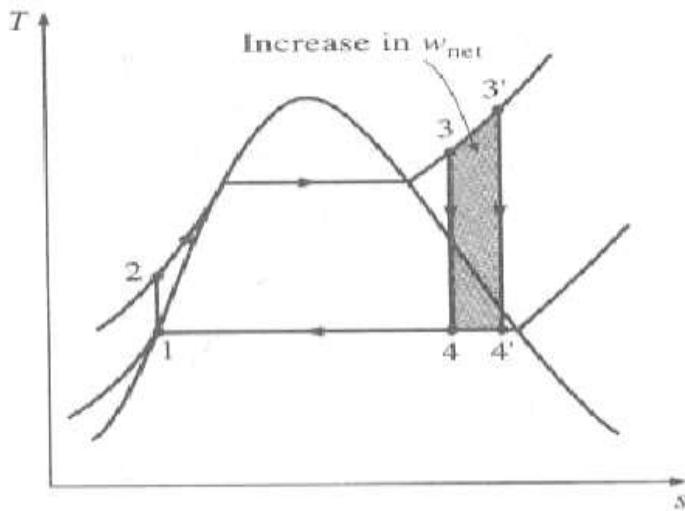


Fig. 4.15 (a) Schematic representation of an practical Rankine cycle by Superheating the steam to high temperatures

III. Increasing the Boiler pressure:-

Increasing the operating pressure of the boiler, automatically raises the temperature at which boiling takes place. This raises the average temperature at which heat is added to the steam and thus raises the thermal efficiency of the cycle.

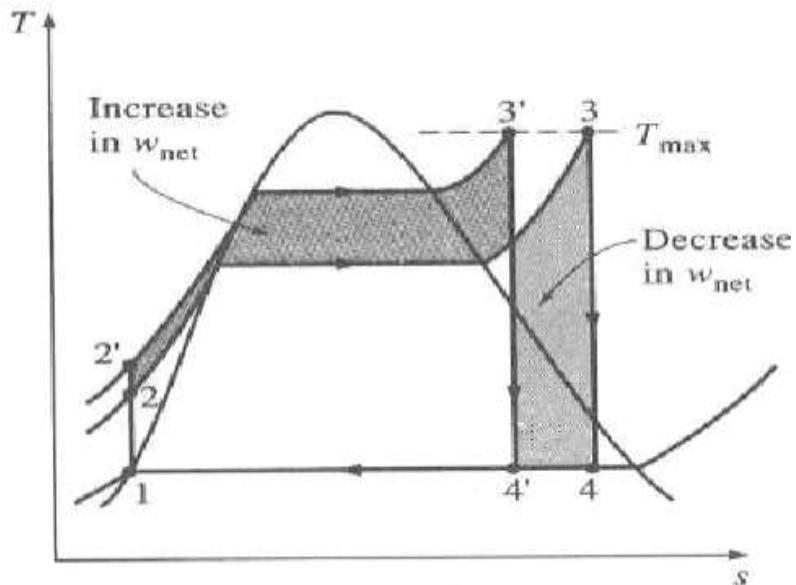


Fig. 4.15 (a) Schematic representation of an practical Rankine cycle by Increasing the Boiler pressure

Solved problems:

Example 1: A 0.1 m³ rigid tank contains steam initially at 500 kPa and 200°C. The steam is now allowed to cool until the temperature drops to 50°C. Determine the amount of heat transfer during this process and the final pressure in the tank.

State 1: P₁ = 500 kPa, T₁ = 200°C

$$v_1 = 0.4249 \text{ m}^3/\text{kg}, u_1 = 2642.9 \text{ kJ/kg}$$

State 2: v₂ = v₁ = 0.4269 m³/kg

$$T_2 = 50^\circ\text{C} \longrightarrow v_f = 0.001 \text{ m}^3/\text{kg}$$

$$v_g = 12.03 \text{ m}^3/\text{kg}$$

$$u_f = 209.32 \text{ kJ/kg}$$

$$u_g = 2443.5 \text{ kJ/kg}$$

$$P_2 = P_{\text{sat}} @ 50^\circ\text{C} = \mathbf{12.349 \text{ kPa}}$$

$$v_2 = v_f + x_2 v_{fg}$$

$$0.4249 = 0.001 + x_2(12.03 - 0.001)$$

$$x_2 = 0.0352$$

$$u_2 = u_f + x_2 u_g$$

$$= 209.32 + (0.0352)(2443.5 - 209.32)$$

$$= 288.0 \text{ kJ/kg}$$

$$m = V/u = (0.1 \text{ m}^3/\text{kg})/(0.4249 \text{ m}^3/\text{kg})$$

$$= 0.235 \text{ kg}$$

$$-Q_{\text{out}} = \Delta U = m(u_2 - u_1)$$

$$Q_{\text{out}} = m(u_1 - u_2)$$

$$= (0.235)(2642.9 - 288)$$

$$= \mathbf{553.4 \text{ kJ}}$$

Example 2: A piston/cylinder contains 50 kg of water at 200 kPa with a volume of 0.1 m³. Stop in the cylinder is placed to restrict the enclosed volume to 0.5 m³. The water is now heated until the piston reaches the stops. Find the necessary heat transfer.

Solution:

At 200 kPa,

$$v_f = 0.001061 \text{ m}^3/\text{kg}$$



$$v_{fg} = 0.88467 \text{ m}^3/\text{kg}$$

$$h_f = 504.68 \text{ kJ/kg}$$

$$h_{fg} = 2201.96 \text{ kJ/kg}$$

This is a constant pressure process. Hence,

$$Q = \Delta H$$

The specific volume initially,

$$v_i = 0.1 / 50 = 0.002 \text{ m}^3/\text{kg}$$

$$\begin{aligned} v &= v_f + x v_{fg} \\ &= 0.001061 + x (0.88467) \end{aligned}$$

$$\text{Therefore, } x = (0.002 - 0.001061) / 0.88467$$

$$= 0.001061$$

$$\begin{aligned} h &= h_f + x h_{fg} \\ &= 504.68 + 0.001061(2201.96) \\ &= 507.017 \text{ kJ/kg} \end{aligned}$$

$$v_{final} = 0.5 / 50 = 0.01 \text{ m}^3/\text{kg}$$

$$v = v_f + x v_{fg}$$

$$\text{Therefore, } x = (0.01 - 0.001061) / 0.88467$$

$$= 0.01$$

$$\begin{aligned} h_{final} &= 504.68 + 0.01(2201.96) \\ &= 526.69 \text{ kJ/kg} \end{aligned}$$

$$Q = \Delta H = 50 (526.69 - 507.017)$$

$$= \mathbf{983.65 \text{ kJ/kg}}$$

Example 3: A rigid insulated tank is separated into two rooms by a stiff plate. Room A of 0.5 m³ contains air at 250 kPa, 300 K and room B of 1 m³ has air at 150 kPa, 1000 K. The plate is removed and the air comes to a uniform state without any heat transfer. Find the final pressure and temperature. The system comprises of room A and B together. This is a constant internal energy process as there is no heat and work exchange with the surroundings.

$$\begin{aligned} m_A &= P_A V_A / RT_A \\ &= (250 \times 1000 \times 0.5) / (287 \times 300) \\ &= 1.452 \text{ kg} \end{aligned}$$

$$m_B = P_B V_B / RT_B$$



$$= (150 \times 1000 \times 1.0) / (287 \times 1000)$$

$$= 0.523 \text{ kg}$$

$$\Delta U_A + \Delta U_B = 0$$

Let T_f be the final temperature at equilibrium

$$m_A (T_f - 300) + m_B (T_f - 1000) = 0$$

$$1.452 (T_f - 300) + 0.523 (T_f - 1000) = 0$$

$$T_f = 485.37 \text{ K}$$

$$P_f = (1.452 + 0.523) \times 287 \times 485.37 / 1.5$$

$$= 183.41 \text{ kPa}$$

Example 4: A piston / cylinder assembly contains 0.1m^3 of superheated steam at 10 bar and 400°C . If the steam is allowed to expand reversibly and adiabatically to a pressure of 3 bar, calculate the work done by the steam.

Solution:

At 10 bar and 400°C ,

$$v = 0.3065 \text{ m}^3/\text{kg}$$

$$h = 3264.4 \text{ kJ/kg}$$

$$s = 7.4665 \text{ kJ/kg K}$$

At 3 bar,

$$s_g = 6.9909 \text{ kJ/kg K}$$

This is an isentropic process as initial entropy value is greater than s_g at 3 bar, the steam is superheated at the end of the process.

At 3 bar and 200°C ,

$$s = 7.3119 \text{ kJ/kg K} \text{ and at } 300^\circ\text{C}, s = 7.7034 \text{ kJ/kg K}$$

Therefore, the final state is having a temperature between 200°C and 300°C .

Equating $s_i = s_{final}$,

Find the enthalpy and specific volume by interpolation. Then calculate u_i and u_{final} .

The work done = $\Delta U = m(u_i - u_{final})$

Example 5 (Nozzle)

Nitrogen gas flows into a convergent nozzle at 200 kPa, 400 K and very low velocity. It flows out of the nozzle at 100 kPa, 330 K. If the nozzle is insulated, find the exit velocity.

$$V_i = 0$$

Adiabatic nozzle

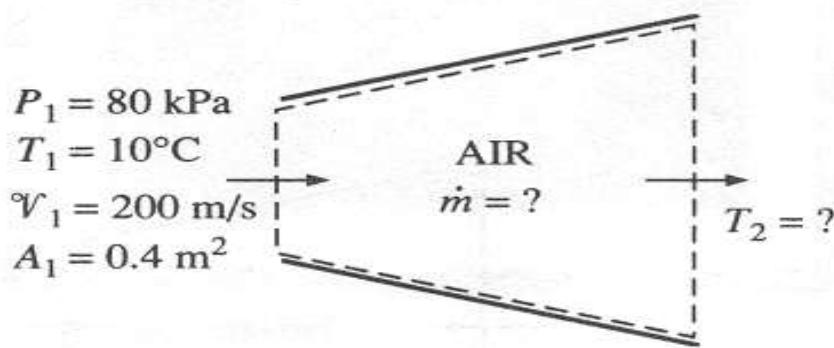
The SSSF equation:

$$\begin{aligned} V_e^2/2 &= (h_i - h_e) = Cp(T_i - T_e) \\ &= \{\gamma Ru/M(\gamma-1)\} (T_i - T_e) \\ &= \{1.4 * 8314/(28*0.4)\}(400-330) \\ &= 72747.5 \text{ m}^2/\text{s}^2 \end{aligned}$$

$$\text{We get, } V_e = 381.44 \text{ m/s}$$

Example 6 (Diffuser)

Air at 10°C and 80 kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m^2 . The air leaves the diffuser with a velocity that is very small compared with the inlet velocity. Determine (a) the mass flow rate of the air and (b) the temperature of the air leaving the diffuser.



Solution:

Assumptions: This is a steady flow process. Air is an ideal gas. The potential energy change is zero. Kinetic energy at diffuser exit is negligible. There are no work interactions. Heat transfer is negligible.

To determine the mass flow rate, we need the specific volume of air.

$$v_1 = RT_1 / P_1 = 0.287 * 283 / 80 = 1.015 \text{ m}^3/\text{kg}$$

$$m = 1/v_1(V_1A_1) = (200 * 0.4) / 1.015 = 78.8 \text{ kg/s}$$

For steady flow, mass flow through the diffuser is constant.

$$(b) (h_1 + V_1^2/2) = (h_2 + V_2^2/2) \text{ (since } Q = 0, W = 0, \text{ and } \Delta PE = 0\text{)}$$

$$h^2 = h_1 - (V_2^2 - V_1^2)/2$$

The exit velocity of a diffuser is very small and therefore neglected.

$$h_2 = h_1 + V_1^2/2$$

$$T_2 = T_1 + V_1^2/2C_p$$

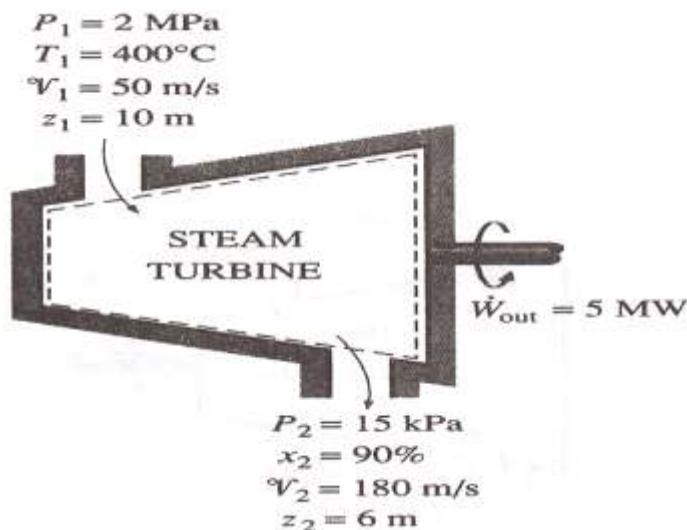
$$T_2 = 283 + 2002/(2*1004)$$

$$= 302.92 \text{ K}$$

Example 7 Power generation by a steam turbine

The power output of an adiabatic steam turbine is 5 MW, and the inlet and exit conditions of the steam are as indicated in the figure.

- Compare the magnitude of Δh , ΔKE , and ΔPE
- Determine the work done per unit mass of the steam flowing through the turbine
- Calculate the mass flow rate of the steam.



Solution:

We take the turbine as a system. The control volume is shown in the figure. The system, the inlet and exit velocities do work and elevations are given and thus the kinetic and potential energies are to be considered. At the inlet, the steam is in superheated vapor state.

$$h_1 = 3247.6 \text{ kJ/kg}$$

At the turbine exit, we have a saturated liquid-vapor mixture at 15 kPa pressure. The enthalpy at this state is

$$\begin{aligned} h_2 &= hf + x_2 hfg \\ &= 225.94 + 0.9 * 2373.1 \\ &= 2361.73 \text{ kJ/kg} \end{aligned}$$

$$\Delta h = h_2 - h_1 \\ = 2361.73 - 3247.6 = \mathbf{-885.87 \text{ kJ/kg}}$$

$$\Delta ke = (V_2^2 - V_1^2)/2 = (1802 - 502)/2 * 1000 \\ = \mathbf{14.95 \text{ kJ/kg}}$$

$$\Delta Pe = g(Z_2 - Z_1) = 9.807 * (6 - 10)/1000 \\ = \mathbf{-0.04 \text{ kJ/kg}}$$

$$w_{out} = -[(h_2 - h_1) + (V_2^2 - V_1^2)/2 + g(Z_2 - Z_1)] \\ = -[-885.87 + 14.95 - 0.04] \\ = \mathbf{870.96 \text{ kJ/kg}}$$

d) The required mass flow rate for a 5MW power output is $5000/870.96 = \mathbf{5.74 \text{ kg/s}}$

Exercises

1. Define internal energy.
2. Express mathematically first law of thermodynamic for the following.
 - a. a closed system undergoing a process
 - b. a stationary system of fixed mass undergoing a change of state
 - c. a closed system undergoing a cycle.
 - d. an open system.
 - e. an open system with steady-state flow conditions.
3. Define flow energy and enthalpy.
4. For a stationary system of fixed mass undergoing a process such that its volume remains constant, $Q_{12} = \Delta U(T/F)$
5. $dQ = dh - vdp$ for closed system undergoing a process (T/F).
6. Define specific heat at (a) constant pressure (b) constant volume
7. Determine the power of the cycle comprising four processes in which the heat transfers are: 50 kJ/kg, -20 kJ/kg, -71 J/kg and 12 kJ/kg having 100 cycles per minute.

[48.3 kW]

8. Write the steady flow energy equation and explain the terms involved in it.
9. Show that energy is a property of the system.
10. What are conditions for steady flow process?



11. A piston-cylinder assembly contains 1kg of nitrogen at 100 kPa. The initial volume is 0.5 m³. Heat is transferred to the substance in an amount necessary to cause a slow expansion at constant temperature. This process is terminated when the final volume is twice the initial volume.

[34.7 kJ]

12. 2 kg of air enclosed in a rigid container receives 0.2 kJ of paddle wheel work and 0.5 kJ of electrical energy per second. Heat loss from the system is 0.6 kJ/s. If the initial temperature is 25°C what will be the temperature after 5 minutes?

[45.9°C]

13. A well insulated, frictionless piston-cylinder assembly contains 0.5 kg of air initially at 75°C and 300 kPa. An electric - resistance heating element inside the cylinder is energized and causes the air temperature to reach 150°C. The pressure of the air is maintained constant throughout the process. Determine the work for the process and the amount of electrical work.

{Hint $Q_{net} - W_{net} = \Delta U$; $W_{net} = W_b + W_{electric}$ }

[-26.9 kJ ; -37.7 kJ]

14. A cylinder contains 168 litres of a gas at a pressure of 1 bar and temperature of 47°C. If this gas is compressed to one-twelfth of its volume, pressure is then 21 bar. Find

- index of compression
- change in internal energy
- heat rejected during compression

Take $C_p = 1.089$ and $C_v = 0.837$ both in kJ/kg

[1.225 ; 41.81 kJ ; -14.05 kJ]

15. a. A mass of 10 kg is falling from a height of 100 m from the datum. What will be the velocity when it reaches a height of 20 m from the datum? Take the total heat loss from the mass when it falls from 100 m height to 20 m height is 5 kJ.

[8.68 m/s]

- b. An insulated box containing carbon dioxide gas falls from a balloon 3.5 km above the earth's surface. Determine the temperature rise of the carbon dioxide when box hits the ground.

Take $C_V = 0.6556 \text{ kJ/kg}$

[52.37°C]

16. A working substance flows at a rate of 5 kg/s into a steady flow system at 6 bar, 2000 kJ/kg of internal energy and $0.4 \text{ m}^3/\text{kg}$ specific volume with a velocity of 300 m/s. It leaves at 10 bar, 1600 kJ/kg internal energy, $1.2 \text{ m}^3/\text{kg}$ specific volume with a velocity of 150 m/s. The inlet is 10m above the outlet. The work transfer to the surroundings is 3 MW. Estimate the heat transfer and indicate the direction.

[5630 kJ/s]

17. An air compressor takes in air at 100 kPa, 40°C and discharges it at 690 kPa, 208°C . The initial and final internal energy values for the air are 224 and 346 kJ/kg respectively. The cooling water around the cylinders removes 70 kJ/kg from the air. Neglecting changes in kinetic and potential energy, calculate the work.

[100.216 kJ/kg]

18. A perfect gas of $c_p = 1.1 \text{ kJ/kg}$ flows through a turbine at a rate of 3 kg/s. The inlet and exit velocity are 30 and 130 m/s respectively. The initial and final temperatures are 650°C and 250°C respectively. Heat loss is 45 kJ/s. Find the power developed.

[1251 kW]

19. In a turbine 4500 kg/min of air expands polytropically from 425 kPa and 1360 K to 101 kPa. The exponent n is equal to 1.45 for the process. Find the Shaft work and heat.

[33939 kW; -2927 kJ/s]

20. Air flow through a nozzle from a pressure of 500 kPa to a final pressure of 100 kPa. The enthalpy decrease by 100 kJ/kg. The flow is adiabatic and the inlet velocity is very low. Calculate the exit velocity.

[447.2 m/s]



21. A closed system undergoes a cycle consisting of three process 1-2, 2-3 and 3-1. Given that $Q_{12} = 30 \text{ kJ}$, $Q_{23} = 10 \text{ kJ}$, $w_{12} = 5 \text{ kJ}$, $w_{31} = 5 \text{ kJ}$ and $\Delta E_{31} = 15 \text{ kJ}$, determine Q_{31} , w_{23} , ΔE_{12} and ΔE_{23} .

$$[20 \text{ kJ} ; 50 \text{ kJ} ; 25 \text{ kJ} ; -40 \text{ kJ}]$$

22. The following cycle involves 3 kg of air : Polytropic compression from 1 to 2 where $P_1 = 150 \text{ kPa}$, $T_1 = 360 \text{ K}$, $P_2 = 750 \text{ kPa}$ and $n = 1.1$; constant-pressure cooling from 2 to 3; and constant - temperature heating from 3 to 1. Draw the pV diagram and find temperatures, pressures and volumes at each state and determine the net work and heat.

$$[150 \text{ kPa} ; 2.066 \text{ m}^3 ; 360 \text{ K} ; 750 \text{ kPa} ; 0.478 \text{ m}^3 ; \\ 416.72 \text{ K} ; 750 \text{ kPa} ; 0.414 \text{ m}^3 ; 360 \text{ K} ; -35 \text{ kJ}]$$

23. A cycle, composed of three processes, is:

Polytropic compression ($n = 1.5$) from 137 kPa and 38°C to state 2 ; constant pressure process from state 2 to state 3 ; constant volume process form state 3 and to state 1. The heat rejected in process 3-1 is 1560 kJ/kg and the substance is air. Determine

- (a) the pressures, temperatures and specific volumes around the cycle
- (b) the heat transfer in process 1-2
- (c) the heat transfer in process 2-3
- (d) work done in each process and
- (e) net work done in the cycle

$$[137 \text{ kPa} ; 0.6515 \text{ m}^3/\text{kg} ; 311.0 \text{ K} ; 1095 \text{ kPa} ; 0.1630 \text{ m}^3/\text{kg} ; \\ 621.8 \text{ K} ; 1095 \text{ kPa} ; 0.6515 \text{ m}^3/\text{kg} ; 2487.0 \text{ K} ; 44.44 \text{ kJ} ; \\ 1872.25 \text{ kJ} ; -178 \text{ kJ} ; 534.9 \text{ kJ} ; 0 ; 356.9 \text{ kJ}]$$

24. 0.15 m^3 of air at a pressure of 900 kPa and 300°C is expanded at constant pressure to 3 time its initial volume. It is then expanded polytropically following the law $PV^{1.5} = C$ and finally compressed back to initial state isothermally. Calculate

- (a) heat received
- (b) heat rejected
- (c) efficiency of the cycle



[944.5kJ ; -224.906 kJ ; 0.291]

25. A piston and cylinder device contains 1 kg of air, initially, $v = 0.8 \text{ m}^3/\text{kg}$ and $T = 298 \text{ K}$. The air is compressed in a slow frictionless process to a specific volume of $0.2 \text{ m}^3/\text{kg}$ and a temperature of 580 K according to the equation $pV^{1.3} = 0.75$ (p in bar, v in m^3/kg). If C_V of air is 0.78 kJ/kg determine :

- (a) work and
- (b) heat transfer (both in kJ)

[-137.85 kJ ; 82.11 kJ]

26. The internal energy of a closed system is given by $U = 100 + 50 T + 0.04 T^2$ in Joules, and the heat absorbed by $Q = 4000 + 16 T$ in Joules, where T is in Kelvin. If the system changes from 500 K to 1000 K , what is the work done ?

[47 kJ]

27. One kg of air, volume 0.05 m^3 , pressure 20 bar expands reversibly according to the law $pv^{1.3} = C$ until the volume is doubled. It is then cooled at constant pressure to initial volume and further heat at constant volume so that it returns back to initial process. Calculate the net work done by air.

[21.98 kJ]

28. Air at the rate of 14 kg/s expands from 3 bar, 150°C to 1 bar reversibly and adiabatically. Find the exit temperature and power developed. Neglect the changes in kinetic and potential energy. [309 k ; 1.603 kW]

29. Specific internal energy of a certain substance can be expressed as follows:

$$u = 831.0 + 0.617 pv$$

Where u is the specific internal energy in kJ/kg

p is the pressure in k Pa

v is the specific volume in m^3/kg

One kg of such substance expands from 850 kPa , $0.25 \text{ m}^3/\text{kg}$ to 600 kPa , $0.5 \text{ m}^3/\text{kg}$. Find the work done and heat transferred. [176.06 kJ ; 230 kJ]

30. A cylinder of 8 cm internal diameter is fitted with a piston loaded by a coil spring of stiffness 140 N/cm of compression. The cylinder contains 0.0005 m³ of air at 15°C and 3 bar. Find the amount of heat which must be supplied for the piston to a distance of 4 cm. Sketch the process on a p-V diagram.

[0.417 kJ]

31. An air conditioning system for a computer room in a tower block draws in air on the roof at a height of 100 m with a velocity of 25 m/s. The air is at 28°C. The air is discharged at a height of 10 m with a velocity of 2 m/s at 14°C. The mass flow rate is 2 kg/s, and a heat transfer of -40.73 kW cools the air before it is discharged. Calculate the rate of work for the air passing through the system. Take C_p for air as 1005 J/kgK.

[- 10.23 kW]

32. A diffuser reduces the velocity of an air stream from 300 m/s to 30 m/s. If the inlet pressure and temperature are 1.01 bar and 315°C, determine the outlet pressure. Find also the area required for the diffuser to pass a mass flow of 9 kg/s.

[4.586 bar, 0.17 m²]

33. A centrifugal air compressor operating at steady state has an air intake of 1.2 kg/min. Inlet and exit conditions are as follows:

Properties	p (kPa)	T°C	u kJ/kg	v m ³ /kg
Inlet	100	0	195.14	0.784
Exit	200	50	230.99	0.464

If the heat loss is negligible, find the power input.

[1.005 kW]

34. A household gas cylinder initially evacuated is filled by 15 kg gas supply of enthalpy 625 kJ/kg. After filling, the gas in the cylinder has the following parameters :

pressure = 10 bar ;
enthalpy = 750 kJ/kg and
specific volume = 0.0487 m³/kg.

Evaluate the heat received by the cylinder from the surroundings.

[1144.5 kJ]

35. 0.56 m^3 of air at 0.2 MPa is contained in a fully insulated rigid vessel. The vessel communicates through a valve with a pipe line carrying high pressure air at 300 K temperature. The valve is opened and the air is allowed to flow into the tank until the pressure of air in the tank is raised to 1MPa . Determine the mass of air that enters the tank. Neglect kinetic energy of the incoming air.

[**3.72 kg**]

36. An insulated rigid tank contains 8 kg of air at 1.5 bar pressure and 310 K temperature. It is filled with air from a large reservoir at 15 bar and 335 K . If the air behaves as a perfect gas, make calculations for the amount of air added and its temperature.

[**47.6 kg ; 446.04K**]

37. A pressure vessel contains a gas at an initial pressure of 3.5 MN/m^2 and at a temperature of 60°C . It is connected through a valve to a vertical cylinder in which there is a piston. The valve is opened, gas enters the vertical cylinder, and work is done in lifting the piston. The valve is closed and the pressure and the temperature of the remaining gas in the cylinder are 1.7 MN/m^2 and 25°C , respectively. Determine the temperature of the gas in the vertical cylinder if the process is assumed to be adiabatic. Take $\gamma = 1.4$.

[**267.6 K**]

38. A pressure vessel is connected, via a valve, to a gas main in which a gas is maintained at a constant pressure and temperature of 1.4 MN/m^2 and 85°C , respectively. The pressure vessel is initially evacuated. The valve is opened and a mass of 2.7 kg of gas passes into the pressure vessel. The valve is closed and the pressure and temperature of the gas in the pressure vessel are then 700 KN/m^2 and 60°C , respectively. Determine the heat transfer to or from the gas in the vessel. Determine the volume of the vessel and the volume of the gas before transfer.

For the gas, take $C_p = 0.88 \text{ kJ/kgK}$, $C_v = 0.67$. Neglect velocity of the gas in the main

[**$-248.2 \text{ kJ ; } 0.27 \text{ m}^3 ; 0.145 \text{ m}^3$**]

CHAPTER FIVE

THE SECOND LAW OF THERMODYNAMICS AND ENTROPY

5.1 Limitations of First Law of Thermodynamics

The First Law of Thermodynamics is used to calculate end states of a system as it evolves, it does not answer the following questions:

- In what direction does a spontaneous process go
- What is the maximum possible work

In all the internal combustion engines fuel and air mixture is supplied at room temperature. This mixture undergoes combustion inside the engine and gives out work. Exhaust gases coming out of the engine are always at higher temperature, indicating that some heat is taken away into atmosphere. Hence, in all the IC engines only a part of the heat is converted into work. From the above expression we understand that if any attempt is made to convert all the heat into work, our effort will go in vain. *This limitation in the extent of energy conversion has also not been addressed in first law of thermodynamics.*

5.2 The Second law of Thermodynamics

The second law of thermodynamics is a general principle which places constraints upon the direction of heat transfer and the attainable efficiencies of heat engines. In so doing, it goes beyond the limitations imposed by the first law of thermodynamics. In this chapter, we will see two second law thermodynamics statements.

Kelvin Planck's statement:

It is impossible to construct a device, for a system that operates in a cycle to generate continuous work while transferring heat with a single reservoir.

The term thermal reservoir refers to a very large system in stable equilibrium, to which or from which, any amount of heat can be transferred at constant temperature. A thermal reservoir supplying heat continuously at constant temperature is known as **source** (Example: Sun). A thermal reservoir receiving heat continuously at constant temperature is known as **sink**. (Examples: River, Sea).

From Kelvin-Planck statement it is clear that for any system to operate in a cycle and to give out work continuously it should interact with a minimum of two reservoirs at different temperatures. The system will receive heat from the high temperature reservoir and reject heat to the low temperature reservoir. Such devices are known as heat engines. Performance (or) Efficiency of a heat engine can be expressed as the ratio of desired output to the required input. In a heat engine the desired output is net work output and the required input is total heat input

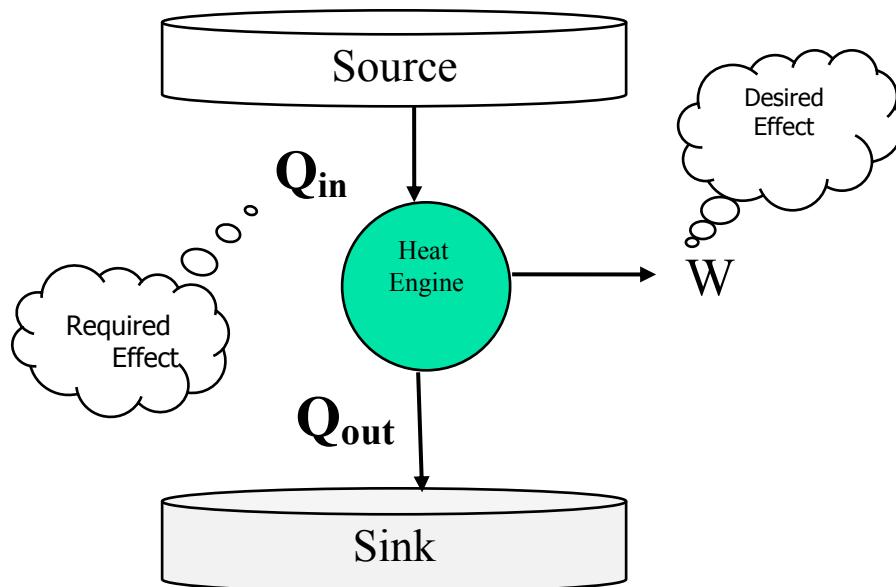


Figure 5.1 Heat Engine

$$\eta = \frac{W_{net}}{Q_{in}} \quad (5.1)$$

From first law of thermodynamics

$$\Sigma Q = \Sigma W$$

$$Q_{in} - Q_{out} = W_{net} \quad (4.2)$$

Clausius statement:

No process is possible whose sole result is the transfer of heat from a cooler to a hotter body.

Devices that are used to transfer heat from a body at lower temperature to a body at higher temperature are known as refrigerators (or) heat pumps. If the high temperature side is atmosphere it is a refrigerator. If the low temperature side is atmosphere it is known as a heat

pump. The performance index here is called coefficient of performance (COP). In refrigerator (and heat pumps) the performance is the ratio of two independent parameters and hence the possibility of getting the value more than unity is always there. But the term efficiency is restricted to a maximum of unity. Hence the term efficiency is not used here.

$$COP = \frac{\text{Desired Effect}}{\text{Required Effect}}$$

Taking work as external agency, for refrigerators (Figure 5.2)

$$COP = \frac{Q_2}{W}$$

From first law

$$\Sigma Q = \Sigma W$$

$$Q_1 - Q_2 = W$$

$$COP = \frac{Q_2}{Q_1 - Q_2} \quad (5.3)$$

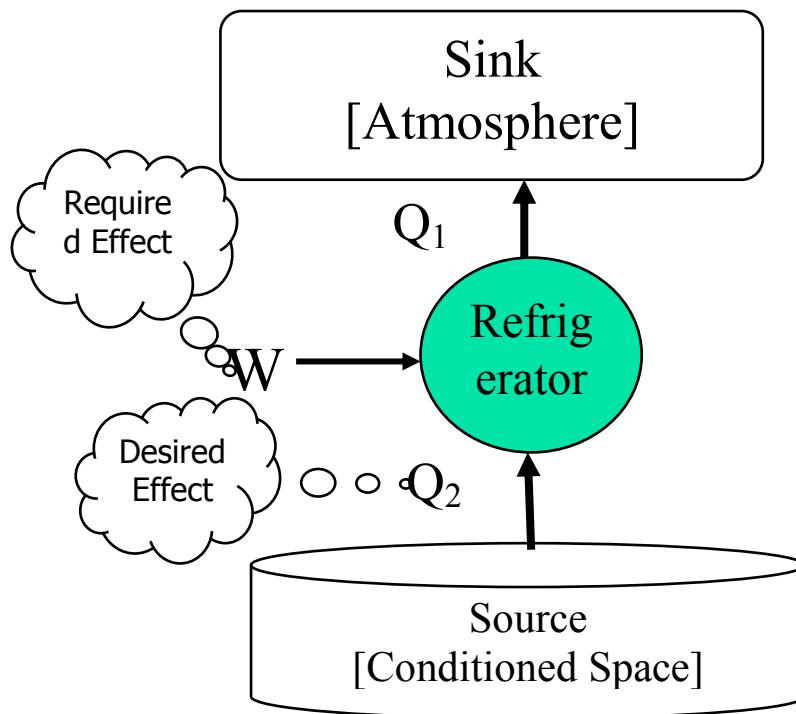


Figure 5.2 Refrigerator

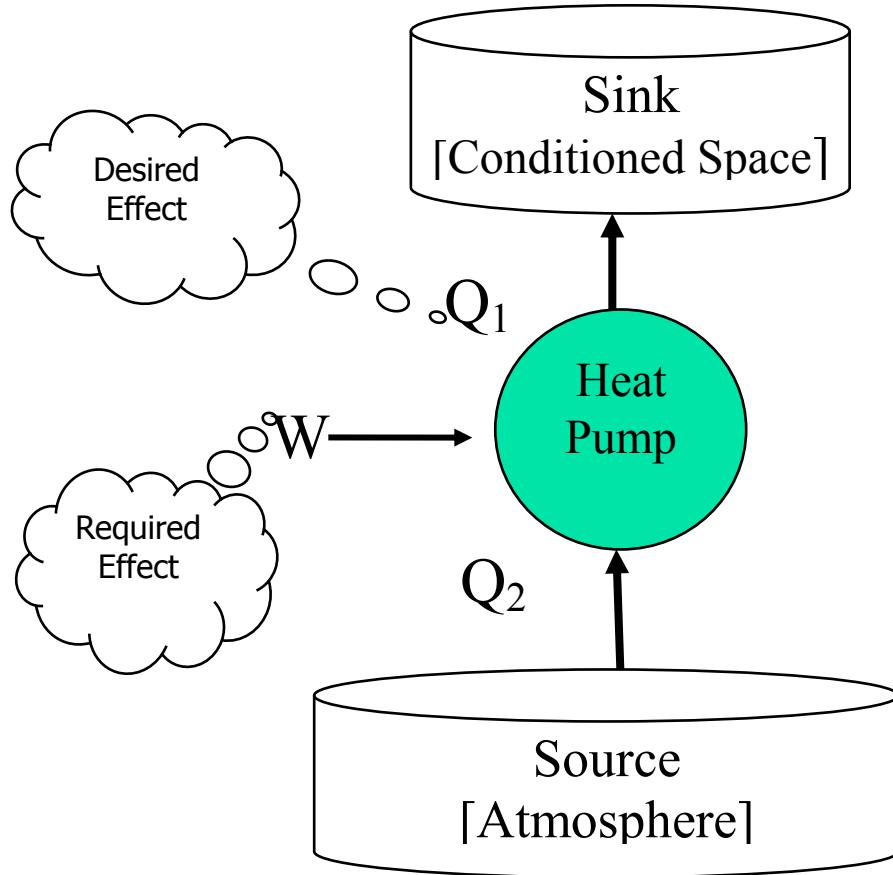


Figure 5.3 Heat Pump

Similarly for a heat pumps (Figure 5.3)

$$COP = \frac{\text{Desired Effect}}{\text{Required Effect}} \quad (5.4)$$

$$COP = \frac{Q_1}{W}$$

$$\text{Since, } Q_1 + Q_2 = W$$

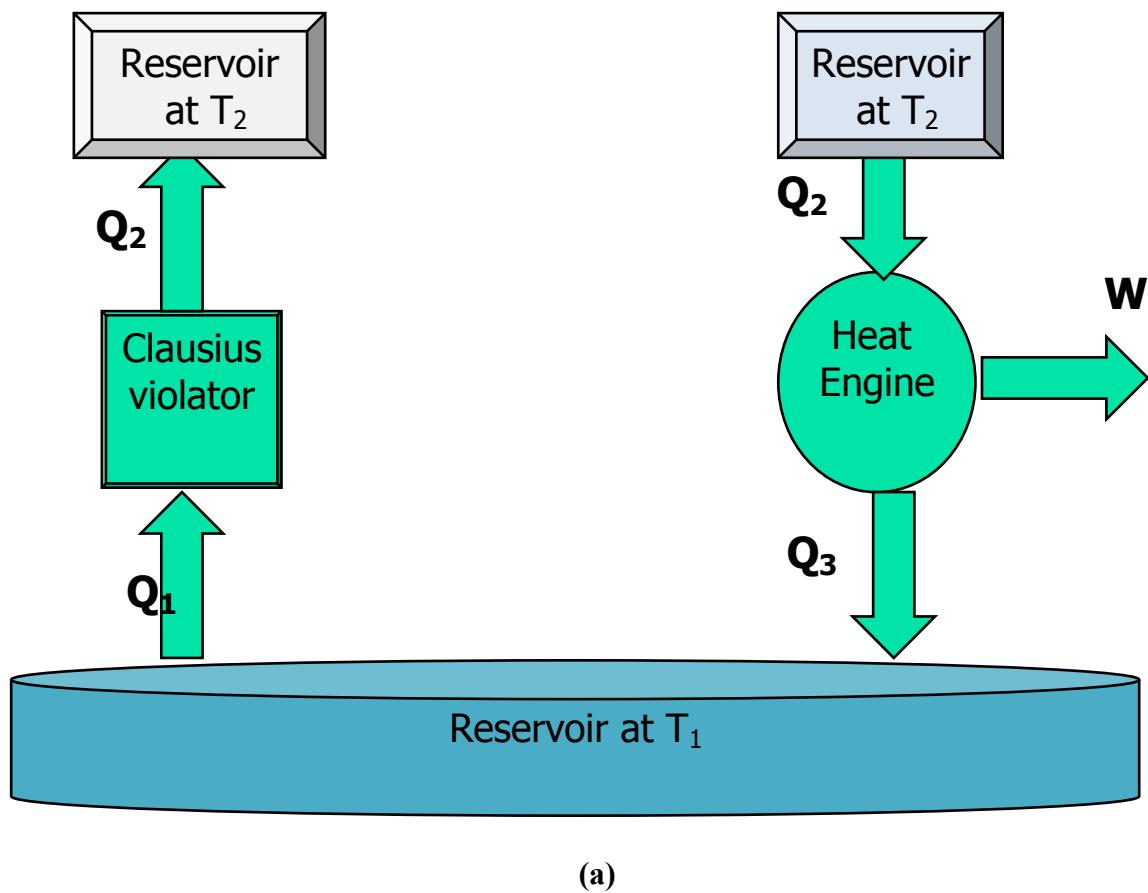
$$COP = \frac{Q_1}{Q_1 - Q_2} \quad (5.5)$$

5.3 Equivalence of Kelvin-Planck and Clausius Statements

The Clausius and Kelvin-Planck statements of the second law are entirely equivalent. This equivalence can be demonstrated by showing that the violation of either statement can result in violation of the other one. Referring to Figure 5.4(a) the device marked Clausius violator is

pumping Q_1 amount of heat from a low temperature reservoir at T_1 to a high temperature reservoir at T_2 without the aid of any external agency. This is an impossible arrangement.

If such an arrangement is possible it would also violate Kelvin-Planck statement. Let a heat engine operating between the same reservoirs at T_2 and T_1 take in Q_2 as heat input at T_2 . It converts a part of this heat into work and rejects heat Q_3 to the sink at T_1 . Since the Clausius violator is rejecting the same quantity Q_2 at T_2 , it can be supplied directly into the heat engine so that the reservoir at T_2 can be eliminated. This combination as shown in Figure 5.4 (b) is producing continuous work with a single reservoir at T_1 . Hence it violates the Kelvin-Planck statement.



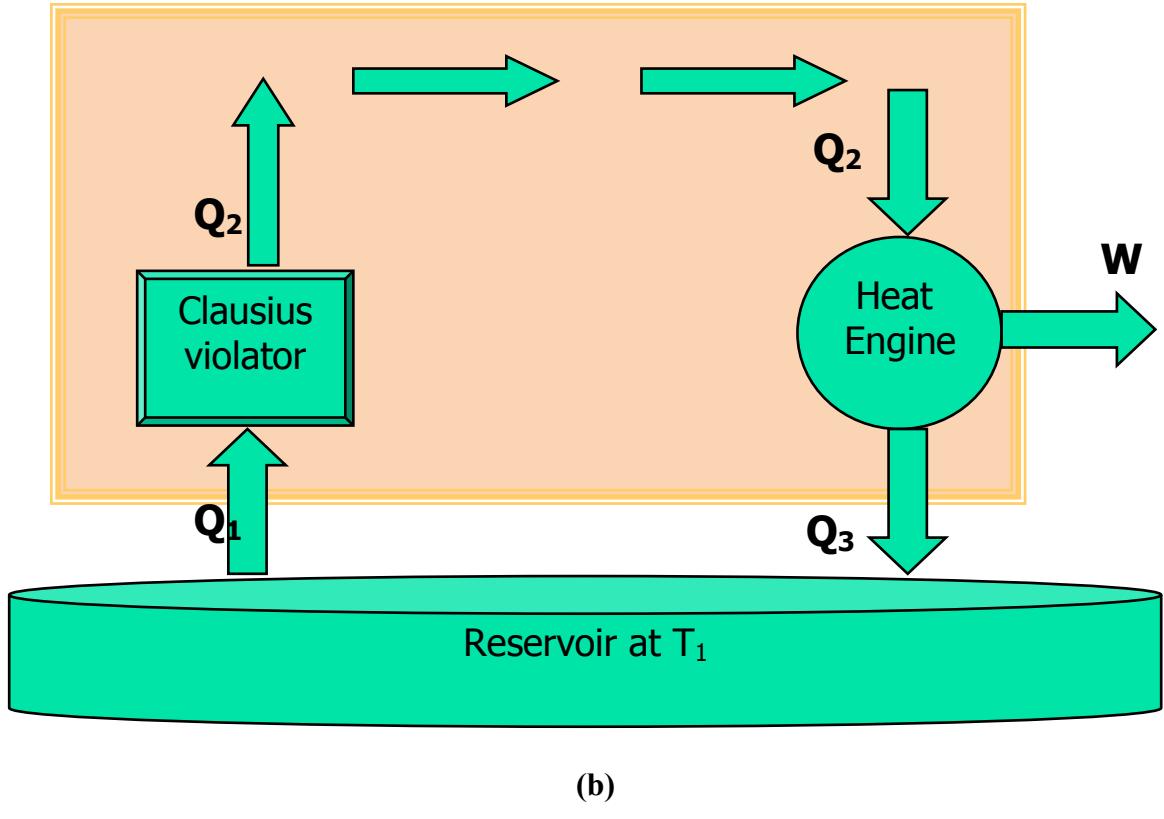


Figure 5.4 Illustration of the equivalence of Clausius and Kelvin-Planck's statement

Referring to Figure 5.4 a Kelvin-planck violator is converting all heat Q_H taken from the reservoir at T_H into work. If such an impossible heat engine is assumed to exist it will violate the Clausius statement. Consider a refrigerator pumping Q_L heat from the low temperature reservoir at T_L to the reservoir at higher temperature T_H . Combined with the Kelvin-Planck violator, the arrangement is pumping Q_L heat from T_L to T_H , without any external agency. Hence it violate the Clausius statement.

5.4 Reversible Process

A process is said to be reversible if it can be reversed without leaving any trace on the surroundings. For example, let a system be taken from state 1 to state 2 with a work transfer of +5 kJ and heat transfer of -10 kJ. If the process is reversible, while taking the system from state 2 to state 1, the work transfer must be -5 kJ and heat transfer must be +10 kJ. So that, both the system and surroundings are returned to their initial states at the end of the process 2 to 1.

5.5 Irreversibility and Causes of Irreversibility

The factors that make a process irreversible are known as irreversibilities. Various forms of irreversibilities are listed below.

- a) **Friction:** Friction occurs at the interface of two bodies moving relative to each other. It is the main cause of irreversibility in many processes. Energy spent in overcoming friction is dissipated in the form of heat which can never be restored.
- b) **Heat transfer:** Once heat is transferred from a body at higher temperature to a body at lower temperature, it can never be reversed without the aid of an external agency.
- c) **Unresisted expansion:** Consider a vessel with two chambers as given in the arrangement as shown in Fig. 5.6. If the members separating the gas from vacuum are removed, gas will expand and occupy the entire space. Since the expansion has no influence on the surroundings, there is no work output in this process. But to restore the initial arrangement, a definite work input is required.
- d) **Mixing of two gases:** Consider a vessel with two chambers, one with O_2 and the other with N_2 . When the member separating O_2 & N_2 is removed, uniform mixing is taking place without any work output. But such a process can not be reversed without any work input.
- e) **Throttling:** It is a totally irreversible process. Gas or vapour will expand through a restricted passage with its pressure decreasing rapidly without any work output. Such an expansion can not be reversed.

5.6 Externally and internally reversible processes

As mentioned earlier if no irreversibilities occur outside the system boundaries during the process, it is known as externally reversible. If no irreversibilities occur within the boundary of the system during a process, it is known as internally reversible process. For such a process, the path of the reverse process will follow exactly that of the forward process in any property diagram. To be totally reversible or simply reversible both external and internal irreversibilities must be ensured.

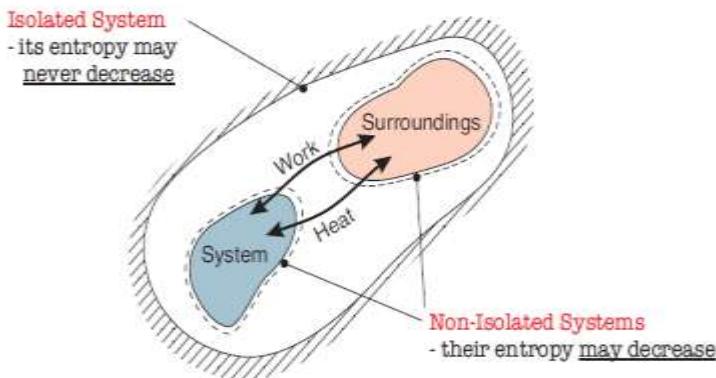
5.7 Entropy

The second law of thermodynamics states:

The entropy of an isolated system can never decrease. When an isolated system reaches equilibrium, its entropy attains the maximum value possible under the constraints of the system. Unlike mass and energy, entropy can be produced but it can never be destroyed. That is, the entropy of a system plus its surroundings (i.e. an isolated system) can never decrease (2nd law).

$$\left. \begin{array}{l} P_m = m_2 - m_1 = 0 \text{ (conservation of mass)} \\ P_E = E_2 - E_1 = 0 \text{ (conservation of energy)} \end{array} \right\} \text{1st law of thermodynamics}$$

$$P_S = S_{gen} = S_2 - S_1 \geq 0 \text{ 2nd law of thermodynamics}$$



The Clausius inequality applied to this irreversible cycle can be written as

$$\text{in general} \Rightarrow dS \geq \frac{\delta Q}{T}$$

Since the process B is internally reversible, this process can be reversed, and therefore

$$\int_1^2 \left(\frac{\delta Q}{T} \right)_A \underset{\text{reversible}}{\equiv} \int_1^2 dS_A \underset{\text{it is a property}}{\equiv} \int_1^2 dS_C$$

Or

$$\therefore \int_1^2 dS_C > \int_1^2 \left(\frac{\delta Q}{T} \right)_C \quad (6.6)$$

As defined in equation 6.5, since the process B being reversible the integral on the left hand side can be expressed as

$$\text{or } S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}$$

For a reversible process the elemental heat transfer

$$dQ = Tds = \text{Area of the strip}$$

To get the total heat transfer the above equation should be integrated between the limits 1 and 2, so that, we get

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} \quad (6.8)$$

Note: (we will see in chapter 6 in detail)

- For an isothermal process

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T}$$

- For reversible adiabatic process $S_2 - S_1 = 0$.

5.8 The Carnot Cycle

In 1824, Nicholas Sadi Carnot proposed a classical ideal cycle consisting of four processes. All processes are individually reversible and hence the cycle as a whole is a reversible cycle. The most efficient heat engine cycle is the Carnot cycle, consisting of two isothermal processes and two adiabatic processes. The Carnot cycle can be thought of as the most efficient heat engine cycle allowed by physical laws. With the practice of using reversible processes the study of the second law by disclosing a principle consisting of the following propositions.

1. No engine can be more efficient than a reversible engine operating between the same high temperature and low temperature reservoirs. Here the term heat reservoir is taken to mean either a heat source or a heat sink.
2. The efficiencies of all reversible engines operating between the same constant temperature reservoirs are the same.
3. The efficiency of a reversible engine depends only upon the temperatures of the heat source and heat receiver.

The processes that make up the Carnot cycle are:

Process 1-2

The working substance is taken in a piston cylinder arrangement as given in Figure 5.8(a). Heat is added reversibly and isothermally from a high temperature reservoir at TH. Since the process

is to be reversible, the temperature T_H of the reservoir should be equal to or infinitesimally greater than that of the working substance.

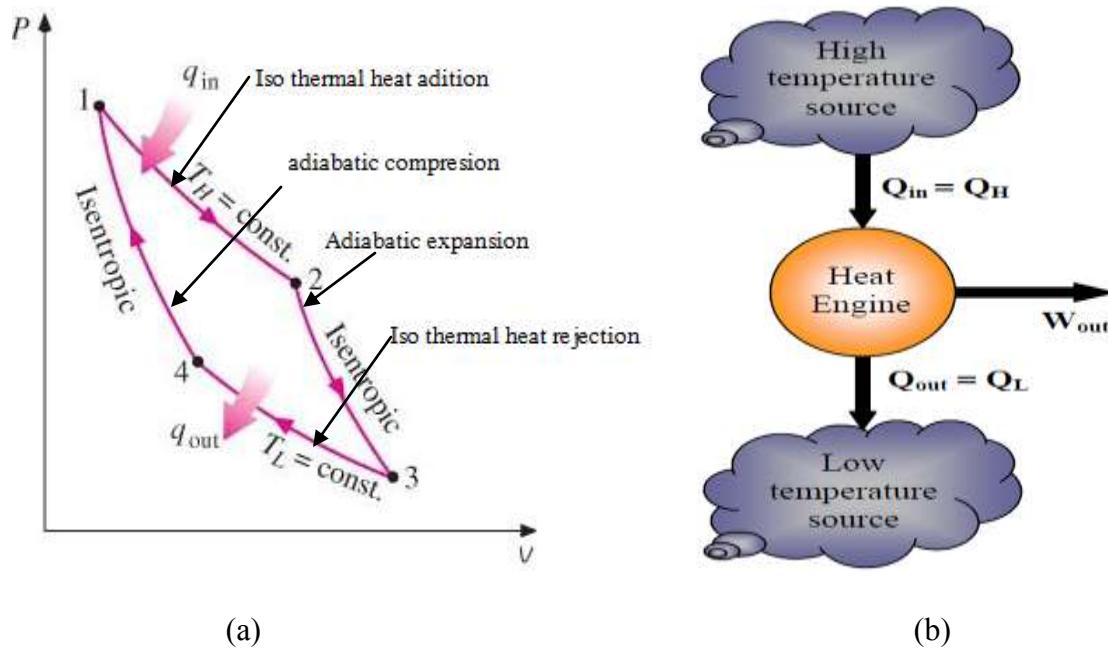


Figure 5.4 (a) P vs. V diagram and (b) heat engine illustration of Carnot cycle

Process 2-3

The working substance is allowed to expand reversibly and adiabatically until its temperature falls down to T_L . The process is represented by Figure 4.8(b)

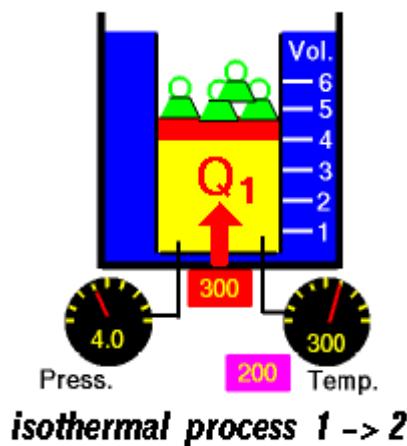


Figure 5.8(a)

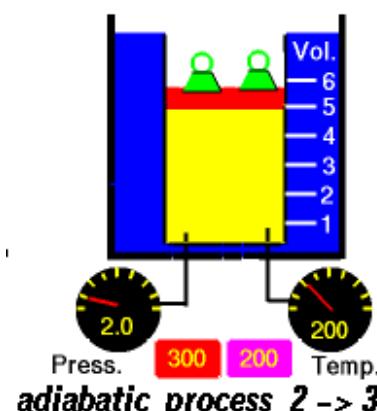


Figure 5.8(b)

Process 3-4

Heat is rejected by the working substance to a low temperature reservoir kept T_L or at temperature infinitesimally smaller than T_L .

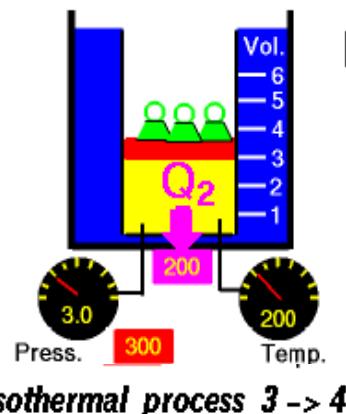


Figure 5.8(c)

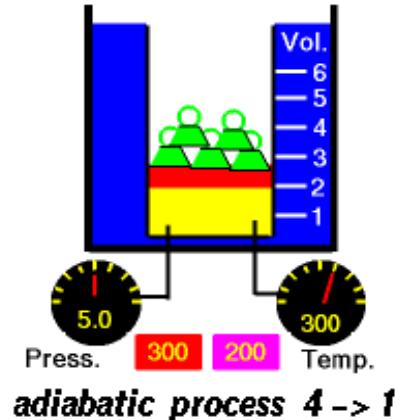


Figure 5.8(d)

Process 4-1

The working substance is then compressed reversibly and adiabatically until its temperature becomes T_H and the cycle continues. The cycle has been represented in a p-V diagram in Figure 4.9. The included area represents the net work done in the cycle. From first law of thermodynamics net workdone is equal to net heat transfer in the cycle. Since Q_H is the heat added to system and Q_L is the heat rejected by the system, the neat heat transfer is $Q_H - Q_L$.

$$\text{Efficiency of Carnot Engine} = \frac{W_{net}}{Q_{in}}$$

$$= \frac{Q_H - Q_L}{Q_{in}}$$

$$= 1 - \frac{Q_L}{Q_{in}}$$

Where, $Q_L = 3W_4 + U_4 - U_3$

Since the process is isothermal $U_4 = U_3$

$$\therefore Q_L = 3W_4$$

$$= P_3 V_3 \ln \left[\frac{P_3}{P_4} \right]$$

$$= mRT_L \ln \left[\frac{p_3}{p_4} \right]$$

$$\text{Similarly } Q_H = mRT_H \ln \left[\frac{p_2}{p_1} \right]$$

Process 2-3 is reversible adiabatic

$$\frac{T_2}{T_3} = \left[\frac{p_2}{p_3} \right]^{\left(\frac{\gamma-1}{\gamma} \right)} = \frac{T_H}{T_L}$$

Process 4-1 is also reversible adiabatic

$$\therefore \frac{T_1}{T_4} = \left[\frac{p_1}{p_4} \right]^{\left(\frac{\gamma-1}{\gamma} \right)} = \frac{T_H}{T_L}$$

From the above two expressions

$$\frac{p_2}{p_3} = \frac{p_1}{p_4}$$

$$\frac{p_2}{p_1} = \frac{p_3}{p_4}$$

Substituting the above condition we get

$$\begin{aligned} \eta_{Carnot} &= 1 - \frac{Q_L}{Q_{in}} = 1 - \frac{mRT_L \ln \left(\frac{p_3}{p_4} \right)}{mRT_L \ln \left(\frac{p_2}{p_1} \right)} \\ &= 1 - \frac{T_L}{T_H} \end{aligned}$$

It shows that efficiency of carnot engine is purely a function of T_H and T_L . Since the carnot cycle being completely reversible, if carried out in reverse direction, the magnitudes of all energy transfers remain the same but their sign change. This reversed carnot cycle can be applied for a refrigerator or a heat pump. Figure 4.10 shows the p-V diagram of a reversed carnot cycle.

Solved Problems

EXAMPLE 5.1:

A steam power plant receives 280 GJ/hr from a furnace. Heat is rejected at the rate of 145 GJ/hr and there is an additional 8 GJ loss through the pipes of the plant.

- a) What is the net power output from the plant?

$$\dot{W}_{\text{net}} = \dot{Q}_{\text{net}} = 280 - 145 - 8(\text{GJ} / \text{hr})$$

$$\dot{W}_{\text{net}} = 127 \frac{\text{GJ}}{\text{hr}} * \frac{10^3 \frac{\text{MJ}}{\text{GJ}}}{3600 \frac{\text{s}}{\text{hr}}} = 35.3 \text{MW}$$

- b) What is the plant efficiency, η ?

$$\eta = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{in}}} = \frac{127 \text{GJ} / \text{hr}}{280 \text{GJ} / \text{hr}} = 0.45$$

OR

$$\eta = 1 - \frac{\dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}} = 1 - \frac{(145 + 8)}{280} = 0.45$$

EXAMPLE 5.2:

A solar power plant has an efficiency of 0.03 and a net power output of 100 kw. At what rate must solar heat be collected for this plant?

$$\dot{Q}_{\text{in}} = \dot{Q}_{\text{h}} = \frac{\dot{W}_{\text{NET}}}{\eta} = \frac{100 \text{kw}}{0.03} = 3,333 \text{kw}$$

At what rate is heat rejected?

$$\dot{W}_{\text{NET}} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}} = \dot{Q}_{\text{h}} - \dot{Q}_{\text{l}}$$

$$\dot{Q}_{\text{l}} = 3,333 - 100 \text{kw} = 3,233 \text{kw}$$

EXAMPLE 5.3:

The compressor of a refrigerator runs 6 hours per day in order to continuously remove heat (24 hours/day) from the cold box at a rate of 1,200 kJ/hr. The coefficient of performance (COP_R) is 2.5. Find the required power input.

Solution:

$$COP_R = \frac{\dot{Q}_{\text{in}}}{\dot{W}_{\text{in}}} = \frac{\dot{Q}_{\text{in}} * 24 \text{hr} / d}{\dot{W}_{\text{in}} * 6 \text{hr} / d}$$

$$\dot{W}_{\text{in}} = \frac{\dot{Q}_{\text{in}}}{COP_R} * \frac{24}{6} = \frac{1,200 \text{kJ} / \text{hr} * 4}{2.5} = 1,920 \text{kJ} / \text{hr}$$

$$\frac{1,920 \text{kJ} / \text{hr}}{3600 \text{s} / \text{hr}} = 0.533 \text{kw}$$

EXAMPLE 5.4:

A house is to be cooled by an air conditioner with a $COP_R = 2.5$. The house contains 800 kg air at an initial temperature of 32°C . The house air is to be cooled to 20°C in 15 minutes. a) Find the required power input to the compressor.

Solution:

Write the 1st Law on the house air:

$$Q = \Delta U = mC_v(T_2 - T_1) = 800 \text{ kg}(0.72 \text{ kJ/kg-K})(20-32)\text{K} = -6,912 \text{ kw}$$

$Q_L = 6,912 \text{ kw}$ heat input to air conditioner. The rate of heat transfer required is:

$$\dot{Q}_L = \frac{6,915 \text{ kJ}}{15 \text{ min}} * \frac{1 \text{ min}}{60 \text{ s}} = 7.68 \text{ kW}$$

$$\dot{W}_{IN} = \frac{\dot{Q}_L}{COP_R} = \frac{7.68 \text{ kW}}{2.5} = 3.07 \text{ kW}$$

- a) What is the rate at which heat is rejected to the outdoors?

$$W_{IN} = Q_H - Q_L$$

$$7.68 \text{ kW} = Q_H - 3.07 \text{ kW}$$

$$Q_H = 10.8 \text{ kW}$$

EXAMPLE 5.5:

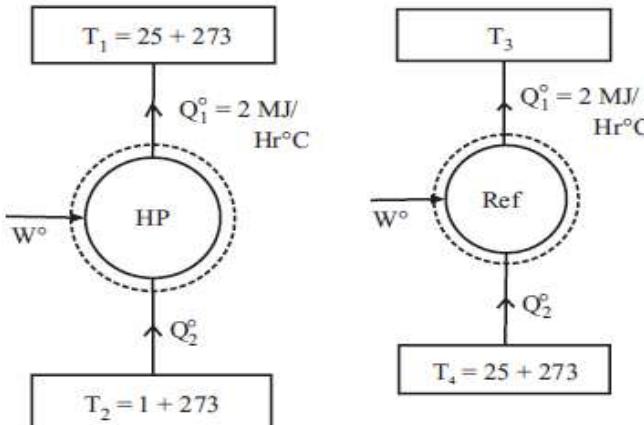
Heat pump is used for heating the premises in winter and cooling the same during summer such that temperature inside remains 25°C . Heat transfer across the walls and roof is found 2MJ per hour per degree temperature difference between interior and exterior. Determine the minimum power required for operating the pump in winter when outside temperature is 1°C and also give the maximum temperature in summer for which the device shall be capable of maintaining the premises at desired temperature for same power input.

Given that:

Temperature inside the room $T_1 = 25^\circ\text{C}$

Heat transferred across the wall = 2MJ/hr $^\circ\text{C}$

Outside temperature $T_2 = 1^\circ\text{C}$



To maintain the room temperature 25°C the heat transferred to the room = Heat transferred across the walls and roof.

$$Q_1 = 2 \times 106 \times (25 - 1)/3600 = 1.33 \times 104 \text{ J/sec} = 13.33 \text{ KW}$$

For heat pump

$$\text{COP} = T_1/(T_1 - T_2) = 298/(298 - 274) = 12.4167$$

Also COP = Heat delivered / Net work done = Q_1/W_{net}

$$12.4167 = 1.333 \times 104/W_{\text{net}}$$

$$W_{\text{net}} = 1073.83 \text{ J/sec} = 1.074 \text{ KW}$$

Thus the minimum power required by heat pump = 1.074 KW

Again, if the device works as refrigerator (in summer) Heat transfer

$$Q_1 = \{2 \times 106 / (60 \times 60)\} \times (T_3 - 298) \text{ Watt}$$

$$\text{Now COP} = Q_1/W_{\text{net}} = T_4/(T_3 - T_4)$$

$$[2 \times 106 \times (T_3 - 298)]/[60 \times 60 \times 1073.83] = 298/(T_3 - 298)$$

$$T_3 = 322 \text{ K} = 490 \text{ C}$$

EXAMPLE 5.6:

A cold storage of 100 Tonnes of refrigeration capacity runs at 1/4th of its carnot COP. Inside temperature is -15°C and atmospheric temperature is 35°C . Determine the power required to run the plant. Take one tonnes of refrigeration as 3.52KW.

Sol: Given that $T_{\text{atm}} = 35 + 273 = 308 \text{ K}$

$$T_{\text{inside}} = -15 + 273 = 258 \text{ K}$$

$$\text{COP} = T_{\text{inside}} / (T_{\text{atm}} - T_{\text{inside}}) = 258 / (308 - 258) = 5.16$$

$$\text{Again COP} = Q/W$$

$$5.16 \times \frac{1}{4} = 100 \times 3.52 / W$$

$$W = 272.87 \text{ KW}$$

Power required to run the plant is 272.87KW

EXAMPLE 5.7:

A reversible heat engine operates between two reservoirs at temperature of 600°C and 40°C . The Engine drives a reversible refrigerator which operates between reservoirs at temperature of 40°C and -20°C . The heat transfer to the heat engine is 2000KJ and net work output of combined engine refrigerator plant is 360KJ. Evaluate the heat transfer to the refrigerator and the net heat transfer to the reservoir at 40°C .

Solution:

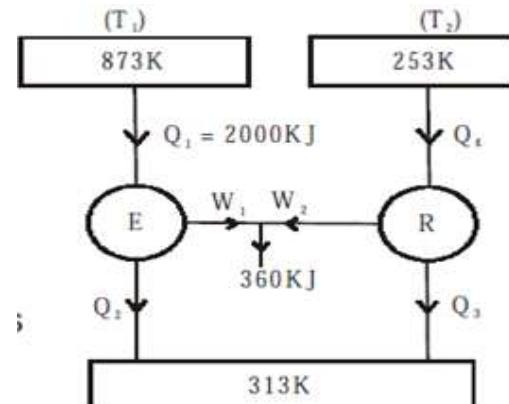
$$T_1 = 600 + 273 = 873\text{K}$$

$$T_2 = 40 + 273 = 313\text{K}$$

$$T_3 = -20 + 273 = 253\text{K}$$

Heat transfer to engine = 200KJ

Net work output of the plant = 360KJ



Efficiency of heat engine cycle,

$$\eta = 1 - T_2/T_1 = 1 - 313/873 = 0.642$$

$$W_1/Q_1 = 0.642 W_1 = 0.642 \times 2000 = 1284\text{KJ} \quad \dots \dots \dots \quad (i)$$

$$\text{C.O.P.} = T_3/(T_2 - T_3) = 253/(313 - 253) = 4.216$$

$$Q_4/W_2 = 4.216 \quad \dots \dots \dots \quad (ii)$$

$$W_1 - W_2 = 360; W_2 = W_1 - 360$$

$$W_2 = 1284 - 360 = 924\text{KJ}$$

From equation (ii)

$$Q_4 = 4.216 \times 924 = 3895.6\text{KJ}$$

$$Q_3 = Q_4 + W_2 = 3895.6 + 924$$

$$Q_3 = 4819.6\text{KJ} \dots \dots \text{ANS}$$

$$Q_2 = Q_1 - W_1 = 2000 - 1284$$

$$Q_2 = 716\text{KJ} \dots \dots \text{ANS}$$

Heat rejected to reservoir at 400°C = $Q_2 + Q_3 = 716 + 4819.6$

Heat rejected to reservoir at 400°C = 5535.6KJ

Heat transfer to refrigerator, $Q_4 = 3895.6\text{KJ}$

PROBLEMS

1. Describe an imaginary process that satisfies the second law but violates the first law of thermodynamics.
2. Describe an imaginary process that violates both the first and the second laws of thermodynamics.
3. An experimentalist claims to have raised the temperature of a small amount of water to 150°C by transferring heat from high-pressure steam at 120°C. Is this a reasonable claim? Why? Assume no refrigerator or heat pump is used in the process.
4. What is a thermal energy reservoir? Give some examples.
5. Consider the process of baking potatoes in a conventional oven. Can the hot air in the oven be treated as a thermal energy reservoir? Explain.
6. Consider the energy generated by a TV set. What is a suitable choice for a thermal energy reservoir? Heat Engines and Thermal Efficiency
7. Is it possible for a heat engine to operate without rejecting any waste heat to a low-temperature reservoir? Explain.
8. What are the characteristics of all heat engines?
9. Consider a pan of water being heated (a) by placing it on an electric range and (b) by placing a heating element in the water. Which method is a more efficient way of heating water? Explain.
10. Baseboard heaters are basically electric resistance heaters and are frequently used in space heating. A home owner claims that her 5-year-old baseboard heaters have a conversion efficiency of 100 percent. Is this claim in violation of any thermodynamic laws? Explain.
11. What is the Kelvin–Planck expression of the second law of thermodynamics?
12. Does a heat engine that has a thermal efficiency of 100 percent necessarily violate (a) the first law and (b) the second law of thermodynamics? Explain.
13. In the absence of any friction and other irreversibilities, can a heat engine have an efficiency of 100 percent? Explain.
14. Are the efficiencies of all the work-producing devices, including the hydroelectric power plants, limited by the Kelvin–Planck statement of the second law? Explain.

-
15. A 600-MW steam power plant, which is cooled by a nearby river, has a thermal efficiency of 40 percent. Determine the rate of heat transfer to the river water. Will the actual heat transfer rate be higher or lower than this value? Why?
16. A steam power plant receives heat from a furnace at a rate of 280 GJ/h. Heat losses to the surrounding air from the steam as it passes through the pipes and other components are estimated to be about 8 GJ/h. If the waste heat is transferred to the cooling water at a rate of 145 GJ/h, determine (a) net power output and (b) the thermal efficiency of this power plant.
Answers: (a) 35.3 MW, (b) 45.4 percent
17. A car engine with a power output of 110 hp has a thermal efficiency of 28 percent. Determine the rate of fuel consumption if the heating value of the fuel is 19,000 Btu/lbm.
18. A steam power plant with a power output of 150 MW consumes coal at a rate of 60 tons/h. If the heating value of the coal is 30,000 kJ/kg, determine the overall efficiency of this plant.
Answer: 30.0 percent
19. An automobile engine consumes fuel at a rate of 28 L/h and delivers 60 kW of power to the wheels. If the fuel has a heating value of 44,000 kJ/kg and a density of 0.8 g/cm³, determine the efficiency of this engine. Answer: 21.9 percent
20. Solar energy stored in large bodies of water, called solar ponds, is being used to generate electricity. If such a solar power plant has an efficiency of 4 percent and a net power output of 350 kW, determine the average value of the required solar energy collection rate, in Btu/h.
21. In 2001, the United States produced 51 percent of its electricity in the amount of 1.878 □ 1012 kWh from coal-fired power plants. Taking the average thermal efficiency to be 34 percent, determine the amount of thermal energy rejected by the coal-fired power plants in the United States that year.
22. The Department of Energy projects that between the years 1995 and 2010, the United States will need to build new power plants to generate an additional 150,000 MW of electricity to meet the increasing demand for electric power. One possibility is to build coal-fired power plants, which cost \$1300 per kW to construct and have an efficiency of 34 percent. Another possibility is to use the clean-burning Integrated Gasification Combined Cycle (IGCC) plants where the coal is subjected to heat and pressure to gasify it while removing sulfur and particulate matter from it. The gaseous coal is then burned in a gas turbine, and part of the waste heat from the exhaust gases is recovered to generate steam for the steam turbine.

Currently the construction of IGCC plants costs about \$1500 per kW, but their efficiency is about 45 percent. The average heating value of the coal is about 28,000,000 kJ per ton (that is, 28,000,000 kJ of heat is released when 1 ton of coal is burned). If the IGCC plant is to recover its cost difference from fuel savings in five years, determine what the price of coal should be in \$ per ton. 6–25 Reconsider Prob. 6–24. Using EES (or other) software, investigate the price of coal for varying simple payback periods, plant construction costs, and operating efficiency.

23. Repeat Prob. 6–24 for a simple payback period of three years instead of five years.
24. A heat pump that is used to heat a house has a COP of 2.5. That is, the heat pump delivers 2.5 kWh of energy to the house for each 1 kWh of electricity it consumes. Is this a violation of the first law of thermodynamics? Explain.
25. A refrigerator has a COP of 1.5. That is, the refrigerator removes 1.5 kWh of energy from the refrigerated space for each 1 kWh of electricity it consumes. Is this a violation of the first law of thermodynamics? Explain.
26. What is the Clausius expression of the second law of thermodynamics?
27. Show that the Kelvin–Planck and the Clausius expressions of the second law are equivalent.
28. A household refrigerator with a COP of 1.2 removes heat from the refrigerated space at a rate of 60 kJ/min. Determine (a) the electric power consumed by the refrigerator and (b) the rate of heat transfer to the kitchen air.

Answers:(a) 0.83 kW, (b) 110 kJ/min

29. An air conditioner removes heat steadily from a house at a rate of 750 kJ/min while drawing electric power at a rate of 6 kW. Determine (a) the COP of this air conditioner and (b) the rate of heat transfer to the outside air.

Answers:(a) 2.08, (b) 1110 kJ/min

30. A household refrigerator that has a power input of 450 W and a COP of 2.5 is to cool five large watermelons, 10 kg each, to 8°C. If the watermelons are initially at 20°C, determine how long it will take for the refrigerator to cool them. The watermelons can be treated as water whose specific heat is 4.2 kJ/kg · °C. Is your answer realistic or optimistic? Explain.

Answer: 2240 s

CHAPTER SIX

ENTROPY

The first law of thermodynamics treats all forms of work and heat on an equal basis: they all add up to the total energy, which then must be conserved. As far as the first law is concerned, there is no difference of quality between the different forms of energy. However, observations do show that heat and work are not equal: one can always transform work to heat, but the reverse is much more complicated and often not possible. Entropy is defined in terms of a calculus operation, and no direct physical picture of it can be given. In this chapter, Clausius inequality, which forms the basis for the definition of entropy, will be discussed first.

6.1 The Clausius Inequality

Consider two heat engines operating between two reservoirs kept at temperature T_H and T_L as shown in the Figure 6.1. Of the two heat engines, one is reversible and the other is irreversible.

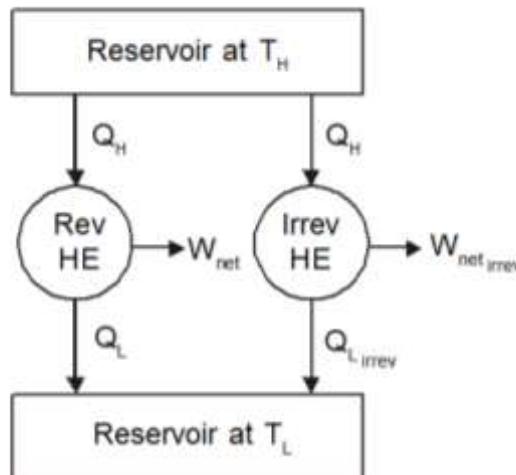


Figure 6.1: The system considered in the development of the Clausius inequality.

For the reversible heat engine it has already been proved that

$$\begin{aligned}\frac{Q_H}{Q_L} &= \frac{T_H}{T_L} \\ \frac{Q_H}{T_H} - \frac{Q_L}{T_L} &= 0 \\ \oint \left(\frac{dQ}{T} \right)_{rev} &= 0\end{aligned}$$

As discussed earlier, the work output from the irreversible engine should be less than that of the reversible engine for the same heat input Q_H . Therefore $Q_{L,Irrev}$ will be greater than $Q_{L,Rev}$. Let us define

$$Q_{L,Irrev} = Q_{L,Rev} + dQ$$

Then

$$\begin{aligned}\oint \left(\frac{dQ}{T} \right)_{Irrev} &= \frac{Q_H}{T_H} - \frac{Q_{L,Irrev}}{T_L} \\ &= \frac{Q_H}{T_H} - \frac{Q_{L,Rev}}{T_L} - \frac{dQ}{T_L} \\ &= 0 - \frac{dQ}{T_L} \\ &< 0\end{aligned}$$

By combining this result with that of a reversible engine we get

$$\oint \left(\frac{dQ}{T} \right)_{Irrev} \leq 0 \quad (6.1)$$

This is known as *Clausius inequality*.

6.2 Entropy

Clausius inequality forms the basis for the definition of a new property known as entropy. Consider a system taken from state 1 to state 2 along a reversible path A as shown in Figure 6.2. Let the system be brought back to the initial state 1 from state 2 along a reversible path B. Now the system has completed one cycle. Applying Clausius inequality we get

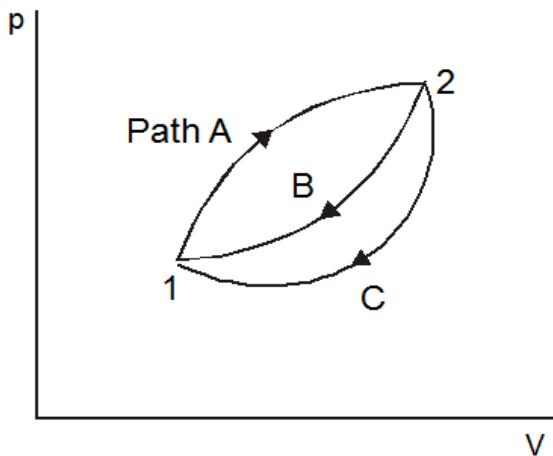


Figure 6.2: The entropy change between two specified states is the same whether the process is reversible or irreversible.

$$\oint \frac{dQ}{T} = 0 \quad (6.2)$$

$$\int_1^2 \left(\frac{dQ}{T} \right)_A + \int_2^1 \left(\frac{dQ}{T} \right)_B = 0$$

Instead of taking the system from state2 to state1 along B, consider another reversible path C. Then for this cycle 1-A-2-C-1, applying Clausius inequality:

$$\oint \frac{dQ}{T} = 0 \quad (6.3)$$

$$\int_1^2 \left(\frac{dQ}{T} \right)_A + \int_2^1 \left(\frac{dQ}{T} \right)_C = 0$$

Comparing 6.2 & 6.3

Hence, it can be concluded that the quantity is a point function, independent of the path followed. Therefore it is a property of the system. Using the symbol S for entropy we can write

$$dS \equiv \left(\frac{\delta Q}{T} \right)_{rev}, \text{ integrating } \rightarrow S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T} \right)_{rev} \quad (6.4)$$

For a reversible process

6.3 Entropy change for an irreversible process

The relationship between the entropy change and heat transfer across the boundary during an irreversible processes can be illustrated with a simple cycle composed of two processes, one of which is internally reversible and the other is irreversible, as shown in Figure 6.3. The Clausius inequality applied to this irreversible cycle can be written as

$$\text{in general } \Rightarrow dS \geq \frac{\delta Q}{T}$$

Since the process B is internally reversible, this process can be reversed, and therefore

$$\int_1^2 \left(\frac{\delta Q}{T} \right)_A \underset{\text{reversible}}{\equiv} \int_1^2 dS_A \underset{\text{it is a property}}{\equiv} \int_1^2 dS_C$$

$$\text{Or } \therefore \int_1^2 dS_C > \int_1^2 \left(\frac{\delta Q}{T} \right)_C \quad (6.6)$$

As defined in equation 6.5, since the process B being reversible the integral on the left hand side can be expressed as

$$\text{or } S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T} \quad (6.7)$$

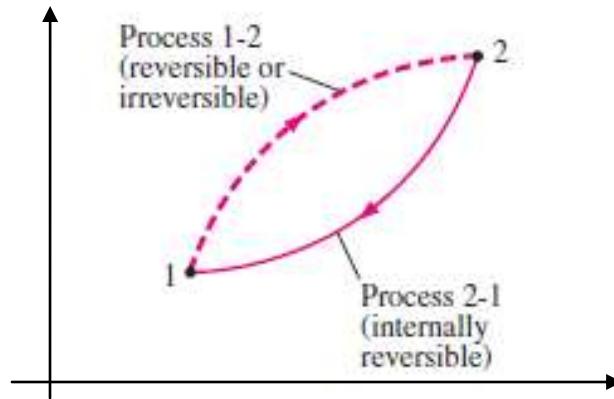


Figure 6.3: A cycle composed of a reversible and an irreversible process.

6.4 Temperature - Entropy diagram

In a T-s diagram consider a strip of thickness ds with mean height T as shown in Figure 6.4 below. Then Tds gives the area of the strip.

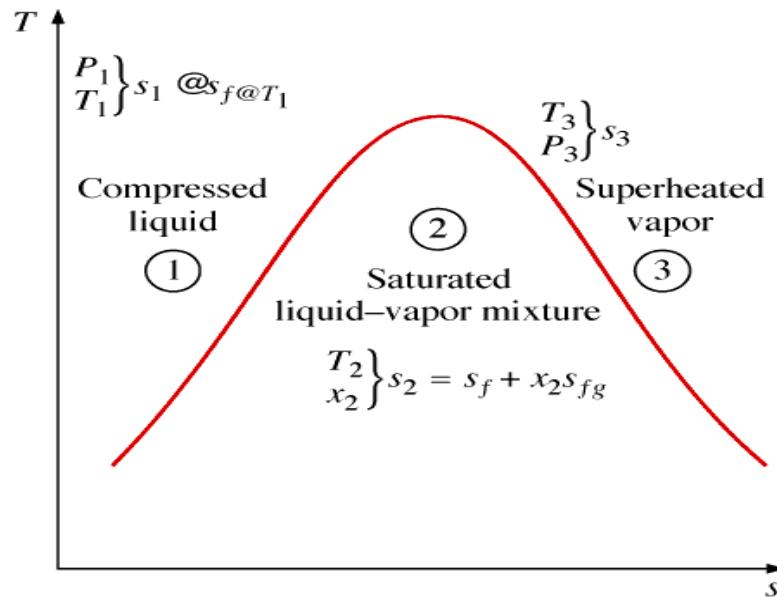


Figure 6.4: The entropy of a pure substance is determined from the tables (like other properties).

For a reversible process the elemental heat transfer

$$dQ = Tds = \text{Area of the strip}$$

To get the total heat transfer the above equation should be integrated between the limits 1 and 2, so that, we get

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} \quad (6.8)$$

This is equivalent to the area under a curve representing the process in a T-S diagram as shown in the Fig 5.4.

Note:

- For an isothermal process

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T}$$

- For reversible adiabatic process $S_2 - S_1 = 0$.

6.5 Change in Entropy

A) Solids and liquids

Change in entropy is:

$$ds = dq/T$$

Where $dq = du + pdv$

For solids and liquids

$$pdv = 0$$

$$ds = C \cdot dT/T$$

Where C - is the specific heat

$$s_2 - s_1 = C_{avg} \ln(T_2/T_1) \quad (6.9)$$

B) For ideal gases change in entropy

Recall the 1st and 2nd T·ds relationships. We substitute the ideal gas law for the last terms:

$$T \cdot ds = du + P \cdot dv = Cv \cdot dT + R \cdot T \cdot dv/v$$

Substituting

$$du = CvdT, \quad \text{We get}$$

$$T \cdot ds = Cv \cdot dT + R \cdot T \cdot dv/v$$

Divide by T and integrate:

$$s_2 - s_1 = C_{v,avg} \ln(T_2/T_1) + R \cdot \ln(v_2/v_1) \quad (6.10a)$$

Also $T \cdot ds = dh - v \cdot dP$

Substituting $dh = CpdT$, and we get



$$T \cdot ds = Cp \cdot dT - R \cdot T \cdot dP/P$$

Divide by T and integrate:

$$s_2 - s_1 = C_{p,\text{avg}} \ln(T_2/T_1) - R \cdot \ln(P_2/P_1) \quad (6.10b)$$

6.6 Principle of Increase in Entropy

$$\Delta S_{\text{total}} = \frac{Q}{T} + S_{\text{gen}} \quad ; \text{ Where } S_{\text{gen}} = \text{generated entropy}$$

For an isolated system undergoing a process

$$S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{sys}} + \Delta S_{\text{surr}} \geq 0 \quad (6.11)$$

Consider a system interacting with its surroundings. Let the system and its surroundings are included in a boundary forming an isolated system. Since all the reactions are taking place within the combined system, we can express

$$\Delta S_{\text{total}} = \sum_{i=1}^N \Delta S_i > 0 \quad (6.12)$$

Whenever a process occurs entropy of the universe (System plus surroundings) will increase if it is irreversible and remain constant if it is reversible. Since all the processes in practice are irreversible, entropy of universe always increases

$$\text{ie., } (\Delta s)_{\text{universe}} > 0 \quad (6.13)$$

This is known as principle of increase of entropy.

Summary

$$S_{\text{gen}} \begin{cases} > 0 & \text{irreversible process} \\ = 0 & \text{reversible process} \\ < 0 & \text{impossible process} \end{cases}$$

6.7 Adiabatic Efficiency of Compressors and Turbines

In steady flow compressors and turbines reversible adiabatic process is assumed to be the ideal process. But due to the irreversibilities caused by friction between the flowing fluid and impellers, the process is not reversible though it is adiabatic. Percentage deviation of this process from the ideal process is expressed in terms of adiabatic efficiency.

(a) Compressors:

Since compressors are work consuming devices actual work required is more than ideal work.

$$\eta_{isen,comp} \equiv \frac{\text{Isentropic compressor work}}{\text{Actual compressor work}} = \frac{w_s}{w_a} \quad (6.14)$$

For compressors handling ideal gases

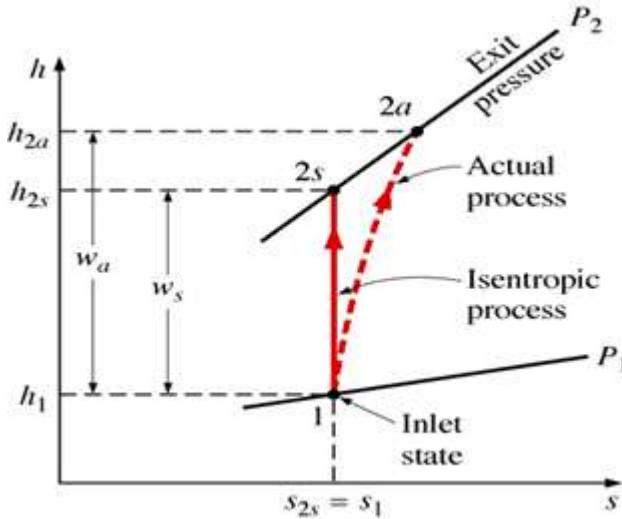


Figure 6.5: Percentage deviation of irreversibilities of compressors

$$\eta_{isen,comp} \equiv \frac{h_{2s} - h_1}{h_{2a} - h_1} \quad (6.15)$$

$0.75 < \eta_{isen,comp} \leq 0.85$ for Well-designed compressors.

(b) Turbines:

In turbine due to irreversibilities the actual work output is less than the isentropic work.

$$\eta_{isen,turb} \equiv \frac{\text{Actual turbine work}}{\text{Isentropic turbine work}} \quad (6.16)$$

For turbines handling ideal gases

$$\eta_{Turbine} = \frac{h_1 - h_{2a}}{h_1 - h_{2s}} \quad (6.17)$$

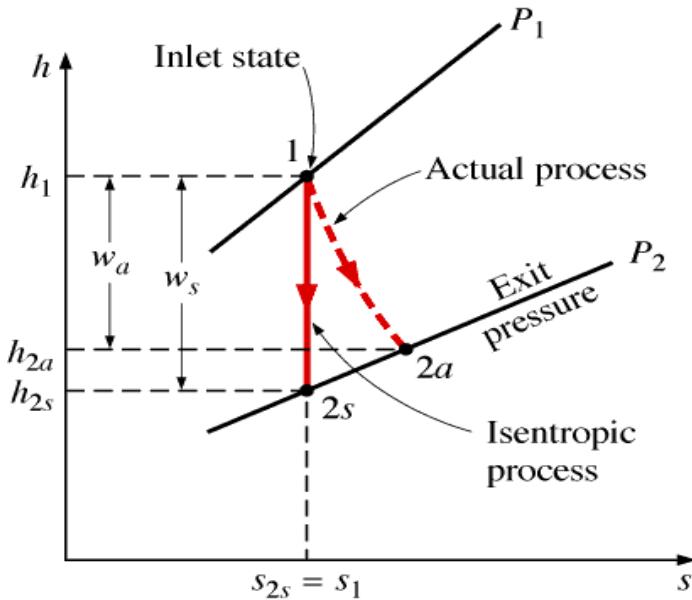


Figure 6.5: Percentage deviation of irreversibilities of turbines

$$\eta_{Turbine} = \frac{h_1 - h_{2a}}{h_1 - h_{2s}} \quad (6.17)$$

Solved Problems:

Example: 6.1

A body at 200°C undergoes an reversible isothermal process. The heat energy removed in the process is 7875 J. Determine the change in the entropy of the body.

System : Closed system

Known : $T_1 = T_2$
 $= 200^{\circ}\text{C}$
 $= 473 \text{ K}$

$Q_{\text{rejected}} = 7875 \text{ J}$ and $S_{\text{gen}}=0$

Process: Isothermal

To find: Δs

Analysis : $S_2 - S_1 = Q_{\text{rejected}}/T$; for an isothermal process

$$\begin{aligned} &= 7875/473 \\ &= - 16.65 \text{ J/K.} \end{aligned}$$

Comment: Entropy decreases as heat is removed from the system.

Example: 6.2

A mass of 5 kg of liquid water is cooled from 100°C to 20°C . Determine the change in entropy.



System : Closed system

Known : Mass of water = 5kg

$$T_1 = 100^\circ\text{C} = 373 \text{ K}$$

$$T_2 = 20^\circ\text{C} = 293 \text{ K}$$

Process : Constant pressure

To find : Change in entropy

Diagrams:

Assumptions: 1) The process is reversible

2) The specific heat of liquid water is constant

Analysis : $S_2 - S_1 = m C_{p,\text{avg}} \ln(T_2/T_1) - R \ln(p_2/p_1)$

For this problem

$$p_2 = p_1 \text{ & } C_p = 4.186$$

$$\therefore S_2 - S_1 = 5 * 4.186 \ln(293/373)$$

$$= -5.053 \text{ kJ}$$

Comment: Entropy decreases as heat is removed from the system.

Example: 6.3

Air is compressed isothermally from 100 kPa to 800 kPa. Determine the change in specific entropy of the air.

System: Closed/Open

Known: $p_1 = 100 \text{ kPa}$

$$p_2 = 800 \text{ kPa}$$

To find: ΔS - change in Specific entropy

Analysis : $\Delta S = C_{p,\text{avg}} \ln(T_2/T_1) - R \ln(p_2/p_1)$

$$= -R \ln(p_2/p_1) \quad [\text{Since the process is isothermal}]$$

$$= -0.287 \times \ln(800/100)$$

$$= -0.597 \text{ kJ/kgK.}$$

Example: 6.4

Liquid water enters a 10 kW pump at 100 kPa pressure at a rate of 5 kg/s. Determine the highest pressure the liquid water can have at the exit of the pump. Neglect the kinetic and potential energy changes of water and take the specific volume of water to be 0.001 m³/kg.



Conservation of Mass

$$\frac{dM}{d\tau} \Big|_{CV} = \dot{m}_{in} - \dot{m}_{out} \Rightarrow \dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

Conservation of Energy

Assume no energy storage, no heat transfer. Neglect changes in potential & kinetic energy.

$$\dot{E}_{system}^{\uparrow} = \dot{m}_{in} \cdot [h_{in} + ke_{in} + pe_{in}] - \dot{m}_{out} \cdot [h_{out} + ke_{out} + pe_{out}] + \dot{Q}_{in}^{\uparrow} - \dot{W}_{shaft} + \dots$$

Then:

$$\dot{W}_{shaft} = \dot{m} \cdot [(h_{in} - h_{out})]$$

Second Law Analysis

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{generated}$$

Assume an adiabatic process, $\delta Q = 0$ and a reversible process, $S_{gen} = 0$.

$$S_2 - S_1 = 0$$

If we then recall the 2nd T·dS relationship

$$T^{\uparrow} dS = dh - v \cdot dP$$

So that,

$$dh = v \cdot dP$$

Substitute this result back into the 1st Law result:

$$\dot{W}_{shaft} = -V \cdot \Delta P$$

$$10 \text{ kW} = -[(5 \text{ kg/s}) \cdot (0.001 \text{ m}^3/\text{kg})] \cdot [P_2 - 100 \text{ kPa}]$$

$$P_2 = 2100 \text{ kPa}$$

Example: 6.5

An insulated rigid vessel is divided into two chambers of equal volumes. One chamber contains air at 500 K and 2 MPa. The other chamber is evacuated. If the two chambers are connected, what would be the entropy change?

System: Closed system



Process: Unresisted expansion

Known: $T_1 = 500 \text{ K}$

$$p_1 = 2 \times 10^3 \text{ kPa}$$

To find: Entropy change

Analysis : $s_2 - s_1 = m C_{p,\text{avg}} \ln(T_2/T_1) - R \ln(p_2/p_1)$

After expansion air will occupy the entire volume of the container.

$$\therefore V_2 = 2V_1$$

Also $W_2 = 0$ since it is an unresisted expansion

$Q_{12} = 0$ since the vessel is insulated

Applying the first law of thermodynamics

$$Q_{12} = \Delta U + W_2$$

Therefore $\Delta U = 0$

For air $m c_v (T_2 - T_1) = 0$

i.e. $T_2 = T_1$

$$\begin{aligned} \text{Hence } s_2 - s_1 &= R \cdot \ln(v_2/v_1) \\ &= 0.287 \ln(2v_1/v_1) \\ &= 0.199 \text{ kJ/kgK} \end{aligned}$$

Comment : Though the process is adiabatic entropy increases as the process involving un resisted expansion is an irreversible process.

Example 6.6

A piston–cylinder device contains a liquid–vapor mixture of water at 300 K. During a constant-pressure process, 750 kJ of heat is transferred to the water. As a result, part of the liquid in the cylinder vaporizes. Determine the entropy change of the water during this process.

Solution:

Heat is transferred to a liquid–vapor mixture of water in a piston– cylinder device at constant pressure. The entropy change of water is to be determined.

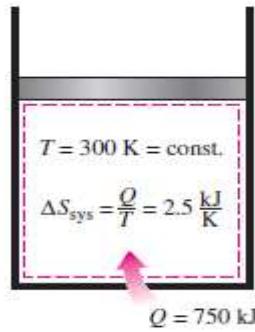


Figure 6.6: Schematic for Example 6.6.

Assumptions: No irreversibilities occur within the system boundaries during the process.

Analysis: We take the entire water (liquid _ vapor) in the cylinder as the system (Fig. 6–6). This is a closed system since no mass crosses the system boundary during the process. We note that the temperature of the system remains constant at 300 K during this process since the temperature of a pure substance remains constant at the saturation value during a phase change process at constant pressure. The system undergoes an internally reversible, isothermal process, and thus its entropy change can be determined directly from Eq. 7–6 to be

$$\Delta S_{\text{sys, isothermal}} = Q/T_{\text{sys}} = 750 \text{ kJ}/300 \text{ K} \\ = 2.5 \text{ kJ/K}$$

Discussion Note that the entropy change of the system is positive, as expected, since heat transfer is to the system.

Example 6.6

Consider a power plant. At point 1 the working gas has a temperature of $T = 25^\circ\text{C}$. The pressure is 1 bar and the mass flow is $m' = 2 \text{ kg/s}$. After point 1, the air enters a compressor, at which the pressure is increased to 6 bar. (This is point 2.) After this, the flow is heated to $T_3 = 700^\circ\text{C}$. (This is stage 3.) Afterwards, the flow goes through a turbine, at which the pressure is decreased to 1 bar again. (This is stage 4.) The flow is then cooled to $T_1 = 25^\circ\text{C}$. We're now back in stage 1.

We assume that:

1. Air behaves like a thermally and calorically perfect gas with $C_p = 1004 \text{ J/kgK}$, $R=287 \text{ J/kgK}$ and $n = 1.4$.
2. The isentropic efficiency of the compressor is 0.88.
3. The polytropic efficiency of the turbine is 0.85.

Answer the following questions.

1. Depict the evolution of the cycle in the T – s plane.
2. Determine the net power.
3. Determine the heat received from the hot source.
4. Determine the thermal efficiency of the power plant.
5. Determine the Carnot efficiency associated with the present power plant and compare it with the previous result.
6. Verify the first principle.

Solution:

1. Let's draw the T – s graph. We start by drawing two lines of constant pressure. (This can be seen in the graph below.) We now start at point 1. At this point the pressure and temperature are low. When we go to point 2, we don't go straight up, since the process is not isentropic. Instead, we go up and slightly right as well, until we reach the line $p = 6\text{bar}$. We then have found point 2. The heating takes place under constant pressure. So from point 2 to point 3 we stay on the isobaric line $p = 6\text{bar}$. This goes on until we reach $T = 973\text{K}$. This is the position of point 3. The turbine isn't isentropic either. So from point 3 we don't go straight down. Instead, we go down and a bit to the right as well, until we reach the line $p = 1\text{bar}$. This is point 4. From point 4 we return to point 1. Since the cooling occurs at constant pressure, we do this without leaving the line $p = 1\text{bar}$.

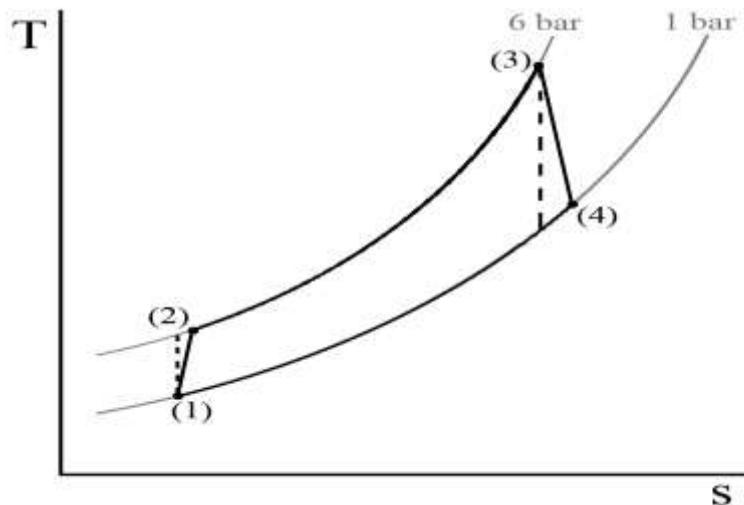


Figure 6.7: The T – s graph of the power plant.

2. Let's just calculate all the temperatures in all the points. First we'll find T_2 .

We know that $P_2/P_1 = 6$. We also know that $T_1 = 298K$. To find T_2 , we have to use the definition of the isentropic efficiency. For compression (and for constant c_p), this definition is

$$\eta_{is} = \frac{T_{2,is} - T_1}{T_2 - T_1}.$$

Here the variable $T_{2,is}$ is the temperature in point 2 if the compression would be performed isentropically. If the compression would be performed isentropically, we would be able to find T_2 using the isentropic relations. So, we can find $T_{2,is}$, using

$$\frac{P_2}{P_1} = \left(\frac{T_{2,is}}{T_1} \right)^{\frac{\gamma}{\gamma-1}}$$

It follows that $T_{2,is} = 497.2K$. We can then find that $T_2 = 524.4K$.

We already know that $T_3 = 973K$. To find T_4 , we have to look at the turbine. The only thing given about the turbine is the polytropic efficiency. If the pressure decreases (which is the case in a turbine), the polytropic efficiency is defined as

$$\eta_{poly} = \frac{n-1}{n} \frac{\gamma}{\gamma-1}.$$

We know γ and η_{poly} . We just need to solve for n . If we do this, we find that

$$n = \frac{\gamma}{\gamma - (\gamma - 1) \eta_{poly}} = 1.321.$$

Since a polytropic efficiency is given, we may assume that the process in the turbine is polytropic. So we have $pV^n = C$, with P the pressure and V the volume. Since the mass m in the turbine is constant (the process is steady), we also have $pvn = C$, with v the specific volume. The perfect gas law states that $v = RT/p$. Using this, we find that also $T^n p^{1-n}$ is constant. This implies that

$$\frac{P_3}{P_4} = \left(\frac{T_3}{T_4} \right)^{\frac{n}{n-1}}.$$

By inserting values, we find that $T_4 = 629.7K$. Now it's time to calculate the net power of the power plant. We know that the power used by the compressor is given by

$$P_{comp} = cpm \cdot (T_2 - T_1) = 455KJ/s.$$

Similarly, the power created by the turbine is given by

$$P_{turb} = cpm \cdot (T_3 - T_4) = 689KJ/s. \quad (1.7)$$



The net power produced by the entire power plant thus becomes

$$P_{\text{net}} = P_{\text{turb}} - P_{\text{comp}} = 234.8 \text{ KJ/s.}$$

This power is produced by the power plant, and thus, in a way, "flows" outward.

3. Let's calculate the heat received from the hot source. This is simply given by

$$Q_{\text{in}} = c_p m (T_3 - T_2) = 900.8 \text{ KJ/s.}$$

4. The thermal efficiency is "useful output" divided by "total input". The input is the heat received from the hot source. The output is the net work done by the power plant. So the thermal efficiency is

$$\eta_{\text{ther}} = \frac{P_{\text{net}}}{Q_{\text{in}}}$$

$$= 234.8 \text{ KJ/s} / 900.8 \text{ KJ/s} = 0.2606 = 26.06\%.$$

5. The Carnot efficiency (the maximally achievable efficiency) can be found using

$$\begin{aligned}\eta_{\text{Carnot}} &= 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H} \\ &= 1 - 298/973 = 0.6937 \\ &= 69.37\%.\end{aligned}$$

6. The first principle states that energy is conserved. The energy going into the system is the heat entering the system Q_{in} . The energy leaving the system is the net work P_{in} and the heat leaving the system Q_{out} . This heat is given by

$$Q_{\text{out}} = c_p m (T_4 - T_1) = 666.1 \text{ KJ/s.}$$

Now we see that

$$Q_{\text{in}} - P_{\text{net}} - Q_{\text{out}} = 900.8 - 234.8 - 666.1 = 0 \text{ KJ/s.}$$

Problems:

1. $S_2 - S_1 = 0$ for _____ processes
2. Entropy is a point function (True / False)
3. Entropy change of universe can never be negative (True / False)
4. All the isentropic processes are reversible adiabatic processes (True / False)
5. What is the difference between adiabatic and isentropic process?
6. A system is losing 500 kJ of heat at a constant temperature of 500 K. What is the change in entropy?



7. Area under any curve in T-s diagram represents _____.
8. $p = \text{constant}$ lines are steeper than $v = \text{constant}$ lines in T-S diagram (True/False)
9. During throttling process entropy _____ (Increases / Decreases) for an ideal gas.
10. Find the entropy change of the universe when 1000 kJ of heat is transferred from 800 K to 500 K.
11. Give the expression for change in entropy during isothermal processes and polytropic processes.
12. Calculate the change in entropy per kg of air when it expands isothermally from 6 bar to 3bar.
13. A closed system undergoes an adiabatic process. Work done on the system is 15 kJ/kg. The entropy change of the system
 - a) is positive
 - b) is negative
 - c) can be positive or negative
14. Give the interpretation of entropy from microscopic point of view.
15. A quantity of gas has an initial pressure, volume and temperature of 140 kPa, 0.14 m^3 and 25°C respectively. It is compressed to a pressure of 1.4 MPa according to the law $pV^{1.25} = C$. Determine the change in entropy
Take $c_p = 1.041 \text{ kJ/kgK}$, $c_v = 0.743 \text{ kJ/kgK}$.

Ans : - 0.207 kJ/kgK

16. 1 kg of air has a volume of 56 litres and a temperature of 190°C . The air then receives heat at constant pressure until its temperature becomes 500°C . From this state the air rejects heat at constant volume until its pressure is reduced to 700 kPa. Determine the change of entropy during each process, stating whether it is an increase or decrease.

Ans : 0.516 kJ/kgK, an increase – 0.88 kJ/kgK, an decrease

17. A quantity of gas has an initial pressure, volume and temperature of 1.1 bar, 0.16 m^3 and 18°C respectively. It is compressed isothermally to a pressure of 6.9 bar. Determine the change of entropy. Take $R = 0.3 \text{ kJ/kgK}$.

Ans : -0.111 kJ/K



-
18. A reversible heat engine shown in figure below operates between three constant temperature reservoirs at 600 K, 400 K and 300 K. It receives 2500 kJ of energy of heat from the reservoir at 600 K and does 1000 kJ of work. Determine the heat interactions with the other two reservoirs.

Ans : $Q_2 = 1008$, $Q_3 = 4926$

19. A block of copper with a mass of 1.5 kg is initially at 700 K. It is allowed to cool by means of heat transfer to the surrounding air at 300 K. Determine the change in entropy of the copper and change in entropy of the universe after copper reaches thermal equilibrium. Assume specific heat of copper is 0.39 kJ/kgK.

Ans : -0.4967 kJ/K , $+0.2843 \text{ kJ/K}$

20. Using the principle of increase in entropy prove that the heat transfer is always from a high-temperature body to a low temperature body.
21. Nitrogen at 420 K and 1.4 MPa is expanded reversibly and adiabatically in a nozzle to exit pressure of 700 kPa. Determine the temperature and velocity of the nitrogen at the exit of the nozzle. Take $\gamma_{\text{N}_2} = 1.40$.

22. A vessel is divided into two temperature by means of a membrane as shown in the figure given below. What will be the final state of air and change in entropy of the universe if the membrane is removed.

Ans : $P_f = 750.14 \text{ kPa}$, $T_f = 65.11^\circ\text{C} = 0.373$

23. A given gaseous system undergoes an isentropic process from state1 to state 2.
- Combine the two relations $pV = RT$ and $pV^\gamma = C$ and show that
 - Integrate the two expressions, using $pV^\gamma = C$ and show that is γ times by comparison.
24. During the isentropic process of 1.36 kg/s of air, the temperature increases from 4.44°C to 115.6°C . For a non-flow process and for a steady flow process find
- Change in internal energy
 - Work done
 - Change in enthalpy
 - Change in entropy and
 - Heat transfer

25. Air at 5 bar, 100°C , expands reversibly in a piston-cylinder arrangement. It expands to 2 bar in an isothermal process. Calculate



- (a) heat transfer per unit mass of air
(b) change in specific internal energy
(c) change in specific entropy
26. One kg of air at 1 bar, 20°C , is compressed according to the law $\text{pv}^{1.3} = \text{constant}$ until the pressure is 5 bar. Calculate the change in entropy and sketch the process on a T-S diagram indicating the area representing the heat flow.
27. 1 kg of air at 1 bar, 25°C , changes its state to 6 bar and a volume of 1 m^3 . Calculate the change of entropy and sketch the initial and final state points on the p-v and T-S fields.
28. 0.5 m^3 ethane (C_2H_4) at 7 bar, 260°C expand isentropically in a cylinder behind a piston to 1 bar, 100°C . Calculate the workdone in expansion assuming ethane as perfect gas. The same mass is now recompressed back to 7 bar according to the law $\text{pv}^{1.35} = \text{constant}$. Calculate the final temperature and the heat transfer. Calculate also the change in entropy and sketch both process on the p-v and T-S fields. Take $C_p = 1.766 \text{ kJ /Kg .K}$ for ethane.
29. A mass m of water at T_1 is mixed with equal mass of water at T_2 at the same pressure in an insulated mixing chamber. Show that the entropy change of the Universe is given as
30. An ideal vapour absorption refrigeration system may be considered as the combination of the reversible heat engine operating a reversible refrigerator as given in the following diagram. Obtain the COP of the refrigeration system which is defined as the ratio of Q_e to Q_g .
32. Vapour absorption heat transformer is a novel device used for upgrading a portion of waste heat from low temperature to high temperature. An ideal vapour absorption heat transformer may be considered as the combination of the reversible heat engine operating a reversible heat pump as given in the following diagram. Obtain the COP of the vapour absorption heat transformer which is defined as the ratio of Q_a to $(Q_g + Q_e)$.



CHAPTER SEVEN

Available Energy, Availability and Irreversibility

From second law of thermodynamics we found that complete conversion of heat into work is not possible in a continuous process. Also it has been proved that the most efficient cycle to produce work is a reversible power cycle (Carnot cycle). Even in carnot cycle, the efficiency of conversion can never be unity and hence to establish a comparison of the work-energy conversion in actual processes, the maximum theoretical work obtainable with respect to some datum must be determined. This chapter is dedicated for this objective.

7.1 Available and Unavailable Energy

The energy content of a system can be divided into two parts

- Available energy, which under ideal conditions may be completely converted into work
- Unavailable energy which is usually rejected as waste

Consider Q units of heat energy available at a temperature T . Available part of energy can be obtained by assuming that the heat is supplied to a Carnot engine. Work obtained from the carnot engine $\left(\frac{T - T_0}{T}\right)Q$ is the available part. The quantity $\left(\frac{T_0}{T}\right)Q$ is the unavailable part. In a T-S diagram these quantities can be represented as shown in the fig 6.1. The term T_0 is the ambient temperature. Hence it can be concluded that the available and unavailable part of energy content of a system depends on the ambient conditions also.

7.2 Reversible Work In A Non-flow Process

From first law of thermodynamics

$$Q_{\text{sys}} - W = U_2 - U_1 \quad 7.1$$

From second law of thermodynamics for a reversible process

$$(\Delta s)_{\text{universe}} = (\Delta s)_{\text{system}} + (\Delta s)_{\text{surroundings}}$$

$$\Delta s_{\text{universe}} = (\Delta s)_{\text{cv}} + (\Delta s)_{\text{surr}} = 0 \quad 7.2$$



Where, $(\Delta s)_{\text{system}} = S_2 - S_1$

$$(\Delta s)_{\text{surroundings}} = \frac{Q_{\text{surr}}}{T_{\text{surr}}} = \frac{-Q_{\text{sys}}}{T_o}$$

Where,

$$Q_{\text{system}} = T_o (S_2 - S_1) \quad 7.3$$

Substituting in 6.1 we get

$$\begin{aligned} T_o(S_2 - S_1) - W &= U_2 - U_1 \\ \therefore W &= (U_2 - U_1) - (S_1 - S_2) \end{aligned}$$

Since the process is reversible W can be represented W_{rev}

$$\therefore W_{\text{rev}} = (U_1 - U_2) - T_o (S_1 - S_2) \quad 7.4$$

This is also the maximum work in the process.

For a closed system, when undergoing change in volume, the work done against the atmospheric pressure:

$$W_{\text{atm}} = p_o (V_2 - V_1)$$

But this work is not an useful work and hence

$$\begin{aligned} W_{\text{max,useful}} &= W_{\text{max}} - W_{\text{atm}} \\ &= [(U_1 - U_2) - T_o (S_1 - S_2)] - p_o (V_2 - V_1) \\ &= (U_1 - U_2) + P_o (V_1 - V_2) - T_o (S_1 - S_2) \end{aligned} \quad 7.5$$

7.3 Reversible Work In A Steady-state Control Volume

Steady flow energy equation for a constant volume is

$$\dot{Q} - \dot{W}_{\text{rev}} = \sum_{\text{out}} \dot{m}_{\text{out}} \left(h + \frac{C^2}{2} + gZ \right) - \sum_{\text{in}} \dot{m}_{\text{in}} \left(h + \frac{C^2}{2} + gZ \right)$$

For a single inlet and outlet

$$\dot{Q} - \dot{W}_{\text{rev}} = \dot{m} \left[(h_2 - h_1) + \left(\frac{C_2^2 - C_1^2}{2} \right) + g(Z_2 - Z_1) \right] \quad 7.6$$

From Second law of thermodynamics

$$\Delta s_{\text{universe}} = (\Delta s)_{\text{cv}} + (\Delta s)_{\text{surr}} = 0$$

Where:

$$\Delta s_{\text{cv}} = \dot{m}[(S_2 - S_1)]$$

$$\Delta s_{sur} = \frac{-\dot{Q}}{T_o}$$

Substituting these values we get

$$\begin{aligned}\dot{m}(s_2 - s_1) &= \frac{\dot{Q}}{T_o} \\ \dot{Q} &= T_o \dot{m}(s_2 - s_1)\end{aligned}$$

From eqn 7.6 neglecting kinetic and potential energy changes

$$\dot{W}_{rev} = \dot{m}[(h_1 - h_2) - T_o(s_1 - s_2)] \quad 7.7$$

In an open system a fixed volume in space known as control volume is taken for analysis. Hence the atmospheric work term $p_0(V_1 - V_2)$ should not be considered. Therefore

$W_{rev} = W_{max,useful}$ for an open system

7.4 Availability

The maximum useful work that can be obtained from the system such that the system comes to a dead state, while exchanging heat only with the surroundings, is known as availability of the system. Here the term dead state means a state where the system is in thermal and mechanical equilibrium with the surroundings.

Therefore for a closed system availability can be expressed as

$$\phi = (U - U_o) + p_o(V - V_o) - T_o(S - S_o)$$

Similarly for an open system

$$\psi = (H - H_o) - T_o(S - S_o)$$

In steady flow systems the exit conditions are assumed to be in equilibrium with the surroundings. The change in availability of a system when it moves from one state to another can be given as:

For a closed system

$$\phi_1 - \phi_2 = (U_1 - U_2) + p_o(V_1 - V_2) - T_o(S_1 - S_2)$$

7.10

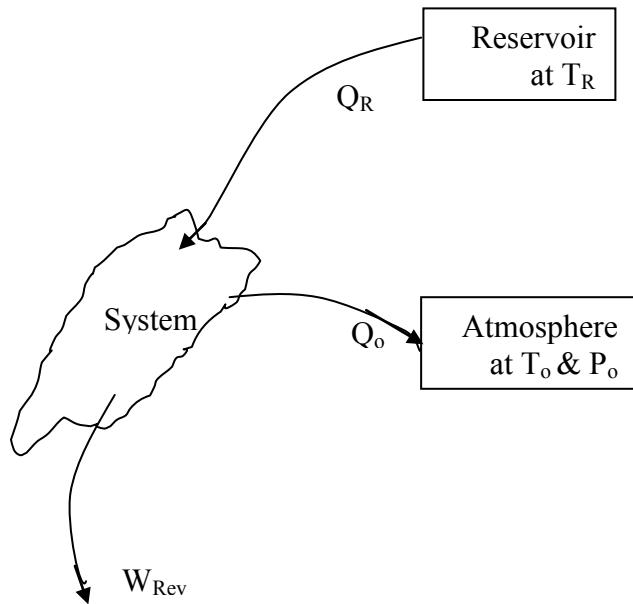
For an open system

$$\psi_1 - \psi_2 = (H_1 - H_2) - T_o(S_1 - S_2).$$

7.11

7.5 Availability Change Involving Heat Exchange with Reservoirs

Consider a system undergoing a change of state while interacting with a reservoir kept at T_R and atmosphere at pressure p_o and temperature T_o . Net heat transfer to the system



$$Q_{net} = Q_R - Q_O.$$

From first law of thermodynamics

$$Q_{net} - W_{rev} = U_2 - U_1 \quad 7.12$$

From second law of thermodynamics, assuming the process to be reversible

$$(\Delta s)_{Res} + (\Delta s)_{atm} + (\Delta s)_{sys} = 0$$

$$\frac{-Q_R}{T_R} + \frac{Q_o}{T_o} + (S_2 - S_1) = 0$$

The negative sign for Q_R shows that the heat is removed from the reservoir.

By rearranging we get

$$Q_o = Q_R \frac{T_o}{T_R} + T_o(S_1 - S_2)$$



Net heat transferred

$$Q_{\text{net}} = Q_R - Q_o$$

$$Q_{\text{net}} = Q_R - Q_R \frac{T_o}{T_R} - T_o(S_1 - S_2) \quad 7.13$$

Substituting 7.13 in 6.12 we get

$$\begin{aligned} Q_R - Q_R \frac{T_o}{T_R} - T_o(S_1 - S_2) - W_{\text{rev}} &= U_2 - U_1 \\ W_{\text{rev}} &= U_1 - U_2 - T_o(S_1 - S_2) + Q_R \left(1 - \frac{T_o}{T_R}\right) \end{aligned} \quad 7.14$$

$$W_{\max, \text{useful}} = U_1 - U_2 + p_o(V_1 - V_2) - T_o(S_1 - S_2) + Q_R \left(1 - \frac{T_o}{T_R}\right) \quad 7.15$$

7.6 Irreversibility

Work obtained in an irreversible process will always be less than that of a reversible process. This difference is termed as irreversibility (i.e) the difference between the reversible work and the actual work for a given change of state of a system is called irreversibility.

$$I = W_{\text{rev}} - W_{\text{act}}$$

Let a stationary closed system receiving Q kJ of heat is giving out W_{act} kJ of work.

From first law of thermodynamics

$$Q - W_{\text{act}} = U_2 - U_1$$

$$W_{\text{act}} = U_1 - U_2 + Q$$

$$W_{\text{rev}} = (U_1 - U_2) - T_o(S_1 - S_2)$$

$$= (U_1 - U_2) + T_0(\Delta s) \text{ system}$$

$$\therefore I = W_{\text{rev}} - W_{\text{act}}$$

$$= (U_1 - U_2) + T_0(\Delta s) \text{ system} - (U_1 - U_2) - Q$$

$$= T_0(\Delta s) \text{ system} - Q \quad \text{Where } Q = -Q_{\text{surroundings}} = T_0(\Delta s) \text{ surroundings}$$

$$= T_0(\Delta s) \text{ system} + T_0 \Delta s_{\text{surroundings}}$$

$$= T_0(\Delta s) \text{ universe}$$

Since (Δs) universe will be positive for an irreversible flow, irreversibility will be zero for a reversible process and will never be negative.

$$I \geq 0$$

Similarly for a steady flow system

$$I = W_{rev} - W_{act}$$

Where;

$$\begin{aligned}\dot{W}_{rev} &= \dot{m}[(h_1 - h_2) - T_o(s_1 - s_2)] \\ W_{act} &= \dot{m}[(h_1 - h_2)] + Q_{sys}\end{aligned}$$

$$Q_{sys} = Q_o = T_o \Delta s_{surroundings}$$

$$\begin{aligned}\text{Therefore;} \quad I &= T_o(S_1 - S_2) + T_o \Delta s_{surroundings} \\ &= T_o [\Delta s_{sys} + \Delta s_{surroundings}] \\ &= T_o [\Delta s_{universe}]\end{aligned}$$

Solved problems:

- In a certain process a vapor while condensing at 420°C transfers heat to water evaporating at 250°C . The resulting steam is used in a power cycle, which rejects heat at 35°C . What is the fraction of the available energy in the heat transfer from the process vapor at 420°C that is lost due to irreversible heat transfer at 250°C .

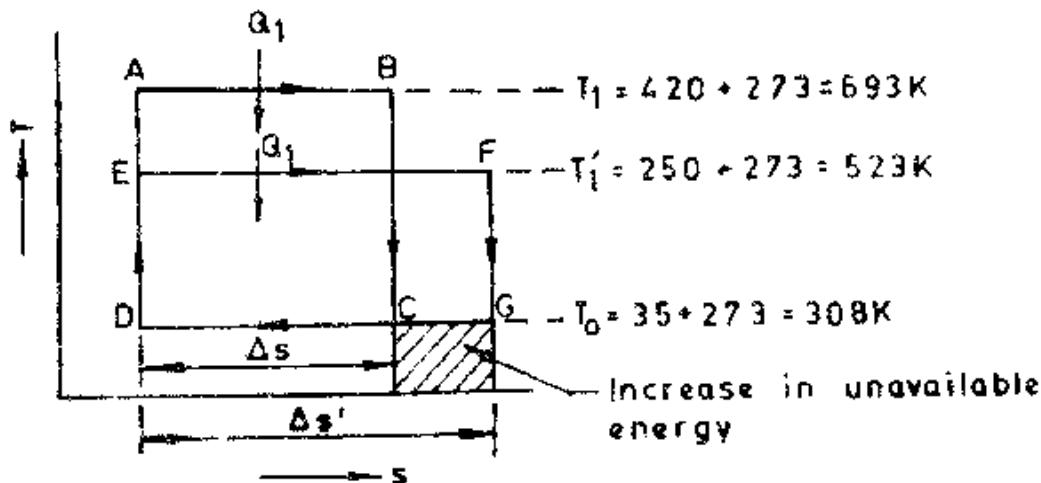


Fig 6: Increase in unavailable energy

Solution:

ABCD would have been the power cycle if there was no temperature difference between the vapor condensing and the water evaporating, and the area under CD would have been the unavailable energy at 35^o C. EFGD is the power cycle when the vapor condenses at 420^o C and the water evaporates at 250^o C. The unavailable energy becomes the area under DG. Therefore the increase in available energy due to irreversible heat transfer is represented by the area under CG.

$$Q_1 = T_1 \Delta S = T_1' \Delta S' = \Delta S / \Delta S' = T_1 / T_1'$$

$$W = \text{work done in cycle ABCD} = (T_1 - T_o) \Delta S$$

$$W = \text{work done in cycle EFGD} = (T_1 - T_o) \Delta S$$

The fraction of energy that becomes unavailable due to irreversible heat transfer

$$\begin{aligned} &= (W - W') / W = [T_o(\Delta S' - \Delta S)] / [(T_1 - T_o) \Delta S] \\ &= T_o [(\Delta S / \Delta S') - 1] / (T_1 - T_o) = T_o (T_1 - T_1') / T_1 (T_1 - T_o) \\ &= [308(693 - 523)] / [523(693 - 308)] = 0.26 \quad \text{Ans.} \end{aligned}$$

2. Air expands through a turbine from 500 kPa, 520^o C to 100 kPa, 300^o C. during expansion 10KJ of heat is lost to the surroundings which is at 98 kPa, 20^o C. neglecting KE and PE changes determine per kg of air a) the decrease in availability b) the maximum work c) the irreversibility.

Solution:

For air the change in entropy is given by $S_2 - S_1 = [mC_p \ln(T_2/T_1) - mR \ln(P_2/P_1)]$

For 1kg of air $s_2 - s_1 = C_p \ln(T_2/T_1) - R \ln(P_2/P_1)$

The change in availability is given by, $(\Psi_1 - \Psi_2) = b_1 - b_2 = (h_1 - T_o s_1) - (h_2 - T_o s_2)$

$$\begin{aligned} &= (h_1 - h_2) - T_o(s_1 - s_2) = C_p(T_1 - T_2) - T_o(C_p \ln(T_2/T_1) - R \ln(P_2/P_1)) \\ &= 1.005(520 - 300) - 293(1.005 \ln(573/793) - 0.287 \ln(1/5)) \\ &= 1.005(220) 293 (-0.4619 + 0.3267) = 221.1 + 39.6 = 260.7 \text{ kJ/kg} \end{aligned}$$

$W_{\max} = \text{Change in availability} = (\Psi_1 - \Psi_2) = 260.7 \text{ kJ/kg}$

From SSSF equation we have

$$Q + h_1 = W + h_2 \text{ or } W = (h_1 - h_2) + Q = 1.005(520 - 300) - 10 = 211.1 \text{ kJ/kg}$$

Thus the irreversibility $I = W_{\max} - W = 260.7 - 211.1 = 49.6 \text{ kJ/kg}$ Ans.

3. Consider a steam turbine that has throttle governor. The steam in the pipeline flowing through the turbine has a pressure of 3 MPa and a temperature of 360 °C. At certain load the steam is throttled in an adiabatic process to 1.5 MPa. Calculate the availability per kg of steam before and after the process and the reversible work and irreversibility per kg of steam for this process. Assume $T_0 = 25^\circ\text{C}$ $p_0 = 1 \text{ bar} = 0.1 \text{ MPa}$

Solution:

The availability at the initial condition

$$\begin{aligned} &= (h_i - h_o) - T_0(s_i - s_o) = (3140.9 - 104.9) - 298 (6.7844 - 0.3664) \\ &= 3036 - 1912.38 = 1123.62 \text{ kJ/kg} \quad \text{Ans.} \end{aligned}$$

Similarly availability at 1.5MPa after adiabatic throttling $= (h_e - h_o) - T_0(s_e - s_o)$

Since in adiabatic throttling $h_e = h_i = 3140 \text{ kJ/kg}$ and adiabatic $Q = 0$.

Therefore s_e from the steam table corresponding to $h_e = 3140.9 \text{ kJ/kg}$ and $1.5 \text{ MPa} = 7.0833 \text{ kJ/kg K}$.

$$\text{Thus } \Psi_e = (3140.9 - 104.9) - 298 (7.0833 - 0.3664) = 3036.13 - 2001.46 = 1034.67 \text{ kJ/kg}$$

$$\text{Hence } W_{\text{rev}} = \Psi_i - \Psi_e = 1123.62 - 1034.67 = 88.95 \text{ kJ/kg}$$

$$\text{Also irreversibility } I = T_0(s_e - s_i) = 298(7.0833 - 6.7844) = 89.07 \text{ as } W_{\text{actual}} \text{ is zero.}$$

4. Consider an air compressor that receives ambient air at 100 kPa, 25°C. It compresses the air to a pressure of 1 MPa, where it exits at a temperature of 540 °K. Since the air and the compressor housing are hotter than ambient it loses 50 kJ per kg air flowing through the compressor. Find the reversible work, reversible heat transfer and irreversibility in the process.

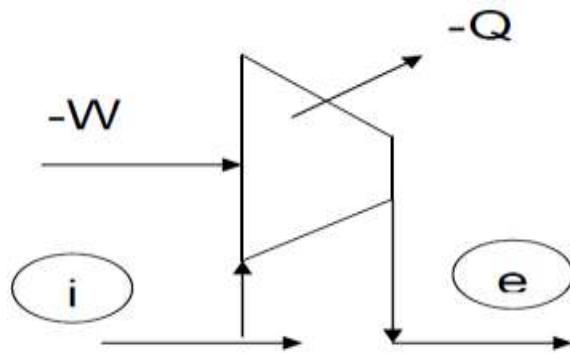


Fig 7

Solution:

It is a non-adiabatic compression with no change in KE and PE. Using SSSF equation, which has single inlet and exit. From the ideal gas tables $h_i = 298.62 \text{ kJ/kg}$ and $h_e = 544.69 \text{ kJ/kg}$, $s_i = 6.8629 \text{ kJ/kgK}$ and $s_e = 7.4664 \text{ kJ/kgK}$.

The energy equation for the actual compressor is

$$W = h_1 - h_2 + Q = 298.62 - 544.69 = -296.07 \text{ kJ/kg}$$

The reversible work for the given change of state is given by

$$\begin{aligned} W_{\text{rev}} &= T_o (s_2 - s_1) - (h_2 - h_1) + Q[1 - (T_o/T_h)] \\ &= 298.2 (7.4664 - 6.8629) - (0.287 \ln 10) - (544.69 - 298.62) + 0 = -263.17 \text{ kJ/kg} \end{aligned}$$

Thus irreversibility $I = w_{\text{rev}} - w = -263.17 - (-296.07) = 32.9 \text{ kJ/kg}$.

5. In a steam boiler, hot gases from a fire transfer heat to water which vaporizes at constant temperature. In a certain case, the gases are cooled from 1100°C to 550°C . The specific heat of gases is 1.005 kJ/kg K and the latent heat of water at 220°C is 1858.5 kJ/kg . All the heat transferred from the gases goes to the water. How much does the total entropy of the combined system of gas and water increase as a result of the reversible heat transfer? Obtain the result on the basis of 1 kg of water evaporated. If the temperature of the surroundings is 30°C , find the increase in unavailable energy due to irreversible heat transfer.

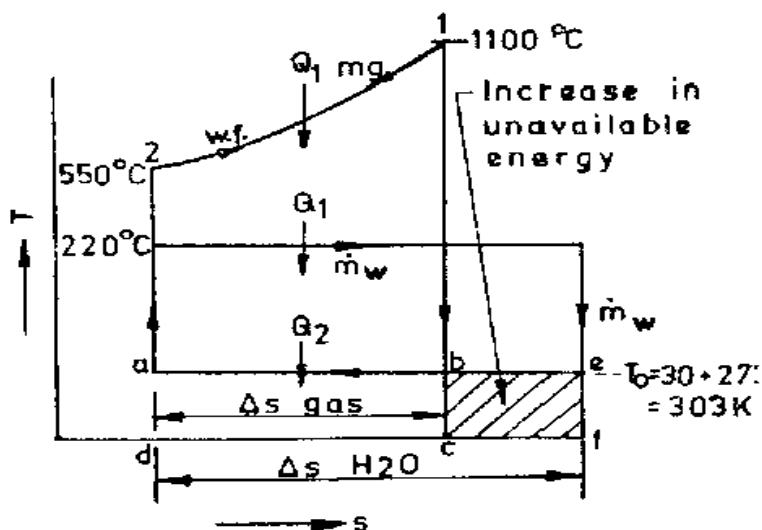
Solution:


Fig 8 : h-s diagram



Gas is cooled from state 1 to state 2 (Fig). For reversible heat transfer, the working fluid in the heat engine would have been heated along 2-1, so that at any instant, the temperature difference between gas and the working fluid is zero. Then 1-b would have been the expansion of the working fluid down to the lowest possible temperature T_o , and the amount of heat rejection would have been given by the area abcd. When water evaporates at 220°C as the gas gets cooled from 1100°C to 550°C . The resulting power cycle has an unavailable energy represented by the area aefd. The increase in unavailable energy due to irreversible heat transfer is thus given by area befc.

$$(\Delta S)_{\text{water}} = \text{Latent heat absorbed} / T = 1858.5 / (273 + 220) = 3.77 \text{ kJ/kg-K}$$

Q_1 = Heat transferred from the gas

= Heat absorbed by water during evaporation

$$= mgC_p g (1100 - 550) = 1 \times 1858.5 \text{ kJ}$$

$$\text{Hence, } mgC_p g = 1858.5 / 550 = 3.38 \text{ kJ/o C}$$

$$\Delta S_{\text{gas}} = (dQ / T) = mg C_p g dT / T$$

$$mgC_p g \ln T_g 2 / T_g 1 = 3.38 \ln 823 / 1373 = -3.38 * 0.51 = -1.725 \text{ kJ/K}$$

$$\text{Hence } \Delta S_{\text{total}} = (\Delta S)_{\text{water}} + (\Delta S)_{\text{gas}}$$

$$= 3.77 - 1.725 = 2.045 \text{ kJ/K}$$

$$\text{Increase in unavailable energy} = T_o (\Delta S)_{\text{total}} = 303 * 2.045 = 620 \text{ kJ.}$$



Problems:

1. 500 kJ of heat from an infinite source at 1000K is supplied to 2 kg of gas initially at 2 bar and 350K in a closed tank. Find the loss in available energy due to above heat transfer. Take C_v as 0.8 kJ/kg and surrounding temperature as 300K.
2. 1000Kj of heat leaves hot gases at 1673K from a firebox of a boiler and goes to steam at 523K. Atmospheric temperature is 293K. Divide the energy into available and unavailable portions (i) as it leaves the hot gases (ii) as it enters the steam
3. 2 kg of air at 5 bar and 353K expands adiabatically in a closed system until its volume is doubled and its temperature becomes equal to that of surroundings, which is at 1 bar and 278K. Calculate (i) the maximum work (ii) the change in availability (iii) The irreversibility.
4. In a heat exchanger of parallel flow type, water enters at 323K and leaves at 353K while oil of specific gravity 0.8 enters at 523K and leaves at 373K. The specific heat of oil is 2.5 kJ/kgK and surrounding temperature is 300K. Determine the loss in availability on the basis of 1 kg of oil flow per second.
5. A pressure vessel has a volume of 1 m³ and contains air at 1.4 MPa, 175⁰C. The air is cooled to 25⁰C by heat transfer to the surroundings at 25⁰C. Calculate the availability in the initial and final states and the irreversibility of the process.
6. Calculate the available energy in 40 kg of water at 75⁰ C with respect to the surroundings at 50 C, the pressure of water being 1 atm.
7. A 5 kg copper block at a temperature of 200⁰C is dropped into an insulated tank containing 100 kg oil at a temperature of 30⁰ C. Find the increase in entropy of the universe due to this process when copper block and the oil reach thermal equilibrium. Assume that the specific heats of copper and oil are respectively 0.4 kJ/kgK and 2.1 kJ /kgK.
8. 0.5 kg of ice block at 10⁰ C is brought into contact with 5 kg copper block at 80⁰ C in an insulated container. Determine the change in entropy of
 - i) Ice block.
 - ii) Copper block.
 - iii) The universe.



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9. Calculate the availability and unavailability of a system that absorbs 15000kJ of heat from a heat source at 500K temperatures while the environment is at 290 K temperature.
 10. 0.2 kg of air initially at 575 K temperature receives 300 kJ of heat reversibly at constant pressure. Determine the available and unavailable energies of the heat added.

Take C_p for air = 1.005 kJ / kg K and temperature of surroundings 300 K.

11. A closed system contains 2 kg of air during an adiabatic expansion process there occurs a change in its pressure from 500kPa to 100 kPa and in its temperature from 350 K to 320 K. if the volume doubles during the process make calculations for maximum work, the change in availability and irreversibility. Take for air $C_v = 0.718 \text{ kJ/kg K}$ and $R = 0.287 \text{ kJ/kgK}$. The surrounding conditions may be assumed to be 100 kPa and 300 K. A system at 500 K receives 7200kJ/min from a source at 1000 K. The temperature of atmosphere is 300 K. assuming that the temperature of the system and source remain constant during heat transfer find out
 - i. The entropy produced during heat transfer.
 - ii. The decrease in available energy after heat transfer.
12. 15 kg of water is heated in an insulated tank by a churning process from 300 K to 340 K. If the surrounding temperature is 300 K, find the loss in availability for the process
13. 5.0 kg of air at 550 K and 4 bar is enclosed in a closed system. Determine,
 - i) The availability of the system if the surrounding pressure and temperature are 1 bar and 290 K respectively.
 - ii) If the air is cooled at constant pressure to the atmospheric temperature, find availability and effectiveness.

Table A-1

Molar mass, gas constant, and critical-point properties

Substance	Formula	Molar mass, <i>M</i> kg/kmol	Gas constant, <i>R</i> kJ/kg · K*	Critical-point properties		
				Temperature, K	Pressure, MPa	Volume, m ³ /kmol
Air	—	28.97	0.2870	132.5	3.77	0.0883
Ammonia	NH ₃	17.03	0.4882	405.5	11.28	0.0724
Argon	Ar	39.948	0.2081	151	4.86	0.0749
Benzene	C ₆ H ₆	78.115	0.1064	562	4.92	0.2603
Bromine	Br ₂	159.808	0.0520	584	10.34	0.1355
<i>n</i> -Butane	C ₄ H ₁₀	58.124	0.1430	425.2	3.80	0.2547
Carbon dioxide	CO ₂	44.01	0.1889	304.2	7.39	0.0943
Carbon monoxide	CO	28.011	0.2968	133	3.50	0.0930
Carbon tetrachloride	CCl ₄	153.82	0.05405	556.4	4.56	0.2759
Chlorine	Cl ₂	70.906	0.1173	417	7.71	0.1242
Chloroform	CHCl ₃	119.38	0.06964	536.6	5.47	0.2403
Dichlorodifluoromethane (R-12)	CCl ₂ F ₂	120.91	0.06876	384.7	4.01	0.2179
Dichlorofluoromethane (R-21)	CHCl ₂ F	102.92	0.08078	451.7	5.17	0.1973
Ethane	C ₂ H ₆	30.070	0.2765	305.5	4.48	0.1480
Ethyl alcohol	C ₂ H ₅ OH	46.07	0.1805	516	6.38	0.1673
Ethylene	C ₂ H ₄	28.054	0.2964	282.4	5.12	0.1242
Helium	He	4.003	2.0769	5.3	0.23	0.0578
<i>n</i> -Hexane	C ₆ H ₁₄	86.179	0.09647	507.9	3.03	0.3677
Hydrogen (normal)	H ₂	2.016	4.1240	33.3	1.30	0.0649
Krypton	Kr	83.80	0.09921	209.4	5.50	0.0924
Methane	CH ₄	16.043	0.5182	191.1	4.64	0.0993
Methyl alcohol	CH ₃ OH	32.042	0.2595	513.2	7.95	0.1180
Methyl chloride	CH ₃ Cl	50.488	0.1647	416.3	6.68	0.1430
Neon	Ne	20.183	0.4119	44.5	2.73	0.0417
Nitrogen	N ₂	28.013	0.2968	126.2	3.39	0.0899
Nitrous oxide	N ₂ O	44.013	0.1889	309.7	7.27	0.0961
Oxygen	O ₂	31.999	0.2598	154.8	5.08	0.0780
Propane	C ₃ H ₈	44.097	0.1885	370	4.26	0.1998
Propylene	C ₃ H ₆	42.081	0.1976	365	4.62	0.1810
Sulfur dioxide	SO ₂	64.063	0.1298	430.7	7.88	0.1217
Tetrafluoroethane (R-134a)	CF ₃ CH ₂ F	102.03	0.08149	374.3	4.067	0.1847
Trichlorofluoromethane (R-11)	CCl ₃ F	137.37	0.06052	471.2	4.38	0.2478
Water	H ₂ O	18.015	0.4615	647.3	22.09	0.0568
Xenon	Xe	131.30	0.06332	289.8	5.88	0.1186

*The unit kJ/kg · K is equivalent to kPa · m³/kg · K. The gas constant is calculated from $R = R_u/M$, where $R_u = 8.314 \text{ kJ/kmol} \cdot \text{K}$ and M is the molar mass.Source: K. A. Kobe and R. E. Lynn, Jr., *Chemical Review* 52 (1953), pp. 117–236; and ASHRAE, *Handbook of Fundamentals* (Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1993), pp. 16.4 and 36.1.

Table A-2

APPENDIX 1

Ideal-gas specific heats of various common gases

(a) At 300 K

Gas	Formula	Gas constant, R kJ/kg · K	C_p kJ/kg · K	C_v kJ/kg · K	k
Air	—	0.2870	1.005	0.718	1.400
Argon	Ar	0.2081	0.5203	0.3122	1.667
Butane	C_4H_{10}	0.1433	1.7164	1.5734	1.091
Carbon dioxide	CO_2	0.1889	0.846	0.657	1.289
Carbon monoxide	CO	0.2968	1.040	0.744	1.400
Ethane	C_2H_6	0.2765	1.7662	1.4897	1.186
Ethylene	C_2H_4	0.2964	1.5482	1.2518	1.237
Helium	He	2.0769	5.1926	3.1156	1.667
Hydrogen	H_2	4.1240	14.307	10.183	1.405
Methane	CH_4	0.5182	2.2537	1.7354	1.299
Neon	Ne	0.4119	1.0299	0.6179	1.667
Nitrogen	N_2	0.2968	1.039	0.743	1.400
Octane	C_8H_{18}	0.0729	1.7113	1.6385	1.044
Oxygen	O_2	0.2598	0.918	0.658	1.395
Propane	C_3H_8	0.1885	1.6794	1.4909	1.126
Steam	H_2O	0.4615	1.8723	1.4108	1.327

Note: The unit kJ/kg · K is equivalent to kJ/kg · °C.

Source: Gordon J. Van Wylen and Richard E. Sonntag, *Fundamentals of Classical Thermodynamics*, English/SI Version, 3rd ed. (New York: John Wiley & Sons, 1986), p. 687, Table A.8SI.

Table A-2

Ideal-gas specific heats of various common gases (*Continued*)

(b) At various temperatures

Temperature, K	C_p kJ/kg · K	C_v kJ/kg · K	k	C_p kJ/kg · K	C_v kJ/kg · K	k	C_p kJ/kg · K	C_v kJ/kg · K	k
	Air			Carbon dioxide, CO_2			Carbon monoxide, CO		
250	1.003	0.716	1.401	0.791	0.602	1.314	1.039	0.743	1.400
300	1.005	0.718	1.400	0.846	0.657	1.288	1.040	0.744	1.399
350	1.008	0.721	1.398	0.895	0.706	1.268	1.043	0.746	1.398
400	1.013	0.726	1.395	0.939	0.750	1.252	1.047	0.751	1.395
450	1.020	0.733	1.391	0.978	0.790	1.239	1.054	0.757	1.392
500	1.029	0.742	1.387	1.014	0.825	1.229	1.063	0.767	1.387
550	1.040	0.753	1.381	1.046	0.857	1.220	1.075	0.778	1.382
600	1.051	0.764	1.376	1.075	0.886	1.213	1.087	0.790	1.376
650	1.063	0.776	1.370	1.102	0.913	1.207	1.100	0.803	1.370
700	1.075	0.788	1.364	1.126	0.937	1.202	1.113	0.816	1.364
750	1.087	0.800	1.359	1.148	0.959	1.197	1.126	0.829	1.358
800	1.099	0.812	1.354	1.169	0.980	1.193	1.139	0.842	1.353
900	1.121	0.834	1.344	1.204	1.015	1.186	1.163	0.866	1.343
1000	1.142	0.855	1.336	1.234	1.045	1.181	1.185	0.888	1.335
Hydrogen, H_2				Nitrogen, N_2			Oxygen, O_2		
250	14.051	9.927	1.416	1.039	0.742	1.400	0.913	0.653	1.398
300	14.307	10.183	1.405	1.039	0.743	1.400	0.918	0.658	1.395
350	14.427	10.302	1.400	1.041	0.744	1.399	0.928	0.668	1.389
400	14.476	10.352	1.398	1.044	0.747	1.397	0.941	0.681	1.382
450	14.501	10.377	1.398	1.049	0.752	1.395	0.956	0.696	1.373
500	14.513	10.389	1.397	1.056	0.759	1.391	0.972	0.712	1.365
550	14.530	10.405	1.396	1.065	0.768	1.387	0.988	0.728	1.358
600	14.546	10.422	1.396	1.075	0.778	1.382	1.003	0.743	1.350
650	14.571	10.447	1.395	1.086	0.789	1.376	1.017	0.758	1.343
700	14.604	10.480	1.394	1.098	0.801	1.371	1.031	0.771	1.337
750	14.645	10.521	1.392	1.110	0.813	1.365	1.043	0.783	1.332
800	14.695	10.570	1.390	1.121	0.825	1.360	1.054	0.794	1.327
900	14.822	10.698	1.385	1.145	0.849	1.349	1.074	0.814	1.319
1000	14.983	10.859	1.380	1.167	0.870	1.341	1.090	0.830	1.313

Source: Kenneth Wark, *Thermodynamics*, 4th ed. (New York: McGraw-Hill, 1983), p. 783, Table A-4M. Originally published in *Tables of Thermal Properties of Gases*, NBS Circular 564, 1955.

Table A-4

Saturated water—Temperature table

H₂O

Temp., <i>T</i> °C	Specific volume, m ³ /kg			Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
	Sat. press., <i>P</i> _{sat} kPa	Sat. liquid, <i>v</i> _f	Sat. vapor, <i>v</i> _g	Sat. liquid, <i>u</i> _f	Evap., <i>u</i> _{fg}	Sat. vapor, <i>u</i> _g	Sat. liquid, <i>h</i> _f	Evap., <i>h</i> _{fg}	Sat. vapor, <i>h</i> _g	Sat. liquid, <i>s</i> _f	Evap., <i>s</i> _{fg}	Sat. vapor, <i>s</i> _g
0.01	0.6113	0.001000	206.14	0.0	2375.3	2375.3	0.01	2501.3	2501.4	0.000	9.1562	9.1562
5	0.8721	0.001000	147.12	20.97	2361.3	2382.3	20.98	2489.6	2510.6	0.0761	8.9496	9.0257
10	1.2276	0.001000	106.38	42.00	2347.2	2389.2	42.01	2477.7	2519.8	0.1510	8.7498	8.9008
15	1.7051	0.001001	77.93	62.99	2333.1	2396.1	62.99	2465.9	2528.9	0.2245	8.5569	8.7814
20	2.339	0.001002	57.79	83.95	2319.0	2402.9	83.96	2454.1	2538.1	0.2966	8.3706	8.6672
25	3.169	0.001003	43.36	104.88	2304.9	2409.8	104.89	2442.3	2547.2	0.3674	8.1905	8.5580
30	4.246	0.001004	32.89	125.78	2290.8	2416.6	125.79	2430.5	2556.3	0.4369	8.0164	8.4533
35	5.628	0.001006	25.22	146.67	2276.7	2423.4	146.68	2418.6	2565.3	0.5053	7.8478	8.3531
40	7.384	0.001008	19.52	167.56	2262.6	2430.1	167.57	2406.7	2574.3	0.5725	7.6845	8.2570
45	9.593	0.001010	15.26	188.44	2248.4	2436.8	188.45	2394.8	2583.2	0.6387	7.5261	8.1648
50	12.349	0.001012	12.03	209.32	2234.2	2443.5	209.33	2382.7	2592.1	0.7038	7.3725	8.0763
55	15.758	0.001015	9.568	230.21	2219.9	2450.1	230.23	2370.7	2600.9	0.7679	7.2234	7.9913
60	19.940	0.001017	7.671	251.11	2205.5	2456.6	251.13	2358.5	2609.6	0.8312	7.0784	7.9096
65	25.03	0.001020	6.197	272.02	2191.1	2463.1	272.06	2346.2	2618.3	0.8935	6.9375	7.8310
70	31.19	0.001023	5.042	292.95	2176.6	2469.6	292.98	2333.8	2626.8	0.9549	6.8004	7.7553
75	38.58	0.001026	4.131	313.90	2162.0	2475.9	313.93	2321.4	2635.3	1.0155	6.6669	7.6824
80	47.39	0.001029	3.407	334.86	2147.4	2482.2	334.91	2308.8	2643.7	1.0753	6.5369	7.6122
85	57.83	0.001033	2.828	355.84	2132.6	2488.4	355.90	2296.0	2651.9	1.1343	6.4102	7.5445
90	70.14	0.001036	2.361	376.85	2117.7	2494.5	376.92	2283.2	2660.1	1.1925	6.2866	7.4791
95	84.55	0.001040	1.982	397.88	2102.7	2500.6	397.96	2270.2	2668.1	1.2500	6.1659	7.4159
Sat. press., MPa												
100	0.10135	0.001044	1.6729	418.94	2087.6	2506.5	419.04	2257.0	2676.1	1.3069	6.0480	7.3549
105	0.12082	0.001048	1.4194	440.02	2072.3	2512.4	440.15	2243.7	2683.8	1.3630	5.9328	7.2958
110	0.14327	0.001052	1.2102	461.14	2057.0	2518.1	461.30	2230.2	2691.5	1.4185	5.8202	7.2387
115	0.16906	0.001056	1.0366	482.30	2041.4	2523.7	482.48	2216.5	2699.0	1.4734	5.7100	7.1833
120	0.19853	0.001060	0.8919	503.50	2025.8	2529.3	503.71	2202.6	2706.3	1.5276	5.6020	7.1296
125	0.2321	0.001065	0.7706	524.74	2009.9	2534.6	524.99	2188.5	2713.5	1.5813	5.4962	7.0775
130	0.2701	0.001070	0.6685	546.02	1993.9	2539.9	546.31	2174.2	2720.5	1.6344	5.3925	7.0269
135	0.3130	0.001075	0.5822	567.35	1977.7	2545.0	567.69	2159.6	2727.3	1.6870	5.2907	6.9777
140	0.3613	0.001080	0.5089	588.74	1961.3	2550.0	589.13	2144.7	2733.9	1.7391	5.1908	6.9299
145	0.4154	0.001085	0.4463	610.18	1944.7	2554.9	610.63	2129.6	2740.3	1.7907	5.0926	6.8833
150	0.4758	0.001091	0.3928	631.68	1927.9	2559.5	632.20	2114.3	2746.5	1.8418	4.9960	6.8379
155	0.5431	0.001096	0.3468	653.24	1910.8	2564.1	653.84	2098.6	2752.4	1.8925	4.9010	6.7935
160	0.6178	0.001102	0.3071	674.87	1893.5	2568.4	675.55	2082.6	2758.1	1.9427	4.8075	6.7502
165	0.7005	0.001108	0.2727	696.56	1876.0	2572.5	697.34	2066.2	2763.5	1.9925	4.7153	6.7078
170	0.7917	0.001114	0.2428	718.33	1858.1	2576.5	719.21	2049.5	2768.7	2.0419	4.6244	6.6663
175	0.8920	0.001121	0.2168	740.17	1840.0	2580.2	741.17	2032.4	2773.6	2.0909	4.5347	6.6256
180	1.0021	0.001127	0.19405	762.09	1821.6	2583.7	763.22	2015.0	2778.2	2.1396	4.4461	6.5857
185	1.1227	0.001134	0.17409	784.10	1802.9	2587.0	785.37	1997.1	2782.4	2.1879	4.3586	6.5465
190	1.2544	0.001141	0.15654	806.19	1783.8	2590.0	807.62	1978.8	2786.4	2.2359	4.2720	6.5079
195	1.3978	0.001149	0.14105	828.37	1764.4	2592.8	829.98	1960.0	2790.0	2.2835	4.1863	6.4698

Table A-4

APPENDIX 1

H₂O

Saturated water—Temperature table (Concluded)

Temp., <i>T</i> °C	Specific volume, m ³ /kg			Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
	Sat. press., <i>P_{sat}</i> MPa	Sat. liquid, <i>v_f</i>	Sat. vapor, <i>v_g</i>	Sat. liquid, <i>u_f</i>	Evap., <i>u_{fg}</i>	Sat. vapor, <i>u_g</i>	Sat. liquid, <i>h_f</i>	Evap., <i>h_{fg}</i>	Sat. vapor, <i>h_g</i>	Sat. liquid, <i>s_f</i>	Evap., <i>s_{fg}</i>	Sat. vapor, <i>s_g</i>
200	1.5538	0.001157	0.12736	850.65	1744.7	2595.3	852.45	1940.7	2793.2	2.3309	4.1014	6.4323
205	1.7230	0.001164	0.11521	873.04	1724.5	2597.5	875.04	1921.0	2796.0	2.3780	4.0172	6.3952
210	1.9062	0.001173	0.10441	895.53	1703.9	2599.5	897.76	1900.7	2798.5	2.4248	3.9337	6.3585
215	2.104	0.001181	0.09479	918.14	1682.9	2601.1	920.62	1879.9	2800.5	2.4714	3.8507	6.3221
220	2.318	0.001190	0.08619	940.87	1661.5	2602.4	943.62	1858.5	2802.1	2.5178	3.7683	6.2861
225	2.548	0.001199	0.07849	963.73	1639.6	2603.3	966.78	1836.5	2803.3	2.5639	3.6863	6.2503
230	2.795	0.001209	0.07158	986.74	1617.2	2603.9	990.12	1813.8	2804.0	2.6099	3.6047	6.2146
235	3.060	0.001219	0.06537	1009.89	1594.2	2604.1	1013.62	1790.5	2804.2	2.6558	3.5233	6.1791
240	3.344	0.001229	0.05976	1033.21	1570.8	2604.0	1037.32	1766.5	2803.8	2.7015	3.4422	6.1437
245	3.648	0.001240	0.05471	1056.71	1546.7	2603.4	1061.23	1741.7	2803.0	2.7472	3.3612	6.1083
250	3.973	0.001251	0.05013	1080.39	1522.0	2602.4	1085.36	1716.2	2801.5	2.7927	3.2802	6.0730
255	4.319	0.001263	0.04598	1104.28	1596.7	2600.9	1109.73	1689.8	2799.5	2.8383	3.1992	6.0375
260	4.688	0.001276	0.04221	1128.39	1470.6	2599.0	1134.37	1662.5	2796.9	2.8838	3.1181	6.0019
265	5.081	0.001289	0.03877	1152.74	1443.9	2596.6	1159.28	1634.4	2793.6	2.9294	3.0368	5.9662
270	5.499	0.001302	0.03564	1177.36	1416.3	2593.7	1184.51	1605.2	2789.7	2.9751	2.9551	5.9301
275	5.942	0.001317	0.03279	1202.25	1387.9	2590.2	1210.07	1574.9	2785.0	3.0208	2.8730	5.8938
280	6.412	0.001332	0.03017	1227.46	1358.7	2586.1	1235.99	1543.6	2779.6	3.0668	2.7903	5.8571
285	6.909	0.001348	0.02777	1253.00	1328.4	2581.4	1262.31	1511.0	2773.3	3.1130	2.7070	5.8199
290	7.436	0.001366	0.02557	1278.92	1297.1	2576.0	1289.07	1477.1	2766.2	3.1594	2.6227	5.7821
295	7.993	0.001384	0.02354	1305.2	1264.7	2569.9	1316.3	1441.8	2758.1	3.2062	2.5375	5.7437
300	8.581	0.001404	0.02167	1332.0	1231.0	2563.0	1344.0	1404.9	2749.0	3.2534	2.4511	5.7045
305	9.202	0.001425	0.019948	1359.3	1195.9	2555.2	1372.4	1366.4	2738.7	3.3010	2.3633	5.6643
310	9.856	0.001447	0.018350	1387.1	1159.4	2546.4	1401.3	1326.0	2727.3	3.3493	2.2737	5.6230
315	10.547	0.001472	0.016867	1415.5	1121.1	2536.6	1431.0	1283.5	2714.5	3.3982	2.1821	5.5804
320	11.274	0.001499	0.015488	1444.6	1080.9	2525.5	1461.5	1238.6	2700.1	3.4480	2.0882	5.5362
330	12.845	0.001561	0.012996	1505.3	993.7	2498.9	1525.3	1140.6	2665.9	3.5507	1.8909	5.4417
340	14.586	0.001638	0.010797	1570.3	894.3	2464.6	1594.2	1027.9	2622.0	3.6594	1.6763	5.3357
350	16.513	0.001740	0.008813	1641.9	776.6	2418.4	1670.6	893.4	2563.9	3.7777	1.4335	5.2112
360	18.651	0.001893	0.006945	1725.2	626.3	2351.5	1760.5	720.3	2481.0	3.9147	1.1379	5.0526
370	21.03	0.002213	0.004925	1844.0	384.5	2228.5	1890.5	441.6	2332.1	4.1106	0.6865	4.7971
374.14	22.09	-0.003155	0.003155	2029.6	0	2029.6	2099.3	0	2099.3	4.4298	0	4.4298

Source: Tables A-4 through A-8 are adapted from Gordon J. Van Wylen and Richard E. Sonntag, *Fundamentals of Classical Thermodynamics*, English/SI Version, 3rd ed. (New York: John Wiley & Sons, 1986), pp. 635–651. Originally published in Joseph H. Keenan, Frederick G. Keyes, Philip G. Hill, and Joan G. Moore, *Steam Tables*, SI Units (New York: John Wiley & Sons, 1978).

Table A-5

Saturated water—Pressure table

H₂O

Press., P kPa	Sat. temp., <i>T_{sat}</i> °C	Specific volume, m ³ /kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
		Sat. liquid, <i>v_f</i>	Sat. vapor, <i>v_g</i>	Sat. liquid, <i>u_f</i>	Evap., <i>u_{fg}</i>	Sat. vapor, <i>u_g</i>	Sat. liquid, <i>h_f</i>	Evap., <i>h_{fg}</i>	Sat. vapor, <i>h_g</i>	Sat. liquid, <i>s_f</i>	Evap., <i>s_{fg}</i>	Sat. vapor, <i>s_g</i>
0.6113	0.01	0.001000	206.14	0.00	2375.3	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	9.1562
1.0	6.98	0.001000	129.21	29.30	2355.7	2385.0	29.30	2484.9	2514.2	0.1059	8.8697	8.9756
1.5	13.03	0.001001	87.98	54.71	2338.6	2393.3	54.71	2470.6	2525.3	0.1957	8.6322	8.8279
2.0	17.50	0.001001	67.00	73.48	2326.0	2399.5	73.48	2460.0	2533.5	0.2607	8.4629	8.7237
2.5	21.08	0.001002	54.25	88.48	2315.9	2404.4	88.49	2451.6	2540.0	0.3120	8.3311	8.6432
3.0	24.08	0.001003	45.67	101.04	2307.5	2408.5	101.05	2444.5	2545.5	0.3545	8.2231	8.5776
4.0	28.96	0.001004	34.80	121.45	2293.7	2415.2	121.46	2432.9	2554.4	0.4226	8.0520	8.4746
5.0	32.88	0.001005	28.19	137.81	2282.7	2420.5	137.82	2423.7	2561.5	0.4764	7.9187	8.3951
7.5	40.29	0.001008	19.24	168.78	2261.7	2430.5	168.79	2406.0	2574.8	0.5764	7.6750	8.2515
10	45.81	0.001010	14.67	191.82	2246.1	2437.9	191.83	2392.8	2584.7	0.6493	7.5009	8.1502
15	53.97	0.001014	10.02	225.92	2222.8	2448.7	225.94	2373.1	2599.1	0.7549	7.2536	8.0085
20	60.06	0.001017	7.649	251.38	2205.4	2456.7	251.40	2358.3	2609.7	0.8320	7.0766	7.9085
25	64.97	0.001020	6.204	271.90	2191.2	2463.1	271.93	2346.3	2618.2	0.8931	6.9383	7.8314
30	69.10	0.001022	5.229	289.20	2179.2	2468.4	289.23	2336.1	2625.3	0.9439	6.8247	7.7686
40	75.87	0.001027	3.993	317.53	2159.5	2477.0	317.58	2319.2	2636.8	1.0259	6.6441	7.6700
50	81.33	0.001030	3.240	340.44	2143.4	2483.9	340.49	2305.4	2645.9	1.0910	6.5029	7.5939
75	91.78	0.001037	2.217	384.31	2112.4	2496.7	384.39	2278.6	2663.0	1.2130	6.2434	7.4564
Press., MPa												
0.100	99.63	0.001043	1.6940	417.36	2088.7	2506.1	417.46	2258.0	2675.5	1.3026	6.0568	7.3594
0.125	105.99	0.001048	1.3749	444.19	2069.3	2513.5	444.32	2241.0	2685.4	1.3740	5.9104	7.2844
0.150	111.37	0.001053	1.1593	466.94	2052.7	2519.7	467.11	2226.5	2693.6	1.4336	5.7897	7.2233
0.175	116.06	0.001057	1.0036	486.80	2038.1	2524.9	486.99	2213.6	2700.6	1.4849	5.6868	7.1717
0.200	120.23	0.001061	0.8857	504.49	2025.0	2529.5	504.70	2201.9	2706.7	1.5301	5.5970	7.1271
0.225	124.00	0.001064	0.7933	520.47	2013.1	2533.6	520.72	2191.3	2712.1	1.5706	5.5173	7.0878
0.250	127.44	0.001067	0.7187	535.10	2002.1	2537.2	535.37	2181.5	2716.9	1.6072	5.4455	7.0527
0.275	130.60	0.001070	0.6573	548.59	1991.9	2540.5	548.89	2172.4	2721.3	1.6408	5.3801	7.0209
0.300	133.55	0.001073	0.6058	561.15	1982.4	2543.6	561.47	2163.8	2725.3	1.6718	5.3201	6.9919
0.325	136.30	0.001076	0.5620	572.90	1973.5	2546.4	573.25	2155.8	2729.0	1.7006	5.2646	6.9652
0.350	138.88	0.001079	0.5243	583.95	1965.0	2548.9	584.33	2148.1	2732.4	1.7275	5.2130	6.9405
0.375	141.32	0.001081	0.4914	594.40	1956.9	2551.3	594.81	2140.8	2735.6	1.7528	5.1647	6.9175
0.40	143.63	0.001084	0.4625	604.31	1949.3	2553.6	604.74	2133.8	2738.6	1.7766	5.1193	6.8959
0.45	147.93	0.001088	0.4140	622.77	1934.9	2557.6	623.25	2120.7	2743.9	1.8207	5.0359	6.8565
0.50	151.86	0.001093	0.3749	639.68	1921.6	2561.2	640.23	2108.5	2748.7	1.8607	4.9606	6.8213
0.55	155.48	0.001097	0.3427	655.32	1909.2	2564.5	665.93	2097.0	2753.0	1.8973	4.8920	6.7893
0.60	158.85	0.001101	0.3157	669.90	1897.5	2567.4	670.56	2086.3	2756.8	1.9312	4.8288	6.7600
0.65	162.01	0.001104	0.2927	683.56	1886.5	2570.1	684.28	2076.0	2760.3	1.9627	4.7703	6.7331
0.70	164.97	0.001108	0.2729	696.44	1876.1	2572.5	697.22	2066.3	2763.5	1.9922	4.7158	6.7080
0.75	167.78	0.001112	0.2556	708.64	1866.1	2574.7	709.47	2057.0	2766.4	2.0200	4.6647	6.6847
0.80	170.43	0.001115	0.2404	720.22	1856.6	2576.8	721.11	2048.0	2769.1	2.0462	4.6166	6.6628
0.85	172.96	0.001118	0.2270	731.27	1847.4	2578.7	732.22	2039.4	2771.6	2.0710	4.5711	6.6421
0.90	175.38	0.001121	0.2150	741.83	1838.6	2580.5	742.83	2031.1	2773.9	2.0946	4.5280	6.6226
0.95	177.69	0.001124	0.2042	751.95	1830.2	2582.1	753.02	2023.1	2776.1	2.1172	4.4869	6.6041
1.00	179.91	0.001127	0.19444	761.68	1822.0	2583.6	762.81	2015.3	2778.1	2.1387	4.4478	6.5865
1.10	184.09	0.001133	0.17753	780.09	1806.3	2586.4	781.34	2000.4	2871.7	2.1792	4.3744	6.5536
1.20	187.99	0.001139	0.16333	797.29	1791.5	2588.8	798.65	1986.2	2784.8	2.2166	4.3067	6.5233
1.30	191.64	0.001144	0.15125	813.44	1777.5	2591.0	814.93	1972.7	2787.6	2.2515	4.2438	6.4953

Table A-5

Saturated water—Pressure table (*Concluded*)

Sat. vapor, s_g	Specific volume, m ³ /kg				Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K			
	Press., MPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g	
9.1562		1.40	195.07	0.001149	0.14084	828.70	1764.1	2592.8	830.30	1957.7	2790.0	2.2842	4.1850	6.4693
8.9756		1.50	198.32	0.001154	0.13177	843.16	1751.3	2594.5	844.89	1947.3	2792.2	2.3150	4.1298	6.4448
3.8279		1.75	205.76	0.001166	0.11349	876.46	1721.4	2597.8	878.50	1917.9	2796.4	2.3851	4.0044	6.3896
3.7237		2.00	212.42	0.001177	0.09963	906.44	1693.8	2600.3	908.79	1890.7	2799.5	2.4474	3.8935	6.3409
3.6432		2.25	218.45	0.001187	0.08875	933.83	1668.2	2602.0	936.49	1865.2	2801.7	2.5035	3.7937	6.2972
3.5776		2.5	223.99	0.001197	0.07998	959.11	1644.0	2603.1	962.11	1841.0	2803.1	2.5547	3.7028	6.2575
3.4746		3.0	233.90	0.001217	0.06668	1004.78	1599.3	2604.1	1008.42	1795.7	2804.2	2.6457	3.5412	6.1869
3.3951		3.5	242.60	0.001235	0.05707	1045.43	1558.3	2603.7	1049.75	1753.7	2803.4	2.7253	3.4000	6.1253
3.2515		4	250.40	0.001252	0.04978	1082.31	1520.0	2602.3	1087.31	1714.1	2801.4	2.7964	3.2737	6.0701
3.1502		5	263.99	0.001286	0.03944	1147.81	1449.3	2597.1	1154.23	1640.1	2794.3	2.9202	3.0532	5.9734
3.0085		6	275.64	0.001319	0.03244	1205.44	1384.3	2589.7	1213.35	1571.0	2784.3	3.0267	2.8625	5.8892
.9085		7	285.88	0.001351	0.02737	1257.55	1323.0	2580.5	1267.00	1505.1	2772.1	3.1211	2.6922	5.8133
.8314		8	295.06	0.001384	0.02352	1305.57	1264.2	2569.8	1316.64	1441.3	2758.0	3.2068	2.5364	5.7432
.7686		9	303.40	0.001418	0.02048	1350.51	1207.3	2557.8	1363.26	1378.9	2742.1	3.2858	2.3915	5.6722
.6700		10	311.06	0.001452	0.018026	1393.04	1151.4	2544.4	1407.56	1317.1	2724.7	3.3596	2.2544	5.6141
.5939		11	318.15	0.001480	0.015987	1433.7	1096.0	2529.8	1450.1	1255.5	2705.6	3.4295	2.1233	5.5527
.4564		12	324.75	0.001527	0.014263	1473.0	1040.7	2513.7	1491.3	1193.3	2684.9	3.4962	1.9962	5.4924
		13	330.93	0.001567	0.012780	1511.1	985.0	2496.1	1531.5	1130.7	2662.2	3.5606	1.8718	5.4323
		14	336.75	0.001611	0.011485	1548.6	928.2	2476.8	1571.1	1066.5	2637.6	3.6232	1.7485	5.3717
		15	342.24	0.001658	0.010337	1585.6	869.8	2455.5	1610.5	1000.0	2610.5	3.6848	1.6249	5.3098
.3594		16	347.44	0.001711	0.009306	1622.7	809.0	2431.7	1650.1	930.6	2580.6	3.7461	1.4994	5.2455
.2844		17	352.37	0.001770	0.008364	1660.2	744.8	2405.0	1690.3	856.9	2547.2	3.8079	1.3698	5.1777
.2233		18	357.06	0.001840	0.007489	1698.9	675.4	2374.3	1732.0	777.1	2509.1	3.8715	1.2329	5.1044
.1717		19	361.54	0.001924	0.006657	1739.9	598.1	2338.1	1776.5	688.0	2464.5	3.9388	1.0839	5.0228
.1271		20	365.81	0.002036	0.005834	1785.6	507.5	2293.0	1826.3	583.4	2409.7	4.0139	0.9130	4.9269
.0878		21	369.89	0.002207	0.004952	1842.1	388.5	2230.6	1888.4	446.2	2334.6	4.1075	0.6938	4.8013
.0527		22	373.80	0.002742	0.003568	1961.9	125.2	2087.1	2022.2	143.4	2165.6	4.3110	0.2216	4.5327
.0209		22.09	374.14	0.003155	0.003155	2029.6	0	2029.6	2099.3	0	2099.3	4.4298	0	4.4298

Table A-6

THERMODYNAMICS

H₂O

Superheated water

T °C	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg · K	
<i>P = 0.01 MPa (45.81°C)*</i>					<i>P = 0.05 MPa (81.33°C)</i>				<i>P = 0.10 MPa (99.63°C)</i>				
Sat. [†]	14.674	2437.9	2584.7	8.1502	3.240	2483.9	2645.9	7.5939	1.6940	2506.1	2675.5	7.3594	
50	14.869	2443.9	2592.6	8.1749	3.418	2511.6	2682.5	7.6947	1.6958	2506.7	2676.2	7.3614	
100	17.196	2515.5	2687.5	8.4479	3.889	2585.6	2780.1	7.9401	1.9364	2582.8	2776.4	7.6134	
150	19.512	2587.9	2783.0	8.6882	4.356	2659.9	2877.7	8.1580	2.172	2658.1	2875.3	7.8343	
200	21.825	2661.3	2879.5	8.9038	4.820	2735.0	2976.0	8.3556	2.406	2733.7	2974.3	8.0333	
250	24.136	2736.0	2977.3	9.1002	5.284	2811.3	3075.5	8.5373	2.639	2810.4	3074.3	8.2158	
300	26.445	2812.1	3076.5	9.2813	6.209	2968.5	3278.9	8.8642	3.103	2967.9	3278.2	8.5435	
400	31.063	2968.9	3279.6	9.6077	7.134	3132.0	3488.7	9.1546	3.565	3131.6	3488.1	8.8342	
500	35.679	3132.3	3489.1	9.8978	8.057	3302.2	3705.1	9.4178	4.028	3301.9	3704.4	9.0976	
600	40.295	3302.5	3705.4	10.1608	8.981	3479.4	3928.5	9.6599	4.490	3479.2	3928.2	9.3398	
700	44.911	3479.6	3928.7	10.4028	9.904	3663.6	4158.9	9.8852	4.952	3663.5	4158.6	9.5652	
800	49.526	3663.8	4159.0	10.6281	10.828	3854.9	4396.3	10.0967	5.414	3854.8	4396.1	9.7767	
900	54.141	3855.0	4396.4	10.8396	11.751	4052.9	4640.5	10.2964	5.875	4052.8	4640.3	9.9764	
1000	58.757	4053.0	4640.6	11.0393	12.674	4257.4	4891.1	10.4859	6.337	4257.3	4891.0	10.1659	
1100	63.372	4257.5	4891.2	11.2287	13.597	4467.8	5147.7	10.6662	6.799	4467.7	5147.6	10.3463	
1200	67.987	4467.9	5147.8	11.4091	14.521	4683.6	5409.6	10.8382	7.260	4683.5	5409.5	10.5183	
1300	72.602	4683.7	5409.7	11.5811	<i>P = 0.20 MPa (120.23°C)</i>					<i>P = 0.30 MPa (133.55°C)</i>			
Sat.	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919	0.4625	2553.6	2738.6	6.8959	
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761.0	7.0778	0.4708	2564.5	2752.8	6.9299	
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115	0.5342	2646.8	2860.5	7.1706	
250	1.1988	2731.2	2971.0	7.7086	0.7964	2728.7	2967.6	7.5166	0.5951	2726.1	2964.2	7.3789	
300	1.3162	2808.6	3071.8	7.8926	0.8753	2806.7	3069.3	7.7022	0.6548	2804.8	3066.8	7.5662	
400	1.5493	2966.7	3276.6	8.2218	1.0315	2965.6	3275.0	8.0330	0.7726	2964.4	3273.4	7.8985	
500	1.7814	3130.8	3487.1	8.5133	1.1867	3130.0	3486.0	8.3251	0.8893	3129.2	3484.9	8.1913	
600	2.013	3301.4	3704.0	8.7770	1.3414	3300.8	3703.2	8.5892	1.0055	3300.2	3702.4	8.4558	
700	2.244	3478.8	3927.6	9.0194	1.4957	3478.4	3927.1	8.8319	1.1215	3477.9	3926.5	8.6987	
800	2.475	3663.1	4158.2	9.2449	1.6499	3662.9	4157.8	9.0576	1.2372	3662.4	4157.3	8.9244	
900	2.705	3854.5	4395.8	9.4566	1.8041	3854.2	4395.4	9.2692	1.3529	3853.9	4395.1	9.1362	
1000	2.937	4052.5	4640.0	9.6563	1.9581	4052.3	4639.7	9.4690	1.4685	4052.0	4639.4	9.3360	
1100	3.168	4257.0	4890.7	9.8458	2.1121	4256.8	4890.4	9.6585	1.5840	4256.5	4890.2	9.5256	
1200	3.399	4467.5	5147.5	10.0262	2.2661	4467.2	5147.1	9.8389	1.6996	4467.0	5146.8	9.7060	
1300	3.630	4683.2	5409.3	10.1982	2.4201	4683.0	5409.0	10.0110	1.8151	4682.8	5408.8	9.8780	
<i>P = 0.50 MPa (151.86°C)</i>					<i>P = 0.60 MPa (158.85°C)</i>				<i>P = 0.80 MPa (170.43°C)</i>				
Sat.	0.3749	2561.2	2748.7	6.8213	0.3157	2567.4	2756.8	6.7600	0.2404	2576.8	2769.1	6.6628	
200	0.4249	2642.9	2855.4	7.0592	0.3520	2638.9	2850.1	6.9665	0.2608	2630.6	2839.3	6.8158	
250	0.4744	2723.5	2960.7	7.2709	0.3938	2720.9	2957.2	7.1816	0.2931	2715.5	2950.0	7.0384	
300	0.5226	2802.9	3064.2	7.4599	0.4344	2801.0	3061.6	7.3724	0.3241	2797.2	3056.5	7.2328	
350	0.5701	2882.6	3167.7	7.6329	0.4742	2881.2	3165.7	7.5464	0.3544	2878.2	3161.7	7.4089	
400	0.6173	2963.2	3271.9	7.7938	0.5137	2962.1	3270.3	7.7079	0.3843	2959.7	3267.1	7.5716	
500	0.7109	3128.4	3483.9	8.0873	0.5920	3127.6	3482.8	8.0021	0.4433	3126.0	3480.6	7.8673	
600	0.8041	3299.6	3701.7	8.3522	0.6697	3299.1	3700.9	8.2674	0.5018	3297.9	3699.4	8.1333	
700	0.8969	3477.5	3925.9	8.5952	0.7472	3477.0	3925.3	8.5107	0.5601	3476.2	3924.2	8.3770	
800	0.9896	3662.1	4156.9	8.8211	0.8245	3661.8	4156.5	8.7367	0.6181	3661.1	4155.6	8.6033	
900	1.0822	3853.6	4394.7	9.0329	0.9017	3853.4	4394.4	8.9486	0.6761	3852.8	4393.7	8.8153	
1000	1.1747	4051.8	4639.1	9.2328	0.9788	4051.5	4638.8	9.1485	0.7340	4051.0	4638.2	9.0153	
1100	1.2672	4256.3	4889.9	9.4224	1.0559	4256.1	4889.6	9.3381	0.7919	4255.6	4889.1	9.2050	
1200	1.3596	4466.8	5146.6	9.6029	1.1330	4466.5	5146.3	9.5185	0.8497	4466.1	5145.9	9.3855	
1300	1.4521	4682.5	5408.6	9.7749	1.2101	4682.3	5408.3	9.6906	0.9076	4681.8	5407.9	9.5575	

*The temperature in parentheses is the saturation temperature at the specified pressure.

[†]Properties of saturated vapor at the specified pressure.

Table A-6

APPENDIX I

Superheated water (*Continued*)

$\text{I/kg} \cdot \text{K}$	T	v	u	h	s	v	u	h	s	v	u	h	s	
	$^{\circ}\text{C}$	m^3/kg	kJ/kg	kJ/kg	$\text{kJ/kg} \cdot \text{K}$	m^3/kg	kJ/kg	kJ/kg	$\text{kJ/kg} \cdot \text{K}$	m^3/kg	kJ/kg	kJ/kg	$\text{kJ/kg} \cdot \text{K}$	
		$P = 1.00 \text{ MPa (179.91}^{\circ}\text{C)}$					$P = 1.20 \text{ MPa (187.99}^{\circ}\text{C)}$					$P = 1.40 \text{ MPa (195.07}^{\circ}\text{C)}$		
7.3594	Sat.	0.19444	2583.6	2778.1	6.5865	0.16333	2588.8	2784.8	6.5233	0.14084	2592.8	2790.0	6.4693	
7.3614	200	0.2060	2621.9	2827.9	6.6940	0.16930	2612.8	2815.9	6.5898	0.14302	2603.1	2803.3	6.4975	
7.6134	250	0.2327	2709.9	2942.6	6.9247	0.19234	2704.2	2935.0	6.8294	0.16350	2698.3	2927.2	6.7467	
7.8343	300	0.2579	2793.2	3051.2	7.1229	0.2138	2789.2	3045.8	7.0317	0.18228	2785.2	3040.4	6.9534	
8.0333	350	0.2825	2875.2	3157.7	7.3011	0.2345	2872.2	3153.6	7.2121	0.2003	2869.2	3149.5	7.1360	
8.2158	400	0.3066	2957.3	3263.9	7.4651	0.2548	2954.9	3260.7	7.3774	0.2178	2952.5	3257.5	7.3026	
8.5435	500	0.3541	3124.4	3478.5	7.7622	0.2946	3122.8	3476.3	7.6759	0.2521	3121.1	3474.1	7.6027	
8.8342	600	0.4011	3296.8	3697.9	8.0290	0.3339	3295.6	3696.3	7.9435	0.2860	3294.4	3694.8	7.8710	
.0976	700	0.4478	3475.3	3923.1	8.2731	0.3729	3474.4	3922.0	8.1881	0.3195	3473.6	3920.8	8.1160	
.3398	800	0.4943	3660.4	4154.7	8.4996	0.4118	3659.7	4153.8	8.4148	0.3528	3659.0	4153.0	8.3431	
.5652	900	0.5407	3852.2	4392.9	8.7118	0.4505	3851.6	4392.2	8.6272	0.3861	3851.1	4391.5	8.5556	
.7767	1000	0.5871	4050.5	4637.6	8.9119	0.4892	4050.0	4637.0	8.8274	0.4192	4049.5	4636.4	8.7559	
.9764	1100	0.6335	4255.1	4888.6	9.1017	0.5278	4254.6	4888.0	9.0172	0.4524	4254.1	4887.5	8.9457	
.1659	1200	0.6798	4465.6	5145.4	9.2822	0.5665	4465.1	5144.9	9.1977	0.4855	4464.7	5144.4	9.1262	
.3463	1300	0.7261	4681.3	5407.4	9.4543	0.6051	4680.9	5407.0	9.3698	0.5186	4680.4	5406.5	9.2984	
5183		$P = 1.60 \text{ MPa (201.41}^{\circ}\text{C)}$					$P = 1.80 \text{ MPa (207.15}^{\circ}\text{C)}$					$P = 2.00 \text{ MPa (212.42}^{\circ}\text{C)}$		
	Sat.	0.12380	2596.0	2794.0	6.4218	0.11042	2598.4	2797.1	6.3794	0.09963	2600.3	2799.5	6.3409	
8959	225	0.13287	2644.7	2857.3	6.5518	0.11673	2636.6	2846.7	6.4808	0.10377	2628.3	2835.8	6.4147	
9299	250	0.14184	2692.3	2919.2	6.6732	0.12497	2686.0	2911.0	6.6066	0.11144	2679.6	2902.5	6.5453	
1706	300	0.15862	2781.1	3034.8	6.8844	0.14021	2776.9	3029.2	6.8226	0.12547	2772.6	3023.5	6.7664	
3789	350	0.17456	2866.1	3145.4	7.0694	0.15457	2863.0	3141.2	7.0100	0.13857	2859.8	3137.0	6.9563	
5662	400	0.19005	2950.1	3254.2	7.2374	0.16847	2947.7	3250.9	7.1794	0.15120	2945.2	3247.6	7.1271	
8985	500	0.2203	3119.5	3472.0	7.5390	0.19550	3117.9	3469.8	7.4825	0.17568	3116.2	3467.6	7.4317	
1913	600	0.2500	3293.3	3693.2	7.8080	0.2220	3292.1	3691.7	7.7523	0.19960	3290.9	3690.1	7.7024	
4558	700	0.2794	3472.7	3919.7	8.0535	0.2482	3471.8	3918.5	7.9983	0.2232	3470.9	3917.4	7.9487	
5987	800	0.3086	3658.3	4152.1	8.2808	0.2742	3657.6	4151.2	8.2258	0.2467	3657.0	4150.3	8.1765	
3244	900	0.3377	3850.5	4390.8	8.4935	0.3001	3849.9	4390.1	8.4386	0.2700	3849.3	4389.4	8.3895	
1362	1000	0.3668	4049.0	4635.8	8.6938	0.3260	4048.5	4635.2	8.6391	0.2933	4048.0	4634.6	8.5901	
3360	1100	0.3958	4253.7	4887.0	8.8837	0.3518	4253.2	4886.4	8.8290	0.3166	4252.7	4885.9	8.7800	
5256	1200	0.4248	4464.2	5143.9	9.0643	0.3776	4463.7	5143.4	9.0096	0.3398	4463.3	5142.9	8.9607	
7060	1300	0.4538	4679.9	5406.0	9.2364	0.4034	4679.5	5405.6	9.1818	0.3631	4679.0	5405.1	9.1329	
3780		$P = 2.50 \text{ MPa (223.99}^{\circ}\text{C)}$					$P = 3.00 \text{ MPa (233.90}^{\circ}\text{C)}$					$P = 3.50 \text{ MPa (242.60}^{\circ}\text{C)}$		
	Sat.	0.07998	2603.1	2803.1	6.2575	0.06668	2604.1	2804.2	6.1869	0.05707	2603.7	2803.4	6.1253	
6228	225	0.08027	2605.6	2806.3	6.2639									
1158	250	0.08700	2662.6	2880.1	6.4085	0.07058	2644.0	2855.8	6.2872	0.05872	2623.7	2829.2	6.1749	
3844	300	0.09890	2761.6	3008.8	6.6438	0.08114	2750.1	2993.5	6.5390	0.06842	2738.0	2977.5	6.4461	
328	350	0.10976	2851.9	3126.3	6.8403	0.09053	2843.7	3115.3	6.7428	0.07678	2835.3	3104.0	6.6579	
089	400	0.12010	2939.1	3239.3	7.0148	0.09936	2932.8	3230.9	6.9212	0.08453	2926.4	3222.3	6.8405	
716	450	0.13014	3025.5	3350.8	7.1746	0.10787	3020.4	3344.0	7.0834	0.09196	3015.3	3337.2	7.0052	
673	500	0.13993	3112.1	3462.1	7.3234	0.11619	3108.0	3456.5	7.2338	0.09918	3103.0	3450.9	7.1572	
333	600	0.15930	3288.0	3686.3	7.5960	0.13243	3285.0	3682.3	7.5085	0.11324	3282.1	3678.4	7.4339	
770	700	0.17832	3468.7	3914.5	7.8435	0.14838	3466.5	3911.7	7.7571	0.12699	3464.3	3908.8	7.6837	
033	800	0.19716	3655.3	4148.2	8.0720	0.16414	3653.5	4145.9	7.9862	0.14056	3651.8	4143.7	7.9134	
153	900	0.21590	3847.9	4387.6	8.2853	0.17980	3846.5	4385.9	8.1999	0.15402	3845.0	4384.1	8.1276	
153	1000	0.2346	4046.7	4633.1	8.4861	0.19541	4045.4	4631.6	8.4009	0.16743	4044.1	4630.1	8.3288	
153	1100	0.2532	4251.5	4884.6	8.6762	0.21098	4250.3	4883.3	8.5912	0.18080	4249.2	4881.9	8.5192	
355	1200	0.2718	4462.1	5141.7	8.8569	0.22652	4460.9	5140.5	8.7720	0.19415	4459.8	5139.3	8.7000	
355	1300	0.2905	4677.8	5404.0	9.0291	0.24206	4676.6	5402.8	8.9442	0.20749	4675.5	5401.7	8.8723	

Table A-6

Superheated water (Continued)

H₂O

T °C	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg · K
<i>P</i> = 4.0 MPa (250.40°C)					<i>P</i> = 4.5 MPa (257.49°C)					<i>P</i> = 5.0 MPa (263.99°C)		
Sat.	0.04978	2602.3	2801.4	6.0701	0.04406	2600.1	2798.3	6.0198	0.03944	2597.1	2794.3	5.9734
275	0.05457	2667.9	2886.2	6.2285	0.04730	2650.3	2863.2	6.1401	0.04141	2631.3	2838.3	6.0544
300	0.05884	2725.3	2960.7	6.3615	0.05135	2712.0	2943.1	6.2828	0.04532	2698.0	2924.5	6.2084
350	0.06645	2826.7	3092.5	6.5821	0.05840	2817.8	3080.6	6.5131	0.05194	2808.7	3068.4	6.4493
400	0.07341	2919.9	3213.6	6.7690	0.06475	2913.3	3204.7	6.7047	0.05781	2906.6	3195.7	6.6459
450	0.08002	3010.2	3330.3	6.9363	0.07074	3005.0	3323.3	6.8746	0.06330	2999.7	3316.2	6.8186
500	0.08643	3099.5	3445.3	7.0901	0.07651	3095.3	3439.6	7.0301	0.06857	3091.0	3433.8	6.9759
600	0.09885	3279.1	3674.4	7.3688	0.08765	3276.0	3670.5	7.3110	0.07869	3273.0	3666.5	7.2589
700	0.11095	3462.1	3905.9	7.6198	0.09847	3459.9	3903.0	7.5631	0.08849	3457.6	3900.1	7.5122
800	0.12287	3650.0	4141.5	7.8502	0.10911	3648.3	4139.3	7.7942	0.09811	3646.6	4137.1	7.7440
900	0.13469	3843.6	4382.3	8.0647	0.11965	3842.2	4380.6	8.0091	0.10762	3840.7	4378.8	7.9593
1000	0.14645	4042.9	4628.7	8.2662	0.13013	4041.6	4627.2	8.2108	0.11707	4040.4	4625.7	8.1612
1100	0.15817	4248.0	4880.6	8.4567	0.14056	4246.8	4879.3	8.4015	0.12648	4245.6	4878.0	8.3520
1200	0.16987	4458.6	5138.1	8.6376	0.15098	4457.5	5136.9	8.5825	0.13587	4456.3	5135.7	8.5331
1300	0.18156	4674.3	5400.5	8.8100	0.16139	4673.1	5399.4	8.7549	0.14526	4672.0	5398.2	8.7055
<i>P</i> = 6.0 MPa (275.64°C)					<i>P</i> = 7.0 MPa (285.88°C)					<i>P</i> = 8.0 MPa (295.06°C)		
Sat.	0.03244	2589.7	2784.3	5.8892	0.02737	2580.5	2772.1	5.8133	0.02352	2569.8	2758.0	5.7432
300	0.03616	2667.2	2884.2	6.0674	0.02947	2632.2	2838.4	5.9305	0.02426	2590.9	2785.0	5.7906
350	0.04223	2789.6	3043.0	6.3335	0.03524	2769.4	3016.0	6.2283	0.02995	2747.7	2987.3	6.1301
400	0.04739	2892.9	3177.2	6.5408	0.03993	2878.6	3158.1	6.4478	0.03432	2863.8	3138.3	6.3634
450	0.05214	2988.9	3301.8	6.7193	0.04416	2978.0	3287.1	6.6327	0.03817	2966.7	3272.0	6.5551
500	0.05665	3082.2	3422.2	6.8803	0.04814	3073.4	3410.3	6.7975	0.04175	3064.3	3398.3	6.7240
550	0.06101	3174.6	3540.6	7.0288	0.05195	3167.2	3530.9	6.9486	0.04516	3159.8	3521.0	6.8778
600	0.06525	3266.9	3658.4	7.1677	0.05565	3260.7	3650.3	7.0894	0.04845	3254.4	3642.0	7.0206
700	0.07352	3453.1	3894.2	7.4234	0.06283	3448.5	3888.3	7.3476	0.05481	3443.9	3882.4	7.2812
800	0.08160	3643.1	4132.7	7.6566	0.06981	3639.5	4128.2	7.5822	0.06097	3636.0	4123.8	7.5173
900	0.08958	3837.8	4375.3	7.8727	0.07669	3835.0	4371.8	7.7991	0.06702	3832.1	4368.3	7.7351
1000	0.09749	4037.8	4622.7	8.0751	0.08350	4035.3	4619.8	8.0020	0.07301	4032.8	4616.9	7.9384
1100	0.10536	4243.3	4875.4	8.2661	0.09027	4240.9	4872.8	8.1933	0.07896	4238.6	4870.3	8.1300
1200	0.11321	4454.0	5133.3	8.4474	0.09703	4451.7	5130.9	8.3747	0.08489	4449.5	5128.5	8.3115
1300	0.12106	4669.6	5396.0	8.6199	0.10377	4667.3	5393.7	8.5475	0.09080	4665.0	5391.5	8.4842
<i>P</i> = 9.0 MPa (303.40°C)					<i>P</i> = 10.0 MPa (318351.06°C)					<i>P</i> = 12.5 MPa (327.89°C)		
Sat.	0.02048	2557.8	2742.1	5.6772	0.018026	2544.4	2724.7	5.6141	0.013495	2505.1	2673.8	5.4624
325	0.02327	2646.6	2856.0	5.8712	0.019861	2610.4	2809.1	5.7568				
350	0.02580	2724.4	2956.6	6.0361	0.02242	2699.2	2923.4	5.9443	0.016126	2624.6	2826.2	5.7118
400	0.02993	2848.4	3117.8	6.2854	0.02641	2832.4	3096.5	6.2120	0.02000	2789.3	3039.3	6.0417
450	0.03350	2955.2	3256.6	6.4844	0.02975	2943.4	3240.9	6.4190	0.02299	2912.5	3199.8	6.2719
500	0.03677	3055.2	3386.1	6.6576	0.03279	3045.8	3373.7	6.5966	0.02560	3021.7	3341.8	6.4618
550	0.03987	3152.2	3511.0	6.8142	0.03564	3144.6	3500.9	6.7561	0.02801	3125.0	3475.2	6.6290
600	0.04285	3248.1	3633.7	6.9589	0.03837	3241.7	3625.3	6.9029	0.03029	3225.4	3604.0	6.7810
650	0.04574	3343.6	3755.3	7.0943	0.04101	3338.2	3748.2	7.0398	0.03248	3324.4	3730.4	6.9218
700	0.04857	3439.3	3876.5	7.2221	0.04358	3434.7	3870.5	7.1687	0.03460	3422.9	3855.3	7.0536
800	0.05409	3632.5	4119.3	7.4596	0.04859	3628.9	4114.8	7.4077	0.03869	3620.0	4103.6	7.2965
900	0.05950	3829.2	4364.8	7.6783	0.05349	3826.3	4361.2	7.6272	0.04267	3819.1	4352.5	7.5182
1000	0.06485	4030.3	4614.0	7.8821	0.05832	4027.8	4611.0	7.8315	0.04658	4021.6	4603.8	7.7237
1100	0.07016	4236.3	4867.7	8.0740	0.06312	4234.0	4865.1	8.0237	0.05045	4228.2	4858.8	7.9165
1200	0.07544	4447.2	5126.2	8.2556	0.06789	4444.9	5123.8	8.2055	0.05430	4439.3	5118.0	8.0937
1300	0.08072	4662.7	5389.2	8.4284	0.07265	4460.5	5387.0	8.3783	0.05813	4654.8	5381.4	8.2717

Table A-6

APPENDIX 1

Superheated water (*Concluded*)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
<i>P</i> = 15.0 MPa (342.24°C)					<i>P</i> = 17.5 MPa (354.75°C)					<i>P</i> = 20.0 MPa (365.81°C)		
Sat.	0.010337	2455.5	2610.5	5.3098	0.007920	2390.2	2528.8	5.1419	0.005834	2293.0	2409.7	4.9269
350	0.011470	2520.4	2692.4	5.4421	0.012447	2685.0	2902.9	5.7213	0.009942	2619.3	2818.1	5.5540
400	0.015649	2740.7	2975.5	5.8811	0.015174	2844.2	3109.7	6.0184	0.012695	2806.2	3060.1	5.9017
450	0.018445	2879.5	3156.2	6.1404	0.017358	2970.3	3274.1	6.2383	0.014768	2942.9	3238.2	6.1401
500	0.02080	2996.6	3308.6	6.3443	0.019288	3083.9	3421.4	6.4230	0.016555	3062.4	3393.5	6.3348
550	0.02293	3104.7	3448.6	6.5199	0.02106	3191.5	3560.1	6.5866	0.018178	3174.0	3537.6	6.5048
600	0.02491	3208.6	3582.3	6.6776	0.02274	3296.0	3693.9	6.7357	0.019693	3281.4	3675.3	6.6582
650	0.02680	3310.3	3712.3	6.8224	0.02434	3398.7	3824.6	6.8736	0.02113	3386.4	3809.0	6.7993
700	0.02861	3410.9	3840.1	6.9572	0.02738	3601.8	4081.1	7.1244	0.02385	3592.7	4069.7	7.0544
800	0.03210	3610.9	4092.4	7.2040	0.03031	3804.7	4335.1	7.3507	0.02645	3797.5	4326.4	7.2830
900	0.03546	3811.9	4343.8	7.4279	0.03316	4009.3	4589.5	7.5589	0.02897	4003.1	4582.5	7.4925
1000	0.03875	4015.4	4596.6	7.6348	0.03597	4216.9	4846.4	7.7531	0.03145	4211.3	4840.2	7.6874
1100	0.04200	4222.6	4852.6	7.8283	0.03876	4428.3	5106.6	7.9360	0.03391	4422.8	5101.0	7.8707
1200	0.04523	4433.8	5112.3	8.0108	0.04154	4643.5	5370.5	8.1093	0.03636	4638.0	5365.1	8.0442
1300	0.04845	4649.1	5376.0	8.1840	<i>P</i> = 25.0 MPa					<i>P</i> = 30.0 MPa		
375	0.0019731	1798.7	1848.0	4.0320	0.0017892	1737.8	1791.5	3.9305	0.0017003	1702.9	1762.4	3.8722
400	0.006004	2430.1	2580.2	5.1418	0.002790	2067.4	2151.1	4.4728	0.002100	1914.1	1987.6	4.2126
425	0.007881	2609.2	2806.3	5.4723	0.005303	2455.1	2614.2	5.1504	0.003428	2253.4	2373.4	4.7747
450	0.009162	2720.7	2949.7	5.6744	0.006735	2619.3	2821.4	5.4424	0.004961	2498.7	2672.4	5.1962
500	0.011123	2884.3	3162.4	5.9592	0.008678	2820.7	3081.1	5.7905	0.006927	2751.9	2994.4	5.6282
550	0.012724	3017.5	3335.6	6.1765	0.010168	2970.3	3275.4	6.0342	0.008345	2921.0	3213.0	5.9026
600	0.014137	3137.9	3491.4	6.3602	0.011446	3100.5	3443.9	6.2331	0.009527	3062.0	3395.5	6.1179
650	0.015433	3251.6	3637.4	6.5229	0.012596	3221.0	3598.9	6.4058	0.010575	3189.8	3559.9	6.3010
700	0.016646	3361.3	3777.5	6.6707	0.013661	3335.8	3745.6	6.5606	0.011533	3309.8	3713.5	6.4631
800	0.018912	3574.3	4047.1	6.9345	0.015623	3555.5	4024.2	6.8332	0.013278	3536.7	4001.5	6.7450
900	0.021045	3783.0	4309.1	7.1680	0.017448	3768.5	4291.9	7.0718	0.014883	3754.0	4274.9	6.9386
1000	0.02310	3990.9	4568.5	7.3802	0.019196	3978.8	4554.7	7.2867	0.016410	3966.7	4541.1	7.2064
1100	0.02512	4200.2	4828.2	7.5765	0.020903	4189.2	4816.3	7.4845	0.017895	4178.3	4804.6	7.4037
1200	0.02711	4412.0	5089.9	7.7605	0.022589	4401.3	5079.0	7.6692	0.019360	4390.7	5068.3	7.5910
1300	0.02910	4626.9	5354.4	7.9342	0.024266	4616.0	5344.0	7.8432	0.020815	4605.1	5333.6	7.7653
		<i>P</i> = 40.0 MPa					<i>P</i> = 50.0 MPa			<i>P</i> = 60.0 MPa		
375	0.0016407	1677.1	1742.8	3.8290	0.0015594	1638.6	1716.6	3.7639	0.0015028	1609.4	1699.5	3.7141
400	0.0019077	1854.6	1930.9	4.1135	0.0017309	1788.1	1874.6	4.0031	0.0016335	1745.4	1843.4	3.9318
425	0.002532	2096.9	2198.1	4.5029	0.002007	1959.7	2060.0	4.2734	0.0018165	1892.7	2001.7	4.1626
450	0.003693	2365.1	2512.8	4.9459	0.002486	2159.6	2284.0	4.5884	0.002085	2053.9	2179.0	4.4121
500	0.005622	2678.4	2903.3	5.4700	0.003892	2525.5	2720.1	5.1726	0.002956	2390.6	2567.9	4.9321
550	0.006984	2869.7	3149.1	5.7785	0.005118	2763.6	3019.5	5.5485	0.003956	2658.8	2896.2	5.3441
600	0.008094	3022.6	3346.4	6.0144	0.006112	2942.0	3247.6	5.8178	0.004834	2861.1	3151.2	5.6452
650	0.009063	3158.0	3520.6	6.2054	0.006966	3093.5	3441.8	6.0342	0.005595	3028.8	3364.5	5.8829
700	0.009941	3283.6	3681.2	6.3750	0.007727	3230.5	3616.8	6.2189	0.006272	3177.2	3553.5	6.0824
800	0.011523	3517.8	3978.7	6.6662	0.009076	3479.8	3933.6	6.5290	0.007459	3441.5	3889.1	6.4109
900	0.012962	3739.4	4257.9	6.9150	0.010283	3710.3	4224.4	6.7882	0.008508	3681.0	4191.5	6.6805
1000	0.014324	3954.6	4527.6	7.1356	0.011411	3930.5	4501.1	7.0146	0.009480	3906.4	4475.2	6.9127
1100	0.015642	4167.4	4793.1	7.3364	0.012496	4145.7	4770.5	7.2184	0.010409	4124.1	4748.6	7.1195
1200	0.016940	4380.1	5057.7	7.5224	0.013561	4359.1	5037.2	7.4058	0.011317	4338.2	5017.2	7.3083
1300	0.018229	4594.3	5323.5	7.6969	0.014616	4572.8	5303.6	7.5808	0.012215	4551.4	5284.3	7.4837

Table A-7

H₂O

Compressed liquid water

T °C	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m ³ /kg	u kJ/kg	h kJ/kg	s kJ/kg · K
<i>P</i> = 5 MPa (263.99°C)					<i>P</i> = 10 MPa (311.06°C)					<i>P</i> = 15 MPa (342.24°C)		
Sat.	0.0012859	1147.8	1154.2	2.9202	0.0014524	1393.0	1407.6	3.3596	0.0016581	1585.6	1610.5	3.6848
0	0.0009977	0.04	5.04	0.0001	0.0009952	0.09	10.04	0.0002	0.0009928	0.15	15.05	0.0004
20	0.0009995	83.65	88.65	0.2956	0.0009972	83.36	93.33	0.2945	0.0009950	83.06	97.99	0.2934
40	0.0010056	166.95	171.97	0.5705	0.0010034	166.35	176.38	0.5686	0.0010013	165.76	180.78	0.5666
60	0.0010149	250.23	255.30	0.8285	0.0010127	249.36	259.49	0.8258	0.0010105	248.51	263.67	0.8232
80	0.0010268	333.72	338.85	1.0720	0.0010245	332.59	342.83	1.0688	0.0010222	331.48	346.81	1.0656
100	0.0010410	417.52	422.72	1.3030	0.0010385	416.12	426.50	1.2992	0.0010361	414.74	430.28	1.2955
120	0.0010576	501.80	507.09	1.5233	0.0010549	500.08	510.64	1.5189	0.0010522	498.40	514.19	1.5145
140	0.0010768	586.76	592.15	1.7343	0.0010737	584.68	595.42	1.7292	0.0010707	582.66	598.72	1.7242
160	0.0010988	672.62	678.12	1.9375	0.0010953	670.13	681.08	1.9317	0.0010918	667.71	684.09	1.9260
180	0.0011240	759.63	765.25	2.1341	0.0011199	756.65	767.84	2.1275	0.0011159	753.76	770.50	2.1210
200	0.0011530	848.1	853.9	2.3255	0.0011480	844.5	856.0	2.3178	0.0011433	841.0	858.2	2.3104
220	0.0011866	938.4	944.4	2.5128	0.0011805	934.1	945.9	2.5039	0.0011748	929.9	947.5	2.4953
240	0.0012264	1031.4	1037.5	2.6979	0.0012187	1026.0	1038.1	2.6872	0.0012114	1020.8	1039.0	2.6771
260	0.0012749	1127.9	1134.3	2.8830	0.0012645	1121.1	1133.7	2.8699	0.0012550	1114.6	1133.4	2.8576
280					0.0013216	1220.9	1234.1	3.0548	0.0013084	1212.5	1232.1	3.0393
300					0.0013972	1328.4	1342.3	3.2469	0.0013770	1316.6	1337.3	3.2260
320									0.0014724	1431.1	1453.2	3.4247
340									0.0016311	1567.5	1591.9	3.6546
<i>P</i> = 20 MPa (365.81°C)					<i>P</i> = 30 MPa					<i>P</i> = 50 MPa		
Sat.	0.002036	1785.6	1826.3	4.0139								
0	0.0009904	0.19	20.01	0.0004	0.0009856	0.25	29.82	0.0001	0.0009766	0.20	49.03	0.0014
20	0.0009928	82.77	102.62	0.2923	0.0009886	82.17	111.84	0.2899	0.0009804	81.00	130.02	0.2848
40	0.0009992	165.17	185.16	0.5646	0.0009951	164.04	193.89	0.5607	0.0009872	161.86	211.21	0.5527
60	0.0010084	247.68	267.85	0.8206	0.0010042	246.06	276.19	0.8154	0.0009962	242.98	292.79	0.8052
80	0.0010199	330.40	350.80	1.0624	0.0010156	328.30	358.77	1.0561	0.0010073	324.34	374.70	1.0440
100	0.0010337	413.39	434.06	1.2917	0.0010290	410.78	441.66	1.2844	0.0010201	405.88	456.89	1.2703
120	0.0010496	496.76	517.76	1.5102	0.0010445	493.59	524.93	1.5018	0.0010348	487.65	539.39	1.4857
140	0.0010678	580.69	602.04	1.7193	0.0010621	576.88	608.75	1.7098	0.0010515	569.77	622.35	1.6915
160	0.0010885	665.35	687.12	1.9204	0.0010821	660.82	693.28	1.9096	0.0010703	652.41	705.92	1.8891
180	0.0011120	750.95	773.20	2.1147	0.0011047	745.59	778.73	2.1024	0.0010912	735.69	790.25	2.0794
200	0.0011388	837.7	860.5	2.3031	0.0011302	831.4	865.3	2.2893	0.0011146	819.7	875.5	2.2634
220	0.0011695	925.9	949.3	2.4870	0.0011590	918.3	953.1	2.4711	0.0011408	904.7	961.7	2.4419
240	0.0012046	1016.0	1040.0	2.6674	0.0011920	1006.9	1042.6	2.6490	0.0011702	990.7	1049.2	2.6158
260	0.0012462	1108.6	1133.5	2.8459	0.0012303	1097.4	1134.3	2.8243	0.0012034	1078.1	1138.2	2.7860
280	0.0012965	1204.7	1230.6	3.0248	0.0012755	1190.7	1229.0	2.9986	0.0012415	1167.2	1229.3	2.9537
300	0.0013596	1306.1	1333.3	3.2071	0.0013304	1287.9	1327.8	3.1741	0.0012860	1258.7	1323.0	3.1200
320	0.0014437	1415.7	1444.6	3.3979	0.0013997	1390.7	1432.7	3.3539	0.0013388	1353.3	1420.2	3.2868
340	0.0015684	1539.7	1571.0	3.6075	0.0014920	1501.7	1546.5	3.5426	0.0014032	1452.0	1522.1	3.4557
360	0.0018226	1702.8	1739.3	3.8772	0.0016265	1626.6	1675.4	3.7494	0.0014838	1556.0	1630.2	3.6291
380					0.0018691	1781.4	1837.5	4.0012	0.0015884	1667.2	1746.6	3.8101

Table A-8

THERMODYNAMICS

R-134a

Saturated refrigerant-134a—Temperature table

Temp., <i>T</i> °C	Press., <i>P_{sat}</i> MPa	Specific volume, m ³ /kg		Internal energy, kJ/kg		Enthalpy, kJ/kg		Entropy, kJ/kg · K		
		Sat. liquid, <i>v_f</i>	Sat. vapor, <i>v_g</i>	Sat. liquid, <i>u_f</i>	Sat. vapor, <i>u_g</i>	Sat. liquid, <i>h_f</i>	Evap., <i>h_{fg}</i>	Sat. vapor, <i>h_g</i>	Sat. liquid, <i>s_f</i>	
-40	0.05164	0.0007055	0.3569	-0.04	204.45	0.00	222.88	222.88	0.0000	0.9560
-36	0.06332	0.0007113	0.2947	4.68	206.73	4.73	220.67	225.40	0.0201	0.9506
-32	0.07704	0.0007172	0.2451	9.47	209.01	9.52	218.37	227.90	0.0401	0.9456
-28	0.09305	0.0007233	0.2052	14.31	211.29	14.37	216.01	230.38	0.0600	0.9411
-26	0.10199	0.0007265	0.1882	16.75	212.43	16.82	214.80	231.62	0.0699	0.9390
-24	0.11160	0.0007296	0.1728	19.21	213.57	19.29	213.57	232.85	0.0798	0.9370
-22	0.12192	0.0007328	0.1590	21.68	214.70	21.77	212.32	234.08	0.0897	0.9351
-20	0.13299	0.0007361	0.1464	24.17	215.84	24.26	211.05	235.31	0.0996	0.9332
-18	0.14483	0.0007395	0.1350	26.67	216.97	26.77	209.76	236.53	0.1094	0.9315
-16	0.15748	0.0007428	0.1247	29.18	218.10	29.30	208.45	237.74	0.1192	0.9298
-12	0.18540	0.0007498	0.1068	34.25	220.36	34.39	205.77	240.15	0.1388	0.9267
-8	0.21704	0.0007569	0.0919	39.38	222.60	39.54	203.00	242.54	0.1583	0.9239
-4	0.25274	0.0007644	0.0794	44.56	224.84	44.75	200.15	244.90	0.1777	0.9213
0	0.29282	0.0007721	0.0689	49.79	227.06	50.02	197.21	247.23	0.1970	0.9190
4	0.33765	0.0007801	0.0600	55.08	229.27	55.35	194.19	249.53	0.2162	0.9169
8	0.38756	0.0007884	0.0525	60.43	231.46	60.73	191.07	251.80	0.2354	0.9150
12	0.44294	0.0007971	0.0460	65.83	233.63	66.18	187.85	254.03	0.2545	0.9132
16	0.50416	0.0008062	0.0405	71.29	235.78	71.69	184.52	256.22	0.2735	0.9116
20	0.57160	0.0008157	0.0358	76.80	237.91	77.26	181.09	258.35	0.2924	0.9102
24	0.64566	0.0008257	0.0317	82.37	240.01	82.90	177.55	260.45	0.3113	0.9089
26	0.68530	0.0008309	0.0298	85.18	241.05	85.75	175.73	261.48	0.3208	0.9082
28	0.72675	0.0008362	0.0281	88.00	242.08	88.61	173.89	262.50	0.3302	0.9076
30	0.77006	0.0008417	0.0265	90.84	243.10	91.49	172.00	263.50	0.3396	0.9070
32	0.81528	0.0008473	0.0250	93.70	244.12	94.39	170.09	264.48	0.3490	0.9064
34	0.86247	0.0008530	0.0236	96.58	245.12	97.31	168.14	265.45	0.3584	0.9058
36	0.91168	0.0008590	0.0223	99.47	246.11	100.25	166.15	266.40	0.3678	0.9053
38	0.96298	0.0008651	0.0210	102.38	247.09	103.21	164.12	267.33	0.3772	0.9047
40	1.0164	0.0008714	0.0199	105.30	248.06	106.19	162.05	268.24	0.3866	0.9041
42	1.0720	0.0008780	0.0188	108.25	249.02	109.19	159.94	269.14	0.3960	0.9035
44	1.1299	0.0008847	0.0177	111.22	249.96	112.22	157.79	270.01	0.4054	0.9030
48	1.2526	0.0008989	0.0159	117.22	251.79	118.35	153.33	271.68	0.4243	0.9017
52	1.3851	0.0009142	0.0142	123.31	253.55	124.58	148.66	273.24	0.4432	0.9004
56	1.5278	0.0009308	0.0127	129.51	255.23	130.93	143.75	274.68	0.4622	0.8990
60	1.6813	0.0009488	0.0114	135.82	256.81	137.42	138.57	275.99	0.4814	0.8973
70	2.1162	0.0010027	0.0086	152.22	260.15	154.34	124.08	278.43	0.5302	0.8918
80	2.6324	0.0010766	0.0064	169.88	262.14	172.71	106.41	279.12	0.5814	0.8827
90	3.2435	0.0011949	0.0046	189.82	261.34	193.69	82.63	276.32	0.6380	0.8655
100	3.9742	0.0015443	0.0027	218.60	248.49	224.74	34.40	259.13	0.7196	0.8117

Source for Tables A-11 through A-13: M. J. Moran and H. N. Shapiro, *Fundamentals of Engineering Thermodynamics*, 2nd ed. (New York: John Wiley & Sons, 1992), pp. 710–15. Originally based on equations from D. P. Wilson and R. S. Basu, "Thermodynamic Properties of a New Stratospherically Safe Working Fluid—Refrigerant-134a," *ASHRAE Trans.* 94, Pt. 2 (1988), pp. 2095–118. Used with permission.

Table A-11

Saturated refrigerant-134a—Pressure tables



THERMODYNAMICS

Table A-12

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Superheated refrigerant-134a

Table A-12

Superheated refrigerant-134a (Concluded)