# Fundamentals of
# THERMODYNAMICS

## Partha Haldar

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# THERMODYNAMICS

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Dedicated to my son

# Rivan

# Chapter 1

**Thermodynamics:**

Thermodynamics can be defined as the science of energy. Although everybody has a feeling of what energy is, it is difficult to give a precise definition for it. Energy can be viewed as the ability to cause changes.

The name thermodynamics stems from the Greek words 'therme' (heat) and 'dynamis' (power).

One of the most fundamental laws of nature is the conservation of energy principle. It states that during an interaction, energy can change from one form to another but the total amount of energy remains constant. That is, energy cannot be created or destroyed.

The first law of thermodynamics is simply an expression of the conservation of energy principle, and it asserts that energy is a thermodynamic property. The second law of thermodynamics asserts that energy has quality as well as quantity, and actual processes occur in the direction of decreasing quality of energy. For example, a cup of hot coffee left on a table eventually cools, but a cup of cool coffee in the same room never gets hot by itself.

**Thermodynamic System:**

A **system** is defined as a *quantity of matter or a region in space chosen forstudy*. The mass or region outside the system is called the **surroundings.**The real or imaginary surface that separates the system from its surroundingsis called the **boundary.**

Theboundary of a system can be fixed or movable. Note that the boundary is thecontact surface shared by both the system and the surroundings. Mathematically speaking, the boundary has zero thickness, and thus it can neither contain any mass nor occupy any volume in space.
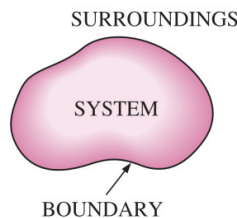


Fig. System, surrounding and boundary

**Classification of Systems:**

Systems may be considered to be *closed* or *open,* depending on whether afixed mass or a fixed volume in space is chosen for study.

A **closed system**(also known as a **control mass**) consists of a fixed amount of mass, and nomass can cross its boundary. That is, no mass can enter or leave a closedsystem. But energy, in the form of heat or work, cancross the boundary.
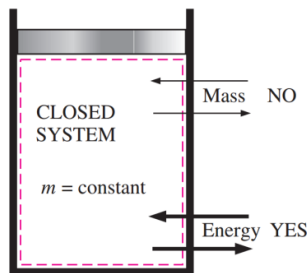


Fig.: Mass cannotcross the boundary of a closedsystem but energy can.

If, as a special case, even energy is not allowed to cross the boundary,that system is called an **isolated system.***No work is done in an isolated system.*

An **open system,** or a **control volume,** as it is often called, is a properlyselected region in space. It usually encloses a device that involvesmass flow such as a compressor, turbine, or nozzle. Flow through thesedevices is best studied by selecting the region within the device as thecontrol volume. **Both mass and energy can cross the boundary of a control volume**.

The boundaries of a control volume are called a control surface, and they can be real or imaginary. In the case of a nozzle, the inner surface of the nozzle forms the real part of the boundary, and the entrance and exit areas form the imaginary part, since there are no physical surfaces there. A control volume can be fixed in size and shape, as in the case of a nozzle, or it may involve a moving boundary. A control volume can also involve heat and workinteractions just as a closed system, in addition to mass interaction.
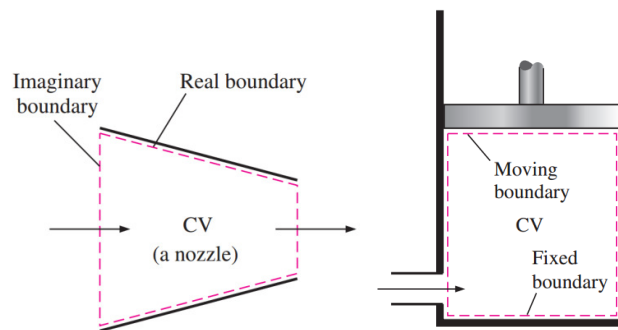
Fig.: A control volume can involve fixed, moving, real, and imaginary boundaries.

**Properties of a System:**

Any characteristic of a system is called a **property.** Some familiar propertiesare pressure $P$, temperature $T$, volume $V$, and mass $m$.

Properties are considered to be either *intensive* or *extensive*.

**Intensiveproperties** are those that are **independent of the mass** of a system, such astemperature, pressure, and density.

**Extensive properties** are those whosevalues depend on the size or extent of the system. Total mass, total volumeand total momentum are some examples of extensive properties. Extensive properties per unit mass are called **specific properties.** Someexamples of specific properties are specific volume ($v = V/m$) and specific energy ($e = E/m$).
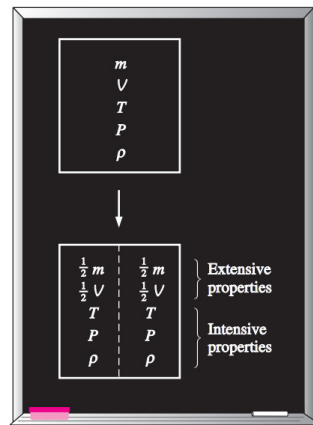
Fig.: Criterion to differentiate intensive andextensive properties.

**State and Equilibrium:**

Consider a system not undergoing any change. At this point, all the propertiescan be measured or calculated throughout the entire system, whichgives us a set of properties that completely describes the condition, or the**state,** of the system. At a given state, all the properties of a system havefixed values. If the value of even one property changes, the state will changeto a different one.
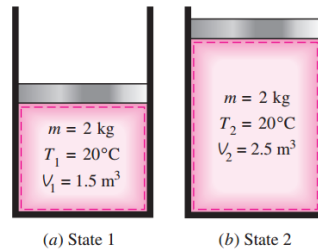


(a) State 1　　　(b) State 2

Fig.: A system at two different states.

Thermodynamics deals with *equilibrium* states. The word **equilibrium** implies a state of balance. In an equilibrium state there are no unbalancedpotentials (or driving forces) within the system.

There are many types of equilibrium, and a system is not in thermodynamicequilibrium unless the conditions of all the relevant types of equilibriumare satisfied.

A system is in **thermal equilibrium** if thetemperature is the same throughout the entire system. **Mechanical equilibrium** is related to pressure,and a system is in mechanical equilibrium if there is no change in pressureat any point of the system with time. If a system involves two phases, it is in **phaseequilibrium** when the mass of each phase reaches an equilibrium level andstays there. Finally, a system is in **chemical equilibrium** if its chemicalcomposition does not change with time, that is, no chemical reactions occur.A system will not be in equilibrium unless all the relevant equilibrium criteria are satisfied.

**The State Postulate:**

As noted earlier, the state of a system is described by its properties. But we know from experience that we do not need to specify all the properties in order to fix a state. Once a sufficient number of properties are specified, the rest of the properties assume certain values automatically. That is, specifying a certain number of properties is sufficient to fix a state. The number of properties required to fix the state of a system is given by the state postulate:

The state of a simple compressible system is completely specified by two independent, intensive properties.

The state postulate requires that the two properties specified be independent to fix the state. Two properties are independent if one property can be varied while the other one is held constant. Temperature and specific volume, for example, are always independent properties, and together they can fix the state of a simple compressible system.
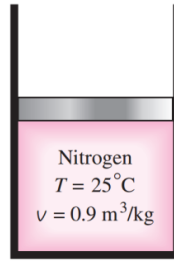
Fig.: The state of nitrogen is fixed by two independent, intensive properties.

**Thermodynamic Processes:**

Any change that a system undergoes from one equilibrium state to another is called a **process,** and the series of states through which a system passes during a process is called the **path** of the process.
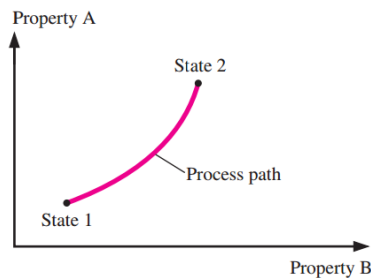


Fig.: A process between states 1 and 2 and the process path.

To describe a process completely, one should specify the initial and final states of the process, as well as the path it follows, and the interactions with the surroundings. When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times, it is called a **quasistatic,** or **quasi-equilibrium, process.** A quasi-equilibrium process can be viewed as a sufficiently slow process that allows the system to adjust itself internally so that properties in one part of the system do not change any faster than those at other parts.

When a gas in a piston-cylinder device is compressed suddenly, the molecules near the face of the piston will not have enough time to escape and they will have to pile up in a small region in front of the piston, thus creating a high-pressure region there. Because of this pressure difference, the system can no longer be said to be in equilibrium, and this makes the entire process **non-quasi-equilibrium**. However, if the piston is moved slowly, the molecules will have sufficient time to redistribute and there will not be a molecule pileup in front of the piston. As a result, the pressure inside the cylinder will always be nearly uniform and will rise at the same rate at all locations. Since equilibrium is maintained at all times, this is a quasi-equilibrium process**. It should be pointed out that a quasi-equilibrium process is an idealized process and is not a true representation of an actual process**.

(a) Slow compression
(quasi-equilibrium)

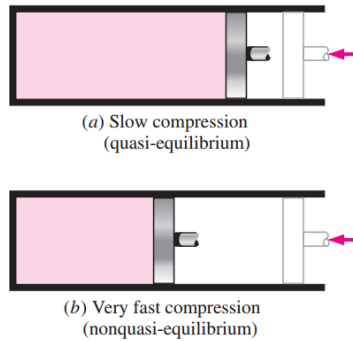(b) Very fast compression
(nonquasi-equilibrium)

Fig.: Quasi-equilibrium and non-quasi-equilibrium compression processes.

But many actual processes closely approximate it, and they can be modelled as quasi-equilibrium with negligible error. Engineers are interested in quasi-equilibrium processes for two reasons. **First**, they are easy to analyze; **second**, work-producing devices deliver the most work when they operate on quasi-equilibrium processes. Therefore, quasi-equilibrium processes serve as standards to which actual processes can be compared.

An **isothermal process** is a process during which the temperature T remains constant.

An **isobaricprocess** is a process during which the pressure P remains constant.

An **isochoric (or isometric)**process is a process during which the specific volume $v$remains constant. A system is said to have undergone a cycle if it returns to its initial state at the end of the process. That is, for a cycle the initial and final states are identical.

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**The Steady-Flow Process:**

The term **steady** implies no change with time. The opposite of steady is unsteady, or transient. The term **uniform**, however, implies no change with location over a specified region. **Steady-flow process** can be defined as a process during which a fluid flows through a control volumesteadily.
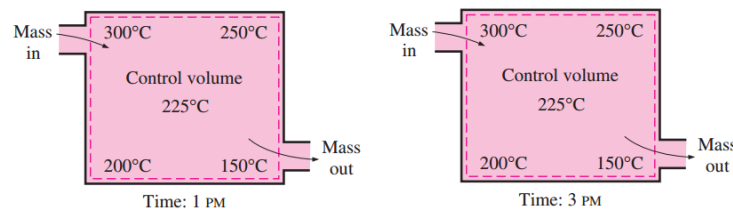


Fig.: During a steady flow process, fluid properties within the control volume may change with position but not with time.

Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems. Some cyclic devices, such as reciprocating engines or compressors, do not satisfy any of the conditions stated above since the flow at the inlets and the exits will be pulsating and not steady.

**Reversible and Irreversible Processes:**

A reversible process is defined as a process that can be reversed without leaving any trace on the surroundings. That is, both the system and the surroundings are returned to their initial states at the end of the reverse process. This is possible only if the net heat and net work

exchange between the system and the surroundings is zero for the combined (original and reverse) process. Processes that are not reversible are called irreversible processes.

**Irreversibilities:**

Irreversibilities include friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelasticdeformation of solids, and chemical reactions. The presence of any of these effects renders a process irreversible.

**Internally and Externally Reversible Processes:**

A process is called internally reversible if no irreversibilities occur within the boundaries of the system during the process. The quasi-equilibrium process is an example of an internally reversible process.

Consider a can of cold soda left in a warm room. Heat is transferred from the warmer room air to the cooler soda. The only way this process can be reversed and the soda restored to its original temperature is to provide refrigeration, which requires some work input. At the end of the reverse process, the soda will be restored to its initial state, but the surroundings will not be. So this is an internally reversible process if the can is considered as the system.

A process is called externally reversible if no irreversibilities occur outside the system boundaries during the process. Heat transfer between a reservoir and a system is an externally reversible process if the outer surface of the system is at the temperature of the reservoir.

A process is called totally reversible, or simply reversible, if it involves no irreversibilities within the system or its surroundings. Atotally reversible process involves no heat transfer through a finite temperature difference, no non-quasi-equilibrium changes, and no friction or other dissipative effects.


**The Zeroth Law of Thermodynamics:**

The zeroth law of thermodynamics states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.

It may seem silly that such an obvious fact is called one of the basic laws of thermodynamics. However, it cannot be concluded from the other laws of thermodynamics, and it serves as a basis for the validity of temperature measurement. By replacing the third body with a thermometer, the zeroth law can be restated as two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact. The zeroth law was first formulated and labelled by R. H. Fowler in 1931. As the name suggests, its value as a fundamental physical principle was recognized more than half a century after the formulation of the first and the second laws of thermodynamics. It was named the zeroth law since it should have preceded the first and the second laws of thermodynamics.

# Chapter 2

**Forms of Energy of a System:**

Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the total energy (E) of a system.

The total energy of a system can be divided in two groups: macroscopic and microscopic. The macroscopic forms of energy are those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies. The microscopic forms of energy are those related to the molecular structure of a system and the degree of the molecular activity, and they are independent of outside reference frames. The sum of all the microscopic forms of energy is called the internal energy of a system and is denoted by U.

$$Total\ energy = E = U + KE + PE = U + m\frac{V^2}{2} + mgz$$

For **stationary systems**, the changes in kinetic and potential energies are zero. Therefore the total energy change is equal to change in internal energy. Most closed systems remain stationary during a process and thus experience no change in their kinetic and potential energies. Closed systems whose velocity and elevation of the center of gravity remain constant during a process are frequently referred to as stationary systems.

**Problem 1: Wind speed is 8.5 m/sec. wind energy per unit mass =?**
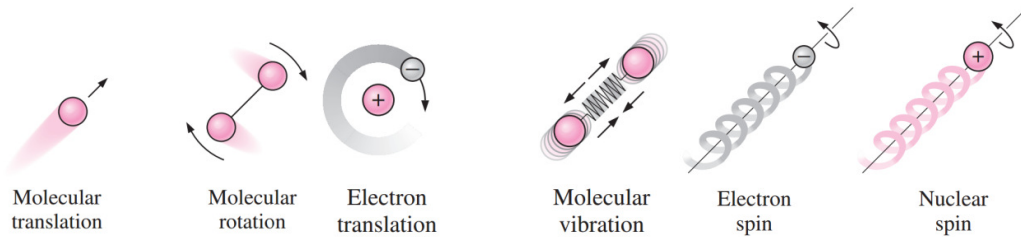
Answer:

$$\text{Wind energy per unit mass} = \frac{1}{2}v^2 = 36.125\ J/kg$$

**Some Physical Insight to Internal Energy:**

Internal energy is defined as the sum of all the microscopic forms of energy of a system. It is related to the molecular structure and the degree of molecular activity and can be viewed as the sum of the kinetic and potential energies of the molecules.

To have a better understanding of internal energy, let us examine a system at the molecular level. The molecules of a gas move through space with some velocity, and thus possess some kinetic energy. This is known as the translational energy. The atoms of polyatomic molecules rotate about an axis, and the energy associated with this rotation is the rotational kinetic energy. The atoms of a polyatomic molecule may also vibrate about their common center of mass, and the energy associated with this back-and-forth motion is the vibrational kinetic energy. For gases, the kinetic energy is mostly due to translational and rotational motions, with vibrational motion becoming significant at higher temperatures. The electrons in an atom rotate about the nucleus, and thus possess rotational kinetic energy. Electrons at outer orbits have larger kinetic energies. Electrons also spin about their axes, and the energy associated with this motion is the spin energy. Other particles in the nucleus of an atom also possess spin energy. The portion of the internal energy of a system associated with the kinetic energies of the molecules is called the sensible energy. The average velocity and the degree of activity of the molecules are proportional to the temperature of the gas. Therefore, at higher temperatures, the molecules possess higher kinetic energies, and as a result the system has a higher internal energy.

| Molecular translation | Molecular rotation | Electron translation | Molecular vibration | Electron spin | Nuclear spin |

If sufficient energy is added to the molecules of a solid or liquid, the molecules overcome these molecular forces and break away, turning the substance into a gas. This is a phase-change process. Because of this added energy, a system in the gas phase is at a higher internal energy level than it is in the solid or the liquid phase. The internal energy associated with the phase of a system is called the latent energy.

The internal energy associated with the atomic bonds in a molecule is called chemical energy. The tremendous amount of energy associated with the strong bonds within the nucleus of the atom itself is called nuclear energy. We need not be concerned with nuclear energy in thermodynamics unless, of course, we deal with fusion or fission reactions.

**Mechanical Energy:**

The mechanical energy can be defined as the form of energy that can be converted to mechanical work completely and directly by an ideal mechanical device such as an ideal turbine. Kinetic and potential energies are the familiar forms of mechanical energy. Thermal energy is not mechanical energy, however, since it cannot be converted to work directly and completely.

Therefore, the mechanical energy of a flowing fluid can be expressed on a unit mass basis as:

$$e_{mech} = \frac{P}{\rho} + \frac{V^2}{2} + gz$$

=flow energy + kinetic energy + potential energy

Then the mechanical energy change of a fluid during incompressible ($\rho = constant$) flow becomes

$$\Delta e_{mech} = \frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(Z_2 - Z_1)$$

In the absence of any losses, the mechanical energy change represents the mechanical work supplied to the fluid ($\Delta e_{mech} > 0$) or extracted from the fluid ($\Delta e_{mech} < 0$).

**Mechanisms of Energy Transfer to or from a system, $E_{in}$ and $E_{out}$:**

Energy can be transferred to or from a system in three forms: heat, work and mass flow.

**Heat Transfer**: 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*. Heat transfer to a system (heat gain) increases the energy of the molecules and thus the internal energy of the system and heat transfer from a system (heat loss) decreases it.

Heat is energy in transition. It is recognized only as it crosses the boundary of a system. Consider the hot baked potato,the potato contains energy, but this energy is heat transfer only as it passes through the skin of the potato (the system boundary) to reach the air, as shown in Fig. Once in the surroundings, the transferred heat becomes part of the internal energy of the surroundings. Thus, in thermodynamics, the term heat simply means heat transfer.
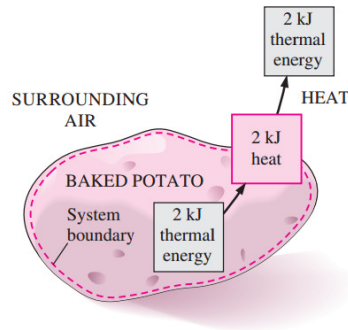
Fig.: Energy is recognized as heat transfer only as it crosses the system boundary

A process during which there is no heat transfer is called an adiabatic process. There are two ways a process can be adiabatic: Either the system is well insulated so that only a negligible amount of heat can pass through the boundary or both the system and the surroundings are at the same temperature and therefore there is no driving force (temperature difference) for heat transfer. An adiabatic process should not be confused with an isothermal process. Even though there is no heat transfer during an adiabatic process, the energy content and thus the temperature of a system can still be changed by other means such as work.
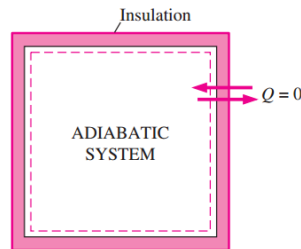


Fig.: During an adiabatic process, a system exchanges no heat with its surroundings

**Work Transfer**: If the energy crossing the boundary of a closed system is not heat, it must be work.

The generally accepted formal sign convention for heat and work interactions is as follows: heat transfer to a system and work done by a system are positive; heat transfer from a system and work done on a system are negative.

**Mass Flow**: When mass enters a system, the energy of the system increases because mass carries energy with it. Likewise, when some mass leaves the system, the energy contained within the system decreases because the leaving mass takes out some energy with it. For example, when some hot water is taken out of a water heater and is replaced by the same amount of cold water, the energy content of the hot-water tank (the control volume) decreases as a result of this mass interaction.
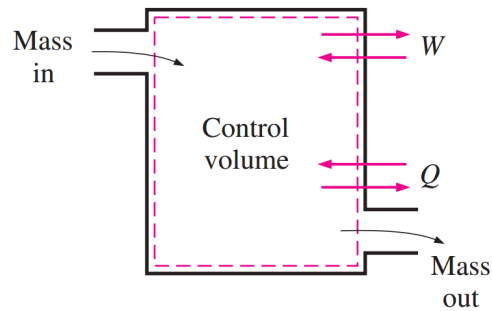
Fig.: The energy content of a control volume can be changed by mass flow as well as heat and work interactions

**More on Heat and work Transfer:**

Heat is easy to recognize: Its driving force is a temperature difference between the system and its surroundings. Then we can simply say that an energy interaction that is not caused by a temperature difference between a system and its surroundings is work.

Heat and work are energy transfer mechanisms between a system and its surroundings, and there are many similarities between them:

a) Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are boundary phenomena.

b) Systems possess energy, but not heat or work.

c) Both are associated with a process, not a state. Unlike properties, heat or work has no meaning at a state.

d) Both are path functions (i.e., their magnitudes depend on the path followed during a process as well as the end states).

**Path functions** have **inexact differentials** designated by the symbol $\delta$. Therefore, a differential amount of heat or work is represented by $\delta Q$ or $\delta W$, respectively, instead of $dQ$ or $dW$. Properties, however, are **point functions** (i.e., they depend on the state only, and not on how a system reaches that state), and they have **exact differentials** designated by the symbol $d$. A small change in volume, for example, is represented by $dV$, and the total volume change during a process between states 1 and 2 is

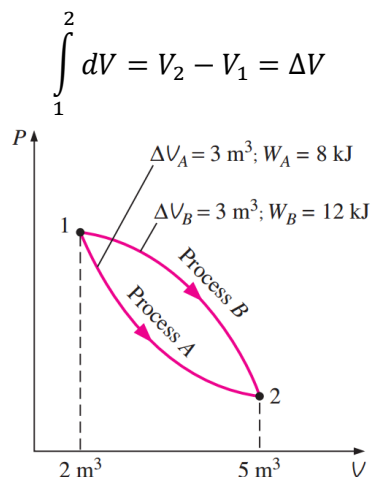$$\int_{1}^{2} dV = V_2 - V_1 = \Delta V$$



Fig.: Properties are point functions; but heat and work are path functions (their magnitudes depend on the path followed)

The total work done during process 1–2, however, is

$$\int_1^2 \delta W = W_{12} \ (Not \ \Delta W)$$

That is, the total work is obtained by following the process path and adding the differential amounts of work ($\delta W$) done along the way. The integral of $\delta W$ is not $W_2 - W_1$ (i.e., the work at state 2 minus work at state 1), which is meaningless since work is not a property and systems do not possess work at a state.

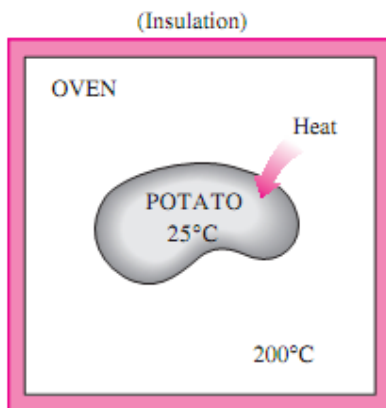**Problem 1:**

(Insulation)
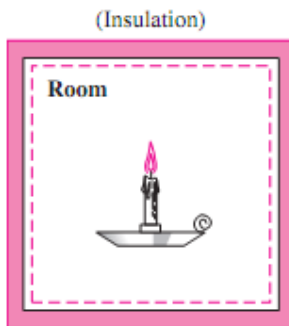
Room

**A candle is burning in a well-insulated room. Taking the room (the air plus the candle) as the system, determine (a) if there is any heat transfer during this burning process and (b) if there is any change in the internal energy of the system.**

Answer: (a) Heat is recognized as it crosses the boundaries. Since the room is well insulated, we have an adiabatic system and no heat will pass through the boundaries. Therefore, Q=0 for this process.

(b) The internal energy involves energies that exist in various forms (sensible, latent, chemical and nuclear). During the process just described, part of the chemical energy is converted to sensible energy. Since there is no increase or decrease in the total internal energy change of the system =0.

**Problem 2:**

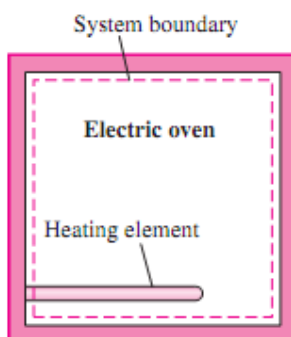(Insulation)

OVEN

Heat

POTATO
25°C

200°C

**A potato initially at room temperature (25°C) is being baked in an oven that is maintained at 200°C, as shown in Fig. Is there any heat transfer during this baking process?**

Answer: This is not a well-defined problem since the system is not specified. Let us assume that we are observing the potato, which will be our system. Then the skin of the potato can be viewed as the system boundary. Part of the energy in the oven will pass through the skin to the potato. Since the driving force for this energy transfer is a temperature difference, this is a heat transfer process.
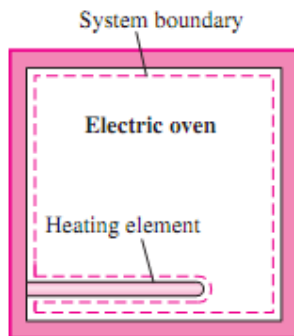
**Problem 3:**

System boundary

Electric oven

Heating element

**A well-insulated electric oven is being heated through its heating element. If the entire oven, including the heating element, is taken to be the system, determine whether this is a heat or work interaction.**

Answer: For this problem, the interior surfaces of the oven form the system boundary, as shown in Fig. The energy

content of the oven obviously increases during this process, as evidenced by a rise in temperature. This energy transfer to the oven is not caused by a temperature difference between the oven and the surrounding air. Instead, it is caused by electrons crossing the system boundary and thus doing work. Therefore, this is a work interaction.



**Problem 4: A well-insulated electric oven is being heated through its heating element. If the system is taken as only the air in the oven without the heating element, determine whether this is a heat or work interaction.**

Answer: The system boundary will include the outer surface of the heating element and will not cut through it, as shown in Fig. Therefore, no electrons will be crossing the system boundary at any point. Instead, the energy generated in the interior of the heating element will be transferred to the air around it as a result of the temperature difference between the heating element and the air in the oven. Therefore, this is a heat transfer process.

Discussion: For both cases, the amount of energy transfer to the air is the same. These two examples show that an energy transfer can be heat or work, depending on how the system is selected.

## THE FIRST LAW OF THERMODYNAMICS:

The *first law of thermodynamics is* also known as *the conservation of energy principle.* The first law of thermodynamics states that ***energy can be neither created nor destroyed during a process; it can only change forms.***

***So the first law of thermodynamics can be stated as follows for a process:***

If Q is the amount of heat transferred to the system and W is the amount of work transferred from the system during the process, the net energy transfer (Q-W) will be stored into the system. The energy stored into the system is neither heat nor work it is known as the internal energy of the system.

$$\therefore Q - W = \Delta E \quad Or, Q = W + \Delta E$$

For an isolated system, there is no interaction of the system with the surrounding.

For an isolated system dQ=0

dW=0

hence, dE=0 or, E=constant

**The energy of an isolated system is always constant.**

**Example 1:**

First, we consider some processes that involve heat transfer but no work interactions. The potato baked in the oven is a good example. As a result of heat transfer to the potato, the energy of the potato will increase. If we disregard any mass transfer (moisture loss from the potato), the increase in the total energy of the potato becomes equal to the amount of heat transfer. That is, if 5 kJ of heat is transferred to the potato, the energy increase of the potato will also be 5 kJ.
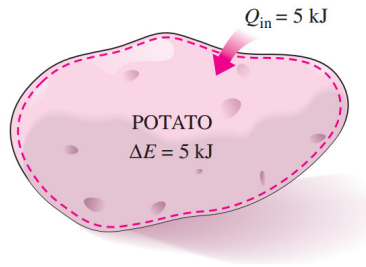
Fig.: The increase in the energy of a potato in an oven is equal to the amount of heat transferred to it

**Example 2:**

Consider the heating of water in a pan on top of a range. If 15 kJ of heat is transferred to the water from the heating element and 3 kJ of it is lost from the water to the surrounding air, the increase in energy of the water will be equal to the net heat transfer to water, which is 12 kJ.
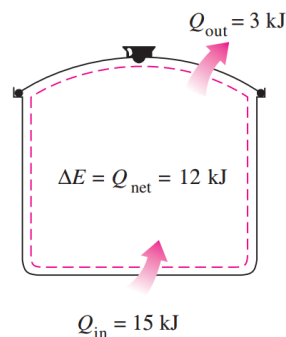


Fig.: In the absence of any work interactions, the energy change of a system is equal to the net heat transfer

**Example 3:**

Now consider a well-insulated (i.e., adiabatic) room heated by an electric heater as our system (Fig.). As a result of electrical work done, the energy of the system will increase. Since the system is adiabatic and cannot have any heat transfer to or from the surroundings (Q=0), the conservation of energy principle dictates that the electrical work done on the system must equal the increase in energy of the system.
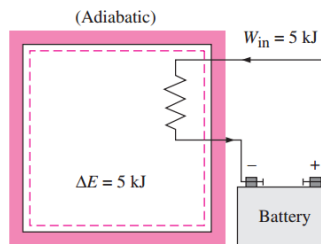


Fig.: The work (electrical) done on an adiabatic system is equal to the increase in the energy of the system

**Example 4:**

Next, let us replace the electric heater with a paddle wheel (Fig.). As a result of the stirring process, the energy of the system will increase. Again, since there is no heat interaction between the system and its surroundings (Q=0), the shaft work done on the system must show up as an increase in the energy of the system.

(Adiabatic)

$\Delta E = 8$ kJ

$W_{sh,\,in} = 8$ kJ
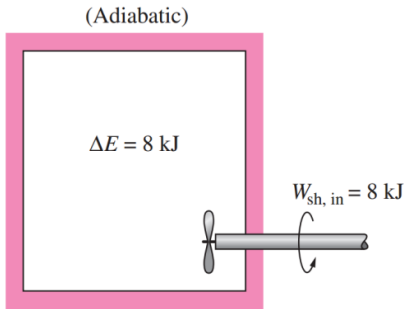
Fig.: The work (shaft) done on an adiabatic system is equal to the increase in the energy of the system

**Example 5:**

Many of you have probably noticed that the temperature of air rises when it is compressed (Fig.). This is because energy is transferred to the air in the form of boundary work. In the absence of any heat transfer (Q=0), the entire boundary work will be stored in the air as part of its total energy. The conservation of energy principle again requires that the increase in the energy of the system be equal to the boundary work done on the system.

$W_{b,\,in} = 10$ kJ

$\Delta E = 10$ kJ
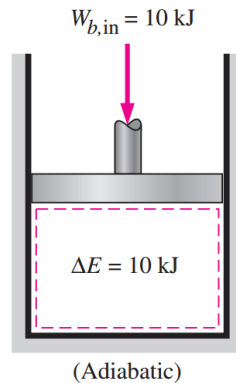
(Adiabatic)

Fig.: The work (boundary) done on an adiabatic system is equal to the increase in the energy of the system.

**Example 6:**

We can extend these discussions to systems that involve various heat and work interactions simultaneously. For example, if a system gains 12 kJ of heat during a process while 6 kJ of work is done on it, the increase in the energy of the system during that process is 18 kJ (Fig.). That is, the change in the energy of a system during a process is simply equal to the net energy transfer to (or from) the system.

$Q_{out} = 3$ kJ

$\Delta E = (15 - 3) + 6$
$\quad = 18$ kJ

$W_{sh,\,in} = 6$ kJ

$Q_{in} = 15$ kJ
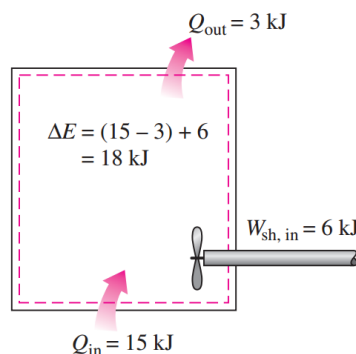
Fig.: The energy change of a system during a process is equal to the net work and heat transfer between the system and its surroundings

**Energy Balance:**

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.

$$(Total\ energy\ entring\ the\ system) - (Total\ energy\ leaving\ the\ system)$$
$$= (Change\ in\ total\ energy\ of\ the\ system)$$
$$or, E_{in} - E_{out} = \Delta E_{system}$$

The change in the total energy of a system during a process is the sum of the changes in its internal, kinetic, and potential energies and can be expressed as:

$$\Delta E = \Delta U + \Delta KE + \Delta PE$$

Noting that energy can be transferred in the forms of heat, work and mass, and that the net transfer of a quantity is equal to the difference between the amounts transferred in and out, the energy balance can be written more explicitly as:

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass\ in} - E_{mass\ out}) = \Delta E_{system}$$

Case 1: For stationary systems, the changes in kinetic and potential energies are zero. Therefore the total energy change is equal to change in internal energy.

Case 2: For a closed system undergoing a cycle, the initial and final states are identical, and thus $\Delta E_{system} = E_2 - E_1 = 0$. Noting that a closed system does not involve any mass flow across its boundaries, the energy balance for a cycle can be expressed in terms of heat and work interactions as:

$$W_{net\ out} = Q_{net\ in}$$

That is, the net work output during a cycle is equal to net heat input.
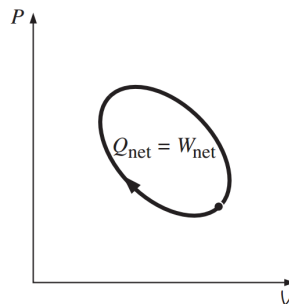


Fig.: Energy balance for a cyclic process

**So the first law of thermodynamics for a closed system undergoing a cycle can be stated as:**

When a closed system (control mass) undergoes a cycle, the cyclic integral of heat is always proportional to the cyclic integral of work.

**Prove that internal energy is a property:**

Let us assume that we have one system which is undergoing a change of state from initial state 1 to another state 2 via following the path A as shown in following figure. System is returning to initial state i.e. state 1 from state 2 via following the path B. Here, we can say that system is undergoing in a cycle 1-2-1 as shown in figure.
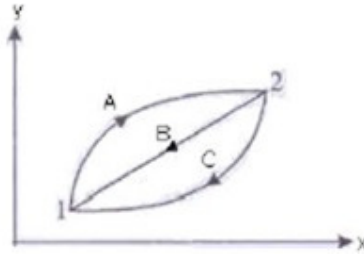
Let us recall the "first law of thermodynamics for a system undergoing a change of state" and apply for path A, where system is changing its state from state 1 to state 2. We will have following equation

$$Q_A - W_A = \Delta E_A$$

Similarly, we will have following equation when system is changing its state from state 2 to state 1 via following the path B.

$$Q_B - W_B = \Delta E_B$$

We have already seen that system is undergoing in a cycle 1-2-1 as displayed in above figure. Hence, we will use the concept of "first law of thermodynamics for a system undergoing a cycle". Let us see the equation for system which constitutes a cycle 1-2-1 and we will have following equation.

$$\sum_{Cycle} W = \sum_{cycle} Q$$

$$W_A + W_B = Q_A + Q_B$$
$$W_B - Q_B = Q_A - W_A$$
$$-(Q_B - W_B) = Q_A - W_A$$
$$-(\Delta E_B) = \Delta E_A$$

Let us assume that system is returning to initial state 1 from state 2 via following the path C, in that case we will go ahead similarly as we have gone above and finally we will have following equation
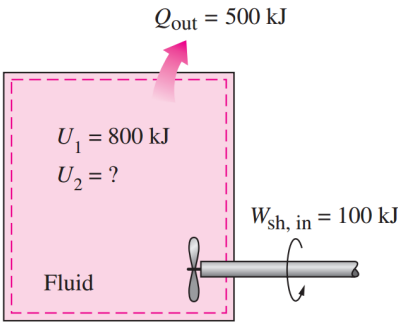
$$-(\Delta E_C) = \Delta E_A$$

Now if we will look the end result for first case where system is returning to initial state by following the path B and of second case where system is returning to initial state by following the path C, what we will secure here that change in system energy is same in both cases and it will not depend over the path followed by the system to return to its initial state.

Therefore we can conclude that system energy will have some definite magnitude for each state of the system and it will not depend over the path followed by the system and hence energy will be considered as a point function and also a property of the system.

**Problem 1:**
A rigid tank contains a hot fluid that is cooled while being stirred by a paddle wheel. Initially, the internal energy of the fluid is 800 kJ. During the cooling process, the fluid loses 500 kJ of heat, and the paddle wheel does 100 kJ of work on the fluid. Determine the final internal energy of the fluid. Neglect the energy stored in the paddle wheel.

$Q_{out} = 500 \text{ kJ}$

$U_1 = 800 \text{ kJ}$
$U_2 = ?$

$W_{sh, in} = 100 \text{ kJ}$

Fluid

$$\underbrace{E_{in} - E_{out}}_{Net\ energy\ transfer\ by\ heat,work\ and\ mass} = \underbrace{\Delta E_{system}}_{Change\ in\ internal,kinetic,potential\ energy}$$

$$W_{shaft,in} - Q_{out} = \Delta U = U_2 - U_1$$
$$100 - 500 = U_2 - 800$$
$$or, U_2 = 400 \text{ kJ}$$

Therefore, the final internal energy of the system is 400 kJ.

**Problem:** A paddle wheel used for mixing and stirring of fluids turns 600 rpm when 2·5 Nm torque is applied to it. What is power transmitted to the liquid by the wheel?

**Answer:**

$$\dot{W}_{Shaft} = 2\pi \dot{n}T = 2\pi \times \frac{600}{60} \times 2.5 \times \frac{1}{1000} \text{ kW} = 0.157 \text{ kW}$$

**During one cycle the working fluid in an engine engages in the work interaction 15 kJ to the fluid and 44 kJ from the fluid and there are three heat interactions, two of which are known as 75 kJ to the fluid and 40 kJ from the fluid. Find out the magnitude and direction of the third heat transfer.**

**Answer:** $W_1 = -15 \text{ kJ}, W_2 = 44 \text{ kJ}, Q_1 = 75 \text{ kJ}, Q_2 = -40 \text{ kJ}, Q_3 = ?$

For the cyclic process we know that,

$$\oint dQ = \oint dW$$

$$or, 75 - 40 + Q_3 = -15 + 44$$

$$or, Q_3 = -6 \text{ kJ}$$

So the heat will flow out from the system.

**A system contained in a piston and cylinder machine passes through a complete cycle of four processes. The sum of all heat transferred during a cycle is -350kJ. The system completes 200 cycles per minute. Complete the following table showing the method for each item, and compute the net rate of work output in kW.**

| Process | Q (kJ/min) | W (kJ/min) | $\Delta U$ (kJ/min) |
|---------|------------|------------|---------------------|
| 1-2 | 0 | 4340 | - |
| 2-3 | 42000 | 0 | - |

| 3-4 | -4200 | - | -73200 |
|:---:|:---:|:---:|:---:|
| 4-1 | - | - | - |

**Answer:**

For the process $1 - 2$,

$$Q_{1-2} = \Delta U + W_{1-2}$$

$$or, 0 = \Delta U + 4340$$

$$or, \Delta U = -4340 \ kJ/min$$

For the process $2 - 3$,

$$Q_{2-3} = \Delta U + W_{2-3}$$

$$or, 42000 = \Delta U + 0$$

$$or, \Delta U = 42000 \ kJ/min$$

For the process $3 - 4$,

$$Q_{3-4} = \Delta U + W_{3-4}$$

$$or, -4200 = -73200 + W_{3-4}$$

$$or, W_{3-4} = 69000 \ kJ/min$$

The sum of all heat transferred during a cycle is -350kJ.

So, $\oint Q = -350 \times 200 = -70000 \ kJ/min$

$$\therefore Q_{1-2} + Q_{2-3} + Q_{3-4} + Q_{4-1} = -70000$$

$$or, Q_{4-1} = -107800 \ kJ/min$$

Now, internal energy being a property, $\oint u = 0$

$$or, -4340 + 42000 - 73200 + \Delta U_{4-1} = 0$$

$$or, \Delta U_{4-1} = 35540 \ kJ/min$$

Now,

$$Q_{4-1} = \Delta U + W_{4-1}$$

$$or, W_{4-1} = -1433340 \ kJ/min$$


**Total Energy of a Flowing Fluid**

As we have seen the total energy of a simple compressible system consists of three parts: internal, kinetic, and potential energies. On a unit-mass basis, it is expressed as

$$e = u + ke + pe = u + \frac{v^2}{2} + gz \quad (kJ/kg)$$

where V is the velocity and $z$ is the elevation of the system relative to some external reference point.

The fluid entering or leaving a control volume possesses an additional form of energy-the flow energy, Pv. P is the fluid pressure. Then the total energy of a flowing fluid on a unit-mass basis becomes

$$\theta = Pv + e = Pv + u + \frac{v^2}{2} + gz$$

But the combination $Pv + u$ has been defined as the enthalpy h. So the relation reduces to:

$$\theta = h + \frac{v^2}{2} + gz \quad (kJ/kg)$$

**MOVING BOUNDARY WORK: -**

During the expansion or compression of a gas in a piston-cylinder device, part of the boundary (the inner face of the piston) moves back and forth. Therefore, the expansion and compression work is often called moving boundary work, or simply boundary work. Consider the gas enclosed in the piston–cylinder device shown in Fig.
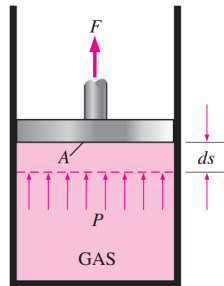


The initial pressure of the gas is $P$, the total volume is $V$, and the cross sectional area of the piston is $A$. If the piston is allowed to move distance ds in a quasi-equilibrium manner, the differential work done during this process is,

$$\delta W_b = Fds = PAds = PdV$$

The total boundary work done during the entire process as the piston moves is obtained by adding all the differential works from the initial state to the final state:

$$W_b = \int_1^2 PdV$$

The area under the process curve on a P-V diagram is equal, in magnitude, to the work done during a quasi-equilibrium expansion or compression process of a closed system.
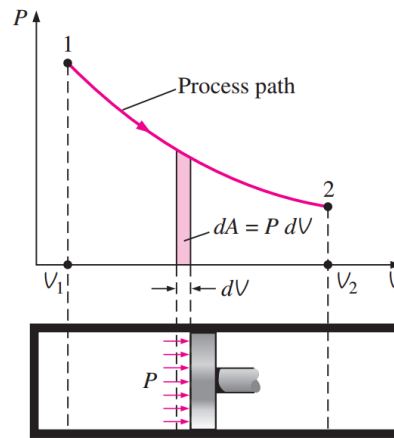
The boundary work done during a process depends on the path followed as well as the end states.



$W_A = 10 \text{ kJ}$
$W_B = 8 \text{ kJ}$
$W_C = 5 \text{ kJ}$
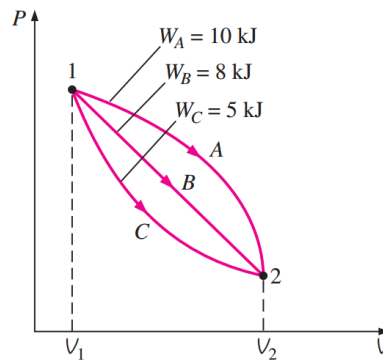
If work were not a path function, no cyclic devices (car engines, power plants) could operate as work-producing devices. The work produced by these devices during one part of the cycle would have to be consumed during another part, and there would be no net work output. The cycle shown in Fig. produces a net work output because the work done by the system during the expansion process (area under path A) is greater than the work done on the system during the compression part of the cycle (area under path B), and the difference between these two is the net work done during the cycle (the colored area).
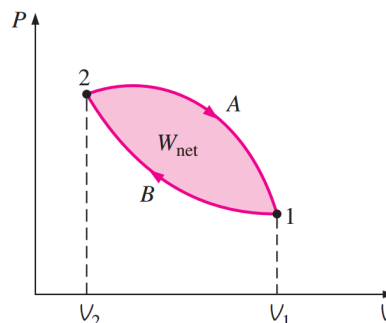


Fig. The net work done during a cycle is the difference between the work done by the system and the work done on the system

**Problem 1: A rigid tank contains air at 500 kPa and 150°C. As a result of heat transfer to the surroundings, the temperature and pressure inside the tank drop to 65°C and 400 kPa, respectively. Determine the boundary work done during this process.**

Answer: A sketch of the system and the P-V diagram of the process are shown in Fig.
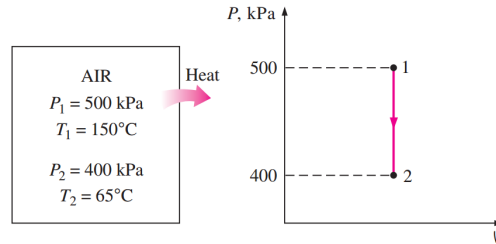


The boundary work can be determined from equation to be

$$W_b = \int_1^2 P \, dv = 0 \quad \text{since } dv \text{ is zero.}$$

**Problem 2: A non flow quasi static reversible process occurs for which p=(-2V+16) bar, where V is the volume in m³. What is the work done when volume changes from 2 m³ to 6 m³.**

Answer: $1 \, bar = 10^5 N/m^2$

$$W_{1-2} = \int_2^6 pdV = \int_2^6 (-2V + 16) \times 10^5 = 32 \times 10^5 Joule$$

**Boundary Work for a Constant-Pressure Process:**
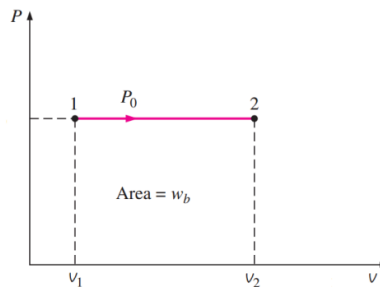


$$W_b = \int_1^2 P \, dv = P_0 \int_1^2 dv = P_0(v_2 - v_1)$$

**Isothermal Compression of an Ideal Gas:**

**A piston-cylinder device initially contains 0.4 m³ of air at 100 kPa and 80°C. The air is now compressed to 0.1 m³ in such a way that the temperature inside the cylinder remains constant. Determine the work done during this process.**

For an ideal gas at constant temperature $T_0$,
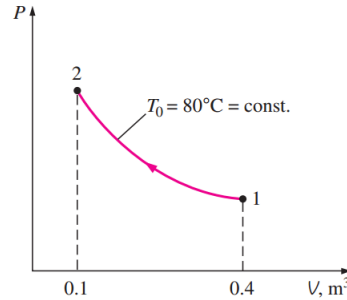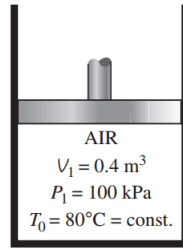
$$Pv = mRT_0 = C$$

$$or, P = \frac{C}{v}$$

$$W_b = \int_1^2 P\,dv = \int_1^2 \frac{C}{v}\,dv = C\int_1^2 \frac{dv}{v} = C\,ln\frac{v_2}{v_1} = P_1 v_1\,ln\frac{v_2}{v_1} = P_2 v_2\,ln\frac{v_2}{v_1} = mRT_0\,ln\frac{v_2}{v_1}$$

*Similarly, the ratio $\frac{v_2}{v_1}$ can be replaced by $\frac{P_1}{P_2}$*

$$W_b = -55.5\ kJ$$

The negative sign indicates that this work is done on the system (a work input), which is always the case for compression processes.

**Work done by a substance in a reversible non-flow manner is in accordance with $V = \frac{150}{P} m^3$, where P is in bar. Determine the work done on or by the system as pressure increases from 10 to 100 bar. Indicate whether it is a compression process or expansion process.**

**Answer:** Given,

$$V = \frac{150}{P}$$

So $V_1 = \frac{150}{10} = 15 m^3$ and $V_2 = \frac{150}{100} = 1.5 m^3$

Again $P = \frac{150}{V}\ bar = \frac{150}{V} \times 10^5\ N/m^2$

So work done $W_{1-2} = \int_{15}^{1.5} P dV = \int_{15}^{1.5} \left(\frac{150}{V} \times 10^5\right) dV = -3.454 \times 10^7\ Joule$

This work is done on the system. It is therefore compression work.

[4-23] A piston-cylinder device initially contains 0.25 kg of nitrogen gas at 130 kPa and 180°C. The nitrogen is now expanded isothermally to a pressure of 80 kPa. Determine the boundary work done during this process.

**R=0.2968 kJ/Kg.K**

*Analysis* We first determine initial and final volumes from ideal gas relation, and find the boundary work using the relation for isothermal expansion of an ideal gas

$$V_1 = \frac{mRT}{P_1} = \frac{(0.25\,\text{kg})(0.2968\,\text{kJ/kg.K})(180+273\,\text{K})}{(130\,\text{kPa})} = 0.2586\,\text{m}^3$$

$$V_2 = \frac{mRT}{P_2} = \frac{(0.25\,\text{kg})(0.2968\,\text{kJ/kg.K})(180+273\,\text{K})}{80\,\text{kPa}} = 0.4202\,\text{m}^3$$

$$W_b = P_1V_1 \ln\left(\frac{V_2}{V_1}\right) = (130\,\text{kPa})(0.2586\,\text{m}^3)\ln\left(\frac{0.4202\,\text{m}^3}{0.2586\,\text{m}^3}\right) = \textbf{16.3 kJ}$$

N₂
130 kPa
180°C
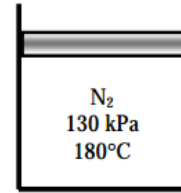
## Polytropic Process: -

During actual expansion and compression processes of gases, pressure and volume are often related by $Pv^n = C$, where $n$ and $C$ are constants. A process of this kind is called a **polytropic process**. Below we develop a general expression for the work done during a polytropic process. The pressure for a polytropic process can be expressed as, $P = Cv^{-n}$
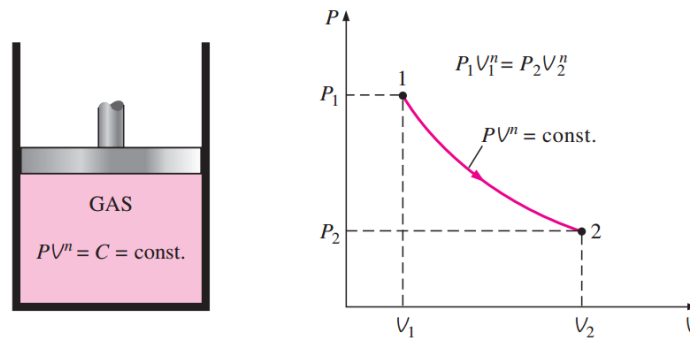


$$W_b = \int_1^2 P\,dv = \int_1^2 Cv^{-n}\,dv = C\frac{v_2^{-n+1} - v_1^{-n+1}}{-n+1} = \frac{P_2v_2 - P_1v_1}{1-n} = \frac{mR(T_2 - T_1)}{1-n}$$

For the special case of n=1 the boundary work becomes equivalent to the isothermal process.

**A mass of gas is compressed in a quasi static process from 80 kPa, 0.1 m³ to 0.4 MPa, 0.03 m³. Assuming that the pressure and volume are related by $PV^n = Constant$, find the work done by the gas system.**

**Answer:** $P_1 = 80\,kPa, V_1 = 0.1m^3, P_2 = 0.4\,MPa = 400\,kPa, V_2 = 0.03m^3$

We know that, $P_1V_1{}^n = P_2V_2{}^n$ Or, $n = 1.33$

$$W_b = \int_1^2 P\,dv = \int_1^2 Cv^{-n}\,dv = C\frac{v_2^{-n+1} - v_1^{-n+1}}{-n+1} = \frac{P_2v_2 - P_1v_1}{1-n} = -12.12\,KJ$$

Consider a gas contained in a piston cylinder assembly as the system. The gas is initially at a pressure of 500 kPa occupies a volume of 0.2 m³. The gas is taken to the final state where pressure is equal to 100 kPa by the following two different processes.

a) The volume of the gas is inversely proportional to the process.

b) The process follow the path $pv^n = constant$, where n=1.4. Calculate the work done by the gas in each case.

Ans: (a)

$$P_1 = 500 \, kPa$$

$$P_2 = 100 \, kPa$$

$$V_1 = 0.2 \, m^3$$

$$Pv = C$$

$$or, P = \frac{C}{v}$$

$$W_b = \int_1^2 P \, dv = \int_1^2 \frac{C}{v} \, dv = C \int_1^2 \frac{dv}{v} = C \ln \frac{v_2}{v_1} = P_1 v_1 \ln \frac{v_2}{v_1} = P_1 v_1 \ln \frac{P_1}{P_2} = 160.94 \, kJ$$

Ans: (b)

$$Pv^n = C$$

$$\therefore P_1 V_1{}^n = P_2 V_2{}^n$$

$$or, V_2 = \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} V_1$$

$$or, V_2 = 0.6314 \, m^3$$

$$W_b = \frac{P_2 v_2 - P_1 v_1}{1 - n} = 92.15 \, kJ$$

**In a cylinder piston arrangement, 3 kg of an ideal gas are expanded adiabatically from a temperature of 135°C to 35°C and it is found to perform 160 kJ of work during the process while its enthalpy change is 315 kJ. Determine the specific heats at constant volume and constant pressure and characteristic gas constant.**

**Answer:**

The given mass of ideal gas m=3kg

$$T_1 = 135 + 273 = 408 \, K$$

$$T_2 = 35 + 273 = 308 \, K$$

$$Work \, done = W = 160 \, kJ$$

$$Enthalpy \, change = H = 315 \, kJ$$

We have to find out: $C_p =?, C_v =? \, and \, R =?$

Work done during adiabatic process=

$$W_b = \frac{P_2 v_2 - P_1 v_1}{1 - \gamma} = \frac{mR(T_2 - T_1)}{1 - \gamma}$$

$$or, 160000 = \frac{3 \times R(308 - 408)}{1 - 1.4}$$

$$or, R = 0.213 \, kJ/kg.K$$

Again,

$$H = mC_p(T_1 - T_2)$$

$$or, 315 = 3 \times C_p \times 100$$

$$or, C_p = 1.05 \, kJ/kg.K$$

Further we know that,

$$C_p - C_v = R$$

$$or, C_v = 0.837 \, kJ/kg.K$$

**A fluid at a pressure of 3.5 bar and with specific volume of 0.2 m3/kg is contained in a piston-cylinder arrangement. The fluid expands reversibly to a pressure of 0.8 bar according to the law $pv^2 = constant.$ Determine the work done by the fluid on the piston.**

$$W = \int_1^2 pdV = C\int_1^2 \frac{dV}{V^2} = C\left[\frac{1}{V_1} - \frac{1}{V_2}\right]$$

Now, $C = p_1V_1^2 = 0.14$

$$V_2 = \sqrt{\frac{C}{p_2}} = 0.418 \, m^3$$

$$\therefore W = 36.507 \, kJ/kg$$

[4-21] Carbon dioxide contained in a piston-cylinder device is compressed from 0.3 to 0.1 m³. During the process, the pressure and volume are related by P = aV⁻², where a = 8 kPa-m⁶. Calculate the work done on the carbon dioxide during this process.

**4-21** CO₂ gas in a cylinder is compressed until the volume drops to a specified value. The pressure changes during the process with volume as $P = aV^{-2}$. The boundary work done during this process is to be determined.

*Assumptions* The process is quasi-equilibrium.

*Analysis* The boundary work done during this process is determined from

$$W_{b,out} = \int_1^2 PdV = \int_1^2 \left(\frac{a}{V^2}\right)dV = -a\left(\frac{1}{V_2} - \frac{1}{V_1}\right)$$

$$= -(8 \, kPa \cdot m^6)\left(\frac{1}{0.1 \, m^3} - \frac{1}{0.3 \, m^3}\right)\left(\frac{1 \, kJ}{1 \, kPa \cdot m^3}\right)$$

$$= -53.3 \, kJ$$
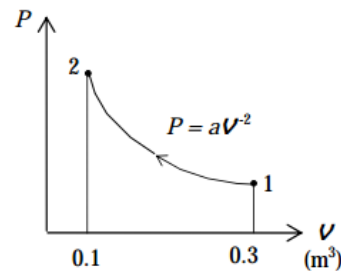
*Discussion* The negative sign indicates that work is done on the system (work input).

[4-24] A piston-cylinder device contains 0.15 kg of air initially at 2 MPa and 350°C. The air is first expanded isothermally to 500 kPa, then compressed polytropically with a polytrophic exponent of 1.2 to the initial pressure, and finally compressed at the constant pressure to the initial state. Determine the boundary work for each process and the net work of the cycle.

**4-24** A piston-cylinder device contains air gas at a specified state. The air undergoes a cycle with three processes. The boundary work for each process and the net work of the cycle are to be determined.

***Properties*** The properties of air are $R = 0.287$ kJ/kg.K , $k = 1.4$ (Table A-2a).

***Analysis*** For the isothermal expansion process:

$$V_1 = \frac{mRT}{P_1} = \frac{(0.15\,\text{kg})(0.287\,\text{kJ/kg.K})(350+273\,\text{K})}{(2000\,\text{kPa})} = 0.01341\,\text{m}^3$$

$$V_2 = \frac{mRT}{P_2} = \frac{(0.15\,\text{kg})(0.287\,\text{kJ/kg.K})(350+273\,\text{K})}{(500\,\text{kPa})} = 0.05364\,\text{m}^3$$

$$W_{b,1-2} = P_1 V_1 \ln\left(\frac{V_2}{V_1}\right) = (2000\,\text{kPa})(0.01341\,\text{m}^3)\ln\left(\frac{0.05364\,\text{m}^3}{0.01341\,\text{m}^3}\right) = \textbf{37.18 kJ}$$
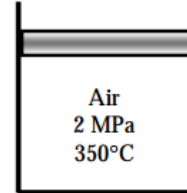
For the polytropic compression process:

$$P_2 V_2^n = P_3 V_3^n \longrightarrow (500\,\text{kPa})(0.05364\,\text{m}^3)^{1.2} = (2000\,\text{kPa})V_3^{1.2} \longrightarrow V_3 = 0.01690\,\text{m}^3$$

$$W_{b,2-3} = \frac{P_3 V_3 - P_2 V_2}{1-n} = \frac{(2000\,\text{kPa})(0.01690\,\text{m}^3) - (500\,\text{kPa})(0.05364\,\text{m}^3)}{1-1.2} = \textbf{-34.86 kJ}$$

For the constant pressure compression process:

$$W_{b,3-1} = P_3(V_1 - V_3) = (2000\,\text{kPa})(0.01341 - 0.01690)\,\text{m}^3 = \textbf{-6.97 kJ}$$

The net work for the cycle is the sum of the works for each process

$$W_{net} = W_{b,1-2} + W_{b,2-3} + W_{b,3-1} = 37.18 + (-34.86) + (-6.97) = \textbf{-4.65 kJ}$$

## INTERNAL ENERGY, ENTHALPY AND SPECIFIC HEATS OF IDEAL GASES

**Internal energy:**

For an ideal gas the internal energy is a function of the temperature only.

$$u = u(T)$$
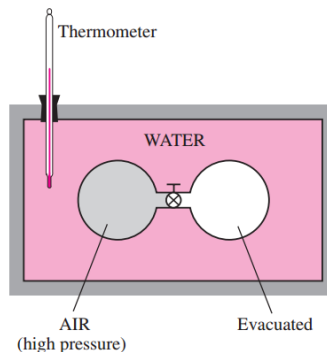
Fig.: Schematic of the experimental apparatus used by Joule

In his classical experiment, Joule submerged two tanks connected with a pipe and a valve in a water bath, as shown in Fig. Initially, one tank contained air at a high pressure and the other tank was evacuated. When thermal equilibrium was attained, he opened the valve to let air pass from one tank to the other until the pressures equalized. Joule observed no change in the temperature of the water bath and assumed that no heat was transferred to or from the air. Since there was also no work done, he concluded that the internal energy of the air did not change even though the volume and the pressure changed. Therefore, he reasoned, the internal energy is a function of temperature only and not a function of pressure or specific volume. (Joule later showed that for gases that deviate significantly from ideal-gas behavior, the internal energy is not a function of temperature alone.)

## SPECIFIC HEATS:

The specific heat is defined as the energy required raising the temperature of a unit mass of a substance by one degree.

In thermodynamics, there are two kinds of specific heats: **specific heat at constant volume** $C_v$ and **specific heat at constant pressure** $C_p$.

The specific heat at constant volume can be viewed as the energy required raising the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

$$C_v = \left(\frac{\delta u}{\delta T}\right)_v$$

This implies the change in internal energy with temperature at constant volume.

$$du = C_v(T)dT$$

$$\Delta u = u_2 - u_1 = \int_1^2 C_v(T)dT$$

The specific heat at constant pressure can be viewed as the energy required raising the temperature of the unit mass of a substance by one degree as the pressure is maintained constant.

$$C_p = \left(\frac{\delta h}{\delta T}\right)_p$$

This implies the change in enthalpy with temperature at constant pressure.

$$dh = C_p(T)dT$$

$$\Delta h = h_2 - h_1 = \int_1^2 C_p(T)dT$$

For ideal gas: $C_P$ and $C_V$ are function of T.  For perfect gas $C_P$ and $C_V$ are constant.

## ENTHALPY:

Enthalpy of a substance, $h = u + Pv = u + RT$

It is an intensive property of a system.

Since R is constant and $u = u(T)$, it follows that the enthalpy of an ideal gas, is also a function of temperature only: $h = h(T)$.

Since $u$ and $h$ depend only on temperature for an ideal gas, the specific heats $C_V$ and $C_P$ also depend, at most, on temperature only.

Special Case: We know that for a closed stationary system of unit mass,

$$dq = du + Pdv$$

At constant pressure, $Pdv = d(Pv)$

Hence, $(dq)_p = du + d(Pv)$

Or, $(dq)_p = d(u + Pv) = dh$

**Specific Heat Relations of Ideal Gases:**

A special relationship between $C_p$ and $C_v$ for ideal gases can be obtained by differentiating the relation $h = u + RT$, which yields

$$dh = du + R\,dT$$

$$\text{Or, } C_p dT = C_v dT + RdT$$

$$\text{Or, } C_p = C_v + R$$

Ideal-gas property called the specific heat ratio $\gamma$, defined as:

$$\gamma = \frac{C_p}{C_v}$$

The specific ratio also varies with temperature, but this variation is very mild. For monatomic gases, its value is essentially constant at 1.667. Many diatomic gases, including air, have a specific heat ratio of about 1.4 at room temperature.

**Problem 1: During certain process, the heat capacity of a system is given by $C_n = 0.4 + 0.004T\ kJ/kg°C$. If the mass of the gas is 8 kg and its temperature changes from 20°C to 120°C find: (a) heat transferred, (b) mean specific heat of the gas.**

Answer:

(a) $Q = \int mC_n dT = 8\int_{20}^{120}(0.4 + 0.004T)dT = 544\ kJ$

(b) We know that,

$$Q = mC_n dT$$

$$or, 544 = 8 \times C_n \times (120 - 20)$$

$$or, C_n = 0.68\ kJ/kg°C$$

**Problem 2: An insulated rigid tank initially contains 0.7 kg of helium at 27°C and 350 kPa. A paddle wheel with a power rating of 0.015 kW is operated within the tank for 30 min. Determine (a) the final temperature and (b) the final pressure of the helium gas.**

$$For\ Helium\ gas\ c_{v,avg} = 3.15\frac{kJ}{kg.K}$$
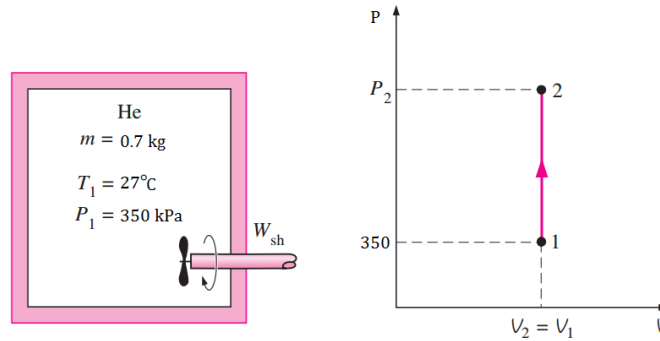


Constant specific heats can be used for helium. The system is stationary and thus the kinetic and potential energy changes are zero, ΔKE=ΔPE=0 and ΔE=ΔU. The volume of the tank is constant, and thus there is no boundary work. The system is adiabatic and thus there is no heat transfer. We take the contents of the tank as the system. This is a closed system since no mass crosses the system boundary during the process.

The amount of paddle-wheel work done on the system is:

$$W_{sh} = (0.015 \times 30 \times 60)kJ = 27\ kJ$$

Under the stated assumptions and observations, the energy balance on the system can be expressed as:

$$\underbrace{E_{in} - E_{out}}_{Net\ energy\ transfer\ by\ heat,work\ and\ mass} = \underbrace{\Delta E_{system}}_{Change\ in\ internal,kinetic,potential\ energy}$$

$$\therefore W_{sh} = \Delta U = m(u_2 - u_1) = mc_{v,avg}(T_2 - T_1)$$

$$or, 27 = 0.7 \times 3.15 \times (T_2 - 300)$$

$$or, T_2 = 39.24°C$$

Now, The final pressure is determined from the ideal-gas relation:

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2}$$

$$or, \frac{350}{300} = \frac{P_2}{312.24}\ (Volume\ remaining\ constant)$$

$$or, P_2 = 364.29\ kPa$$

**Flow work and Total Energy of a Flowing Fluid:**

Control volumes involve mass flow across their boundaries, and some work is required to push the mass into or out of the control volume. This work is known as the flow work, or flow energy, and is necessary for maintaining a continuous flow through a control volume.

To obtain a relation for flow work, consider a fluid element of volume $V$ as shown in Fig. The fluid immediately upstream forces this fluid element to enter the control volume; thus, it can be regarded as an imaginary piston. The fluid element can be chosen to be sufficiently small so that it has uniform properties throughout.
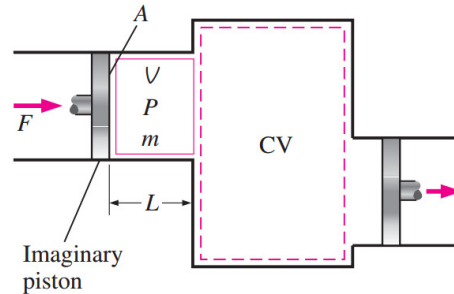
Fig.: Schematic for flow work

(a) Before entering

(b) After entering
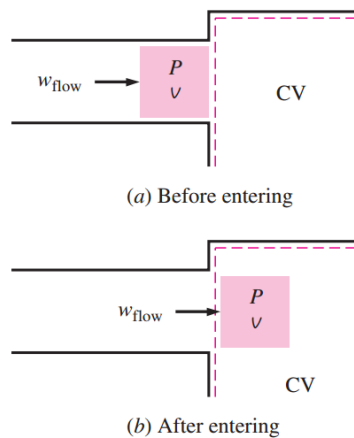
Fig.: Flow work is the energy needed to push a fluid into or out of a control volume, and it is equal to $Pv$

If the fluid pressure is P and the cross-sectional area of the fluid element is A, the force applied on the fluid element by the imaginary piston is

$$F = PA$$

To push the entire fluid element into the control volume, this force must act through a distance L. Thus, the work done in pushing the fluid element across the boundary (i.e., the flow work) is

$$W_{Flow} = FL = PAL = PV$$

The flow work relation is the same whether the fluid is pushed into or out of the control volume.

The total energy of a simple compressible system consists of three parts: internal, kinetic, and potential energies. On a unit-mass basis for a non-flowing fluid, it is expressed as

$$e = u + ke + pe = u + \frac{V^2}{2} + gz$$

The fluid entering or leaving a control volume possesses an additional form of energy—the flow energy $Pv$. Then the total energy of a flowing fluid on a unit-mass basis (denoted by $\theta$) becomes

$$\theta = Pv + e = Pv + (u + ke + pe) = Pv + u + \frac{V^2}{2} + gz = h + \frac{V^2}{2} + gz$$

**Energy Analysis of Steady-Flow Systems:**

Let us consider a certain set of assumptions that lead to a reasonable model for this type of process, which we refer to as the steady-state steady flow process.

1. The control volume does not move relative to the coordinate frame.

2. The state of the mass at each point in the control volume does not vary with time.

3. As for the mass that flows across the control surface, the mass flux and the state of this mass at each discrete area of flow on the control surface do not vary with time.

During a steady-flow process, the total energy content of a control volume remains constant ($E_{CV}$ = constant), and thus the change in the total energy of the control volume is zero ($\Delta E_{CV}=0$). Therefore, the amount of energy entering a control volume in all forms (by heat, work, and mass) must be equal to the amount of energy leaving it. Then the rate form of the general energy balance reduces for a steady-flow process to

$$[\dot{Q} + \dot{W} + \sum \dot{m}\,(h + \frac{V^2}{2} + gz)]_{inlet} = [\dot{Q} + \dot{W} + \sum \dot{m}\,(h + \frac{V^2}{2} + gz)]_{outlet}$$

**Some Steady-Flow Engineering Devices**

Many engineering devices operate essentially under the same conditions for long periods of time. The components of a steam power plant (turbines, compressors, heat exchangers, and pumps), for example, operate nonstop for months before the system is shut down for maintenance. Therefore, these devices can be conveniently analyzed as steady-flow devices. In this section, some common steady-flow devices are described, and the thermodynamic aspects of the flow through them are analyzed. The conservation of mass and the conservation of energy principles for these devices are illustrated with examples.

**Nozzles and Diffusers**

Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses.

A nozzle is a device that increases the velocity of a fluid at the expense of pressure.

A diffuser is a device that increases the pressure of a fluid by slowing it down.

That is, nozzles and diffusers perform opposite tasks. The cross-sectional area of a nozzle decreases in the flow direction for subsonic flows and increases for supersonic flows. The reverse is true for diffusers.

The rate of heat transfer between the fluid flowing through a nozzle or a diffuser and the surroundings is usually very small ($\dot{Q} = 0$) since the fluid has high velocities, and thus it does not spend enough time in the device for any significant heat transfer to take place. Nozzles and diffusers typically involve no work ($\dot{W} = 0$) and any change in potential energy is negligible ($\Delta pe = 0$). But nozzles and diffusers usually involve very high velocities, and as a fluid passes through a nozzle or diffuser, it experiences large changes in its velocity. Therefore, the kinetic energy changes must be accounted for in analyzing the flow through these devices ($\Delta ke \neq 0$).
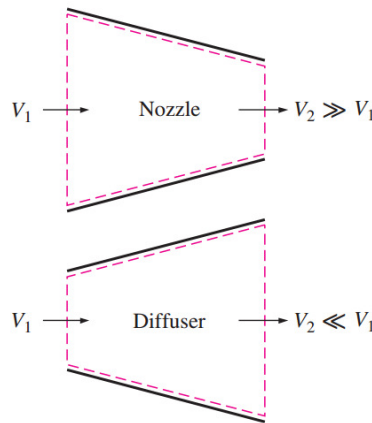


Fig.: Nozzles and diffusers are shaped so that they cause large changes in fluid velocities and thus kinetic energies

**Problem: At the inlet to a certain nozzle the specific enthalpy of the fluid is 3025 kJ/kg and the velocity is 60 m/s. At the exit from the nozzle the enthalpy is 2790 kJ/kg. The nozzle is horizontal and there is negligible heat loss from it. i) Find the velocity at the nozzle exit. ii) If the inlet area is 0.1 m² and specific volume at inlet is 0.19 m³/kg, find the rate of flow of fluid. iii) If the specific volume at the nozzle exit is 0.5 m³/kg, find the exit area of the nozzle.**

**Answer:**

(i) Under stated assumptions and observations, the energy balance for this steady-flow system can be expressed in the rate form as:

$$[\dot{Q} + \dot{W} + \sum \dot{m}\,(h + \frac{V^2}{2} + gz)]_{inlet} = [\dot{Q} + \dot{W} + \sum \dot{m}\,(h + \frac{V^2}{2} + gz)]_{outlet}$$

$$For\ this\ case,\ h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

$$3025000 + \frac{60^2}{2} = 2790000 + \frac{V_2^2}{2}$$

$$.V_2 = 688.2 \ m/s$$

(ii) $A_1 = 0.1 \ m^2, v_1 = 0.19 \frac{m^3}{kg}, V_1 = 60 \frac{m}{s}$

$$\dot{m}_1 = A_1 V_1 \rho_1 = 0.1 \times 60 \times \frac{1}{0.19} = 31.6 \frac{kg}{s}$$

(iii) $v_2 = 0.5 \frac{m^3}{kg}$

$$\dot{m}_2 = A_2 V_2 \rho_2 = \frac{A_2 V_2}{v_2}$$

$$or, 31.6 = \frac{A_2 \times 688.2}{0.5}$$

$$or, A_2 = 0.0229 \ m^2$$

[5-30] Air enters an adiabatic nozzle steadily at 300 kPa,200°C, and 45 m/s and leaves at 100 kPa and 180 m/s. The inlet area of the nozzle is 110 cm². Determine (a) the mass flow rate through the nozzle, (b) the exit temperature of their, and (c) the exit area of the nozzle. [Answers: (a) 1.09 kg/s, (b) 185°C, (c) 79.9 cm²]

*Properties* The gas constant of air is 0.287 kPa.m³/kg.K (Table A-1). The specific heat of air at the anticipated average temperature of 450 K is $c_p$ = 1.02 kJ/kg.°C (Table A-2).

*Analysis* (a) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. Using the ideal gas relation, the specific volume and the mass flow rate of air are determined to be

$P_1$ = 300 kPa
$T_1$ = 200°C       AIR       $P_2$ = 100 kPa
$V_1$ = 45 m/s                $V_2$ = 180 m/s
$A_1$ = 110 cm²

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(473 \text{ K})}{300 \text{ kPa}} = 0.4525 \text{ m}^3/\text{kg}$$

$$\dot{m} = \frac{1}{v_1} A_1 V_1 = \frac{1}{0.4525 \text{ m}^3/\text{kg}} (0.0110 \text{ m}^2)(45 \text{ m/s}) = 1.094 \text{ kg/s}$$
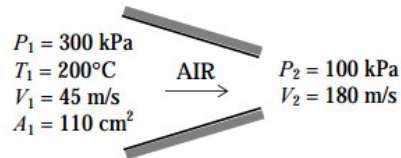
(b) We take nozzle as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta\dot{E}_{system}^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}(h_1 + V_1^2/2) = \dot{m}(h_2 + V_2^2/2) \quad (\text{since } \dot{Q} \cong \dot{W} \cong \Delta pe \cong 0)$$

$$0 = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} \longrightarrow 0 = c_{p,ave}(T_2 - T_1) + \frac{V_2^2 - V_1^2}{2}$$

Substituting,

$$0 = (1.02 \text{ kJ/kg} \cdot \text{K})(T_2 - 200°\text{C}) + \frac{(180 \text{ m/s})^2 - (45 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right)$$

It yields

$$T_2 = 185.2°\text{C}$$

(c) The specific volume of air at the nozzle exit is

$$v_2 = \frac{RT_2}{P_2} = \frac{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(185.2 + 273 \text{ K})}{100 \text{ kPa}} = 1.315 \text{ m}^3/\text{kg}$$

$$\dot{m} = \frac{1}{v_2} A_2 V_2 \longrightarrow 1.094 \text{ kg/s} = \frac{1}{1.315 \text{ m}^3/\text{kg}} A_2(180 \text{ m/s}) \rightarrow A_2 = 0.00799 \text{ m}^2 = 79.9 \text{ cm}^2$$

[5-29] Air at 80 kPa and 127°C enters an adiabatic diffuser steadily at a rate of 6000 kg/h and leaves at 100 kPa. The velocity of the air stream is decreased from 230 to 30 m/s as it passes through the diffuser. Find (a) the exit temperature of the air and (b) the exit area of the diffuser.

*R=0.287 kPa.m3/kg.K*

*Analysis* (a) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take diffuser as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{\text{system}}^{\nearrow 0 \;(\text{steady})}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{m}(h_1 + V_1^2 / 2) = \dot{m}(h_2 + V_2^2/2) \quad (\text{since } \dot{Q} \cong \dot{W} \cong \Delta pe \cong 0)$$
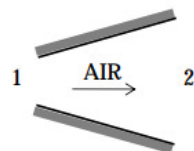
$$0 = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}$$

or,

$$h_2 = h_1 - \frac{V_2^2 - V_1^2}{2} = 400.98 \text{ kJ/kg} - \frac{(30 \text{ m/s})^2 - (230 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) = 426.98 \text{ kJ/kg}$$

From Table A-17,

$$T_2 = 425.6 \text{ K}$$

(b) The specific volume of air at the diffuser exit is

$$v_2 = \frac{RT_2}{P_2} = \frac{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(425.6 \text{ K})}{(100 \text{ kPa})} = 1.221 \text{ m}^3/\text{kg}$$

From conservation of mass,

$$\dot{m} = \frac{1}{v_2} A_2 V_2 \longrightarrow A_2 = \frac{\dot{m} v_2}{V_2} = \frac{(6000/3600 \text{ kg/s})(1.221 \text{ m}^3/\text{kg})}{30 \text{ m/s}} = 0.0678 \text{ m}^2$$

**TABLE A–17**

Ideal-gas properties of air

| T K | h kJ/kg | $P_r$ | u kJ/kg | $v_r$ | s° kJ/kg·K | T K | h kJ/kg | $P_r$ | u kJ/kg | $v_r$ | s° kJ/kg·K |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 200 | 199.97 | 0.3363 | 142.56 | 1707.0 | 1.29559 | 580 | 586.04 | 14.38 | 419.55 | 115.7 | 2.37348 |
| 210 | 209.97 | 0.3987 | 149.69 | 1512.0 | 1.34444 | 590 | 596.52 | 15.31 | 427.15 | 110.6 | 2.39140 |
| 220 | 219.97 | 0.4690 | 156.82 | 1346.0 | 1.39105 | 600 | 607.02 | 16.28 | 434.78 | 105.8 | 2.40902 |
| 230 | 230.02 | 0.5477 | 164.00 | 1205.0 | 1.43557 | 610 | 617.53 | 17.30 | 442.42 | 101.2 | 2.42644 |
| 240 | 240.02 | 0.6355 | 171.13 | 1084.0 | 1.47824 | 620 | 628.07 | 18.36 | 450.09 | 96.92 | 2.44356 |
| 250 | 250.05 | 0.7329 | 178.28 | 979.0 | 1.51917 | 630 | 638.63 | 19.84 | 457.78 | 92.84 | 2.46048 |
| 260 | 260.09 | 0.8405 | 185.45 | 887.8 | 1.55848 | 640 | 649.22 | 20.64 | 465.50 | 88.99 | 2.47716 |
| 270 | 270.11 | 0.9590 | 192.60 | 808.0 | 1.59634 | 650 | 659.84 | 21.86 | 473.25 | 85.34 | 2.49364 |
| 280 | 280.13 | 1.0889 | 199.75 | 738.0 | 1.63279 | 660 | 670.47 | 23.13 | 481.01 | 81.89 | 2.50985 |
| 285 | 285.14 | 1.1584 | 203.33 | 706.1 | 1.65055 | 670 | 681.14 | 24.46 | 488.81 | 78.61 | 2.52589 |
| 290 | 290.16 | 1.2311 | 206.91 | 676.1 | 1.66802 | 680 | 691.82 | 25.85 | 496.62 | 75.50 | 2.54175 |
| 295 | 295.17 | 1.3068 | 210.49 | 647.9 | 1.68515 | 690 | 702.52 | 27.29 | 504.45 | 72.56 | 2.55731 |
| 298 | 298.18 | 1.3543 | 212.64 | 631.9 | 1.69528 | 700 | 713.27 | 28.80 | 512.33 | 69.76 | 2.57277 |
| 300 | 300.19 | 1.3860 | 214.07 | 621.2 | 1.70203 | 710 | 724.04 | 30.38 | 520.23 | 67.07 | 2.58810 |
| 305 | 305.22 | 1.4686 | 217.67 | 596.0 | 1.71865 | 720 | 734.82 | 32.02 | 528.14 | 64.53 | 2.60319 |
| 310 | 310.24 | 1.5546 | 221.25 | 572.3 | 1.73498 | 730 | 745.62 | 33.72 | 536.07 | 62.13 | 2.61803 |
| 315 | 315.27 | 1.6442 | 224.85 | 549.8 | 1.75106 | 740 | 756.44 | 35.50 | 544.02 | 59.82 | 2.63280 |
| 320 | 320.29 | 1.7375 | 228.42 | 528.6 | 1.76690 | 750 | 767.29 | 37.35 | 551.99 | 57.63 | 2.64737 |
| 325 | 325.31 | 1.8345 | 232.02 | 508.4 | 1.78249 | 760 | 778.18 | 39.27 | 560.01 | 55.54 | 2.66176 |
| 330 | 330.34 | 1.9352 | 235.61 | 489.4 | 1.79783 | 780 | 800.03 | 43.35 | 576.12 | 51.64 | 2.69013 |
| 340 | 340.42 | 2.149 | 242.82 | 454.1 | 1.82790 | 800 | 821.95 | 47.75 | 592.30 | 48.08 | 2.71787 |
| 350 | 350.49 | 2.379 | 250.02 | 422.2 | 1.85708 | 820 | 843.98 | 52.59 | 608.59 | 44.84 | 2.74504 |
| 360 | 360.58 | 2.626 | 257.24 | 393.4 | 1.88543 | 840 | 866.08 | 57.60 | 624.95 | 41.85 | 2.77170 |
| 370 | 370.67 | 2.892 | 264.46 | 367.2 | 1.91313 | 860 | 888.27 | 63.09 | 641.40 | 39.12 | 2.79783 |
| 380 | 380.77 | 3.176 | 271.69 | 343.4 | 1.94001 | 880 | 910.56 | 68.98 | 657.95 | 36.61 | 2.82344 |
| 390 | 390.88 | 3.481 | 278.93 | 321.5 | 1.96633 | 900 | 932.93 | 75.29 | 674.58 | 34.31 | 2.84856 |
| 400 | 400.98 | 3.806 | 286.16 | 301.6 | 1.99194 | 920 | 955.38 | 82.05 | 691.28 | 32.18 | 2.87324 |
| 410 | 411.12 | 4.153 | 293.43 | 283.3 | 2.01699 | 940 | 977.92 | 89.28 | 708.08 | 30.22 | 2.89748 |
| 420 | 421.26 | 4.522 | 300.69 | 266.6 | 2.04142 | 960 | 1000.55 | 97.00 | 725.02 | 28.40 | 2.92128 |
| 430 | 431.43 | 4.915 | 307.99 | 251.1 | 2.06533 | 980 | 1023.25 | 105.2 | 741.98 | 26.73 | 2.94468 |
| 440 | 441.61 | 5.332 | 315.30 | 236.8 | 2.08870 | 1000 | 1046.04 | 114.0 | 758.94 | 25.17 | 2.96770 |
| 450 | 451.80 | 5.775 | 322.62 | 223.6 | 2.11161 | 1020 | 1068.89 | 123.4 | 776.10 | 23.72 | 2.99034 |
| 460 | 462.02 | 6.245 | 329.97 | 211.4 | 2.13407 | 1040 | 1091.85 | 133.3 | 793.36 | 23.29 | 3.01260 |
| 470 | 472.24 | 6.742 | 337.32 | 200.1 | 2.15604 | 1060 | 1114.86 | 143.9 | 810.62 | 21.14 | 3.03449 |
| 480 | 482.49 | 7.268 | 344.70 | 189.5 | 2.17760 | 1080 | 1137.89 | 155.2 | 827.88 | 19.98 | 3.05608 |
| 490 | 492.74 | 7.824 | 352.08 | 179.7 | 2.19876 | 1100 | 1161.07 | 167.1 | 845.33 | 18.896 | 3.07732 |
| 500 | 503.02 | 8.411 | 359.49 | 170.6 | 2.21952 | 1120 | 1184.28 | 179.7 | 862.79 | 17.886 | 3.09825 |
| 510 | 513.32 | 9.031 | 366.92 | 162.1 | 2.23993 | 1140 | 1207.57 | 193.1 | 880.35 | 16.946 | 3.11883 |
| 520 | 523.63 | 9.684 | 374.36 | 154.1 | 2.25997 | 1160 | 1230.92 | 207.2 | 897.91 | 16.064 | 3.13916 |
| 530 | 533.98 | 10.37 | 381.84 | 146.7 | 2.27967 | 1180 | 1254.34 | 222.2 | 915.57 | 15.241 | 3.15916 |
| 540 | 544.35 | 11.10 | 389.34 | 139.7 | 2.29906 | 1200 | 1277.79 | 238.0 | 933.33 | 14.470 | 3.17888 |
| 550 | 555.74 | 11.86 | 396.86 | 133.1 | 2.31809 | 1220 | 1301.31 | 254.7 | 951.09 | 13.747 | 3.19834 |
| 560 | 565.17 | 12.66 | 404.42 | 127.0 | 2.33685 | 1240 | 1324.93 | 272.3 | 968.95 | 13.069 | 3.21751 |
| 570 | 575.59 | 13.50 | 411.97 | 121.2 | 2.35531 | | | | | | |

## Turbines and Compressors

In steam, gas, or hydroelectric power plants, the device that drives the electric generator is the turbine. As the fluid passes through the turbine, work is done against the blades, which are attached to the shaft. As a result, the shaft rotates, and the turbine produces work.

Compressors, as well as pumps and fans, are devices used to increase the pressure of a fluid. Work is supplied to these devices from an external source through a rotating shaft. Therefore, compressors involve work inputs.

Even though these three devices function similarly, they do differ in the tasks they perform. A fan increases the pressure of a gas slightly and is mainly used to mobilize a gas. A compressor is capable of compressing the gas to very high pressures. Pumps work very much like compressors except that they handle liquids instead of gases.

Note that turbines produce power output whereas compressors, pumps, and fans require power input.

Heat transfer from turbines is usually negligible ($\dot{Q} \approx 0$) since they are typically well insulated. Heat transfer is also negligible for compressors unless there is intentional cooling. Potential energychanges are negligible for all of these devices ($\Delta pe \cong 0$). The velocitiesinvolved in these devices, with the exception of turbines and fans, are usually too low to cause any significant change in the kinetic energy ($\Delta ke \cong 0$).

The fluid velocities encountered in most turbines are very high, and the fluid experiences a significant change in its kinetic energy. However, this change is usually very small relative to the change in enthalpy, and thus it is often disregarded.

**A turbine operates under steady flow conditions, receiving steam at the following state: pressure 1.2 MPa, temperature 188°C, enthalpy 2785 kJ/kg, velocity 33.3 m/s and elevation 3 m. The steam leaves the turbine at the following state: pressure 20 kPa, enthalpy 2512 kJ/kg, velocity 100 m/s and elevation 0 m. Heat lost to the surroundings at the rate of 0.29 kJ/kg. If the rate of steam flow through the turbine is 0.42 kg/s, what is the power output of the turbine in kW? (10)**

**Answer:**

$$[\dot{Q} + \dot{W} + \sum \dot{m}\,(h + \frac{V^2}{2} + gz)]_{inlet} = [\dot{Q} + \dot{W} + \sum \dot{m}\,(h + \frac{V^2}{2} + gz)]_{outlet}$$

$$or, \dot{W}_{outlet} = 0.42\left[(2785 - 25512) \times 1000 + \frac{33.3^2 - 100^2}{2} + (9.81 \times 3) - 0.29\right]$$

$$= 112.67\ kW$$

[5-57] An adiabatic gas turbine expands air at 1300 kPa and 500°C to 100 kPa and 127°C. Air enters the turbine through a 0.2-m² opening with an average velocity of 40m/s, and exhausts through a 1-m² opening. Determine (a) the mass flow rate of air through the turbine and (b) the power produced by the turbine. [Answers: (a) 46 .9 kg/s, (b) 18.3 MW]

*Properties* The constant pressure specific heat of air at the average temperature of (500+127)/2=314°C=587 K is $c_p$ = 1.048 kJ/kg·K (Table A-2b). The gas constant of air is $R$ = 0.287 kPa·m³/kg·K (Table A-1).

*Analysis* (a) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{system}^{\nearrow 0\ (steady)}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right) + \dot{W}_{out}$$

$$\dot{W}_{out} = \dot{m}\left(h_1 - h_2 + \frac{V_1^2 - V_2^2}{2}\right) = \dot{m}\left(c_p(T_1 - T_2) + \frac{V_1^2 - V_2^2}{2}\right)$$

1.3 MPa
500°C
40 m/s

Turbine
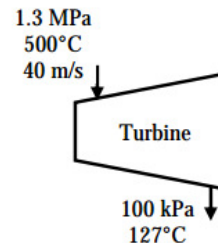
100 kPa
127°C

The specific volume of air at the inlet and the mass flow rate are

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(500+273 \text{ K})}{1300 \text{ kPa}} = 0.1707 \text{ m}^3/\text{kg}$$

$$\dot{m} = \frac{A_1 V_1}{v_1} = \frac{(0.2 \text{ m}^2)(40 \text{ m/s})}{0.1707 \text{ m}^3/\text{kg}} = \textbf{46.88 kg/s}$$

Similarly at the outlet,

$$v_2 = \frac{RT_2}{P_2} = \frac{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(127+273 \text{ K})}{100 \text{ kPa}} = 1.148 \text{ m}^3/\text{kg}$$

$$V_2 = \frac{\dot{m} v_2}{A_2} = \frac{(46.88 \text{ kg/s})(1.148 \text{ m}^3/\text{kg})}{1 \text{ m}^2} = 53.82 \text{ m/s}$$

(b) Substituting into the energy balance equation gives

$$\dot{W}_{out} = \dot{m}\left( c_p (T_1 - T_2) + \frac{V_1^2 - V_2^2}{2} \right)$$

$$= (46.88 \text{ kg/s})\left[ (1.048 \text{ kJ/kg} \cdot \text{K})(500-127)\text{K} + \frac{(40 \text{ m/s})^2 - (53.82 \text{ m/s})^2}{2}\left( \frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right) \right]$$

$$= \textbf{18,300 kW}$$


[5-53] An adiabatic air compressor compresses 10 L/s of air at 120 kPa and 20°C to 1000 kPa and 300°C. Determine (a) the work required by the compressor, in kJ/kg, and (b) the power required to drive the air compressor, in kW.

*Properties* The constant pressure specific heat of air at the average temperature of (20+300)/2=160°C=433 K is $c_p$ = 1.018 kJ/kg·K (Table A-2b). The gas constant of air is $R$ = 0.287 kPa·m$^3$/kg·K (Table A-1).

*Analysis* (*a*) There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the compressor as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{system}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}}^{\nearrow 0 \text{ (steady)}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} + \dot{m}h_1 = \dot{m}h_2 \quad (\text{since } \Delta ke \cong \Delta pe \cong 0)$$

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) = \dot{m}c_p(T_2 - T_1)$$

Thus,

$$w_{in} = c_p(T_2 - T_1) = (1.018 \text{ kJ/kg} \cdot \text{K})(300 - 20)\text{K} = \mathbf{285.0 \ kJ/kg}$$

(*b*) The specific volume of air at the inlet and the mass flow rate are

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(20 + 273 \text{ K})}{120 \text{ kPa}} = 0.7008 \text{ m}^3/\text{kg}$$

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{0.010 \text{ m}^3/\text{s}}{0.7008 \text{ m}^3/\text{kg}} = 0.01427 \text{ kg/s}$$

Then the power input is determined from the energy balance equation to be

$$\dot{W}_{in} = \dot{m}c_p(T_2 - T_1) = (0.01427 \text{ kg/s})(1.018 \text{ kJ/kg} \cdot \text{K})(300 - 20)\text{K} = \mathbf{4.068 \ kW}$$
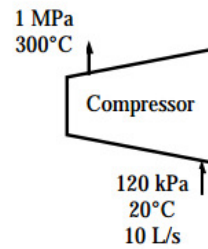
## Throttling Valves:

Throttling valves are any kind of flow-restricting devices that cause a significant pressure drop in the fluid is often accompanied by a large drop in temperature. Some familiar examples are ordinary adjustable valves, capillary tubes, and porous plugs. For single-stream steady-flow device while throttling the equation is $h_2 \cong h_1$.

$$h_1 = u_1 + P_1v_1 = u_2 + P_2v_2 = h_2$$

Thus the final outcome of a throttling process depends on which of the two quantities increases during the process. If the flow energy increases during the process ($P_2v_2 > P_1v_1$), it can do so at the expense of the internal energy. As a result, internal energy decreases, which is usually accompanied by a drop in temperature and vice versa. The temperature of an ideal gas does not change during a throttling ($h = constant$) process since $h = h(T)$.

# Chapter 3

**Introduction to the Second Law of Thermodynamics:**
The first law places no restriction on the direction of a process, but satisfying the first law does not ensure that the process can actually occur. Processes occur in a certain direction, and not in the reverse direction. A process cannot occur unless it satisfies both the first and the second laws of thermodynamics.
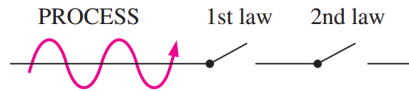


Fig.: A process must satisfy both the first and second laws of thermodynamics to proceed

It is common experience that a cup of hot coffee left in a cooler room eventually cools off. This process satisfies the first law of thermodynamics since the amount of energy lost by the coffee is equal to the amount gained by the surrounding air. Now let us consider the reverse process-the hot coffee getting even hotter in a cooler room as a result of heat transfer from the room air. We all know that this process never takes place. Yet, doing so would not violate the first law as long as the amount of energy lost by the air is equal to the amount gained by the coffee.

The use of the second law of thermodynamics is not limited to identifying the direction of processes, however. The second law also asserts that energy has quality as well as quantity. The first law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to its quality.

**Thermal Energy Reservoirs**
It is very convenient to have a hypothetical body with a relatively large thermal energy capacity (mass × specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature. Such a body is called a thermal energy reservoir. A two-phase system can be modeled as a reservoir also since it can absorb and release large quantities of heat while remaining at constant temperature. Another familiar example of a thermal energy reservoir is the industrial furnace.

A reservoir that supplies energy in the form of heat is called a source, and one that absorbs energy in the form of heat is called a sink.

**The Second Law of Thermodynamics:**
There are two classical statements of the second law, the Kelvin-Planckstatement, which is related to heat engines and the Clausius statement, which is related to refrigerators or heat pumps.

**Kelvin-Planck Statement:**
It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

**Clausius Statement**
It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

**Equivalence of the Two Statements**
The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics. Any device that violates the Kelvin–Planck statement also violates the Clausius statement, and vice versa. This can be demonstrated as follows.
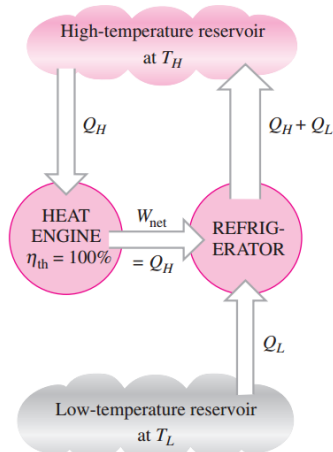
Fig. a: A refrigerator that is powered by a 100 percent efficient heat engine
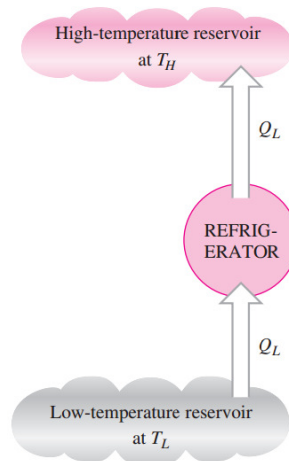


Fig. b: The equivalent refrigerator

Consider the heat-engine-refrigerator combination shown in Fig. 6–27a,operating between the same two reservoirs. The heat engine is assumed to have, in violation of the Kelvin–Planck statement, a thermal efficiency of100 percent, and therefore it converts all the heat $Q_H$ it receives to work W.This work is now supplied to a refrigerator that removes heat in the amountof $Q_L$ from the low-temperature reservoir and rejects heat in the amount of $Q_H + Q_L$ to the high-temperature reservoir. During this process, the high temperature reservoir receives a net amount of heat $Q_L$ (the differencebetween $Q_H + Q_L$ and $Q_H$). Thus, the combination of these two devices canbe viewed as a refrigerator, as shown in Fig. b, that transfers heat in an amount of $Q_L$ from a cooler body to a warmer one without requiring anyinput from outside. This is clearly a violation of the Clausius statement.

Therefore, a violation of the Kelvin–Planck statement results in the violation of the Clausius statement.

It can also be shown in a similar manner that a violation of the Clausius statement leads to the violation of the Kelvin–Planck statement. Therefore, the Clausius and the Kelvin–Planck statements are two equivalent expressions of the second law of thermodynamics.

**Alternative Solution for Equivalence of the Two Statements:**
To prove that violation of the Kelvin-Planck Statement leads to a violation of the Clausius Statement, let us assume that Kelvin-Planck statement is incorrect.
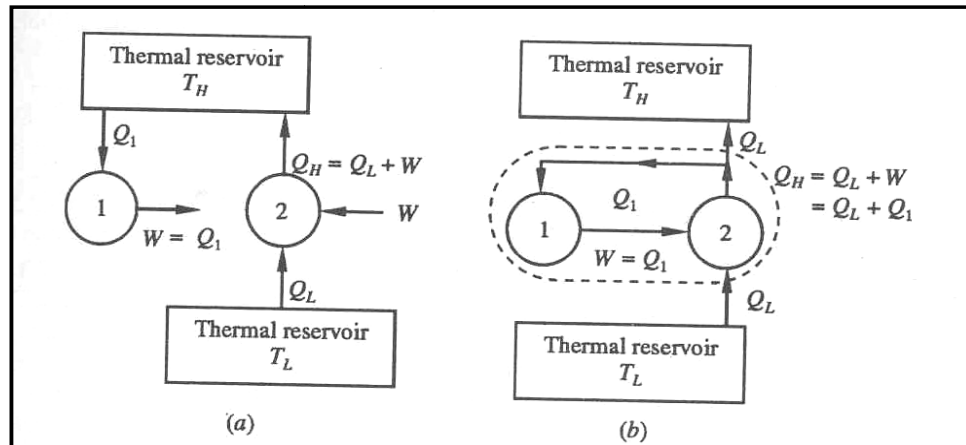


Consider a cyclically working device 1, which absorbs energy $Q_1$ as heat from a thermal reservoir at $T_H$. Equivalent amount of work $W(W=Q_1)$ is performed.

Consider another device 2 operating as a cycle, which absorbs energy $Q_L$ as heat from a low temperature thermal reservoir at $T_L$ and rejects energy $Q_H$ $(Q_H=Q_L+W)$. Such a device does not violate Clausius statement.

If the two devices are now combined, the combined device (enclosed by the dotted boundary) transfers heat $Q_L$ from the low temperature reservoir at $T_L$ to a high temperature reservoir at $T_H$ with out receiving any aid from an external agent, which is the violation of the Clausius statement.
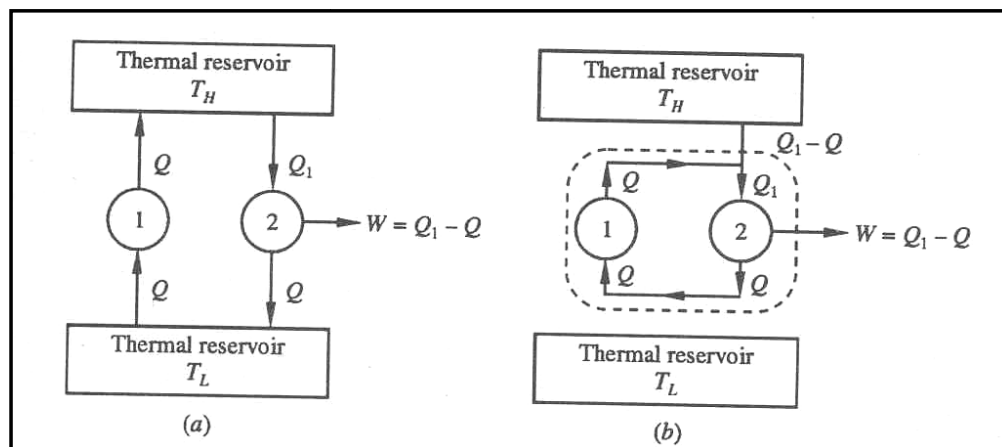


Likewise let us assume that the Clausius statement is incorrect. So we have a device 1, cyclically working transferring heat $Q$ from a low temperature reservoir at $T_L$ to a high temperature thermal reservoir at $T_H$ . Consider another device 2, which absorbs heat $Q_1$ from a high temperature reservoir at $T_H$ does work $W$ and rejects energy $Q$ as heat to the low temperature reservoir at $T_L$ as shown in figure.

If the two devices are combined (shown in figure by a dotted enclosure), then the combined device receives energy ($Q_1$-Q) as heat from a thermal reservoir and delivers equivalent work (W=$Q_1$-Q) in violation of the Kelvin-Planck statement.

Therefore violation of Clausius statement leads to the violation of the Kelvin-Planck statement. Hence, these two statements are equivalent.

**Heat Engines**
Work can easily be converted to other forms of energy, but converting other forms of energy to work is not that easy. The mechanical work done by the shaft shown in Fig, for example, is first converted to the internal energy of the water. This energy may then leave the water as heat. We know from experience that any attempt to reverse this process will fail. That is, transferring heat to the water does not cause the shaft to rotate.
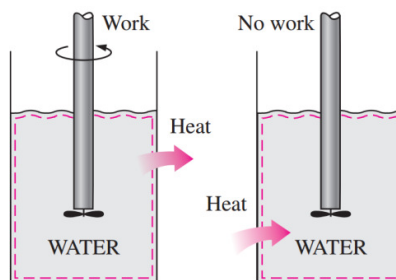


Fig.: Work can always be converted to heat directly and completely, but the reverse is not true

We conclude that work can be converted to heat directly and completely, but converting heat to work requires the use of some special devices. These devices are called heat engines.
Heat engines differ considerably from one another, but all can be characterized by the following:
1. They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor).
2. They convert part of this heat to work (usually in the form of a rotating shaft).
3. They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers).
4. They operate on a cycle.

So cyclic heat engine is a thermodynamic device in which there is net heat transfer to the system and net work transfer from the system.
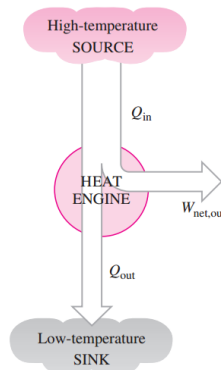
Fig.: Part of the heat received by a heatengine is converted to work, while the rest is rejected to a sink

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

**Refrigerator:**



Warm environment at $T_H > T_L$

$Q_H$

Required input

$W_{net,in}$

R P

Desired output

$Q_L$

Cold refrigerated space at $T_L$
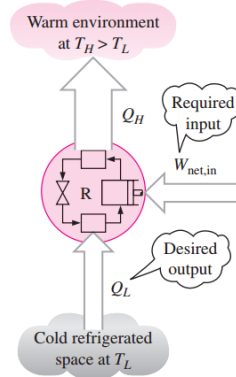
We all know from experience that heat is transferred in the direction of decreasing temperature, that is, from high-temperature mediums to low temperature ones. This heat transfer process occurs in nature without requiring any devices. The reverse process, however, cannot occur by itself. The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called refrigerators.

$$COP_R = \frac{Desired\ output}{Required\ input} = \frac{Q_L}{W_{net,in}} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

Notice that the value of COP$_R$ can be greater than unity. This is in contrast to the thermal efficiency, which can never be greater than 1. In fact, one reason for expressing the efficiency of a refrigerator by another term-the coefficient of performance-is the desire to avoid the oddity of having efficiencies greater than unity.

**Problem 1: COP$_R$=4 then find Q$_H$/Q$_L$=?**

$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

Or, Q$_H$/Q$_L$=1.25

**Heat Pumps:**

Another device that transfers heat from a low-temperature medium to a high-temperature one is the heat pump, shown schematically in Fig. Refrigerators and heat pumps operate on the same cycle but differ in their objectives. The objective of a refrigerator is to maintain the refrigerated space at a low temperature by removing heat from it. Discharging this heat to a higher-temperature medium is merely a necessary part of the operation, not the purpose. The objective of a heat pump, however, is to maintain a heated space at a high temperature. This is accomplished by absorbing heat from a low-temperature source, such as well water or cold outside air in winter, and supplying this heat to the high-temperature medium such as a house.

An ordinary refrigerator that is placed in the window of a house with its door open to the cold outside air in winter will function as a heat pump since it will try to cool the outside by absorbing heat from it and rejecting this heat into the house through the coils behind it.
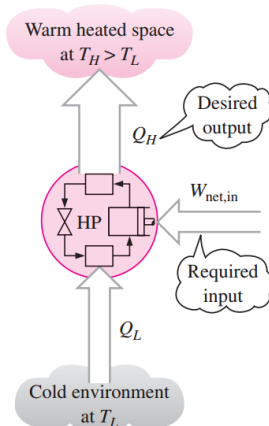


$$COP_{HP} = \frac{Desired\ output}{Required\ input} = \frac{Q_H}{W_{net,in}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

$$\therefore COP_R + 1 = COP_{HP}$$

**[6-22]** An automobile engine consumes fuel at a rate of 22 L/h and delivers 55 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.

**6-22** The power output and fuel consumption rate of a car engine are given. The thermal efficiency of the engine is to be determined.

*Assumptions* The car operates steadily.

*Properties* The heating value of the fuel is given to be 44,000 kJ/kg.

*Analysis* The mass consumption rate of the fuel is

$$\dot{m}_{fuel} = (\rho \dot{V})_{fuel} = (0.8\ kg/L)(22\ L/h) = 17.6\ kg/h$$

The rate of heat supply to the car is

$$\dot{Q}_H = \dot{m}_{coal} q_{HV,coal}$$
$$= (17.6\ kg/h)(44,000\ kJ/kg)$$
$$= 774,400\ kJ/h = 215.1\ kW$$

Then the thermal efficiency of the car becomes

$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_H} = \frac{55\ kW}{215.1\ kW} = 0.256 = \textbf{25.6\%}$$
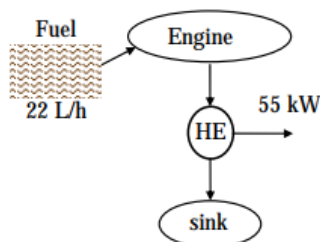
[6-40] An air conditioner produces a 2-kW cooling effect while rejecting 2.5 kW of heat. What is its COP?

**6-40** The cooling effect and the rate of heat rejection of an air conditioner are given. The COP is to be determined.

*Assumptions* The air conditioner operates steadily.

*Analysis* Applying the first law to the air conditioner gives

$$\dot{W}_{net,in} = \dot{Q}_H - \dot{Q}_L = 2.5 - 2 = 0.5\,\text{kW}$$

Applying the definition of the coefficient of performance,

$$\text{COP}_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{2.0\,\text{kW}}{0.5\,\text{kW}} = 4$$
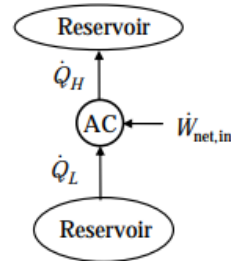


[6-42] A food department is kept at − 12°C by a refrigerator in an environment at 30°C. The total heat gain to the food department is estimated to be 3300 kJ/h and the heat rejection in the condenser is 4800 kJ/h. Determine the power input to the compressor, in kW and the COP of the refrigerator.

**6-42** A refrigerator is used to keep a food department at a specified temperature. The heat gain to the food department and the heat rejection in the condenser are given. The power input and the COP are to be determined.

*Assumptions* The refrigerator operates steadily.

*Analysis* The power input is determined from

$$\dot{W}_{in} = \dot{Q}_H - \dot{Q}_L$$
$$= 4800 - 3300 = 1500\,\text{kJ/h}$$
$$= (1500\,\text{kJ/h})\left(\frac{1\,\text{kW}}{3600\,\text{kJ/h}}\right) = \textbf{0.417 kW}$$

The COP is

$$\text{COP} = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{3300\,\text{kJ/h}}{1500\,\text{kJ/h}} = \textbf{2.2}$$
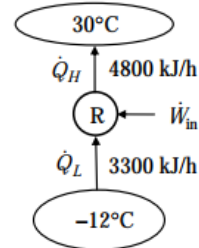


[6-46] A household refrigerator that has a power input of 450 W and a COP of 2.5 is to cool five large watermelons, 10kg each, to 8°C. If the watermelons are initially at 20°C, determine how long it will take for the refrigerator to cool them. The watermelons can be treated as water whose specific heat is 4.2 kJ/kg °C. Is your answer realistic or optimistic? Explain.

**6-46** The COP and the power consumption of a refrigerator are given. The time it will take to cool 5 watermelons is to be determined.

*Assumptions* **1** The refrigerator operates steadily. **2** The heat gain of the refrigerator through its walls, door, etc. is negligible. **3** The watermelons are the only items in the refrigerator to be cooled.

*Properties* The specific heat of watermelons is given to be $c = 4.2$ kJ/kg.°C.

*Analysis* The total amount of heat that needs to be removed from the watermelons is

$$Q_L = (mc\Delta T)_{\text{watermelons}} = 5 \times (10 \text{ kg})(4.2 \text{ kJ/kg} \cdot °C)(20-8)°C = 2520 \text{ kJ}$$

The rate at which this refrigerator removes heat is

$$\dot{Q}_L = (COP_R)(\dot{W}_{\text{net,in}}) = (2.5)(0.45 \text{ kW}) = 1.125 \text{ kW}$$

That is, this refrigerator can remove 1.125 kJ of heat per second. Thus the time required to remove 2520 kJ of heat is

$$\Delta t = \frac{Q_L}{\dot{Q}_L} = \frac{2520 \text{ kJ}}{1.125 \text{ kJ/s}} = \textbf{2240 s} = \textbf{37.3 min}$$

This answer is optimistic since the refrigerated space will gain some heat during this process from the surrounding air, which will increase the work load. Thus, in reality, it will take longer to cool the watermelons.
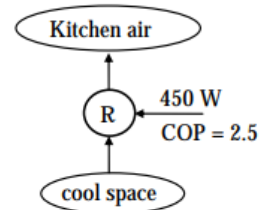
[6-101] A refrigerator operating on the reversed Carnot cycle has a measured work input of 200 kW and heat rejection of 2000 kW to a heat reservoir at 27°C. Determine the cooling load supplied to the refrigerator, in kW, and the temperature of the heat source, in °C. [Answers: 1800 kW, -3 °C]

**6-101** The power input and heat rejection of a reversed Carnot cycle are given. The cooling load and the source temperature are to be determined.

*Assumptions* The refrigerator operates steadily.

*Analysis* Applying the definition of the refrigerator coefficient of performance,

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{\text{net,in}} = 2000 - 200 = \textbf{1800 kW}$$

Applying the definition of the heat pump coefficient of performance,

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{\text{net,in}}} = \frac{1800 \text{ kW}}{200 \text{ kW}} = 9$$

The temperature of the heat source is determined from

$$COP_{R,\text{max}} = \frac{T_L}{T_H - T_L} \longrightarrow 9 = \frac{T_L}{300 - T_L} \longrightarrow T_L = 270 \text{ K} = \textbf{-3°C}$$
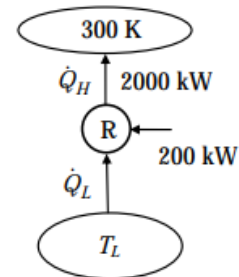
[6-95] A heat pump operates on a Carnot heat pump cycle with a COP of 8.7. It keeps a space at 26°C by consuming 4.25 kW of power. Determine the temperature of the reservoir from which the heat is absorbed and the heating load provided by the heat pump.

**6-95** The power input and the COP of a Carnot heat pump are given. The temperature of the low-temperature reservoir and the heating load are to be determined.

*Assumptions* The heat pump operates steadily.

*Analysis* The temperature of the low-temperature reservoir is

$$COP_{HP,max} = \frac{T_H}{T_H - T_L} \longrightarrow 8.7 = \frac{299 \text{ K}}{(299 - T_L) \text{ K}} \longrightarrow T_L = 264.6 \text{ K}$$

The heating load is

$$COP_{HP,max} = \frac{\dot{Q}_H}{\dot{W}_{in}} \longrightarrow 8.7 = \frac{\dot{Q}_H}{4.25 \text{ kW}} \longrightarrow \dot{Q}_H = 37.0 \text{ kW}$$

[Diagram: 26°C reservoir, $\dot{Q}_H$ up, HP ← 4.25 kW, $\dot{Q}_L$, $T_L$]
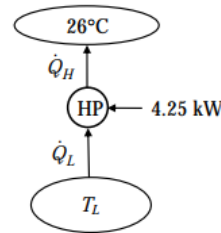
[6-96] A refrigerator is to remove heat from the cooled space at a rate of 300 kJ/min to maintain its temperature at -8°C. If the air surrounding the refrigerator is at 25°C, determine the minimum power input required for this refrigerator.

**6-96** The refrigerated space and the environment temperatures for a refrigerator and the rate of heat removal from the refrigerated space are given. The minimum power input required is to be determined.

*Assumptions* The refrigerator operates steadily.

*Analysis* The power input to a refrigerator will be a minimum when the refrigerator operates in a reversible manner. The coefficient of performance of a reversible refrigerator depends on the temperature limits in the cycle only, and is determined from

$$COP_{R,rev} = \frac{1}{(T_H / T_L) - 1} = \frac{1}{(25 + 273 \text{ K})/(-8 + 273 \text{ K}) - 1} = 8.03$$

The power input to this refrigerator is determined from the definition of the coefficient of performance of a refrigerator,

$$\dot{W}_{net,in,min} = \frac{\dot{Q}_L}{COP_{R,max}} = \frac{300 \text{ kJ/min}}{8.03} = 37.36 \text{ kJ/min} = 0.623 \text{ kW}$$

[Diagram: 25°C reservoir, R, 300 kJ/min, -8°C]
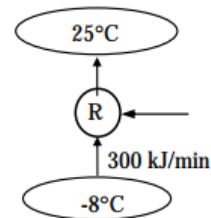
Two reversible heat engines A and B are arranged in series, Engine A is rejecting heat directly to engine B. Engine A receives 200kJ at a temperature of 421°C from a hot source, while engine B is in communication with a cold sink at a temperature of 4.4°C. If the work output of A is twice that of B find (a) the intermediate temperature between A and B, (b) the efficiency of each engine, and (c) the heat rejected to the cold sink.

$$W_A = 2W_B$$

We have to find out $T_2$, $\eta_A$, $\eta_B$ and $Q_3$

We know that $\dfrac{Q_1}{T_1} = \dfrac{Q_2}{T_2} = \dfrac{Q_3}{T_3}$

Let $\dfrac{Q_1}{T_1} = \dfrac{Q_3}{T_3}$

$$\therefore Q_3 = Q_1\left(\dfrac{T_3}{T_1}\right) = 200 \times \dfrac{(4.4+273)}{(421+273)}$$

$$= 79.94kJ = 80kJ$$

Also $\begin{aligned} W_A &= Q_1 - Q_2 \\ W_B &= Q_2 - Q_3 \end{aligned}$

Since $W_A = 2W_B$ (given)

$$\therefore Q_1 - Q_2 = 2Q_2 - 2Q_3$$

or $Q_1 + 2Q_3 = 3Q_2$

Or $Q_2 = \dfrac{200 + 2\times 80}{3} = 119.96kJ$

Now let $\dfrac{Q_1}{T_1} = \dfrac{Q_2}{T_2}$

$$\therefore T_2 = T_1\left(\dfrac{Q_2}{Q_1}\right) = (421+273) \times \dfrac{120}{200}$$

$$= 143.26^0C$$

Hence $\eta_A = \dfrac{T_1 - T_2}{T_1} = \dfrac{421 - 143.26}{421 + 273} = 0.4 = 40\%$

And $\eta_B = \dfrac{T_2 - T_3}{T_2} = \dfrac{143.26 - 4.4}{173.26 + 273} = 0.335 = 33.5\%$

[6-51] A heat pump is used to maintain a house at a constant temperature of 23°C. The house is losing heat to the outside air through the walls and the windows at a rate of 60,000 kJ/h while the energy generated within the house from people, lights, and appliances amounts to 4000 kJ/h. For a COP of 2.5, determine the required power input to the heat pump.

**6-51** The rate of heat loss, the rate of internal heat gain, and the COP of a heat pump are given. The power input to the heat pump is to be determined.

*Assumptions* The heat pump operates steadily.

*Analysis* The heating load of this heat pump system is the difference between the heat lost to the outdoors and the heat generated in the house from the people, lights, and appliances,

$$\dot{Q}_H = 60,000 - 4,000 = 56,000 \text{ kJ}/\text{h}$$

Using the definition of COP, the power input to the heat pump is determined to be

$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{56,000 \text{ kJ/h}}{2.5}\left(\frac{1 \text{ kW}}{3600 \text{ kJ/h}}\right) = 6.22 \text{ kW}$$
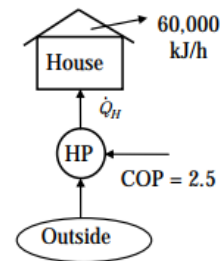


A heat pump heats a house in the winter and then reverses to cool it in the summer. The interior temperature should be 20°C in the winter and 25°C in the summer. Heat transfer through the walls and ceilings is estimated to be 2400 kJ per hour per degree temperature difference between the inside and outside.
a. If the winter outside temperature is 0°C, what is the minimum power required to drive the heat pump?
b. For the same power as in part (a), what is the maximum outside summer temperature for which the house can be maintained at 25°C?

a) Winter:
   House is $T_H$ and ambient
   is at $T_L$
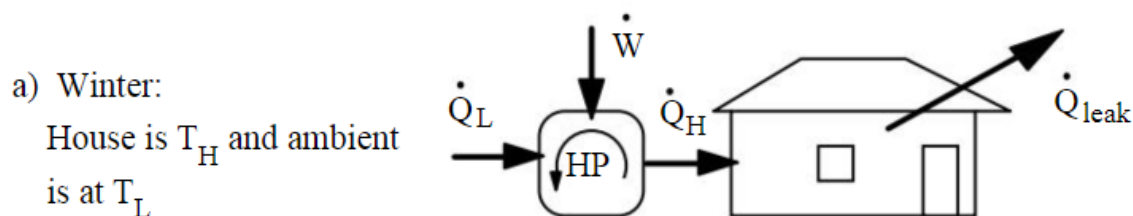


$$T_H = 20°C = 293.2 \text{ K} , \quad T_L = 0°C = 273.2 \text{ K} \quad \text{and} \quad \dot{Q}_H = 2400(20 - 0) \text{ kJ/h}$$

$$\beta' = \dot{Q}_H/\dot{W}_{IN} = 2400 \ (20 - 0)/\ \dot{W}_{IN} = \frac{T_H}{T_H - T_L} = \frac{293.2}{20}$$

$$\Rightarrow \dot{W}_{IN} = 3275 \text{ kJ/h} = \textbf{0.91 kW} \quad \text{(For Carnot cycle)}$$

b)
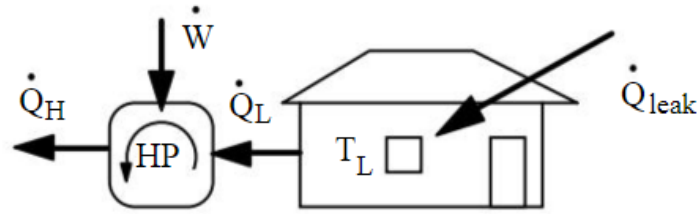


Summer:

$$T_L = T_{house}$$
$$T_H = T_{amb}$$

$$T_L = 25°C = 298.2 \text{ K}, \quad \dot{W}_{IN} = 3275 \text{ kJ/h} \quad \text{and} \quad \dot{Q}_L = 2400(T_H - 298.2) \text{ kJ/h}$$

$$\beta = \frac{\dot{Q}_L}{\dot{W}_{IN}} = \frac{2400(T_H - 298.2)}{3275} = \frac{T_L}{T_H - T_L} = \frac{298.2}{T_H - 298.2}$$

or, $$(T_H - 298.2)^2 = \frac{298.2 \times 3275}{2400} = 406.92$$

$$T_H = 318.4 \text{ K} = \mathbf{45.2°C}$$

**Perpetual-Motion Machines:**

A process cannot take place unless it satisfies both the first and second laws of thermodynamics. Any device that violates either law is called a **perpetual-motion machine**. A device that violates the first law of thermodynamics 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).

**PMM1:**
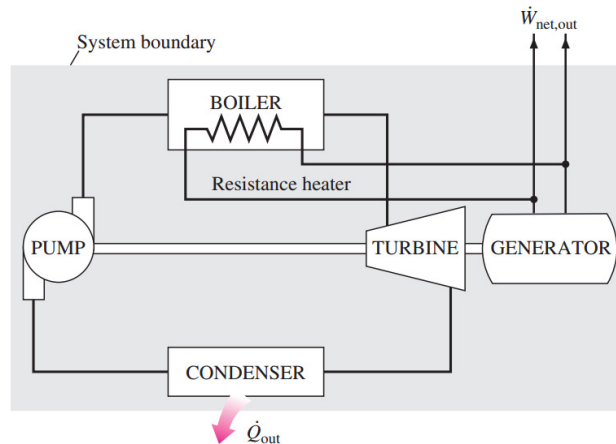


Consider the steam power plant as shown in Fig. It is proposed to heat the steam by resistance heaters placed inside the boiler, instead of by the energy supplied from fossil or nuclear fuels. Part of the electricity generated by the plant is to be used to power the resistors as well as the pump. The rest of the electric energy is to be supplied to the electric network as the net work

output. The inventor claims that once the system is started, this power plant will produce electricity indefinitely without requiring any energy input from the outside.

Well, here is an invention that could solve the world's energy problem-if it works, of course. A careful examination of this invention reveals that the system enclosed by the shaded area is continuously supplying energy to the outside at a rate of $\dot{Q}_{out} + \dot{W}_{net,out}$ without receiving any energy. That is, this system is creating energy at a rate of $\dot{Q}_{out} + \dot{W}_{net,out}$ which is clearly a violation of the first law. Therefore, this wonderful device is nothing more than a PMM1 and does not warrant any further consideration.

**PMM2: -**
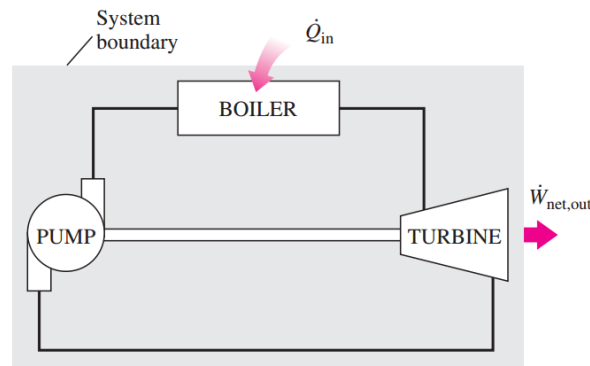


Well, the possibility of doubling the efficiency would certainly be very tempting to plant managers and, if not properly trained, they would probably give this idea a chance, since intuitively they see nothing wrong with it. A student of thermodynamics, however, will immediately label this device as a PMM2, since it works on a cycle and does a net amount of work while exchanging heat with a single reservoir (the furnace) only. It satisfies the first law but violates the second law, and therefore it will not work.

**THE CARNOT CYCLE**

The efficiency of a heat-engine cycle greatly depends on how the individual processes that make up the cycle are executed. The net work, thus the cycle efficiency, can be maximized by using processes that require the least amount of work and deliver the most, that is, by using reversible processes. It is no surprise that the most efficient cycles are reversible cycles, that is, cycles that consist entirely of reversible processes. Probably the best known reversible cycle is the Carnot cycle, first proposed in 1824 by French engineer Sadi Carnot. The Carnot cycle is composed of four reversible processes-two isothermal and two adiabatic and it can be executed either in a closed or a steady-flow system.

Consider a closed system that consists of a gas contained in an adiabatic piston–cylinder device, as shown in Fig. The insulation of the cylinder head is such that it may be removed to bring the cylinder into contact with reservoirs to provide heat transfer. The four reversible processes that make up the Carnot cycle are as follows:

**Reversible Isothermal Expansion** (process 1-2, $T_H$ =constant). Initially(state 1), the temperature of the gas is $T_H$ and the cylinder head is in close contact with a source at temperature $T_H$. The gas is allowed to expandslowly, doing work on the surroundings. As the

gas expands, the temperature of the gas tends to decrease. But as soon as the temperature drops by an infinitesimal amount dT, some heat is transferred from the reservoir into the gas, raising the gas temperature to $T_H$. Thus, the gas temperature is kept constant at $T_H$. Since the temperature difference between the gas and the reservoir never exceeds a differential amount dT, this is a reversible heat transfer process. It continues until the piston reaches position 2. The amount of total heat transferred to the gas during this process is $Q_H$.
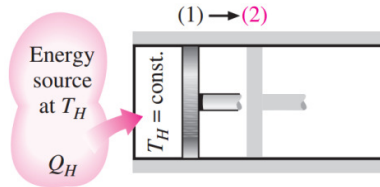


(a) Process 1-2

**Reversible Adiabatic Expansion** (process 2-3, temperature drops from $T_H$ to $T_L$). At state 2, the reservoir that was in contact with the cylinder head is removed and replaced by insulation so that the system becomes adiabatic. The gas continues to expand slowly, doing work on the surroundings until its temperature drops from $T_H$ to $T_L$ (state 3). The piston is assumed to be frictionless and the process to be quasi-equilibrium, so the process is reversible as well as adiabatic.
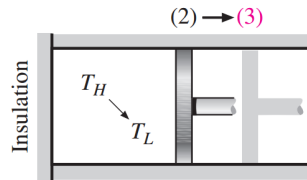


(b) Process 2-3

**Reversible Isothermal Compression** (process 3-4, $T_L$=constant). At state 3, the insulation at the cylinder head is removed, and the cylinder is brought into contact with a sink at temperature $T_L$. Now the piston is pushed inward by an external force, doing work on the gas. As the gas is compressed, its temperature tends to rise. But as soon as it rises by an infinitesimal amount dT, heat is transferred from the gas to the sink, causing the gas temperature to drop to $T_L$. Thus, the gas temperature remains constant at $T_L$. Since the temperature difference between the gas and the sink never exceeds a differential amount dT, this is a reversible heat transfer process. It continues until the piston reaches state 4. The amount of heat rejected from the gas during this process is $Q_L$.
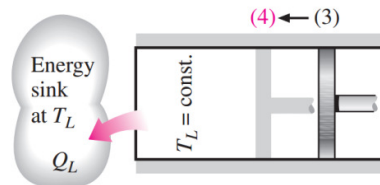


(c) Process 3-4

**Reversible Adiabatic Compression** (process 4-1, temperature rises from $T_L$ to $T_H$). State 4 is such that when the low-temperature reservoir is removed, the insulation is put back on the cylinder head, and the gas is compressed in a reversible manner, the gas returns to its initial state (state 1). The temperature rises from $T_L$ to $T_H$ during this reversible adiabatic compression process, which completes the cycle.
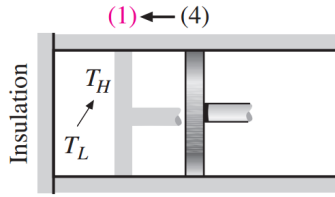
(*d*) Process 4-1

The P-V diagram of this cycle is shown in Fig. Remembering that on a P-V diagram the area under the process curve represents the boundary work for quasi-equilibrium processes, we see that the area under curve 1-2-3 is the work done by the gas during the expansion part of the cycle, and the area under curve 3-4-1 is the work done on the gas during the compression part of the cycle. The area enclosed by the path of the cycle (area 1-2-3-4-1) is the difference between these two and represents the net work done during the cycle.
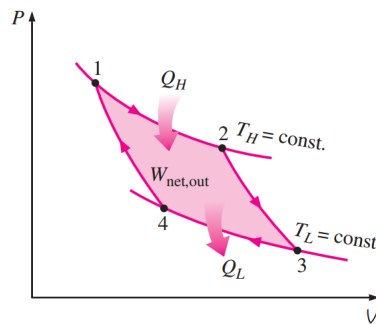


### Carnot principles:

1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.
2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.

### THE CARNOT HEAT ENGINE

The hypothetical heat engine that operates on the reversible Carnot cycle is called the Carnot heat engine. The thermal efficiency of any heat engine, reversible or irreversible, is given by

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{Q_L}{Q_H}$$

For reversible heat engines, the heat transfer ratio in the above relation can be replaced by the ratio of the absolute temperatures of the two reservoirs, as given by

$$\eta_{th} = 1 - \frac{T_L}{T_H}$$

So for reversible heat engine

$$(\frac{Q_L}{Q_H})_{rev} = \frac{T_L}{T_H}$$

The temperatures are in Kelvin scale, and the temperatures on this scale are called absolute temperatures. On the Kelvin scale, the temperature ratios depend on the ratios of heat transfer between a reversible heat engine and the reservoirs and are independent of the physical properties of any substance.

The Carnot Refrigerator and Heat Pump

A refrigerator or a heat pump that operates on the reversed Carnot cycle is called a Carnot refrigerator, or a Carnot heat pump. The coefficient of performance of any refrigerator or heat pump, reversible or irreversible, is given by:

$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

The COPs of all reversible refrigerators or heat pumps can be determined by replacing the heat transfer ratios in the above relations by the ratios of the absolute temperatures of the high- and low-temperature reservoirs.

$$COP_R = \frac{T_L}{T_H - T_L} = \frac{1}{\frac{T_H}{T_L} - 1}$$

$$COP_{HP} = \frac{T_H}{T_H - T_L} = \frac{1}{1 - \frac{T_L}{T_H}}$$

**Which is the more effective way to increase the efficiency of a Carnot engine: to increase $T_1$, keeping $T_2$ constant; or to decrease $T_2$, keeping $T_1$ constant?**

The efficiency of a Carnot engine is given by $\eta_{th} = 1 - \frac{T_2}{T_1}$

Let $T_2$ be decreased by $\Delta T$ with $T_1$ remaining the same.

Thus, $\eta_1 = 1 - \frac{T_2 - \Delta T}{T_1}$

If $T_1$ is increased by the same $\Delta T$ with $T_2$ remaining the same

Then $\eta_2 = 1 - \frac{T_2}{T_1 + \Delta T}$

Thus $\eta_1 - \eta_2 = \frac{T_2}{T_1 + \Delta T} - \frac{T_2 - \Delta T}{T_1} = \frac{(T_1 - T_2)\Delta T + \Delta T^2}{T_1(T_1 + \Delta T)}$

Since $T_1 > T_2$, $\eta_1 - \eta_2 > 0$

The more effective way to increase the cycle efficiency is to decease $T_2$.

[6-107] A Carnot heat engine receives heat from a reservoir at900°C at a rate of 800 kJ/min and rejects the waste heat to the ambient air at 27°C. The entire work output of the heat engine is used to drive a refrigerator that removes heat from the refrigerated space at-5°C and transfers it to the same ambient air at 27°C. Determine (a) the maximum rate of heat removal from the refrigerated space and (b) the total rate of heat rejection to the ambient air. [Answers: (a) 4982 kJ/min, (b) 5782 kJ/min]

**6-107** A Carnot heat engine is used to drive a Carnot refrigerator. The maximum rate of heat removal from the refrigerated space and the total rate of heat rejection to the ambient air are to be determined.

*Assumptions* The heat engine and the refrigerator operate steadily.

*Analysis* (a) The highest thermal efficiency a heat engine operating between two specified temperature limits can have is the Carnot efficiency, which is determined from

$$\eta_{th,max} = \eta_{th,C} = 1 - \frac{T_L}{T_H} = 1 - \frac{300 \text{ K}}{1173 \text{ K}} = 0.744$$

Then the maximum power output of this heat engine is determined from the definition of thermal efficiency to be

$$\dot{W}_{net,out} = \eta_{th}\dot{Q}_H = (0.744)(800 \text{ kJ/min}) = 595.2 \text{ kJ/min}$$

which is also the power input to the refrigerator, $\dot{W}_{net,in}$ .

The rate of heat removal from the refrigerated space will be a maximum if a Carnot refrigerator is used. The COP of the Carnot refrigerator is

$$COP_{R,rev} = \frac{1}{(T_H/T_L)-1} = \frac{1}{(27+273 \text{ K})/(-5+273 \text{ K})-1} = 8.37$$

Then the rate of heat removal from the refrigerated space becomes

$$\dot{Q}_{L,R} = (COP_{R,rev})(\dot{W}_{net,in}) = (8.37)(595.2 \text{ kJ/min}) = 4982 \text{ kJ/min}$$

(b)  The total rate of heat rejection to the ambient air is the sum of the heat rejected by the heat engine ( $\dot{Q}_{L,HE}$ ) and the heat discarded by the refrigerator ( $\dot{Q}_{H,R}$ ),

$$\dot{Q}_{L,HE} = \dot{Q}_{H,HE} - \dot{W}_{net,out} = 800 - 595.2 = 204.8 \text{ kJ/min}$$

$$\dot{Q}_{H,R} = \dot{Q}_{L,R} + \dot{W}_{net,in} = 4982 + 595.2 = 5577.2 \text{ kJ/min}$$

and

$$\dot{Q}_{ambient} = \dot{Q}_{L,HE} + \dot{Q}_{H,R} = 204.8 + 5577.2 = 5782 \text{ kJ/min}$$
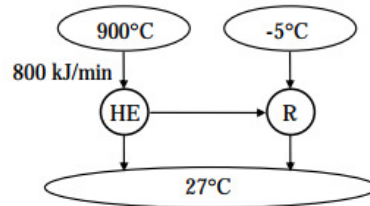
# Chapter 4

**Pure Substance:**

A substance that has <u>a fixed chemical composition</u> throughout is called a **pure substance.** Water, nitrogen, helium, and carbon dioxide, for example, are all pure substances. <u>Even homogeneous mixtures</u> can be called pure substances. However, a mixture of oil and water is not a pure substance. Since oil is not soluble in water, it will collect on top of the water, forming two chemically dissimilar regions.

<u>A mixture of two or more phases of a pure substance</u> is still a pure substance <u>as long as the chemical composition of all phases is the same</u>. A mixture of ice and liquid water, for example, is a pure substance because both phases have the same chemical composition. A mixture of liquid air and gaseous air, however, is not a pure substance since the composition of liquid air is different from the composition of gaseous air, and thus the mixture is no longer chemically homogeneous. This is due to different components in air condensing at different temperatures at a specified pressure.

**Phases of a Pure Substance:**

Even though there are three principal phases**: solid, liquid, and gas**, a substance **may have several phases within a principal phase**, each with a different molecular structure. Carbon, for example, may exist as graphite or diamond in the solid phase. Helium has two liquid phases; iron has three solid phases. Ice may exist at seven different phases at high pressures.

**Compressed Liquid and Saturated Liquid:**

Consider a piston–cylinder device containing liquid water at 20°C and 1 atm pressure. Under these conditions, water exists in the liquid phase, and it is called a **compressed liquid,** or a **subcooled liquid,** meaning that it is *not about to vaporize.* Heat is now transferred to the wateruntil its temperature rises to, say, 40°C. As the temperature rises, the liquidwater expands slightly, and so its specific volume increases. To accommodate this expansion, the piston moves up slightly. The pressure in the cylinder remains constant at 1 atm during this process since it depends on theoutside barometric pressure and the weight of the piston, both of which areconstant. Water is still a compressed liquid at this state since it has notstarted to vaporize.

As more heat is transferred, the temperature keeps rising until it reaches 100°C. At this point water is still a liquid, but any heat addition will cause some of the liquid to vaporize. That is, a phase-change process from liquid to vapour is about to take place. A liquid that is *about tovaporize* is called a **saturated liquid.**

**Saturated Vapour and Superheated Vapour:**

Once boiling starts, the temperature stops rising until the liquid is completely vaporized. Any heat loss from this vapour will cause some of the vapour to condense (phase change from vapour to liquid). A vapour that is *about to condense* is called a **saturated vapour.** A vapour that is *not about to condense* (i.e., not a saturated vapour) is called a **superheated vapour.**

**Saturation Temperature and Saturation Pressure:**

It probably came as no surprise to you that water started to boil at 100°C.Strictly speaking, the statement "water boils at 100°C" is incorrect. The correct statement is "water boils at 100°C at 1 atm pressure." The only reasonwater started boiling at 100°C was because we held the pressure constant at1 atm (101.325 kPa). If the pressure inside the cylinder were raised to 500kPa by adding weights on top of the piston, water would start boiling at151.8°C. That is, the temperature at which water starts boiling depends onthe pressure.At a given

pressure, the temperature at which a pure substance changesphase is called the saturation temperature, $T_{sat}$. Likewise, at a given temperature, the pressure at which a pure substance changes phase is called thesaturation pressure, $P_{sat}$. At a pressure of 101.325 kPa, $T_{sat}$is 99.97°C.

It takes a large amount of energy to melt a solid or vaporize a liquid. The amount of energy absorbed or released during a phase-change process is called the latent heat. More specifically, the amount of energy absorbed during melting is called the latent heat of fusion and is equivalent to the amount of energy released during freezing. Similarly, the amount of energy absorbed during vaporization is called the latent heat of vaporization and is equivalent to the energy released during condensation. The magnitudes of the latent heats depend on the temperature or pressure at which the phase change occurs. At 1 atm pressure, the latent heat of fusion of water is 333.7 kJ/kg and the latent heat of vaporization is 2256.5 kJ/kg.
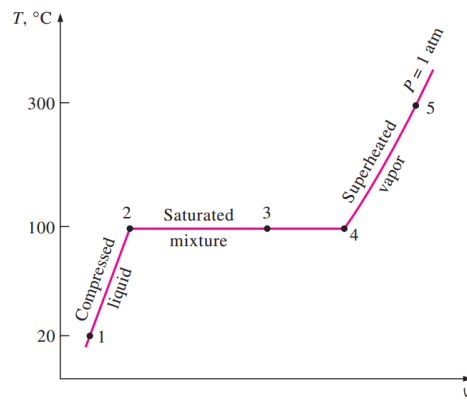


**The T-v Diagram:**
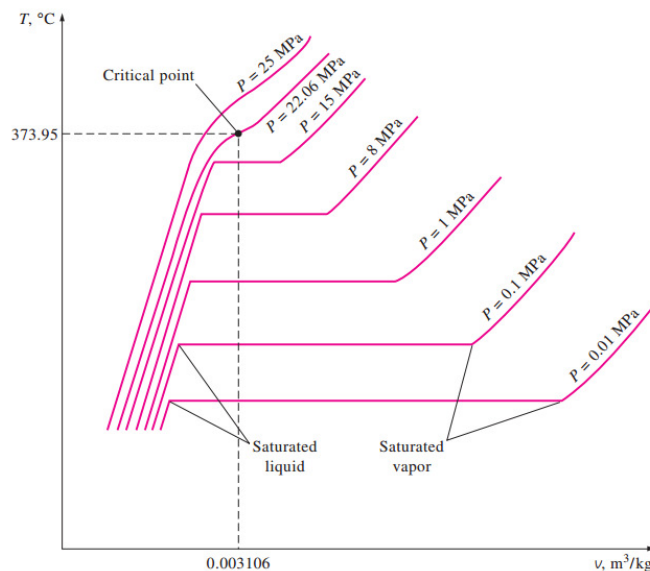


Let us add weights on top of the piston until the pressure inside the cylinder reaches 1 MPa. At this pressure, water has a somewhat smaller specificvolume than it does at 1 atm (101kPa=0.1MPa) pressure. As heat is transferred to the water atthis new pressure, the process follows a path that looks very much like theprocess path at 1 atm pressure, as shown in Fig, but there are somenoticeable differences. First, water starts boiling at a much higher temperature (179.9°C) at this pressure. Second, the specific volume of the saturated liquid is

larger and the specific volume of the saturated vapour is smaller than the corresponding values at 1 atm pressure. That is, the horizontal line that connects the saturated liquid and saturated vapour states is much shorter. As the pressure is increased further, this saturation line continues to shrink, as shown in Fig, and it becomes a point when the pressure reaches 22.06 MPa for the case of water. **This point is called the critical point** and it is defined as the point at which the saturated liquid and saturated vapour states are identical.

The temperature, pressure, and specific volume of a substance at the critical point are called, respectively, the critical temperature $T_{cr}$ critical pressure $P_{cr}$ and critical specific volume $v_{cr}$. The critical-point properties of water are $P_{cr}$=22.06 MPa, $T_{cr}$=373.95°C and $v_{cr}$=0.003106 m3/kg.

At **pressures above the critical pressure**, there is not a distinct phase change process. Instead, the specific volume of the substance continually increases, and at all times there is only one phase present. Eventually, it resembles a vapour, but we can never tell when the change has occurred. Above the critical state, there is no line that separates the compressed liquid region and the superheated vapour region. However, it is customary to refer to the substance as superheated vapour at temperatures above the critical temperature and as compressed liquid at temperatures below the critical temperature.

**The *P-v* Diagram: -**

The general shape of the *P-v* diagram of a pure substance is very much like the *T-v* diagram.

Consider again a piston–cylinder device that contains liquid water at 1 MPa and 150°C. Water at this state exists as a compressed liquid. Now the weights on top of the piston are removed one by one so that the pressure inside the cylinder decreases gradually. The water is allowed to exchange heat with the surroundings so its temperature remains constant. Asthe pressure decreases, the volume of the water increases slightly. When the pressure reaches the saturation-pressure value at the specified temperature (0.4762 MPa), the water starts to boil. **During this vaporization process, both the temperature and the pressure remain constant, but the specific volume increases.** Once the last drop of liquid is vaporized, further reduction in pressure results in a further increase in specific volume.
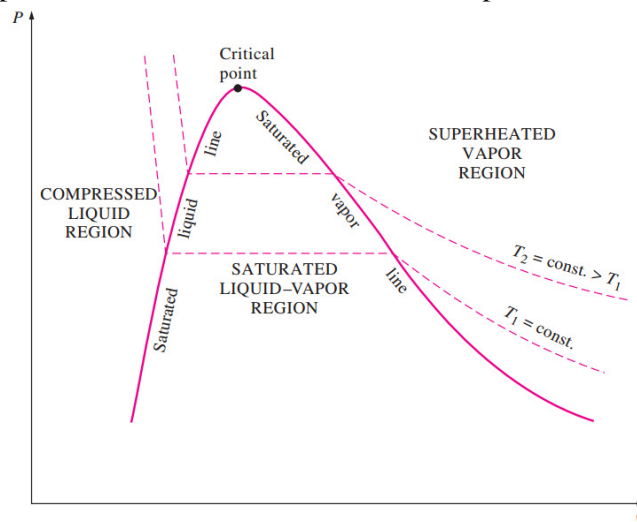


**The *P-T* Diagram: -**

Figure shows the *P-T* diagram of a pure substance. This diagram is often called the phase diagram since all three phases are separated from each other by three lines. **The sublimation line** separates the solid and vapour regions, the **vaporization line** separates the liquid and vapour regions, and the **melting (or fusion) line** separates the solid and liquid regions. **These three lines meet at the triple point, where all three phases coexist in equilibrium.** The vaporization line ends at the **critical point** because no distinction can be made between liquid and vapour phases above the critical point.
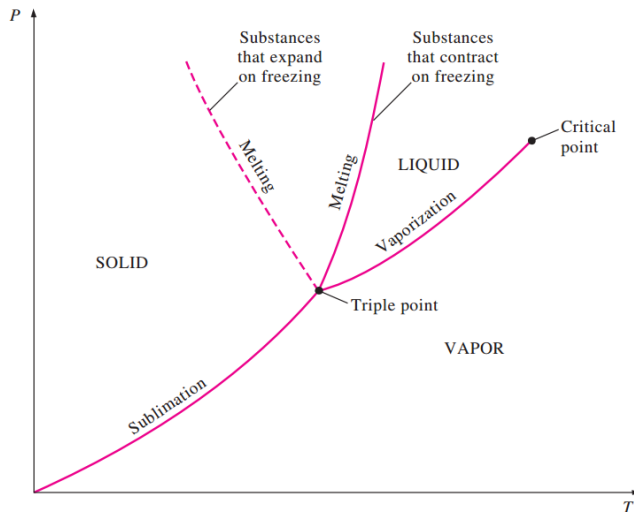


## Steam Table:

Generally two types of steam tables are in use. One is temperature table and another one is pressure table. Therefore, it is more convenient to use temperature table when temperature is given and pressure table when pressure is given.

## Saturated Liquid and Saturated Vapour States:

The subscript *f* is used to denote properties of a saturated liquid, and the subscript *g* to denote the properties of saturated vapour. These symbols are commonly used in thermodynamics. Another subscript commonly used is *fg*, which denotes the difference between the saturated vapour and saturated liquid values of the same property. For example,

$$v_f = specific\ volume\ of\ saturated\ liquid$$

$$v_g = specific\ volume\ of\ saturated\ vapour$$

$$v_{fg} = difference\ between\ v_g\ and\ v_f$$

$$\therefore v_{fg} = v_g - v_f$$

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 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

| | | Specific volume m³/kg | |
|---|---|---|---|
| Sat. Temp. °C $T$ | Sat. press. kPa $P_{sat}$ | Sat. liquid $v_f$ | Sat. vapor $v_g$ |
| 85 | 57.868 | 0.001032 | 2.8261 |
| 90 | 70.183 | 0.001036 | 2.3593 |
| 95 | 84.609 | 0.001040 | 1.9808 |

Specific temperature

Specific volume of saturated liquid

Corresponding saturation pressure

Specific volume of saturated vapor

Saturated Liquid–Vapour Mixture

During a vaporization process, a substance exists as part liquid and part vapour. To analyze this mixture properly, we need to know the proportions of the liquid and vapour phases in the mixture. This is done by defining a new property called the **quality or dryness fraction** $x$ as the ratio of the mass of vapour to the total mass of the mixture:

$$x = \frac{m_{vapor}}{m_{total}} = \frac{m_g}{m_f + m_g}$$

$$where, m_{total} = m_{liquid} + m_{vapor} = m_f + m_g$$

A saturated mixture can be treated as a combination of two subsystems: the saturated liquid and the saturated vapor. However, the amount of mass for each phase is usually not known. Therefore, it is often more convenient to imagine that the two phases are mixed well, forming a homogeneous mixture. Then the properties of this "mixture" will simply be the average properties of the saturated liquid–vapor mixture under consideration. Here is how it is done.

Consider a tank that contains a saturated liquid–vapor mixture. The volume occupied by saturated liquid is $V_f$, and the volume occupied by saturated vapor is $V_g$. The total volume V is the sum of the two:

$$V = V_f + V_g$$

$$V = mv \rightarrow m_{total}v_{avg} = m_f v_f + m_g v_g$$

$$m_{total} = m_f + m_g \rightarrow m_{total}v_{avg} = (m_{total} - m_g)v_f + m_g v_g$$

$$or, v_{avg} = \left(\frac{m_{total} - m_g}{m_{total}}\right)v_f + \frac{m_g}{m_{total}}v_g$$

$$or, v_{avg} = (1 - x)v_f + xv_g$$

$$or, v_{avg} = v_f - xv_f + xv_g$$

$$or, v_{avg} = v_f + x(v_g - v_f)$$

$$or, v_{avg} = v_f + xv_{fg}$$

Similarly,

$$u_{avg} = u_f + xu_{fg}$$

$$h_{avg} = h_f + xh_{fg}$$

**Superheated Vapour:**
In the region to the right of the saturated vapour line and at temperatures above the critical point temperature, a substance exists as superheated vapour. Since the superheated region is a single phase region (vapour phase only), temperature and pressure are no longer dependent properties and they can conveniently be used as the two independent properties in the tables.

**Problem:** A 0.025 $m^3$ vessel contains 0.3 kg of steam at 2 MPa. Determine the quality and enthalpy of steam.

Given $t_{sat} = 212.2°C, v_f = 0.001177 \frac{m^3}{kg}, v_g = 0.0995 \frac{m^3}{kg}, h_f = 908.5 \frac{kJ}{kg}, h_{fg} = 1888.7 \frac{kJ}{kg}, s_f = 2.447 \frac{kJ}{kg.K}, s_{fg} = 3.590 \frac{kJ}{kg.K}$

**Answer:** Specific volume of the steam $= v = \frac{V}{m} = \frac{0.025}{0.3} \frac{m^3}{kg} = 0.083 \frac{m^3}{kg}$

Let $x$ be the quality of the steam.

$$v = v_f + x v_{fg}$$
$$or, 0.083 = 0.001177 + x(0.0995 - 0.001177)$$
$$or, 0.083 = 0.001177 + x(0.0995 - 0.001177)$$
$$or, x = 0.8356$$

The specific enthalpy of the wet steam

$$h = h_f + x h_{fg} = 908.5 + 0.8356 \times 1888.7 = 2486.65 \frac{kJ}{kg}$$

**The Ideal-Gas Equation of State:**
Any equation that relates the pressure, temperature, and specific volume of a substance is called an equation of state.

An ideal gas is defined as a gas whose molecules are spaced far apart so that the behavior of a molecule is not influenced by the presence of other molecules—a situation encountered at low densities.

Gas and vapour are often used as synonymous words. Vapour usually implies a gas that is not far from a state of condensation.

$$PV = mRT$$

P=pressure in Pa

V=volume in m$^3$

m= mass in kg

R=gas constant, different for different gases, $R = \frac{R_u}{M}$ in J/kg.K

$R_u = 8.31447 \frac{kJ}{kmol.K}$

T=temperature in K

At low pressures and high temperatures, the density of a gas decreases, and the gas behaves as an ideal gas under these conditions.

**IS WATER VAPOR AN IDEAL GAS?**
This question cannot be answered with a simple yes or no. It is clear from this figure that at pressures below 10 kPa, water vapour can be treated as an ideal gas, regardless of its temperature, with negligible error (less than 0.1 percent). At higher pressures, however, the ideal gas assumption yields unacceptable errors, particularly in the vicinity of the critical

point and the saturated vapour line (over 100 percent). Therefore, in air-conditioning applications, the water vapour in the air can be treated as an ideal gas with essentially no error since the pressure of the water vapour is very low. In steam power plant applications, however, the pressures involved are usually very high; therefore, ideal-gas relations should not be used.
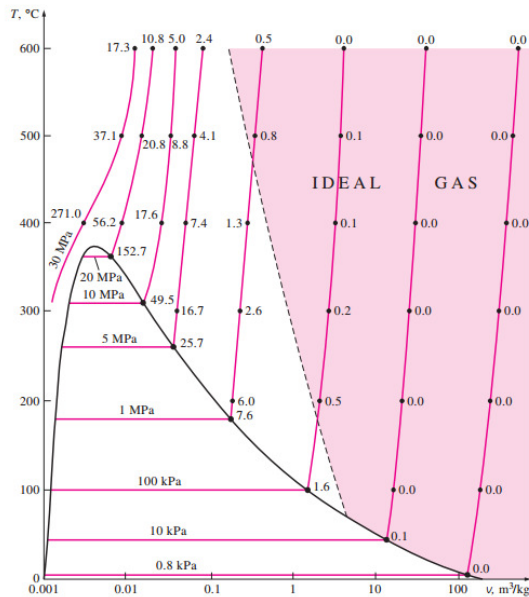


## Compressibility Factor—A Measure of Deviation from Ideal-Gas Behaviour:

Gases deviate from ideal-gas behaviour significantly at states near the saturation region and the critical point. This deviation from ideal-gas behaviour at a given temperature and pressure can accurately be accounted for by the introduction of a correction factor called the compressibility factor Z defined as

$$Pv = ZRT$$

$$v = specific\ volume\ in\ \frac{m^3}{kg}$$

Z=1 for ideal gases. For real gases Z canbe greater than or less than unity. The farther away Z is fromunity, the more the gas deviates from ideal-gas behaviour.

[3-78] A 1-m³ tank containing air at 25°C and 500 kPa is connected through a valve to another tank containing 5 kg of air at 35°C and 200 kPa. Now the valve is opened, and the entire system is allowed to reach thermal equilibrium with the surroundings, which are at 20°C. Determine the volume of the second tank and the final equilibrium pressure of air.

**3-78** Two rigid tanks connected by a valve to each other contain air at specified conditions. The volume of the second tank and the final equilibrium pressure when the valve is opened are to be determined.

*Assumptions* At specified conditions, air behaves as an ideal gas.

*Properties* The gas constant of air is $R = 0.287$ kPa.m³/kg.K (Table A-1).

*Analysis* Let's call the first and the second tanks A and B. Treating air as an ideal gas, the volume of the second tank and the mass of air in the first tank are determined to be

$$V_B = \left(\frac{m_1 RT_1}{P_1}\right)_B = \frac{(5 \text{ kg})(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(308 \text{ K})}{200 \text{ kPa}} = 2.21 \text{ m}^3$$

$$m_A = \left(\frac{P_1 V}{RT_1}\right)_A = \frac{(500 \text{ kPa})(1.0 \text{ m}^3)}{(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(298 \text{ K})} = 5.846 \text{ kg}$$

Thus,

| A | B |
|---|---|
| Air<br>$V = 1$ m³<br>$T = 25°C$<br>$P = 500$ kPa | Air<br>$m = 5$ kg<br>$T = 35°C$<br>$P = 200$ kPa |

$$V = V_A + V_B = 1.0 + 2.21 = 3.21 \text{ m}^3$$
$$m = m_A + m_B = 5.846 + 5.0 = 10.846 \text{ kg}$$

Then the final equilibrium pressure becomes

$$P_2 = \frac{mRT_2}{V} = \frac{(10.846 \text{ kg})(0.287 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(293 \text{ K})}{3.21 \text{ m}^3} = 284.1 \text{ kPa}$$
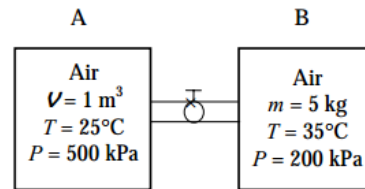
[3-87] Determine the specific volume of superheated water vapor at 15 MPa and 350°C, using (a) the ideal-gas equation,(b) the generalized compressibility chart, and (c) the steam tables. Also determine the error involved in the first two cases. [Answers: (a) 0 .01917 m³/kg, 67.0 percent, (b) 0 .01246 m³/kg, 8.5 percent, (c) 0 .01148 m³/kg]

**3-87** The specific volume of steam is to be determined using the ideal gas relation, the compressibility chart, and the steam tables. The errors involved in the first two approaches are also to be determined.

*Properties* The gas constant, the critical pressure, and the critical temperature of water are, from Table A-1,

$$R = 0.4615 \text{ kPa·m}^3/\text{kg·K}, \qquad T_{cr} = 647.1 \text{ K}, \qquad P_{cr} = 22.06 \text{ MPa}$$

*Analysis* (a) From the ideal gas equation of state,

$$v = \frac{RT}{P} = \frac{(0.4615 \text{ kPa} \cdot \text{m}^3/\text{kg} \cdot \text{K})(623.15 \text{ K})}{15{,}000 \text{ kPa}} = 0.01917 \text{ m}^3/\text{kg} \quad (67.0\% \text{ error})$$

(b) From the compressibility chart (Fig. A-15),

$$\left. \begin{array}{l} P_R = \dfrac{P}{P_{cr}} = \dfrac{10 \text{ MPa}}{22.06 \text{ MPa}} = 0.453 \\[2mm] T_R = \dfrac{T}{T_{cr}} = \dfrac{673 \text{ K}}{647.1 \text{ K}} = 1.04 \end{array} \right\} Z = 0.65$$

| H₂O |
|---|
| 15 MPa |
| 350°C |
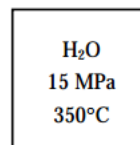
Thus,

$$v = Z v_{ideal} = (0.65)(0.01917 \text{ m}^3/\text{kg}) = 0.01246 \text{ m}^3/\text{kg} \quad (8.5\% \text{ error})$$

(c) From the superheated steam table (Table A-6),

$$\left. \begin{array}{l} P = 15 \text{ MPa} \\ T = 350°C \end{array} \right\} \quad v = 0.01148 \text{ m}^3/\text{kg}$$

[3-32] One kilogram of water fills a 150-L rigid container at an initial pressure of 2 MPa. The container is then cooled to40°C. Determine the initial temperature and the final pressure of the water.

**3-32** A rigid container that is filled with water is cooled. The initial temperature and the final pressure are to be determined.

*Analysis* This is a constant volume process. The specific volume is

$$v_1 = v_2 = \frac{V}{m} = \frac{0.150\,\text{m}^3}{1\,\text{kg}} = 0.150\,\text{m}^3/\text{kg}$$

The initial state is superheated vapor. The temperature is determined to be

$$\left.\begin{array}{l} P_1 = 2\,\text{MPa} \\ v_1 = 0.150\,\text{m}^3/\text{kg} \end{array}\right\} \quad T_1 = \textbf{395°C} \quad (\text{Table A - 6})$$

This is a constant volume cooling process ($v = V/m$ = constant). The final state is saturated mixture and thus the pressure is the saturation pressure at the final temperature:

$$\left.\begin{array}{l} T_2 = 40°\text{C} \\ v_2 = v_1 = 0.150\,\text{m}^3/\text{kg} \end{array}\right\} \quad P_2 = P_{\text{sat @ 40°C}} = \textbf{7.385 kPa} \quad (\text{Table A - 4})$$
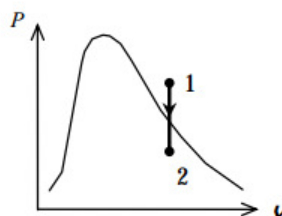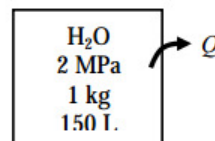
[3-61] 3-61 A piston-cylinder device initially contains 1.4-kg saturated liquid water at 200°C. Now heat is transferred to the water until the volume quadruples and the cylinder contains saturated vapor only. Determine (a) the volume of the tank,(b) the final temperature and pressure, and (c) the internal energy change of the water.

**3-61** Heat is supplied to a piston-cylinder device that contains water at a specified state. The volume of the tank, the final temperature and pressure, and the internal energy change of water are to be determined.

*Properties* The saturated liquid properties of water at 200°C are: $v_f = 0.001157$ m$^3$/kg and $u_f = 850.46$ kJ/kg (Table A-4).

*Analysis* (*a*) The cylinder initially contains saturated liquid water. The volume of the cylinder at the initial state is

$$V_1 = mv_1 = (1.4\,\text{kg})(0.001157\,\text{m}^3/\text{kg}) = 0.001619\,\text{m}^3$$

The volume at the final state is

$$V = 4(0.001619) = \textbf{0.006476 m}^3$$

(*b*) The final state properties are

$$v_2 = \frac{V}{m} = \frac{0.006476\,\text{m}^3}{1.4\,\text{kg}} = 0.004626\,\text{m}^3\,/\text{kg}$$

$$\left.\begin{array}{l} v_2 = 0.004626\,\text{m}^3\,/\text{kg} \\ x_2 = 1 \end{array}\right\} \begin{array}{l} T_2 = \textbf{371.3°C} \\ P_2 = \textbf{21,367 kPa} \\ u_2 = 2201.5\,\text{kJ/kg} \end{array} \quad (\text{Table A-4 or A-5 or EES})$$

(*c*) The total internal energy change is determined from

$$\Delta U = m(u_2 - u_1) = (1.4\,\text{kg})(2201.5 - 850.46)\,\text{kJ/kg} = \textbf{1892 kJ}$$
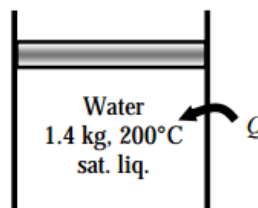
[3-60] A rigid tank contains water vapor at 250°C and an unknown pressure. When the tank is cooled to 124°C, the vapor starts condensing. Estimate the initial pressure in the tank. [Answer: 0 .30 MPa]

**3-60** The water in a rigid tank is cooled until the vapor starts condensing. The initial pressure in the tank is to be determined.

*Analysis* This is a constant volume process ($v = V/m$ = constant), and the initial specific volume is equal to the final specific volume that is

$$v_1 = v_2 = v_{g@124°C} = 0.79270 \text{ m}^3/\text{kg} \quad \text{(Table A-4)}$$

since the vapor starts condensing at 150°C. Then from Table A-6,

$$\left. \begin{array}{l} T_1 = 250°C \\ v_1 = 0.79270 \text{ m}^3/\text{kg} \end{array} \right\} P_1 = \textbf{0.30 MPa}$$

H₂O
$T_1$= 250°C
$P_1$ = ?
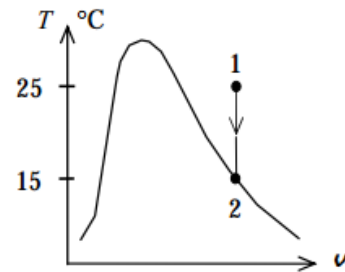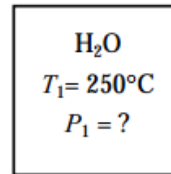
[3-59] A piston-cylinder device contains 0.8 kg of steam at 300°C and 1 MPa. Steam is cooled at constant pressure until one-half of the mass condenses (a) Show the process on a T-v diagram. (b) Find the final temperature. (c) Determine the volume change.

**3-59** Superheated steam in a piston-cylinder device is cooled at constant pressure until half of the mass condenses. The final temperature and the volume change are to be determined, and the process should be shown on a $T$-$v$ diagram.

*Analysis* (b) At the final state the cylinder contains saturated liquid-vapor mixture, and thus the final temperature must be the saturation temperature at the final pressure,

$$T = T_{sat@1 MPa} = \textbf{179.88°C} \qquad \text{(Table A-5)}$$

(c) The quality at the final state is specified to be $x_2 = 0.5$. The specific volumes at the initial and the final states are

$$\left. \begin{array}{l} P_1 = 1.0 \text{ MPa} \\ T_1 = 300°C \end{array} \right\} v_1 = 0.25799 \text{ m}^3/\text{kg} \qquad \text{(Table A-6)}$$

$$\left. \begin{array}{l} P_2 = 1.0 \text{ MPa} \\ x_2 = 0.5 \end{array} \right\} v_2 = v_f + x_2 v_{fg}$$
$$= 0.001127 + 0.5 \times (0.19436 - 0.001127)$$
$$= 0.09775 \text{ m}^3/\text{kg}$$

H₂O
300°C
1 MPa

Thus,

$$\Delta V = m(v_2 - v_1) = (0.8 \text{ kg})(0.09775 - 0.25799)\text{m}^3/\text{kg} = \textbf{-0.1282 m}^3$$
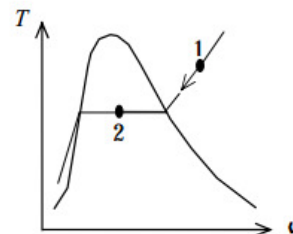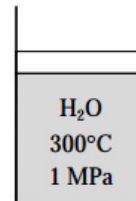
[4-13] 1-m$^3$ of saturated liquid water at 200°C is expanded isothermally in a closed system until its quality is 80 percent. Determine the total work produced by this expansion, in kJ.

$P_1 = P_2 = P_{sat\ @\ 200°C} = 1554.9\ \text{kPa}$

$v_1 = v_{f\ @\ 200°C} = 0.001157\ \text{m}^3/\text{kg}$

$v_2 = v_f + x v_{fg}$
$\quad = 0.001157 + 0.80(0.12721 - 0.001157)$
$\quad = 0.10200\ \text{m}^3/\text{kg}$

The definition of specific volume gives

$V_2 = V_1 \dfrac{v_2}{v_1} = (1\ \text{m}^3)\dfrac{0.10200\ \text{m}^3/\text{kg}}{0.001157\ \text{m}^3/\text{kg}} = 88.16\ \text{m}^3$

The work done during the process is determined from

$W_{b,out} = \displaystyle\int_1^2 P\,dV = P(V_2 - V_1) = (1554.9\ \text{kPa})(88.16 - 1)\text{m}^3\left(\dfrac{1\,\text{kJ}}{1\,\text{kPa}\cdot\text{m}^3}\right) = \mathbf{1.355 \times 10^5\ kJ}$

[Diagram: P (kPa) vs V (m³), showing process from state 1 to state 2 at 1555 kPa, from V = 1 to V = 88.16 m³]

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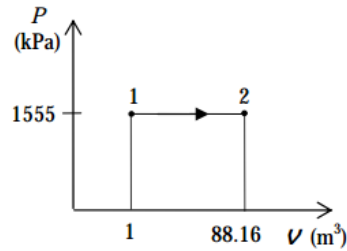
[5-51] Steam enters an adiabatic turbine at 10 MPa and 500°C and leaves at 10 kPa with a quality of 90 percent. Neglecting the changes in kinetic and potential energies, determine the mass flow rate required for a power output of 5 MW.

*Properties* From the steam tables (Tables A-4 through 6)

$\left.\begin{array}{l} P_1 = 10\ \text{MPa} \\ T_1 = 500°C \end{array}\right\} h_1 = 3375.1\ \text{kJ/kg}$

$\left.\begin{array}{l} P_2 = 10\ \text{kPa} \\ x_2 = 0.90 \end{array}\right\} h_2 = h_f + x_2 h_{fg} = 191.81 + 0.90 \times 2392.1 = 2344.7\ \text{kJ/kg}$

[Diagram: turbine with inlet 1 at top, outlet 2 at bottom, labeled H₂O]

*Analysis* There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the turbine as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{system}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}}^{\nearrow 0\ \text{(steady)}} = 0$$

$\dot{E}_{in} = \dot{E}_{out}$

$\dot{m} h_1 = \dot{W}_{out} + \dot{m} h_2 \quad$ (since $\dot{Q} \cong \Delta ke \cong \Delta pe \cong 0$)

$\dot{W}_{out} = -\dot{m}(h_2 - h_1)$

Substituting, the required mass flow rate of the steam is determined to be

$5000\ \text{kJ/s} = -\dot{m}(2344.7 - 3375.1)\ \text{kJ/kg} \longrightarrow \dot{m} = \mathbf{4.852\ kg/s}$
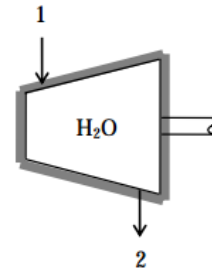
**A steam turbine receives water at 15 MPa, 600°C at the rate of 100 kg/s. in the middle section 20 kg/s is withdrawn at 2 MPa, 350°C and the rest exit the turbine at 75 kPa, 95% quality as shown in figure. Assuming no heat transfer and no change in kinetic energy, find the total turbine work.**
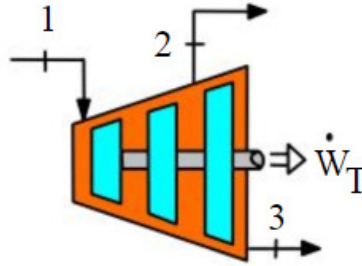


From continuity equation we have:

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3$$

$$or, \dot{m}_3 = 100 - 20 = 80 \ kg/s$$

From energy equation

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_3 h_3 + \dot{W}_T$$

From steam table,

$h_1 = 3582.3$ kJ/kg

$h_2 = 3137$ kJ/kg

$h_3 = h_f + x_3 f_{fg} = 2549.1$ kJ/kg

$$\therefore \dot{W}_T = 91.565 \ mW$$

[5-59] Steam enters a steady-flow turbine with a mass flow rate of 20 kg/s at 600°C, 5 MPa, and a negligible velocity. The steam expands in the turbine to a saturated vapor at 500 kPa where 10 percent of the steam is removed for some other use. The remainder of the steam continues to expand to the turbine exit where the pressure is 10 kPa and quality is 85 percent. If the turbine is adiabatic, determine the rate of work done by the steam during this process. [Answer: 27,790 kW]

*Properties* From the steam tables (Tables A-5 and A-6)

$$P_1 = 5 \text{ MPa} \atop T_1 = 600°C \Big\} h_1 = 3666.9 \text{ kJ/kg}$$

$$P_2 = 0.5 \text{ MPa} \atop x_2 = 1 \Big\} h_2 = 2748.1 \text{ kJ/kg}$$

$$P_3 = 10 \text{ kPa} \atop x_2 = 0.85 \Big\} \begin{array}{l} h_3 = h_f + x h_{fg} \\ = 191.81 + (0.85)(2392.1) = 2225.1 \text{ kJ/kg} \end{array}$$

*Analysis* We take the entire turbine, including the connection part between the two stages, as the system, which is a control volume since mass crosses the boundary. Noting that one fluid stream enters the turbine and two fluid streams leave, the energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{system}^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$
$$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_3 h_3 + \dot{W}_{out}$$
$$\dot{W}_{out} = \dot{m}_1 (h_1 - 0.1 h_2 - 0.9 h_3)$$

Substituting, the power output of the turbine is

$$\dot{W}_{out} = \dot{m}_1 (h_1 - 0.1 h_2 - 0.9 h_3)$$
$$= (20 \text{ kg/s})(3666.9 - 0.1 \times 2748.1 - 0.9 \times 2225.1) \text{ kJ/kg}$$
$$= \mathbf{27,790 \text{ kW}}$$



5 MPa
600°C
20 kg/s

STEAM
20 kg/s

I

II

10 kPa
x=0.85

0.1 MPa
2 kg/s
sat. vap.
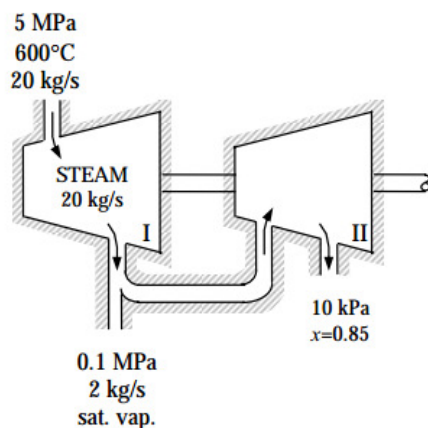
**[5-67]** Saturated liquid-vapor mixture of water, called wet steam, in a steam line at 2000 kPa is throttled to 100 kPa and120°C. What is the quality in the steam line? [Answer: 0.957]

**5-67** Steam is throttled from a specified pressure to a specified state. The quality at the inlet is to be determined.

*Assumptions* **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** Heat transfer to or from the fluid is negligible. **4** There are no work interactions involved.

*Analysis* There is only one inlet and one exit, and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. We take the throttling valve as the system, which is a control volume since mass crosses the boundary. The energy balance for this steady-flow system can be expressed in the rate form as

$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{system}^{\nearrow 0 \ (steady)} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$\dot{m}h_1 = \dot{m}h_2$$
$$h_1 = h_2$$

Throttling valve

Steam 2 MPa → ⊗ 100 kPa 120°C
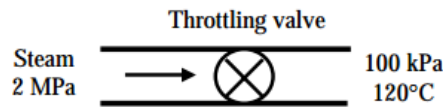
Since $\dot{Q} \cong \dot{W} = \Delta ke \cong \Delta pe \cong 0$.

The enthalpy of steam at the exit is (Table A-6),

$$\left. \begin{array}{l} P_2 = 100 \text{ kPa} \\ T_2 = 120°C \end{array} \right\} h_2 = 2716.1 \text{ kJ/kg}$$

The quality of the steam at the inlet is (Table A-5)

$$\left. \begin{array}{l} P_1 = 2000 \text{ kPa} \\ h_1 = h_2 = 2716.1 \text{ kJ/kg} \end{array} \right\} x_1 = \frac{h_2 - h_f}{h_{fg}} = \frac{2716.1 - 908.47}{1889.8} = \mathbf{0.957}$$

**[3-68]** A 0.3-m$^3$ rigid vessel initially contains saturated liquid-vapor mixture of water at 150° C. The water is now heated until it reaches the critical state. Determine the mass of the liquid water and the volume occupied by the liquid at the initial state.

**3-68** A rigid vessel that contains a saturated liquid-vapor mixture is heated until it reaches the critical state. The mass of the liquid water and the volume occupied by the liquid at the initial state are to be determined.

*Analysis* This is a constant volume process ($v = V/m =$ constant) to the critical state, and thus the initial specific volume will be equal to the final specific volume, which is equal to the critical specific volume of water,

$$v_1 = v_2 = v_{cr} = 0.003106 \text{ m}^3\text{/kg} \quad \text{(last row of Table A-4)}$$

The total mass is

$$m = \frac{V}{v} = \frac{0.3 \text{ m}^3}{0.003106 \text{ m}^3\text{/kg}} = 96.60 \text{ kg}$$

H₂O
150°C



At 150°C, $v_f = 0.001091$ m³/kg and $v_g = 0.39248$ m³/kg (Table A-4). Then the quality of water at the initial state is

$$x_1 = \frac{v_1 - v_f}{v_{fg}} = \frac{0.003106 - 0.001091}{0.39248 - 0.001091} = 0.005149$$

Then the mass of the liquid phase and its volume at the initial state are determined from

$$m_f = (1 - x_1)m_t = (1 - 0.005149)(96.60) = \mathbf{96.10 \text{ kg}}$$
$$V_f = m_f v_f = (96.10 \text{ kg})(0.001091 \text{ m}^3\text{/kg}) = \mathbf{0.105 \text{ m}^3}$$
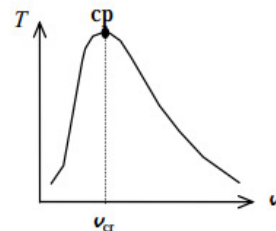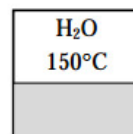
[4-32] A well-insulated rigid tank contains 2 kg of a saturated liquid-vapor mixture of water at 150 kPa. Initially, three-quarters of the mass is in the liquid phase. An electric resistor placed in the tank is connected to a 110-V source and a current of 8 A flows through the resistor when the switch is turned on. Determine how long it will take to vaporize all the liquid in the tank. Also, show the process on a T-v diagram with respect to saturation lines.

*Analysis* We take the contents of the tank as the system. This is a closed system since no mass enters or leaves. Noting that the volume of the system is constant and thus there is no boundary work, the energy balance for this stationary closed system can be expressed as

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

$$W_{e,in} = \Delta U = m(u_2 - u_1) \quad (\text{since } Q = KE = PE = 0)$$

$$VI\Delta t = m(u_2 - u_1)$$



H₂O
V = const.

$W_e$

The properties of water are (Tables A-4 through A-6)

$$\begin{aligned} P_1 &= 150 \text{ kPa} \\ x_1 &= 0.25 \end{aligned} \left| \begin{aligned} v_f &= 0.001053, & v_g &= 1.1594 \text{ m}^3/\text{kg} \\ u_f &= 466.97, & u_{fg} &= 2052.3 \text{ kJ/kg} \end{aligned} \right.$$

$$v_1 = v_f + x_1 v_{fg} = 0.001053 + [0.25 \times (1.1594 - 0.001053)] = 0.29065 \text{ m}^3/\text{kg}$$

$$u_1 = u_f + x_1 u_{fg} = 466.97 + (0.25 \times 2052.3) = 980.03 \text{ kJ/kg}$$

$$\left. \begin{aligned} v_2 &= v_1 = 0.29065 \text{ m}^3/\text{kg} \\ \text{sat.vapor} \end{aligned} \right\} u_2 = u_{g@0.29065 \text{ m}^3/\text{kg}} = 2569.7 \text{ kJ/kg}$$

Substituting,

$$(110 \text{ V})(8 \text{ A})\Delta t = (2 \text{ kg})(2569.7 - 980.03)\text{kJ/kg}\left(\frac{1000 \text{ VA}}{1 \text{ kJ/s}}\right)$$

$$\Delta t = 33613 \text{ s} = \textbf{60.2 min}$$
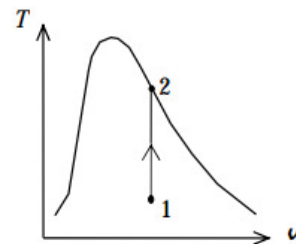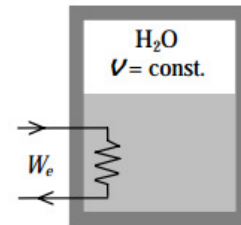
# Chapter 5

**Entropy:**
The second law of thermodynamics often leads to expressions that involve inequalities. An irreversible (i.e., actual) heat engine, for example, is less efficient than a reversible one operating between the same two thermal energy reservoirs. Likewise, an irreversible refrigerator or a heat pump has a lower coefficient of performance (COP) than a reversible one operating between the same temperature limits.

Another important inequality that has major consequences in thermodynamics is the Clausius inequality. It was first stated by the German physicist R. J. E. Clausius (1822–1888), one of the founders of thermodynamics, and is expressed as:

$$\oint \frac{\delta Q}{T} \leq 0$$

That is, the cyclic integral of $\frac{\delta Q}{T}$ is always less than or equal to zero. This inequality is valid for all cycles, reversible or irreversible. The integral symbol with a circle in the middle is used to indicate that the integration is to be performed over the entire cycle. Any heat transfer to or from a system can be considered to consist of differential amounts of heat transfer. Then the cyclic integral of $\frac{\delta Q}{T}$ can be viewed as the sum of all these differential amounts of heat transfer divided by the temperature at the boundary.

$$\oint \left( \frac{\delta Q}{T} \right)_{int\ rev} = 0$$

The equality in the Clausius inequality holds for totally or just internally reversible cycles and the inequality for the irreversible ones.

To develop a relation for the definition of entropy, we have a quantity whose cyclic integral is zero. Let us think for a moment what kind of quantities can have this characteristic.

We know that the cyclic integral of work is not zero. (It is a good thing that it is not. Otherwise, heat engines that work on a cycle such as steam power plants would produce zero net work.) Neither is the cyclic integral of heat.

Now consider the volume occupied by a gas in a piston–cylinder device undergoing a cycle, as shown in Fig. When the piston returns to its initial position at the end of a cycle, the volume of the gas also returns to its initial value. Thus the net change in volume during a cycle is zero. This is also expressed as

$$\oint dv = 0$$

That is, the cyclic integral of volume (or any other property) is zero. Conversely, a quantity whose cyclic integral is zero depends on the state only and not the process path, and thus it is a property. Therefore, the quantity $\left( \frac{\delta Q}{T} \right)_{int\ rev}$ must represent a property in the differential form.

Clausius realized in 1865 that he had discovered a new thermodynamic property, and he chose to name this property entropy. It is designated S and is defined as

$$dS = \left( \frac{\delta Q}{T} \right)_{int\ rev}$$

Entropy is an extensive property of a system. Entropy per unit mass, designated s, is an intensive property and has the unit kJ/kg · K.

The entropy change of a system during a process can be determined by integrating the previous equation between the initial and the final states:

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_{int\ rev}$$

Notice that we have actually defined the change in entropy instead of entropy itself, just as we defined the change in energy instead of the energy itself when we developed the first-law relation. Absolute values of entropy are determined on the basis of the third law of thermodynamics.

The third law of thermodynamics is sometimes stated as follows, regarding the properties of systems in equilibrium at absolute zero temperature: The entropy of a perfect crystal at absolute zero is exactly equal to zero.

Engineers are usually concerned with the changes in entropy. Therefore, the entropy of a substance can be assigned a zero value at some arbitrarily selected reference state, and the entropy values at other states can be determined from above equation by choosing state 1 to be the reference state (S=0) and state 2 to be the state at which entropy is to be determined.

Note that the integral of $\frac{\delta Q}{T}$ gives us the value of entropy change only if the integration is carried out along an internally reversible path between the two states. The integral of $\frac{\delta Q}{T}$ along an irreversible path is not a property, and in general, different values will be obtained when the integration is carried out along different irreversible paths. Therefore, even for irreversible processes, the entropy change should be determined by carrying out this integration along some convenient imaginary internally reversible path between the specified states.
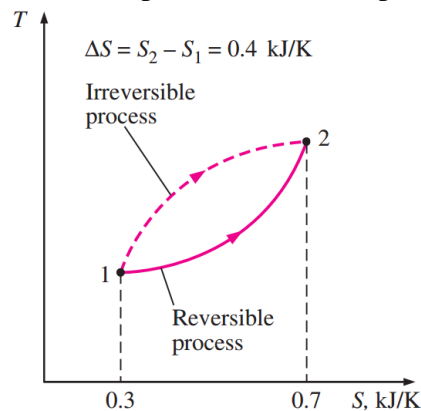


Fig.: The entropy change between two specified states is the same whether the process is reversible or irreversible

**A Special Case: Internally Reversible Isothermal Heat Transfer Processes:**

Recall that isothermal heat transfer processes are internally reversible. Therefore, the entropy change of a system during an internally reversible isothermal heat transfer process can be determined by performing the following integration:

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_{int\,rev} = \int_1^2 \left(\frac{\delta Q}{T_0}\right)_{int\,rev} = \frac{1}{T_0}\int_1^2 (\delta Q)_{int\,rev} = \frac{Q}{T_0}$$

Notice that the entropy change of a system during an internally reversible isothermal process can be positive or negative, depending on the direction of heat transfer. Heat transfer to a system increases the entropy of a system, whereas heat transfer from a system decreases it. In fact, losing heat is the only way the entropy of a system can be decreased.

**Problem:** 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.

**Answer:** 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 following equation:

$$\Delta S = \frac{Q}{T_0} = \frac{750}{300} = 2.5 \; kJ/K$$

Note that the entropy change of the system is positive, as expected, since heat transfer is to the system.

The Increase of Entropy Principle:

Consider a cycle that is made up of two processes: process 1-2, which is arbitrary (reversible or irreversible), and process 2-1, which is internally reversible, as shown in Figure.
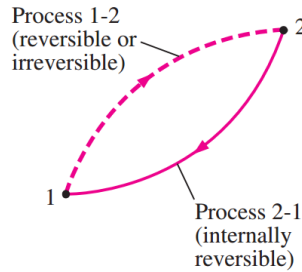


Fig.: A cycle composed of a reversible and an irreversible process.

From the Clausius inequality,

$$\oint \frac{\delta Q}{T} \leq 0$$

$$or, \int_1^2 \frac{\delta Q}{T} + \int_2^1 \left(\frac{\delta Q}{T}\right)_{int\,rev} \leq 0$$

$$or, \int_1^2 \frac{\delta Q}{T} + S_1 - S_2 \leq 0$$

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

The equality holds for an internally reversible process and the inequality for an irreversible process.

We may conclude from this equation that the entropy change of a closed system during an irreversible process is greater than the integral of $\frac{\delta Q}{T}$ evaluated for that process. In the limiting case of a reversible process, these two quantities become equal.

The quantity $\Delta S = S_2 - S_1$ represents the entropy change of the system. For a reversible process, it becomes equal to $\int_1^2 \frac{\delta Q}{T}$, which represents the *entropy transfer* with heat.

The inequality sign in the preceding relations is a constant reminder that the entropy change of a closed system during an irreversible process is always greater than the entropy transfer. That is, some entropy is generated or created during an irreversible process, and this generation is due entirely to the presence of irreversibilities. The entropy generated during a process is called entropy generation and is denoted by $S_{gen}$. Noting that the difference between the entropy change of a closed system and the entropy transfer is equal to entropy generation, equation can be rewritten as an equality as:

$$\Delta S_{system} = S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen}$$

Note that the entropy generation $S_{gen}$ is always a positive quantity or zero. Its value depends on the process, and thus it is not a property of the system. Also, in the absence of any entropy transfer, the entropy change of a system is equal to the entropy generation.

For an isolated system (or simply an adiabatic closed system), the heat transfer is zero.

$$We\ know\ that, S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}$$

$$So, \Delta S_{Isolated\ System} \geq 0$$

This equation can be expressed as the entropy of an isolated system during a process always increases or, in the limiting case of a reversible process, remains constant. In other words, it never decreases. This is known as the increase of entropy principle. Note that in the absence of any heat transfer, entropy change is due to irreversibilities only, and their effect is always to increase entropy.

A system and its surroundings constitute an isolated system since both can be enclosed by a sufficiently large arbitrary boundary across which there is no heat, work, or mass transfer. Therefore, a system and its surroundings can be viewed as the two subsystems of an isolated system, and the entropy change of this isolated system during a process is the sum of the entropy changes of the system and its surroundings, which is equal to the entropy generation since an isolated system involves no entropy transfer.

That is,

$$S_{gen} = \Delta S_{total} = \Delta S_{system} + \Delta S_{surroundings} \geq 0$$

where the equality holds for reversible processes and the inequality for irreversible ones. Since no actual process is truly reversible, we can conclude that some entropy is generated during a process, and therefore the entropy of the universe, which can be considered to be an isolated system, is continuously increasing. The more irreversible a process, the larger the entropy generated during that process.

The increase of entropy principle does not imply that the entropy of a system cannot decrease. The entropy change of a system can be negative during a process, but entropy generation cannot. The increase of entropy principle can be summarized as follows:

$$S_{gen} > 0 \; Irreversible \; process$$
$$= 0 \; Reversible \; process$$
$$< 0 \; Impossible \; process$$

**Isentropic Processes:**

We mentioned earlier that the entropy of a fixed mass can be changed by (1) heat transfer and (2) irreversibilities. Then it follows that the entropy of a fixed mass does not change during a process that is internally reversible and adiabatic. A process during which the entropy remains constant is called an isentropic process.

Many engineering systems or devices such as pumps, turbines, nozzles, and diffusers are essentially adiabatic in their operation, and they perform best when the irreversibilities, such as the friction associated with the process, are minimized. Therefore, an isentropic process can serve as an appropriate model for actual processes. Also, isentropic processes enable us to define efficiencies for processes to compare the actual performance of these devices to the performance under idealized conditions.

**Third law of thermodynamics:**

The entropy of a pure crystalline substance at absolute zero temperature is zero since there is no uncertainty about the state of the molecules at that instant. This statement is known as the third law of thermodynamics.

Being an organized form of energy, work is free of disorder or randomness and thus free of entropy. There is no entropy transfer associated with energy transfer as work. Therefore, in the absence of any friction, the process of raising a weight by a rotating shaft does not produce any entropy. Any process that does not produce a net entropy is reversible, and thus the process just described is a reversible process.

Heat is a form of disorganized energy, so via heat transfer entropy increases.

The Tds Relations and The Entropy Change of Ideal Gases:

Recall that the quantity $\left(\frac{\delta Q}{T}\right)_{int \, rev}$ corresponds to a differential change in the property entropy.

The entropy change for a process, then, can be evaluated by integrating $\frac{\delta Q}{T}$ along some imaginary internally reversible path between the actual end states. For isothermal internally reversible processes, this integration is straightforward. But when the temperature varies during the process, we have to have a relation between $\delta Q$ and T to perform this integration. Finding such relations is what we intend to do in this section.

The differential form of the conservation of energy equation for a closed stationary system (a fixed mass) containing a simple compressible substance can be expressed for an internally reversible process as:

$$\delta Q_{int \, rev} - \delta W_{int \, rev,out} = dU$$
$$\delta Q_{int \, rev} = TdS$$

$$\delta W_{int\ rev,out} = PdV$$
$$\therefore TdS - PdV = dU$$
$$\therefore Tds = Pdv + du \qquad (1)$$
$$We\ know\ that\ h = u + Pv$$
$$or, dh = du + Pdv + vdP$$
$$\therefore Tds = dh - vdP \qquad (2)$$

These *Tds* relations are developed with an internally reversible process in mind since the entropy change between two states must be evaluated along a reversible path. However, the results obtained are valid for both reversible and irreversible processes since entropy is a property and the change in a property between two states is independent of the type of process the system undergoes. Equations (1) and (2) are relations between the properties of a unit mass of a simple compressible system as it undergoes a change of state, and they are applicable whether the change occurs in a closed or an open system.

Explicit relations for differential changes in entropy are obtained by solving for ds:

**Case 1:**

$$Tds = Pdv + du$$
$$or, ds = \frac{Pdv}{T} + \frac{du}{T} = \frac{R}{v}dv + \frac{c_v(T)}{T}dT$$
$$or, s_2 - s_1 = R\ ln\frac{v_2}{v_1} + \int_1^2 \frac{c_v(T)}{T}dT$$
$$(When\ c_v\ is\ constant)s_2 - s_1 = R\ ln\frac{v_2}{v_1} + c_v\ ln\frac{T_2}{T_1}$$

**Case 2:**

$$Tds = dh - vdP$$
$$or, ds = \frac{dh}{T} - \frac{vdP}{T} = \frac{c_p(T)}{T}dT - \frac{R}{P}dP$$
$$or, s_2 - s_1 = \int_1^2 \frac{c_p(T)}{T}dT - R\ ln\frac{P_2}{P_1}$$
$$\left(When\ c_p\ is\ constant\right)s_2 - s_1 = c_p\ ln\frac{T_2}{T_1} - R\ ln\frac{P_2}{P_1}$$

**For solid/ liquid objects**

$$Tds = Pdv + du$$

**dv=0**

$$or, ds = \frac{du}{T} = \frac{c_v(T)}{T}dT$$

$$or, s_2 - s_1 = mc_v\ ln\frac{T_2}{T_1}$$

**[7-32]** A well-insulated rigid tank contains 5 kg of a saturatedliquid-vapor mixture of water at 150 kPa. Initially, three-quartersof the mass is in the liquid phase. An electric resistance heater placed in the tank is now turned on and kept on until allthe liquid in the tank is vaporized. Determine the entropy change of the steam during this process. [Answer: 19.2 kJ/K]

**7-32** An insulated rigid tank contains a saturated liquid-vapor mixture of water at a specified pressure. An electric heater inside is turned on and kept on until all the liquid vaporized. The entropy change of the water during this process is to be determined.

*Analysis* From the steam tables (Tables A-4 through A-6)

$$P_1 = 150 \text{ kPa} \left.\begin{matrix}\end{matrix}\right\} \begin{matrix} v_1 = v_f + x_1 v_{fg} = 0.001053 + (0.25)(1.1594 - 0.001053) = 0.29065 \text{ m}^3/\text{kg} \\ x_1 = 0.25 \end{matrix}$$
$$s_1 = s_f + x_1 s_{fg} = 1.4337 + (0.25)(5.7894) = 2.8810 \text{ kJ/kg} \cdot \text{K}$$

$$\left.\begin{matrix} v_2 = v_1 \\ \text{sat. vapor} \end{matrix}\right\} s_2 = 6.7298 \text{ kJ/kg} \cdot \text{K}$$
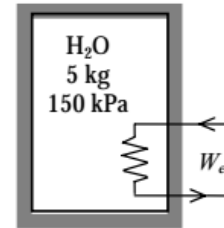
Then the entropy change of the steam becomes

$$\Delta S = m(s_2 - s_1) = (5 \text{ kg})(6.7298 - 2.8810) \text{ kJ/kg} \cdot \text{K} = \mathbf{19.2 \text{ kJ/K}}$$

$H_2O$
5 kg
150 kPa
$W_e$

**[7-57]** Steam enters a steady-flow adiabatic nozzle with alow inlet velocity as a saturated vapor at 6 MPa and expands to 1.2 MPa.(a) Under the conditions that the exit velocity is to be the maximum possible value, sketch the T-s diagram with respect to the saturation lines for this process.(b) Determine the maximum exit velocity of the steam, in m/s.

*Analysis* (b) The inlet state properties are

$$P_1 = 6000 \text{ kPa} \left.\begin{matrix}\end{matrix}\right\} \begin{matrix} h_1 = 2784.6 \text{ kJ/kg} \\ s_1 = 5.8902 \text{ kJ/kg} \cdot \text{K} \end{matrix} \text{(Table A - 5)}$$
$$x_1 = 1$$
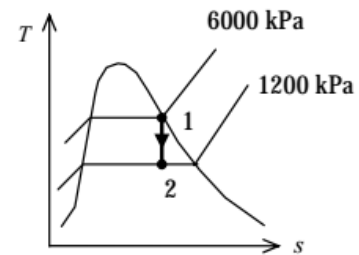
For the maximum velocity at the exit, the entropy will be constant during the process. The exit state enthalpy is (Table A-6)

$$P_2 = 1200 \text{ kPa} \left.\begin{matrix}\end{matrix}\right\} x_2 = \frac{s_2 - s_f}{s_{fg}} = \frac{5.8902 - 2.2159}{4.3058} = 0.8533$$
$$s_2 = s_1 = 5.8902 \text{ kJ/kg} \cdot \text{K} \left.\begin{matrix}\end{matrix}\right\} h_2 = h_f + x h_{fg} = 798.33 + 0.8533 \times 1985.4 = 2492.5 \text{ kJ/kg}$$

6000 kPa
1200 kPa
*T*
1
2
*s*

We take the nozzle as the system, which is a control volume since mass crosses the boundary. Noting that one fluid stream enters and leaves the nozzle, the energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{system}^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right) \quad \text{(since } \dot{W} \cong \dot{Q} \cong \Delta pe \cong 0\text{)}$$

$$h_1 - h_2 = \left(\frac{V_2^2 - V_1^2}{2}\right)$$

Solving for the exit velocity and substituting,

$$h_1 - h_2 = \left(\frac{V_2^2 - V_1^2}{2}\right)$$

$$V_2 = \left[V_1^2 + 2(h_1 - h_2)\right]^{0.5} = \left[(0 \text{ m/s})^2 + 2(2784.6 - 2492.5) \text{ kJ/kg}\left(\frac{1000 \text{ m}^2/\text{s}^2}{1 \text{ kJ/kg}}\right)\right]^{0.5}$$

$$= \mathbf{764.3 \text{ m/s}}$$

**[7-25]** Heat in the amount of 100 kJ is transferred directlyfrom a hot reservoir at 1200 K to a cold reservoir at 600 K.Calculate the entropy change of the two reservoirs and determine if the increase of entropy principle is satisfied.

**7-25** Heat is transferred directly from an energy-source reservoir to an energy-sink. The entropy change of the two reservoirs is to be calculated and it is to be determined if the increase of entropy principle is satisfied.

*Assumptions* The reservoirs operate steadily.

*Analysis* The entropy change of the source and sink is given by

$$\Delta S = \frac{Q_H}{T_H} + \frac{Q_L}{T_L} = \frac{-100\,\text{kJ}}{1200\,\text{K}} + \frac{100\,\text{kJ}}{600\,\text{K}} = \textbf{0.0833 kJ/K}$$

Since the entropy of everything involved in this process has increased, this transfer of heat is **possible**.
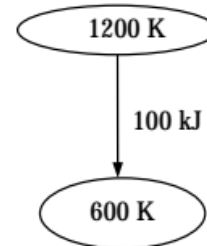


**[7-27]** A completely reversible heat pump produces heat at arate of 300 kW to warm a house maintained at 24°C. Theexterior air, which is at 7°C, serves as the source. Calculate the rate of entropy change of the two reservoirs and determineif this heat pump satisfies the second law according tothe increase of entropy principle.

*Analysis* Since the heat pump is completely reversible, the combination of the coefficient of performance expression, first Law, and thermodynamic temperature scale gives

$$\text{COP}_{HP,rev} = \frac{1}{1 - T_L / T_H} = \frac{1}{1 - (280\,\text{K})/(297\,\text{K})} = 17.47$$



The power required to drive this heat pump, according to the coefficient of performance, is then

$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{\text{COP}_{HP,rev}} = \frac{300\,\text{kW}}{17.47} = 17.17\,\text{kW}$$

According to the first law, the rate at which heat is removed from the low-temperature energy reservoir is

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{net,in} = 300\,\text{kW} - 17.17\,\text{kW} = 282.8\,\text{kW}$$

The rate at which the entropy of the high temperature reservoir changes, according to the definition of the entropy, is

$$\Delta \dot{S}_H = \frac{\dot{Q}_H}{T_H} = \frac{300\,\text{kW}}{297\,\text{K}} = \textbf{1.01 kW/K}$$

and that of the low-temperature reservoir is

$$\Delta \dot{S}_L = \frac{\dot{Q}_L}{T_L} = \frac{-17.17\,\text{kW}}{280\,\text{K}} = \textbf{-1.01 kW/K}$$

The net rate of entropy change of everything in this system is

$$\Delta \dot{S}_{total} = \Delta \dot{S}_H + \Delta \dot{S}_L = 1.01 - 1.01 = \textbf{0 kW/K}$$

as it must be since the heat pump is completely reversible.
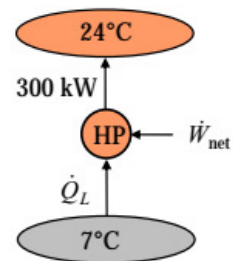
[7-29] Refrigerant-134a enters the coils of the evaporator ofa refrigeration system as a saturated liquid-vapor mixture at a pressure of 160 kPa. The refrigerant absorbs 180 kJ of heatfrom the cooled space, which is maintained at -5°C, andleaves as saturated vapor at the same pressure. Determine (a) the entropy change of the refrigerant, (b) the entropy change of the cooled space, and (c) the total entropy change for this process.

Saturation temperature of R-134a at 160 kPa is (-)15.6°C

Then,   $\Delta S_{refrigerant} = \dfrac{Q_{refrigerant,in}}{T_{refrigerant}} = \dfrac{180 \text{ kJ}}{257.4 \text{ K}} = \mathbf{0.699 \text{ kJ/K}}$

(b) Similarly,

$\Delta S_{space} = -\dfrac{Q_{space,out}}{T_{space}} = -\dfrac{180 \text{ kJ}}{268 \text{ K}} = \mathbf{-0.672 \text{ kJ/K}}$

(c) The total entropy change of the process is

$S_{gen} = \Delta S_{total} = \Delta S_{refrigerant} + \Delta S_{space} = 0.699 - 0.672 = \mathbf{0.027 \text{ kJ/K}}$
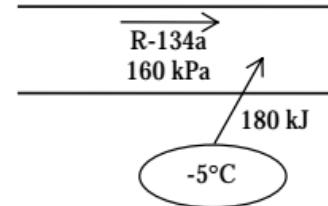
[7-69] A 50-kg iron block and a 20-kg copper block, bothinitially at 80°C, are dropped into a large lake at 15°C. Thermalequilibrium is established after a while as a result of heat transfer between the blocks and the lake water. Determine thetotal entropy change for this process.

*Properties* The specific heats of iron and copper at room temperature are $c_{iron} = 0.45$ kJ/kg.°C and $c_{copper} = 0.386$ kJ/kg.°C (Table A-3).

*Analysis* The thermal-energy capacity of the lake is very large, and thus the temperatures of both the iron and the copper blocks will drop to the lake temperature (15°C) when the thermal equilibrium is established. Then the entropy changes of the blocks become

$\Delta S_{iron} = mc_{avg} \ln\left(\dfrac{T_2}{T_1}\right) = (50 \text{ kg})(0.45 \text{ kJ/kg} \cdot \text{K})\ln\left(\dfrac{288 \text{ K}}{353 \text{ K}}\right) = -4.579 \text{ kJ/K}$

$\Delta S_{copper} = mc_{avg} \ln\left(\dfrac{T_2}{T_1}\right) = (20 \text{ kg})(0.386 \text{ kJ/kg} \cdot \text{K})\ln\left(\dfrac{288 \text{ K}}{353 \text{ K}}\right) = -1.571 \text{ kJ/K}$

We take both the iron and the copper blocks, as the *system*. This is a *closed system* since no mass crosses the system boundary during the process. The energy balance for this system can be expressed as

$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$

$-Q_{out} = \Delta U = \Delta U_{iron} + \Delta U_{copper}$

or,

$Q_{out} = [mc(T_1 - T_2)]_{iron} + [mc(T_1 - T_2)]_{copper}$

Substituting,

$Q_{out} = (50 \text{ kg})(0.45 \text{ kJ/kg} \cdot \text{K})(353 - 288)\text{K} + (20 \text{ kg})(0.386 \text{ kJ/kg} \cdot \text{K})(353 - 288)\text{K}$
$= 1964 \text{ kJ}$

Thus,

$\Delta S_{lake} = \dfrac{Q_{lake,in}}{T_{lake}} = \dfrac{1964 \text{ kJ}}{288 \text{ K}} = 6.820 \text{ kJ/K}$

Then the total entropy change for this process is

$\Delta S_{total} = \Delta S_{iron} + \Delta S_{copper} + \Delta S_{lake} = -4.579 - 1.571 + 6.820 = \mathbf{0.670 \text{ kJ/K}}$
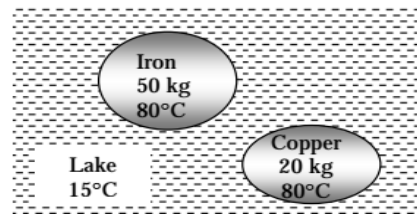
[7-64] A 75-kg copper block initially at 110°C is droppedinto an insulated tank that contains 160 L of water at 15°C.Determine the final equilibrium temperature and the total entropy change for this process.

**Properties** The density and specific heat of water at 25°C are $\rho$ = 997 kg/m$^3$ and $c_p$ = 4.18 kJ/kg.°C. The specific heat of copper at 27°C is $c_p$ = 0.386 kJ/kg.°C (Table A-3).

**Analysis** We take the entire contents of the tank, water + copper block, as the *system*. This is a *closed system* since no mass crosses the system boundary during the process. The energy balance for this system can be expressed as

$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc. energies}}}$$

$$0 = \Delta U$$

or,

$$\Delta U_{Cu} + \Delta U_{water} = 0$$

$$[mc(T_2 - T_1)]_{Cu} + [mc(T_2 - T_1)]_{water} = 0$$

where

$$m_{water} = \rho V = (997 \text{ kg/m}^3)(0.160 \text{ m}^3) = 159.5 \text{ kg}$$

Using specific heat values for copper and liquid water at room temperature and substituting,

$$(75 \text{ kg})(0.386 \text{ kJ/kg} \cdot °\text{C})(T_2 - 110)°\text{C} + (159.5 \text{ kg})(4.18 \text{ kJ/kg} \cdot °\text{C})(T_2 - 15)°\text{C} = 0$$

$$T_2 = \mathbf{19.0°C} = 292 \text{ K}$$

The entropy generated during this process is determined from

$$\Delta S_{copper} = mc_{avg} \ln\left(\frac{T_2}{T_1}\right) = (75 \text{ kg})(0.386 \text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{292.0 \text{ K}}{383 \text{ K}}\right) = -7.85 \text{ kJ/K}$$

$$\Delta S_{water} = mc_{avg} \ln\left(\frac{T_2}{T_1}\right) = (159.5 \text{ kg})(4.18 \text{ kJ/kg} \cdot \text{K}) \ln\left(\frac{292.0 \text{ K}}{288 \text{ K}}\right) = 9.20 \text{ kJ/K}$$

Thus,

$$\Delta S_{total} = \Delta S_{copper} + \Delta S_{water} = -7.85 + 9.20 = \mathbf{1.35 \text{ kJ/K}}$$
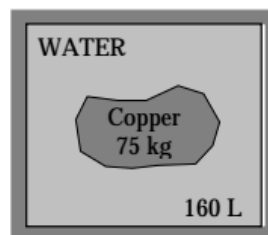
[7-100] A constant-volume tank contains 5 kg of air at 100 kPa and 327°C. The air is cooled to the surroundings temperature of 27°C. Assume constant specific heats at 300 K. (a) Determine the entropy change of the air in the tank during the process, inkJ/K, (b) determine the net entropy change of the universe due to this process, in kJ/K, and (c) sketch the processes for the airin the tank and the surroundings on a single T-s diagram. Be sure to label the initial and final states for both processes.

*Properties* The specific heat of air at room temperature is $c_v = 0.718$ kJ/kg.K (Table A-2a).

*Analysis* (a) The entropy change of air is determined from

$$\Delta S_{air} = mc_v \ln\frac{T_2}{T_1}$$

$$= (5\text{ kg})(0.718\text{ kJ/kg.K})\ln\frac{(27+273)\text{ K}}{(327+273)\text{ K}}$$

$$= -2.488\text{ kJ/K}$$

(b) An energy balance on the system gives

$$Q_{out} = mc_v(T_1 - T_2)$$
$$= (5\text{ kg})(0.718\text{ kJ/kg.K})(327-27)$$
$$= 1077\text{ kJ}$$

The entropy change of the surroundings is

$$\Delta S_{surr} = \frac{Q_{out}}{T_{surr}} = \frac{1077\text{ kJ}}{300\text{ K}} = 3.59\text{ kJ/K}$$

The entropy change of universe due to this process is

$$S_{gen} = \Delta S_{total} = \Delta S_{air} + \Delta S_{surr} = -2.488 + 3.59 = \mathbf{1.10\text{ kJ/K}}$$

Air
5 kg
327°C
100 kPa
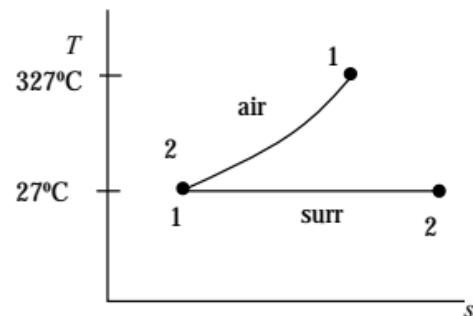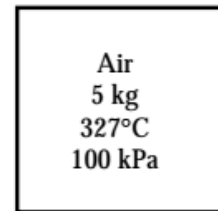
# Chapter 6

**Air-Standard Assumptions:**
1. The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.
2. All the processes that make up the cycle are internally reversible.
3. The combustion process is replaced by a heat-addition process from an external source.
4. The exhaust process is replaced by a heat-rejection process that restores the working fluid to its initial state.

Another assumption that is often utilized to simplify the analysis even more is that air has constant specific heats whose values are determined at room temperature (25°C). When this assumption is utilized, the air-standard assumptions are called the cold-air-standard assumptions. A cycle for which the air-standard assumptions are applicable is frequently referred to as an air-standard cycle.

**An Overview of Reciprocating Engines:**

The basic components of a reciprocating engine are shown in Fig.
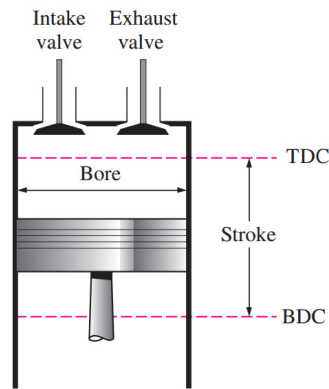


The piston reciprocates in the cylinder between two fixed positions called the top dead centre (TDC)-the position of the piston when it forms the smallest volume in the cylinder-and the bottom dead centre (BDC)-the position of the piston when it forms the largest volume in the cylinder. The distance between the TDC and the BDC is the largest distance that the piston can travel in one direction, and it is called the stroke of the engine. The diameter of the piston is called the bore. The air or air–fuel mixture is drawn into the cylinder through the intake valve, and the combustion products are expelled from the cylinder through the exhaust valve. The minimum volume formed in the cylinder when the piston is at TDC is called the clearance volume. The volume displaced by the piston as it moves between TDC and BDC is called the displacement volume. The ratio of the maximum volume formed in the cylinder to the minimum (clearance) volume is called the compression ratio $r$ of the engine:

$$r = \frac{V_{max}}{V_{min}} = \frac{V_{BDC}}{V_{TDC}}$$

The compression ratio is a volume ratio and should not be confused with the pressure ratio. Another term frequently used in conjunction with reciprocating engines is the mean effective pressure (MEP). It is a fictitious pressure that, if it acted on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle. That is,

$$W_{net} = \text{MEP} \times \text{Piston area} \times \text{Stroke} = \text{MEP} \times \text{Displacement volume}$$

$$MEP = \frac{W_{net}}{v_{max} - v_{min}}$$
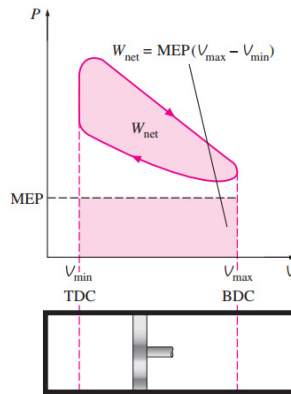


## Otto Cycle:

The Otto cycle is the ideal cycle for spark-ignition reciprocating engines. It is named after Nikolaus A. Otto. In most spark-ignition engines, the piston executes four complete strokes (two mechanical cycles) within the cylinder, and the crankshaft completes two revolutions for each thermodynamic cycle. These engines are called four-stroke internal combustion engines. A schematic of each stroke as well as a P-v diagram for an actual four-stroke spark-ignition engine is given in Fig.



(a) Actual four-stroke spark-ignition engine

(b) Ideal Otto cycle
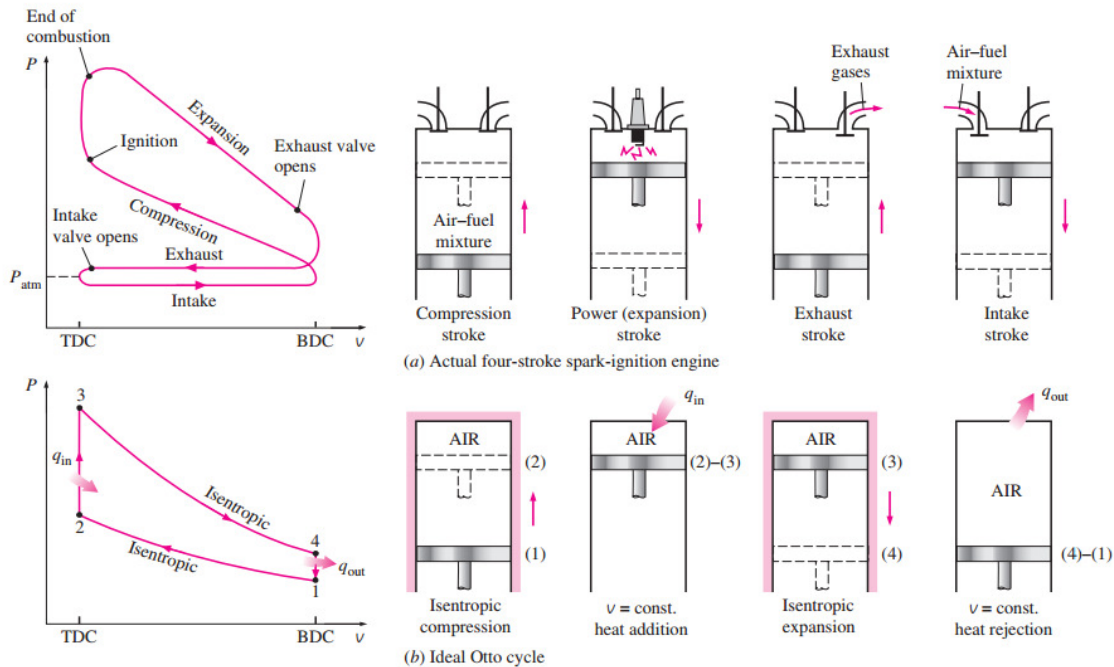
Initially, both the intake and the exhaust valves are closed, and the piston is at its lowest position (BDC). During the compression stroke, the piston moves upward, compressing the air-fuel mixture. Shortly before the piston reaches its highest position (TDC), the spark plug fires and the mixture ignite, increasing the pressure and temperature of the system. The high-pressure gases force the piston down, which in turn forces the crankshaft to rotate, producing a useful work output during the expansion or power stroke. At the end of this stroke, the

piston is at its lowest position (the completion of the first mechanical cycle), and the cylinder is filled with combustion products. Now the piston moves upward one more time, purging the exhaust gases through the exhaust valve (the exhaust stroke), and down a second time, drawing in fresh air–fuel mixture through the intake valve (the intake stroke). Notice that the pressure in the cylinder is slightly above the atmospheric value during the exhaust stroke and slightly below during the intake stroke.

The thermodynamic analysis of the actual four-stroke or two-stroke cycles described is not a simple task. However, the analysis can be simplified significantly if the air-standard assumptions are utilized. It consists of four internally reversible processes:

1-2 isentropic compression

2-3 Constant-volume heat addition

3-4 isentropic expansion

4-1 Constant-volume heat rejection
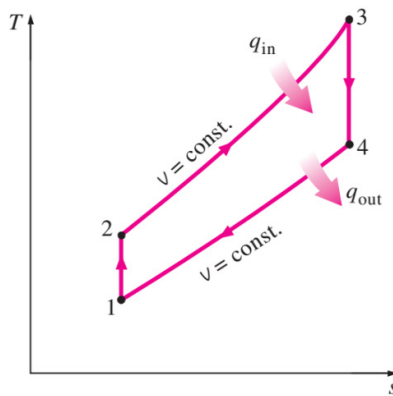


The Otto cycle is executed in a closed system, and disregarding thechanges in kinetic and potential energies, the energy balance for any of theprocesses is expressed, on a unit-mass basis, as

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = \Delta u$$

No work is involved during the two heat transfer processes since both takeplace at constant volume. Therefore, heat transfer to and from the workingfluid can be expressed as:

$$q_{in} = u_3 - u_2 = c_v(T_3 - T_2)$$
$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

Then the thermal efficiency of the ideal Otto cycle under the cold air standard assumptions becomes

$$\eta_{th,otto} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1\left(\frac{T_4}{T_1} - 1\right)}{T_2\left(\frac{T_3}{T_2} - 1\right)}$$

Processes 1-2 and 3-4 are isentropic, and $v_2 = v_3$ and $v_4 = v_1$. Thus,

$$\frac{T_1}{T_2} = (\frac{v_2}{v_1})^{k-1} = (\frac{v_3}{v_4})^{k-1} = \frac{T_4}{T_3}$$

Substituting these equations into the thermal efficiency relation and simplifying give

$$\eta_{th,otto} = 1 - \frac{1}{r^{k-1}}$$

where

$$r = \frac{v_{max}}{v_{min}} = \frac{v_1}{v_2}$$

is the compression ratio and k is the specific heat ratio $c_p./c_v.$
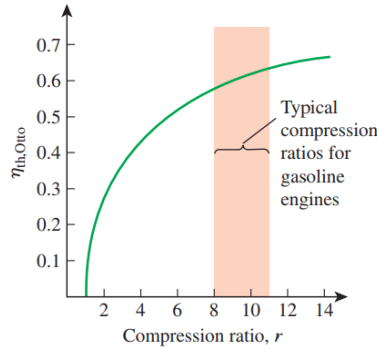


With increase in compression ratio the efficiency increases.

**Diesel Cycle:**
The fuel injection process in diesel engines starts when the piston approaches TDC and continues during the first part of the power stroke. Therefore, the combustion process in these engines takes place over a longer interval. Because of this longer duration, the combustion process in the ideal Diesel cycle is approximated as a constant-pressure heat-addition process. In fact, this is the only process where the Otto and the Diesel cycles differ. The remaining three processes are the same for both ideal cycles.

Process 1-2 is isentropic compression, 2-3 is constant pressure heat addition, 3-4 is isentropic expansion, and 4-1 is constant-volume heat rejection.



(a) P- v diagram      (b) T-s diagram
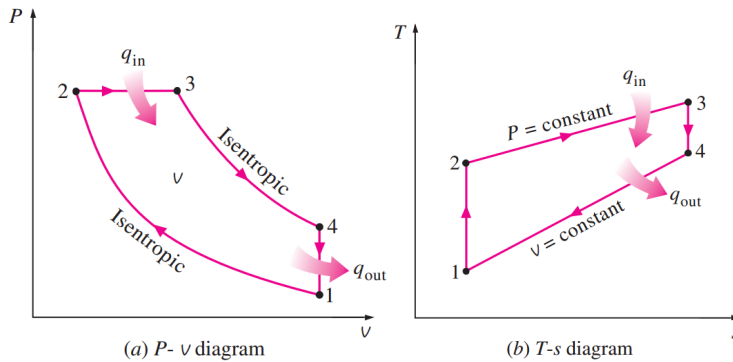
Noting that the Diesel cycle is executed in a piston–cylinder device, which forms a closed system, the amount of heat transferred to the working fluid at constant pressure and rejected from it at constant volume can be expressed as

$$q_{in} - w_{out} = u_3 - u_2$$
$$or, q_{in} = P_2(v_3 - v_2) + (u_3 - u_2) = h_3 - h_2 = c_p(T_3 - T_2)$$
$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$
$$\eta_{th,diesel} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{c_v(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)}$$

We now define a new quantity, the cutoff ratio $r_c$, as the ratio of the cylinder volumes after and before the combustion process:

$$r_c = \frac{v_3}{v_2}$$

$$T_2 = T_1\, r^{\gamma\text{-}1} \;\; ; \;\; r = \frac{V_1}{V_2} = \frac{V_4}{V_2}$$

$$\frac{T_3}{T_2} = \frac{v_3}{v_2} = r_c = \text{cutoff ratio}$$

$$T_3 = r_c\, T_2 = r_c\, T_1\, r^{\gamma\text{-}1}$$

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{\gamma\text{-}1} = T_3\left(\frac{V_4}{V_3}\right)^{\gamma\text{-}1}$$

$$= T_3\left(\frac{V_4}{V_2}\cdot\frac{V_2}{V_3}\right)^{1\text{-}\gamma} = T_3\left(\frac{r}{r_c}\right)^{1\text{-}\gamma}$$

$$= r_c\, T_1\, r^{\gamma\text{-}1}\left(\frac{r}{r_c}\right)^{1\text{-}\gamma} \;\; ; \;\; T_4 = r_c^{\gamma}\, T_1$$

The thermal efficiency relation reduces to:

$$\eta_{th,diesel} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right]$$

An engine working on Otto cycle has an air standard cycle efficiency of 56% and rejects 544kJ/kg of air. The pressure and temperature of air at the beginning of compression are 0.1MPa and 60°C respectively. Take $C_v = 0.78\dfrac{kJ}{kg.K}$

Calculate: (i) the compression ratio of the cycle     (ii) work done/kg of air     (iii) the pressure and temperature at the end of compression  (iv) maximum pressure of the cycle.
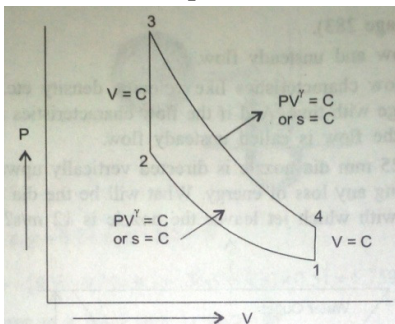
**Data given:** $\eta_{Otto} = 0.56$, $Q_2 = 544$ kJ/kg, $P_1 = 0.1$ MPa and $T_1 = 60 + 273 = 333$ K

$\therefore$
$$\eta_{Otto} = 1 - \frac{1}{r_k^{\gamma-1}} = 0.56$$

or
$$\frac{1}{r_k^{\gamma-1}} = 1 - 0.56 = 0.44$$

or
$$r_k = 7.8 = \text{compression ratio} \left(\textcolor{red}{Ans.}\right)$$

Now $\therefore$
$$\eta_{Otto} = \frac{Q_1 - Q_2}{Q_1} = 0.56$$

or
$$= \frac{Q_2}{Q_1} = 1 - 0.56 = 0.44$$

or
$$= Q_1 = 544 / 0.44 = 1236.36 \text{ kJ/kg}$$

Then
$$W_{net} = Q_1 - Q_2 = 1236.36 - 544 = 692.36 \text{ kJ/kg} \left(\textcolor{red}{Ans.}\right)$$

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = r_k^{\gamma-1} = 7.8^{\gamma-1} = 2.274$$

$T_2 = T_1 \, 2.274 = 757.3$ K Temperature at the end of compression $\left(\textcolor{red}{Ans.}\right)$

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{\gamma} = r_k^{\gamma} = 7.8^{\gamma} = 8.8$$

$P_2 = P_1 \, 8.8 = 1.774$ MPa Pressure at the end of compression $\left(\textcolor{red}{Ans.}\right)$

or
$$= Q_1 = m c_v (T_3 - T_2) = 1236.36 \text{ kJ/kg}$$

$$T_3 = 757.3 + 1236.36 / 0.78 = 2342.37 \text{ K}$$

Now for the process $2 - 3$,

$$\frac{P_3}{T_3} = \frac{P_2}{T_2}$$

or
$$P_3 = T_3 \frac{P_2}{T_2} = 2342.37 \frac{1.774}{757.3} = 5.48 \text{ MPa} \quad \text{Maximum Pressure of the cycle. } \left(\textcolor{red}{Ans.}\right)$$

Find the pressure at an elevation of 3000 m above the sea level by

corresponding p-v and T-S plots.

An engine working on the Otto cycle is supplied with air at 0.1 MPa, 35°C. The compression ratio is 8. Heat supplied is 2100kJ/kg. Calculate the maximum pressure and temperature of the cycle, the cycle efficiency, and the mean effective pressure. (For air, $C_p = 1.005$, and $C_v = 0.718$, and $R = 0.287$ kJ/kg K)

...figeration cycle and also show the

(b) Data given:   $T_1 = 273 + 35 = 308$ K

$P_1 = 0.1$ MPa $= 100$ kN/m²

Heat added,   $Q_1 = 2100$ kJ/kg

$r_k = 8$   and   $\gamma = 1.4$

∴   $\eta_{cycle} = 1 - \dfrac{1}{r_k^{\gamma-1}} = 1 - \dfrac{1}{8^{0.4}} = 0.565$   or   56.5%  ( Ans.)
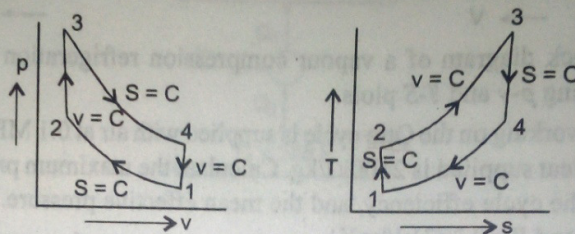


$v_1 = \dfrac{RT_1}{P_1} = \dfrac{0.287 \times 308}{100} = 0.844$ m³/kg

$r_k = \dfrac{v_1}{v_2} = 8 \Rightarrow v_2 = 0.11$ m³/kg

$\dfrac{T_2}{T_1} = \left(\dfrac{v_1}{v_2}\right)^{\gamma-1} = 8^{0.4} = 2.3 \Rightarrow T_2 = T_1 \times 308 = 708.4$ K

Now,   $Q_1 = c_v(T_2 - T_1) = 2100$ kJ/kg $\Rightarrow T_3 = 3633$ K $= T_{max}$  (Ans.)

$\dfrac{P_2}{P_1} = \left(\dfrac{v_1}{v_2}\right)^{\gamma} = 8^{1.4} = 18.37 \Rightarrow P_2 = P_1 \times 18.37 = 1.873$ MPa

Again,   $\dfrac{P_3 v_3}{T_3} = \dfrac{P_2 v_2}{T_2}$

$P_3 = P_{max} = 1.837 \times \dfrac{363}{708} = 9.426$ MPa  (Ans.)

$W_{net} = Q_1 \times \eta_{cycle} = 2100 \times 0.565 = 1186.5$ kJ/kg

$P_m(v_1 - v_2) = 1186.5$ kJ/kg

$P_m = \dfrac{1186.5}{0.884 - 0.11} = 1.533$ MPa  (Ans.)

In a diesel engine, the compression ratio is 13:1 and the fuel is cut off at 8% of the stroke. Find the air standard efficiency of the engine. Take $\gamma = 1.4$
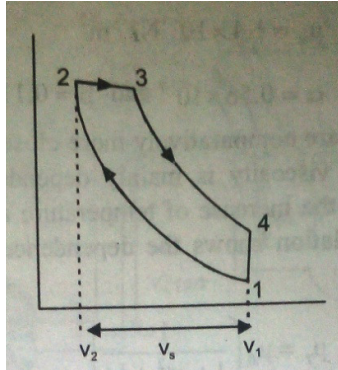


Here cut off = 8% of the stroke.

$$\therefore \quad v_3 = v_2 + 0.08 \; Vs$$
$$= v_2 + 0.08 \; (v_1 - v_2)$$

$$= v_2 + 0.08 \; (13v_2 - v_2) \qquad \left[ \therefore r_2 \frac{v_1}{v_2} = \frac{13}{1} \; \text{or}, v_1 = 13v_2 \right]$$

$$= 1.96 \; v_2$$

$$\frac{v_3}{v_2} = \rho = 1.96$$

$$\eta_{\text{air standard}} = 1 - \frac{1}{r^{\gamma-1}} \cdot \frac{(\rho^\gamma - 1)}{\gamma \; (\rho - 1)}$$

$$= 1 - \frac{1}{13^{1.4-1}} \cdot \left[ \frac{1.96^{1.4} - 1}{1.4 \; (1.96 - 1)} \right]$$

$$= 0.583 = 58.3\%$$

(d) In an ideal air-standard diesel cycle, the pressure and temperature at intake are 1.03 bar and 27°C respectively. The maximum pressure in the cycle is 47 bar and heat supplied during the cycle is 545 kJ/kg. Determine:

(i) the compression ratio
(ii) the temperature at the end of compression
(iii) the temperature at the end of combustion
(iv) the air standard efficiency.

Assume $\gamma = 1.4$ and $C_p = 1.004$ kJ/kg K for air.
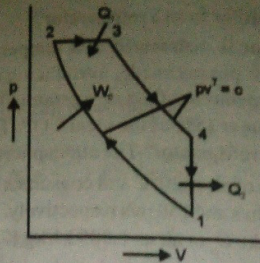


We know $\quad p_1 V_1^\gamma = p_2 V_2^\gamma$

or $\qquad \dfrac{V_2}{V_1} = \left(\dfrac{p_2}{p_1}\right)^{\frac{1}{\gamma}} = \left(\dfrac{47}{1.03}\right)^{\frac{1}{1.4}} = 15.32$

∴ $\qquad$ Compression ratio = 15.32. (Ans.)

Now, $\qquad \dfrac{T_1}{T_2} = \left(\dfrac{V_2}{V_1}\right)^{\gamma-1}$

or $\qquad T_2 = T_1\left(\dfrac{V_1}{V_2}\right)^{\gamma-1} = 300\,(15.32)^{1.4-1} = 897.77$ K (Ans.)

Again, $\qquad Q_1 = C_p(T_3 - T_2)$

or $\qquad 545 = 1.004\,(T_3 - 893.77)$

or $\qquad T_3 = \left(\dfrac{545}{1.004}\right) + 893.77 = 1436.6$ K (Ans.)

So, at the end of compression the temperature is 897.77 K and the temperature at the end of combustion 1436.6 K.

Air standard efficiency $\eta_{diesel} = 1 - \dfrac{1}{r_k^{\gamma-1}}\left\{\dfrac{r_c^\gamma - 1}{\gamma(r_c - 1)}\right\}$

Where, $r_k$ is the compression ratio

$$r_c = \text{cut-off ratio} = \dfrac{V_3}{V_2}$$

For process 2–3

$$\dfrac{V_2}{T_2} = \dfrac{V_3}{T_3} \qquad \text{or} \qquad \dfrac{V_3}{V_2} = \dfrac{T_3}{T_2} = \dfrac{1436.6}{893.77} = 1.61$$

$$\eta_{diesel} = 1 - \dfrac{1}{(15.32)^{1.4-1}}\left\{\dfrac{1.61^{1.4} - 1}{1.4(1.61 - 1)}\right\} = 0.6275 = 62.75\% \quad \text{(Ans.)}$$

# Chapter 7

**The Failure of Carnot Vapour Power Cycle**

The Carnot cycle is the most efficient cycle operating between two specified temperature limits. Hence, we would certainly adopt it as the ideal cycle. However, the Carnot cycle is not a suitable model for power cycles. Throughout the discussions, we assume steam to be the working fluid since it is the working fluid predominantly used in vapour power cycles. Consider a steady-flow Carnot cycle executed within the saturation dome of a pure substance, as shown in Fig.

  (i)  The fluid is heated reversibly and isothermally in a boiler (process 1-2)
  (ii) Expanded isentropically in a turbine (process 2-3)
  (iii)Condensed reversibly and isothermally in a condenser (process 3-4)
  (iv)Compressed isentropically by a compressor to the initial state (process 4-1).



(a)            (b)
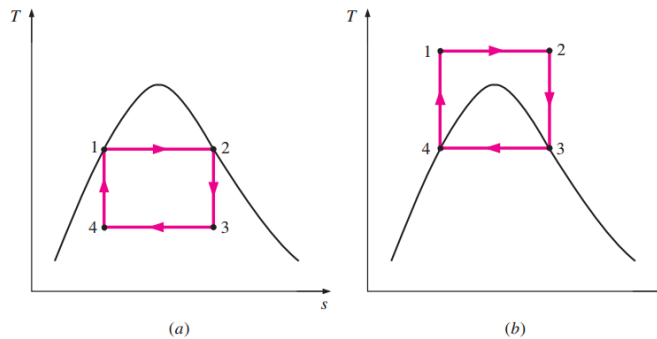
Several impracticalities are associated with this cycle:

1. Isothermal heat transfer to or from a two-phase system is not difficult to achieve in practice since maintaining a constant pressure in the device automatically fixes the temperature at the saturation value. Therefore, processes 1-2 and 3-4 can be approached closely in actual boilers and condensers. For this the maximum temperature has to remain under the critical-point value, which is 374°C for water. Limiting the maximum temperature in the cycle also limits the thermal efficiency. Any attempt to raise the maximum temperature in the cycle involves heat transfer to the working fluid in a single phase, which is not easy to accomplish isothermally.

 2. The isentropic expansion process (process 2-3) can be approximated closely by a well-designed turbine. However, the quality of the steam decreases during this process, as shown on the T-s diagram in Fig. a. Thus the turbine has to handle steam with high moisture content (low quality). The impingement of liquid droplets on the turbine blades causes erosion and is a major source of wear. Thus steam with qualities less than about 90 percent cannot be tolerated in the operation of power plants. This problem could be eliminated by using a working fluid with a very steep saturated vapour line.

3. The isentropic compression process (process 4-1) involves the compression of a liquid–vapour mixture to a saturated liquid. There are two difficulties associated with this process. First, it is not easy to control the condensation process so precisely as to end up with the desired quality at state Second, it is not practical to design a compressor that handles two phases.

Some of these problems could be eliminated by executing the Carnot cycle in a different way, as shown in Fig. b. This cycle, however, presents other problems such as isentropic compression to extremely high pressures and isothermal heat transfer at variable pressures.

Thus we conclude that the Carnot cycle cannot be approximated in actual devices and is not a realistic model for vapour power cycles.

**Rankine Cycle: The Ideal Cycle for Vapor Power Cycles**

Many of the impracticalities associated with the Carnot cycle can be eliminated by superheating the steam in the boiler and condensing it completely in the condenser, as shown schematically on a T-s diagram. The cycle that results is the Rankine cycle, which is the ideal cycle for vapour power plants. The ideal Rankine cycle does not involve any internal irreversibilities and consists of the following four processes:

(i)    (1-2) Isentropic compression in a pump
(ii)   (2-3) Constant pressure heat addition in a boiler
(iii)   (3-4) Isentropic expansion in a turbine
(iv)   (4-1) Constant pressure heat rejection in a condenser
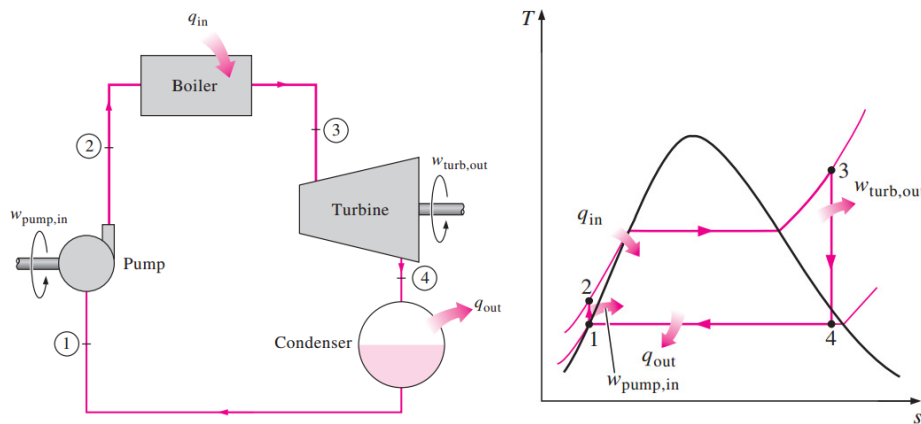


Energy Analysis: -

All four components associated with the Rankine cycle (the pump, boiler, turbine, and condenser) are steady-flow devices.

$$W_{pump\ In} = h_2 - h_1 \ where \ h_1 = h_{f\ @P_1}$$
$$Or, W_{pump\ In} = v(P_2 - P_1) \ where \ v = v_{f\ @P_1}$$
$$q_{\ in} = h_3 - h_2$$
$$W_{turb\ out} = h_3 - h_4$$
$$q_{out} = h_4 - h_1$$

The thermal efficiency of the Rankine cycle is determined from

$$\eta_{th} = \frac{W_{net}}{q_{in}} = 1 - \frac{q\ out}{q_{in}}$$

**Draw the nature of p-v and T-s plot of a Rankine cycle (with saturated steam at the turbine inlet).**

For this answer 1-2-2'-3-4 cycle is correct.
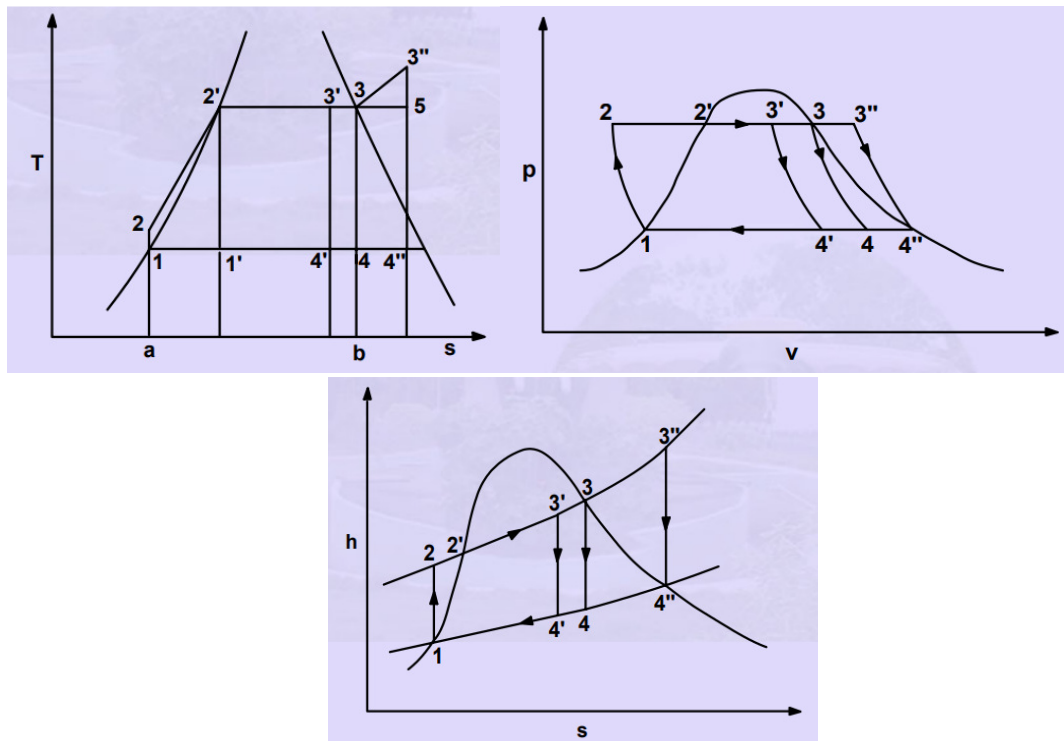
[7-111] Liquid water enters a 25-kW pump at 100-kPa pressure at a rate of 5 kg/s. Determine the highest pressure the liquid water can have at the exit of the pump. Neglect the kinetic and potential energy changes of water, and take the specific volume of water to be 0.001 $m^3$/kg. [Answer: 5100 kPa]

**7-111** Liquid water is to be pumped by a 25-kW pump at a specified rate. The highest pressure the water can be pumped to is to be determined.

*Assumptions* **1** Liquid water is an incompressible substance. **2** Kinetic and potential energy changes are negligible. **3** The process is assumed to be reversible since we will determine the limiting case.

*Properties* The specific volume of liquid water is given to be $v_1 = 0.001$ $m^3$/kg.

*Analysis* The highest pressure the liquid can have at the pump exit can be determined from the reversible steady-flow work relation for a liquid,

$$\dot{W}_{in} = \dot{m}\left( \int_1^2 v\,dP + \Delta ke^{\nearrow 0} + \Delta pe^{\nearrow 0} \right) = \dot{m}v_1(P_2 - P_1)$$

Thus,

$$25 \text{ kJ/s} = (5 \text{ kg/s})(0.001 \text{ m}^3/\text{kg})(P_2 - 100)\text{k Pa}\left(\frac{1 \text{ kJ}}{1 \text{ kPa}\cdot\text{m}^3}\right)$$

It yields

$$P_2 = \textbf{5100 kPa}$$
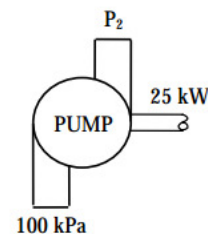
(c) A thermal power plant is to be operated on an ideal Rankine cycle. Steam enters into the turbine at 2 MPa, 400°c and leaves as saturated liquid in the condenser t 10 KPa (0.01 MPa). The mass flow rate of steam is 1 kg/s. Find out the power developed by the turbine and the efficinecy of the cycle. Assume the eficiencies of the turbine and the pump as 0.85 and 0.8 respectively.                                9

10 (c). From the steam table corresponding to pressure $p_1 = 2$ Mpa, 400 c

$$h_1 = 3247.6 \ kJ/kg$$

$$s_1 = 7.1271 \ kJ/kg \ k$$

At 10kPa $h_3 = h_{f2} = 131.8 \ kJ/kg$

$$s_3 = s_{f2} = 0.6491 \ kJ/kg \ k$$

$$h_{fg2} = 2392.8 kJ/kg$$

$$s_{g2} = 8.1510 \ kJ/kg \ k$$

$$v_{f2} = 0.001010 \ m^3/kg$$

$$s_{fg2} = 7.5019 \ kJ/kgk$$

Now $s_1 = s_2$

$\therefore 7.1271 = s_{f2} + x_2 s_{fg2} = 0.6491 + x_2 7.5019$

$$x_2 = \frac{7.1271 - 0.6491}{7.5019} = 0.86$$

$\therefore h_2 = h_{f2} + x_2 h_{fg2}$

$$= 191.8 + 0.86 \ 2392.8 = 2249.608 \ kJ/kg$$

$$W_{net} = W_T - W_P$$

Now $W_P = v_{f2}(p_1 - p_2)/n_P$

$$= 0.001010 \times \left( \frac{2000 - 10}{0.8} \right)$$

$$= 2.512 \ kJ/kg$$

$$W_T = \eta_T (h_1 - h_2) = (3247.6 - 2249.608) \times 0.85$$

$$= 848.29 \ kJ/kg$$

$$W_{net} = (848.29 - 2.512) \ kJ/kg$$

$$= 845.78 \ kJ/kg$$

$$Q_1 = h_1 - h_{fg} = 3247.6 - 191.8$$

$$= 3055.8 \ kJ/kg$$

$\therefore \quad \eta_{cycle} = \dfrac{W_{net}}{Q_1} = \dfrac{845.78}{3055.8} = 0.2767 = 27.67\%$

[10-21] Consider a steam power plant that operates on a simple ideal Rankin cycle and has a net power output of 45MW. Steam enters the turbine at 7 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa by running cooling water from a lake through the tubes of the condenserat a rate of 2000 kg/s. Show the cycle on a T-s diagram with respect to saturation lines, determine (a) thermal efficiencyof the cycle, (b) mass flow rate of the steam, and (c) temperature rise of cooling water. [Answers: (a) 38.9 percent, (b) 36 kg/s, (c) 8.4°C]

**10-21** A steam power plant operates on a simple ideal Rankine cycle between the specified pressure limits. The thermal efficiency of the cycle, the mass flow rate of the steam, and the temperature rise of the cooling water are to be determined.

*Assumptions* **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

*Analysis* (*a*) From the steam tables (Tables A-4, A-5, and A-6),

$$h_1 = h_{f@\,10\,kPa} = 191.81 \text{ kJ/kg}$$
$$v_1 = v_{f@\,10\,kPa} = 0.00101 \text{ m}^3/\text{kg}$$
$$w_{p,in} = v_1(P_2 - P_1)$$



$$= (0.00101 \text{ m}^3/\text{kg})(7{,}000 - 10 \text{ kPa})\left(\frac{1 \text{ kJ}}{1 \text{ kPa} \cdot \text{m}^3}\right)$$
$$= 7.06 \text{ kJ/kg}$$

$$h_2 = h_1 + w_{p,in} = 191.81 + 7.06 = 198.87 \text{ kJ/kg}$$

$$\left.\begin{array}{l} P_3 = 7 \text{ MPa} \\ T_3 = 500°C \end{array}\right\} \begin{array}{l} h_3 = 3411.4 \text{ kJ/kg} \\ s_3 = 6.8000 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left.\begin{array}{l} P_4 = 10 \text{ kPa} \\ s_4 = s_3 \end{array}\right\} x_4 = \frac{s_4 - s_f}{s_{fg}} = \frac{6.8000 - 0.6492}{7.4996} = 0.8201$$

$$h_4 = h_f + x_4 h_{fg} = 191.81 + (0.8201)(2392.1) = 2153.6 \text{ kJ/kg}$$
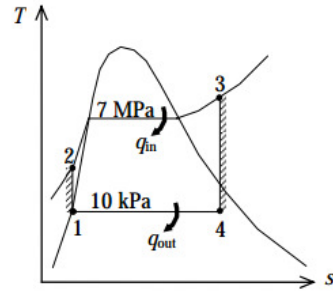
Thus,

$$q_{in} = h_3 - h_2 = 3411.4 - 198.87 = 3212.5 \text{ kJ/kg}$$
$$q_{out} = h_4 - h_1 = 2153.6 - 191.81 = 1961.8 \text{ kJ/kg}$$
$$w_{net} = q_{in} - q_{out} = 3212.5 - 1961.8 = 1250.7 \text{ kJ/kg}$$

and

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{1250.7 \text{ kJ/kg}}{3212.5 \text{ kJ/kg}} = \textbf{38.9\%}$$

(*b*) $$\dot{m} = \frac{\dot{W}_{net}}{w_{net}} = \frac{45{,}000 \text{ kJ/s}}{1250.7 \text{ kJ/kg}} = \textbf{36.0 kg/s}$$

(*c*) The rate of heat rejection to the cooling water and its temperature rise are

$$\dot{Q}_{out} = \dot{m}q_{out} = (35.98 \text{ kg/s})(1961.8 \text{ kJ/kg}) = 70{,}586 \text{ kJ/s}$$

$$\Delta T_{cooling water} = \frac{\dot{Q}_{out}}{(\dot{m}c)_{cooling water}} = \frac{70{,}586 \text{ kJ/s}}{(2000 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot °C)} = \textbf{8.4°C}$$

[10-23] A simple Rankin cycle uses water as the workingfluid. The boiler operates at 6000 kPa and the condenser at50 kPa. At the entrance to the turbine, the temperature is 450°C. The isentropic efficiency of the turbine is 94 percent, pressure and pump losses are negligible, and the water leaving the condenser is sub cooled by 6.3°C. The boiler is sizedfor a mass flow rate of 20 kg/s. Determine the rate at which heat is added in the boiler, the power required to operatethe pumps, the net power produced by the cycle, and the thermal efficiency. [Answers: 59,660 kW, 122 kW, 18,050 kW, 30.3 percent.]

**10-23** A simple Rankine cycle with water as the working fluid operates between the specified pressure limits. The rate of heat addition in the boiler, the power input to the pumps, the net power, and the thermal efficiency of the cycle are to be determined.

*Assumptions* **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

*Analysis* From the steam tables (Tables A-4, A-5, and A-6),

$$\left. \begin{array}{l} P_1 = 50 \text{ kPa} \\ T_1 = T_{\text{sat @ 50 kPa}} - 6.3 = 81.3 - 6.3 = 75°C \end{array} \right| \begin{array}{l} h_1 \cong h_{f@75°C} = 314.03 \text{ kJ/kg} \\ v_1 = v_{f@75°C} = 0.001026 \text{ m}^3/\text{kg} \end{array}$$

$$\begin{aligned} w_{p,in} &= v_1(P_2 - P_1) \\ &= (0.001026 \text{ m}^3/\text{kg})(6000 - 50)\text{kPa} \left( \frac{1 \text{kJ}}{1 \text{kPa} \cdot \text{m}^3} \right) \\ &= 6.10 \text{ kJ/kg} \end{aligned}$$

$$h_2 = h_1 + w_{p,in} = 314.03 + 6.10 = 320.13 \text{ kJ/kg}$$

$$\left. \begin{array}{l} P_3 = 6000 \text{ kPa} \\ T_3 = 450°C \end{array} \right| \begin{array}{l} h_3 = 3302.9 \text{ kJ/kg} \\ s_3 = 6.7219 \text{ kJ/kg} \cdot \text{K} \end{array}$$

$$\left. \begin{array}{l} P_4 = 50 \text{ kPa} \\ s_4 = s_3 \end{array} \right| \begin{array}{l} x_{4s} = \dfrac{s_4 - s_f}{s_{fg}} = \dfrac{6.7219 - 1.0912}{6.5019} = 0.8660 \\ h_{4s} = h_f + x_{4s}h_{fg} = 340.54 + (0.8660)(2304.7) = 2336.4 \text{ kJ/kg} \end{array}$$

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}} \longrightarrow h_4 = h_3 - \eta_T(h_3 - h_{4s}) = 3302.9 - (0.94)(3302.9 - 2336.4) = 2394.4 \text{ kJ/kg}$$
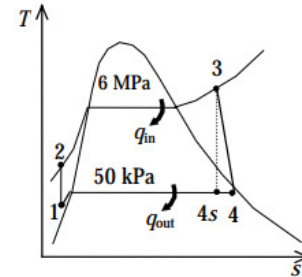
Thus,

$$\dot{Q}_{in} = \dot{m}(h_3 - h_2) = (20 \text{ kg/s})(3302.9 - 320.13)\text{kJ/kg} = \textbf{59,660 kW}$$

$$\dot{W}_{T,out} = \dot{m}(h_3 - h_4) = (20 \text{ kg/s})(3302.9 - 2394.4)\text{kJ/kg} = \textbf{18,170 kW}$$

$$\dot{W}_{P,in} = \dot{m}w_{P,in} = (20 \text{ kg/s})(6.10 \text{ kJ/kg}) = \textbf{122 kW}$$

$$\dot{W}_{net} = \dot{W}_{T,out} - \dot{W}_{P,in} = 18,170 - 122 = \textbf{18,050 kW}$$

and

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{18,050}{59,660} = \textbf{0.3025}$$

# Chapter 8

**Principle of Refrigeration:**

We all know from experience that heat flows in the direction of decreasing temperature, that is, from high-temperature regions to low-temperature ones. This heat-transfer process occurs in nature without requiring any devices. The reverse process, however, cannot occur by itself. The transfer of heat from a low-temperature region to a high-temperature one requires special devices called refrigerators. Refrigerators are cyclic devices, and the working fluids used in the refrigeration cycles are called refrigerants.

The cooling capacity of a refrigeration system-that is, the rate of heat removal from the refrigerated space-is often expressed in terms of **tons of refrigeration**. The capacity of a refrigeration system that can freeze 1 ton(1000 kg) of liquid water at $0°C$ into ice at $0°C$ in 24 h is said to be 1 ton. One ton of refrigeration is equivalent to $211\ kJ/min$.

**The Reversed Carnot Cycle:**

The Carnot cycle is a totally reversible cycle that consists of two reversible isothermal and two isentropic processes. It has the maximum thermal efficiency for given temperature limits, and it serves as a standard against which actual power cycles can be compared.

Since it is a reversible cycle, all four processes that comprise the Carnot cycle can be reversed. Reversing the cycle does also reverse the directions of any heat and work interactions. The result is a cycle that operates in the counter-clockwise direction on a T-s diagram, which is called the reversed Carnot cycle. A refrigerator or heat pump that operates on the reversed Carnot cycle is called a Carnot refrigerator or a Carnot heat pump.

Consider a reversed Carnot cycle executed within the saturation dome of a refrigerant, as shown in Fig. The refrigerant absorbs heat isothermally from a low-temperature source at $T_L$ in the amount of $Q_L$ (process 1-2), is compressed isentropically to state 3 (temperature rises to $T_H$), rejects heat isothermally to a high-temperature sink at $T_H$ in the amount of $Q_H$ (process3-4), and expands isentropically to state 1 (temperature drops to $T_L$). The refrigerant changes from a saturated vapour state to a saturated liquid state in the condenser during process 3-4.
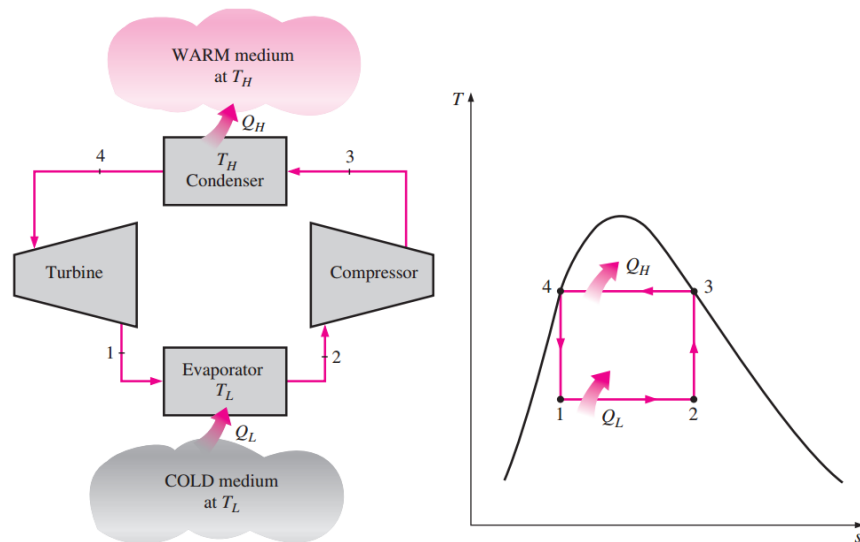


Fig.: Schematic of a Carnot refrigerator and T-s diagram of the reversed Carnot cycle

The reversed Carnot cycle is the most efficient refrigeration cycle operating between two specified temperature levels. Therefore, it is natural to look at it first as a prospective ideal cycle for refrigerators and heat pumps. If we could, we certainly would adapt it as the ideal cycle. As explained below, however, the reversed Carnot cycle is not a suitable model for refrigeration cycles.

The two isothermal heat transfer processes are not difficult to achieve inpractice since maintaining a constant pressure automatically fixes the temperature of a two-phase mixture at the saturation value. Therefore, processes 1-2 and 3-4 can be approached closely in actual evaporators and condensers. However, processes 2-3 and 4-1 cannot be approximated closely in practice.This is because process 2-3 involves the compression of a liquid–vapour mixture, which requires a compressor that will handle two phases, and process 4-1 involves the expansion of high-moisture-content refrigerant in a turbine. It seems as if these problems could be eliminated by executing the reversed Carnot cycle outside the saturation region. But in this case we have difficulty in maintaining isothermal conditions during the heat-absorption and heat-rejection processes. Therefore, we conclude that the reversed Carnot cycle cannot be approximated in actual devices and is not a realistic model for refrigeration cycles. However, the reversed Carnot cycle can serveas a standard against which actual refrigeration cycles are compared.

**The Ideal Vapour-Compression Refrigeration Cycle:**
Many of the impracticalities associated with the reversed Carnot cycle can be eliminated by vaporizing the refrigerant completely before it is compressed and by replacing the turbine with a throttling device, such as an expansion valve or capillary tube. The cycle that results is called the ideal vapour-compression refrigeration cycle, and it is shown schematically and on a T-s diagram in Fig. The vapour-compression refrigeration cycle is the most widely used cycle for refrigerators, air-conditioning systems, and heat pumps. It consists of four processes:

1-2: Isentropic compression in a compressor
2-3: Constant-pressure heat rejection in a condenser
3-4: Throttling in an expansion device
4-1: Constant-pressure heat absorption in an evaporator
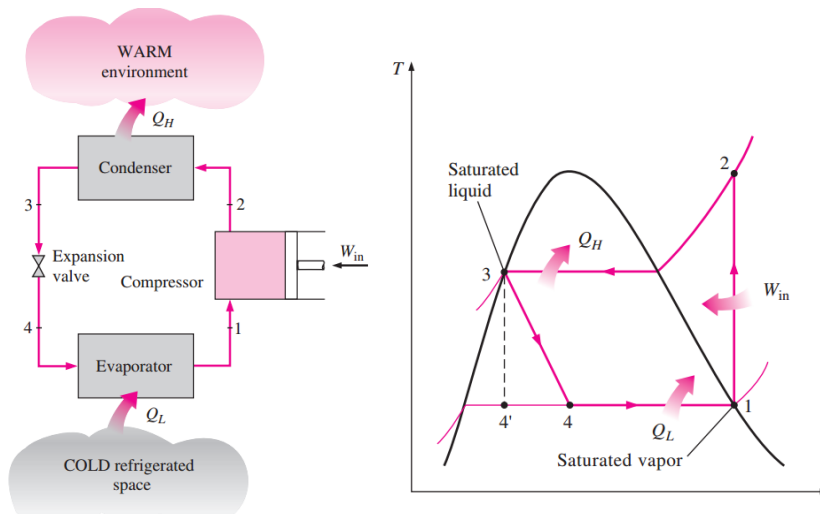
In a household refrigerator, the tubes in the freezer compartment where heat is absorbed by the refrigerant serves as the evaporator. The coils behind the refrigerator, where heat is dissipated to the kitchen air, serve as the condenser.

Another diagram frequently used in the analysis of vapour-compression refrigeration cycles is the P-h diagram, as shown in Fig. below. On this diagram, three of the four processes appear as straight lines, and the heat transfer in the condenser and the evaporator is proportional to the lengths of the corresponding process curves.
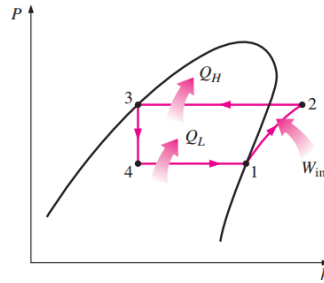


Then the COPs of refrigerators and heat pumps operating on the vapour-compression refrigeration cycle can be expressed as:

$$COP_R = \frac{q_L}{w_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$COP_{HP} = \frac{q_H}{w_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

**A refrigerator uses refrigerant-134a as the working fluid and operates on an ideal vapor-compression refrigeration cycle between 0.14 and 0.8 MPa. If the mass flow rate of the refrigerant is 0.05 kg/s, determine (a) the rate of heat removal from the refrigerated space and the power input to the compressor, (b) the rate of heat rejection to the environment, and (c) the COP of the refrigerator.**

**Enthalpy of R-134a at compressor inlet=239.19kJ/kg, compressor outlet=275.40kJ/kg and condenser outlet=95.48kJ/kg**

(a) The rate of heat removal from the refrigerated space and the power input to the compressor are determined from their definitions:

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = (0.05 \text{ kg/s})[(239.19 - 95.48) \text{ kJ/kg}] = \textbf{7.19 kW}$$

and

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) = (0.05 \text{ kg/s})[(275.40 - 239.19) \text{ kJ/kg}] = \textbf{1.81 kW}$$

(b) The rate of heat rejection from the refrigerant to the environment is

$$\dot{Q}_H = \dot{m}(h_2 - h_3) = (0.05 \text{ kg/s})[(275.40 - 95.48) \text{ kJ/kg}] = \textbf{9.00 kW}$$

It could also be determined from

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{in} = 7.19 + 1.81 = 9.00 \text{ kW}$$

(c) The coefficient of performance of the refrigerator is

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{7.19 \text{ kW}}{1.81 \text{ kW}} = \textbf{3.97}$$
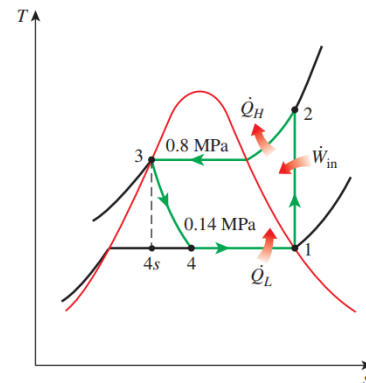
**An ideal vapour-compression refrigeration cycle that uses refrigerant R-134a as its working fluid maintains a condenser at 1000kPa and the evaporator at 4°C. Determine this system's COP and the amount of power required to service a 400kW cooling load. Enthalpy of R-134a at compressor inlet=252.77kJ/kg, compressor outlet=275.29kJ/kg and condenser outlet=107.32kJ/kg**
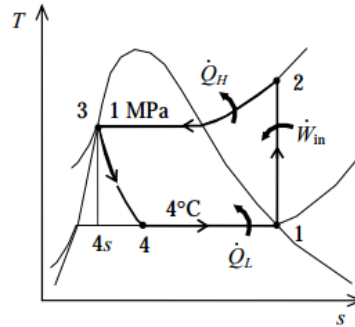


The mass flow rate of the refrigerant is:

$$\dot{Q}_L = \dot{m}(h_1 - h_4) \longrightarrow \dot{m} = \frac{\dot{Q}_L}{h_1 - h_4} = \frac{400 \text{ kJ/s}}{(252.77 - 107.32) \text{ kJ/kg}} = 2.750 \text{ kg/s}$$

The power requirement is

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) = (2.750 \text{ kg/s})(275.29 - 252.77) \text{ kJ/kg} = \mathbf{61.93\, kW}$$

The COP of the refrigerator is determined from its definition,

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{400 \text{ kW}}{61.93 \text{ kW}} = \mathbf{6.46}$$

## TABLE A–4

Saturated water—Temperature table

| Temp., $T$ °C | Sat. press., $P_{sat}$ kPa | 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, $s_g$ |
| 0.01 | 0.6117 | 0.001000 | 206.00 | 0.000 | 2374.9 | 2374.9 | 0.001 | 2500.9 | 2500.9 | 0.0000 | 9.1556 | 9.1556 |
| 5 | 0.8725 | 0.001000 | 147.03 | 21.019 | 2360.8 | 2381.8 | 21.020 | 2489.1 | 2510.1 | 0.0763 | 8.9487 | 9.0249 |
| 10 | 1.2281 | 0.001000 | 106.32 | 42.020 | 2346.6 | 2388.7 | 42.022 | 2477.2 | 2519.2 | 0.1511 | 8.7488 | 8.8999 |
| 15 | 1.7057 | 0.001001 | 77.885 | 62.980 | 2332.5 | 2395.5 | 62.982 | 2465.4 | 2528.3 | 0.2245 | 8.5559 | 8.7803 |
| 20 | 2.3392 | 0.001002 | 57.762 | 83.913 | 2318.4 | 2402.3 | 83.915 | 2453.5 | 2537.4 | 0.2965 | 8.3696 | 8.6661 |
| 25 | 3.1698 | 0.001003 | 43.340 | 104.83 | 2304.3 | 2409.1 | 104.83 | 2441.7 | 2546.5 | 0.3672 | 8.1895 | 8.5567 |
| 30 | 4.2469 | 0.001004 | 32.879 | 125.73 | 2290.2 | 2415.9 | 125.74 | 2429.8 | 2555.6 | 0.4368 | 8.0152 | 8.4520 |
| 35 | 5.6291 | 0.001006 | 25.205 | 146.63 | 2276.0 | 2422.7 | 146.64 | 2417.9 | 2564.6 | 0.5051 | 7.8466 | 8.3517 |
| 40 | 7.3851 | 0.001008 | 19.515 | 167.53 | 2261.9 | 2429.4 | 167.53 | 2406.0 | 2573.5 | 0.5724 | 7.6832 | 8.2556 |
| 45 | 9.5953 | 0.001010 | 15.251 | 188.43 | 2247.7 | 2436.1 | 188.44 | 2394.0 | 2582.4 | 0.6386 | 7.5247 | 8.1633 |
| 50 | 12.352 | 0.001012 | 12.026 | 209.33 | 2233.4 | 2442.7 | 209.34 | 2382.0 | 2591.3 | 0.7038 | 7.3710 | 8.0748 |
| 55 | 15.763 | 0.001015 | 9.5639 | 230.24 | 2219.1 | 2449.3 | 230.26 | 2369.8 | 2600.1 | 0.7680 | 7.2218 | 7.9898 |
| 60 | 19.947 | 0.001017 | 7.6670 | 251.16 | 2204.7 | 2455.9 | 251.18 | 2357.7 | 2608.8 | 0.8313 | 7.0769 | 7.9082 |
| 65 | 25.043 | 0.001020 | 6.1935 | 272.09 | 2190.3 | 2462.4 | 272.12 | 2345.4 | 2617.5 | 0.8937 | 6.9360 | 7.8296 |
| 70 | 31.202 | 0.001023 | 5.0396 | 293.04 | 2175.8 | 2468.9 | 293.07 | 2333.0 | 2626.1 | 0.9551 | 6.7989 | 7.7540 |
| 75 | 38.597 | 0.001026 | 4.1291 | 313.99 | 2161.3 | 2475.3 | 314.03 | 2320.6 | 2634.6 | 1.0158 | 6.6655 | 7.6812 |
| 80 | 47.416 | 0.001029 | 3.4053 | 334.97 | 2146.6 | 2481.6 | 335.02 | 2308.0 | 2643.0 | 1.0756 | 6.5355 | 7.6111 |
| 85 | 57.868 | 0.001032 | 2.8261 | 355.96 | 2131.9 | 2487.8 | 356.02 | 2295.3 | 2651.4 | 1.1346 | 6.4089 | 7.5435 |
| 90 | 70.183 | 0.001036 | 2.3593 | 376.97 | 2117.0 | 2494.0 | 377.04 | 2282.5 | 2659.6 | 1.1929 | 6.2853 | 7.4782 |
| 95 | 84.609 | 0.001040 | 1.9808 | 398.00 | 2102.0 | 2500.1 | 398.09 | 2269.6 | 2667.6 | 1.2504 | 6.1647 | 7.4151 |
| 100 | 101.42 | 0.001043 | 1.6720 | 419.06 | 2087.0 | 2506.0 | 419.17 | 2256.4 | 2675.6 | 1.3072 | 6.0470 | 7.3542 |
| 105 | 120.90 | 0.001047 | 1.4186 | 440.15 | 2071.8 | 2511.9 | 440.28 | 2243.1 | 2683.4 | 1.3634 | 5.9319 | 7.2952 |
| 110 | 143.38 | 0.001052 | 1.2094 | 461.27 | 2056.4 | 2517.7 | 461.42 | 2229.7 | 2691.1 | 1.4188 | 5.8193 | 7.2382 |
| 115 | 169.18 | 0.001056 | 1.0360 | 482.42 | 2040.9 | 2523.3 | 482.59 | 2216.0 | 2698.6 | 1.4737 | 5.7092 | 7.1829 |
| 120 | 198.67 | 0.001060 | 0.89133 | 503.60 | 2025.3 | 2528.9 | 503.81 | 2202.1 | 2706.0 | 1.5279 | 5.6013 | 7.1292 |
| 125 | 232.23 | 0.001065 | 0.77012 | 524.83 | 2009.5 | 2534.3 | 525.07 | 2188.1 | 2713.1 | 1.5816 | 5.4956 | 7.0771 |
| 130 | 270.28 | 0.001070 | 0.66808 | 546.10 | 1993.4 | 2539.5 | 546.38 | 2173.7 | 2720.1 | 1.6346 | 5.3919 | 7.0265 |
| 135 | 313.22 | 0.001075 | 0.58179 | 567.41 | 1977.3 | 2544.7 | 567.75 | 2159.1 | 2726.9 | 1.6872 | 5.2901 | 6.9773 |
| 140 | 361.53 | 0.001080 | 0.50850 | 588.77 | 1960.9 | 2549.6 | 589.16 | 2144.3 | 2733.5 | 1.7392 | 5.1901 | 6.9294 |
| 145 | 415.68 | 0.001085 | 0.44600 | 610.19 | 1944.2 | 2554.4 | 610.64 | 2129.2 | 2739.8 | 1.7908 | 5.0919 | 6.8827 |
| 150 | 476.16 | 0.001091 | 0.39248 | 631.66 | 1927.4 | 2559.1 | 632.18 | 2113.8 | 2745.9 | 1.8418 | 4.9953 | 6.8371 |
| 155 | 543.49 | 0.001096 | 0.34648 | 653.19 | 1910.3 | 2563.5 | 653.79 | 2098.0 | 2751.8 | 1.8924 | 4.9002 | 6.7927 |
| 160 | 618.23 | 0.001102 | 0.30680 | 674.79 | 1893.0 | 2567.8 | 675.47 | 2082.0 | 2757.5 | 1.9426 | 4.8066 | 6.7492 |
| 165 | 700.93 | 0.001108 | 0.27244 | 696.46 | 1875.4 | 2571.9 | 697.24 | 2065.6 | 2762.8 | 1.9923 | 4.7143 | 6.7067 |
| 170 | 792.18 | 0.001114 | 0.24260 | 718.20 | 1857.5 | 2575.7 | 719.08 | 2048.8 | 2767.9 | 2.0417 | 4.6233 | 6.6650 |
| 175 | 892.60 | 0.001121 | 0.21659 | 740.02 | 1839.4 | 2579.4 | 741.02 | 2031.7 | 2772.7 | 2.0906 | 4.5335 | 6.6242 |
| 180 | 1002.8 | 0.001127 | 0.19384 | 761.92 | 1820.9 | 2582.8 | 763.05 | 2014.2 | 2777.2 | 2.1392 | 4.4448 | 6.5841 |
| 185 | 1123.5 | 0.001134 | 0.17390 | 783.91 | 1802.1 | 2586.0 | 785.19 | 1996.2 | 2781.4 | 2.1875 | 4.3572 | 6.5447 |
| 190 | 1255.2 | 0.001141 | 0.15636 | 806.00 | 1783.0 | 2589.0 | 807.43 | 1977.9 | 2785.3 | 2.2355 | 4.2705 | 6.5059 |
| 195 | 1398.8 | 0.001149 | 0.14089 | 828.18 | 1763.6 | 2591.7 | 829.78 | 1959.0 | 2788.8 | 2.2831 | 4.1847 | 6.4678 |
| 200 | 1554.9 | 0.001157 | 0.12721 | 850.46 | 1743.7 | 2594.2 | 852.26 | 1939.8 | 2792.0 | 2.3305 | 4.0997 | 6.4302 |

## TABLE A–4

Saturated water—Temperature table (*Concluded*)

| Temp., $T\,°C$ | Sat. press., $P_{sat}$ kPa | 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, $s_g$ |
| 205 | 1724.3 | 0.001164 | 0.11508 | 872.86 | 1723.5 | 2596.4 | 874.87 | 1920.0 | 2794.8 | 2.3776 | 4.0154 | 6.3930 |
| 210 | 1907.7 | 0.001173 | 0.10429 | 895.38 | 1702.9 | 2598.3 | 897.61 | 1899.7 | 2797.3 | 2.4245 | 3.9318 | 6.3563 |
| 215 | 2105.9 | 0.001181 | 0.094680 | 918.02 | 1681.9 | 2599.9 | 920.50 | 1878.8 | 2799.3 | 2.4712 | 3.8489 | 6.3200 |
| 220 | 2319.6 | 0.001190 | 0.086094 | 940.79 | 1660.5 | 2601.3 | 943.55 | 1857.4 | 2801.0 | 2.5176 | 3.7664 | 6.2840 |
| 225 | 2549.7 | 0.001199 | 0.078405 | 963.70 | 1638.6 | 2602.3 | 966.76 | 1835.4 | 2802.2 | 2.5639 | 3.6844 | 6.2483 |
| 230 | 2797.1 | 0.001209 | 0.071505 | 986.76 | 1616.1 | 2602.9 | 990.14 | 1812.8 | 2802.9 | 2.6100 | 3.6028 | 6.2128 |
| 235 | 3062.6 | 0.001219 | 0.065300 | 1010.0 | 1593.2 | 2603.2 | 1013.7 | 1789.5 | 2803.2 | 2.6560 | 3.5216 | 6.1775 |
| 240 | 3347.0 | 0.001229 | 0.059707 | 1033.4 | 1569.8 | 2603.1 | 1037.5 | 1765.5 | 2803.0 | 2.7018 | 3.4405 | 6.1424 |
| 245 | 3651.2 | 0.001240 | 0.054656 | 1056.9 | 1545.7 | 2602.7 | 1061.5 | 1740.8 | 2802.2 | 2.7476 | 3.3596 | 6.1072 |
| 250 | 3976.2 | 0.001252 | 0.050085 | 1080.7 | 1521.1 | 2601.8 | 1085.7 | 1715.3 | 2801.0 | 2.7933 | 3.2788 | 6.0721 |
| 255 | 4322.9 | 0.001263 | 0.045941 | 1104.7 | 1495.8 | 2600.5 | 1110.1 | 1689.0 | 2799.1 | 2.8390 | 3.1979 | 6.0369 |
| 260 | 4692.3 | 0.001276 | 0.042175 | 1128.8 | 1469.9 | 2598.7 | 1134.8 | 1661.8 | 2796.6 | 2.8847 | 3.1169 | 6.0017 |
| 265 | 5085.3 | 0.001289 | 0.038748 | 1153.3 | 1443.2 | 2596.5 | 1159.8 | 1633.7 | 2793.5 | 2.9304 | 3.0358 | 5.9662 |
| 270 | 5503.0 | 0.001303 | 0.035622 | 1177.9 | 1415.7 | 2593.7 | 1185.1 | 1604.6 | 2789.7 | 2.9762 | 2.9542 | 5.9305 |
| 275 | 5946.4 | 0.001317 | 0.032767 | 1202.9 | 1387.4 | 2590.3 | 1210.7 | 1574.5 | 2785.2 | 3.0221 | 2.8723 | 5.8944 |
| 280 | 6416.6 | 0.001333 | 0.030153 | 1228.2 | 1358.2 | 2586.4 | 1236.7 | 1543.2 | 2779.9 | 3.0681 | 2.7898 | 5.8579 |
| 285 | 6914.6 | 0.001349 | 0.027756 | 1253.7 | 1328.1 | 2581.8 | 1263.1 | 1510.7 | 2773.7 | 3.1144 | 2.7066 | 5.8210 |
| 290 | 7441.8 | 0.001366 | 0.025554 | 1279.7 | 1296.9 | 2576.5 | 1289.8 | 1476.9 | 2766.7 | 3.1608 | 2.6225 | 5.7834 |
| 295 | 7999.0 | 0.001384 | 0.023528 | 1306.0 | 1264.5 | 2570.5 | 1317.1 | 1441.6 | 2758.7 | 3.2076 | 2.5374 | 5.7450 |
| 300 | 8587.9 | 0.001404 | 0.021659 | 1332.7 | 1230.9 | 2563.6 | 1344.8 | 1404.8 | 2749.6 | 3.2548 | 2.4511 | 5.7059 |
| 305 | 9209.4 | 0.001425 | 0.019932 | 1360.0 | 1195.9 | 2555.8 | 1373.1 | 1366.3 | 2739.4 | 3.3024 | 2.3633 | 5.6657 |
| 310 | 9865.0 | 0.001447 | 0.018333 | 1387.7 | 1159.3 | 2547.1 | 1402.0 | 1325.9 | 2727.9 | 3.3506 | 2.2737 | 5.6243 |
| 315 | 10,556 | 0.001472 | 0.016849 | 1416.1 | 1121.1 | 2537.2 | 1431.6 | 1283.4 | 2715.0 | 3.3994 | 2.1821 | 5.5816 |
| 320 | 11,284 | 0.001499 | 0.015470 | 1445.1 | 1080.9 | 2526.0 | 1462.0 | 1238.5 | 2700.6 | 3.4491 | 2.0881 | 5.5372 |
| 325 | 12,051 | 0.001528 | 0.014183 | 1475.0 | 1038.5 | 2513.4 | 1493.4 | 1191.0 | 2684.3 | 3.4998 | 1.9911 | 5.4908 |
| 330 | 12,858 | 0.001560 | 0.012979 | 1505.7 | 993.5 | 2499.2 | 1525.8 | 1140.3 | 2666.0 | 3.5516 | 1.8906 | 5.4422 |
| 335 | 13,707 | 0.001597 | 0.011848 | 1537.5 | 945.5 | 2483.0 | 1559.4 | 1086.0 | 2645.4 | 3.6050 | 1.7857 | 5.3907 |
| 340 | 14,601 | 0.001638 | 0.010783 | 1570.7 | 893.8 | 2464.5 | 1594.6 | 1027.4 | 2622.0 | 3.6602 | 1.6756 | 5.3358 |
| 345 | 15,541 | 0.001685 | 0.009772 | 1605.5 | 837.7 | 2443.2 | 1631.7 | 963.4 | 2595.1 | 3.7179 | 1.5585 | 5.2765 |
| 350 | 16,529 | 0.001741 | 0.008806 | 1642.4 | 775.9 | 2418.3 | 1671.2 | 892.7 | 2563.9 | 3.7788 | 1.4326 | 5.2114 |
| 355 | 17,570 | 0.001808 | 0.007872 | 1682.2 | 706.4 | 2388.6 | 1714.0 | 812.9 | 2526.9 | 3.8442 | 1.2942 | 5.1384 |
| 360 | 18,666 | 0.001895 | 0.006950 | 1726.2 | 625.7 | 2351.9 | 1761.5 | 720.1 | 2481.6 | 3.9165 | 1.1373 | 5.0537 |
| 365 | 19,822 | 0.002015 | 0.006009 | 1777.2 | 526.4 | 2303.6 | 1817.2 | 605.5 | 2422.7 | 4.0004 | 0.9489 | 4.9493 |
| 370 | 21,044 | 0.002217 | 0.004953 | 1844.5 | 385.6 | 2230.1 | 1891.2 | 443.1 | 2334.3 | 4.1119 | 0.6890 | 4.8009 |
| 373.95 | 22,064 | 0.003106 | 0.003106 | 2015.7 | 0 | 2015.7 | 2084.3 | 0 | 2084.3 | 4.4070 | 0 | 4.4070 |

*Source of Data:* Tables A–4 through A–8 are generated using the Engineering Equation Solver (EES) software developed by S. A. Klein and F. L. Alvarado. The routine used in calculations is the highly accurate Steam_IAPWS, which incorporates the 1995 Formulation for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use, issued by The International Association for the Properties of Water and Steam (IAPWS). This formulation replaces the 1984 formulation of Haar, Gallagher, and Kell (NBS/NRC Steam Tables, Hemisphere Publishing Co., 1984), which is also available in EES as the routine STEAM. The new formulation is based on the correlations of Saul and Wagner (J. Phys. Chem. Ref. Data, 16, 893, 1987) with modifications to adjust to the International Temperature Scale of 1990. The modifications are described by Wagner and Pruss (J. Phys. Chem. Ref. Data, 22, 783, 1993). The properties of ice are based on Hyland and Wexler, "Formulations for the Thermodynamic Properties of the Saturated Phases of $H_2O$ from 173.15 K to 473.15 K," *ASHRAE Trans.*, Part 2A, Paper 2793, 1983.

## TABLE A–5

Saturated water—Pressure table

| Press., P kPa | Sat. temp., $T_{sat}$ °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, $s_g$ |
| 1.0 | 6.97 | 0.001000 | 129.19 | 29.302 | 2355.2 | 2384.5 | 29.303 | 2484.4 | 2513.7 | 0.1059 | 8.8690 | 8.9749 |
| 1.5 | 13.02 | 0.001001 | 87.964 | 54.686 | 2338.1 | 2392.8 | 54.688 | 2470.1 | 2524.7 | 0.1956 | 8.6314 | 8.8270 |
| 2.0 | 17.50 | 0.001001 | 66.990 | 73.431 | 2325.5 | 2398.9 | 73.433 | 2459.5 | 2532.9 | 0.2606 | 8.4621 | 8.7227 |
| 2.5 | 21.08 | 0.001002 | 54.242 | 88.422 | 2315.4 | 2403.8 | 88.424 | 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 |
| 4.0 | 28.96 | 0.001004 | 34.791 | 121.39 | 2293.1 | 2414.5 | 121.39 | 2432.3 | 2553.7 | 0.4224 | 8.0510 | 8.4734 |
| 5.0 | 32.87 | 0.001005 | 28.185 | 137.75 | 2282.1 | 2419.8 | 137.75 | 2423.0 | 2560.7 | 0.4762 | 7.9176 | 8.3938 |
| 7.5 | 40.29 | 0.001008 | 19.233 | 168.74 | 2261.1 | 2429.8 | 168.75 | 2405.3 | 2574.0 | 0.5763 | 7.6738 | 8.2501 |
| 10 | 45.81 | 0.001010 | 14.670 | 191.79 | 2245.4 | 2437.2 | 191.81 | 2392.1 | 2583.9 | 0.6492 | 7.4996 | 8.1488 |
| 15 | 53.97 | 0.001014 | 10.020 | 225.93 | 2222.1 | 2448.0 | 225.94 | 2372.3 | 2598.3 | 0.7549 | 7.2522 | 8.0071 |
| 20 | 60.06 | 0.001017 | 7.6481 | 251.40 | 2204.6 | 2456.0 | 251.42 | 2357.5 | 2608.9 | 0.8320 | 7.0752 | 7.9073 |
| 25 | 64.96 | 0.001020 | 6.2034 | 271.93 | 2190.4 | 2462.4 | 271.96 | 2345.5 | 2617.5 | 0.8932 | 6.9370 | 7.8302 |
| 30 | 69.09 | 0.001022 | 5.2287 | 289.24 | 2178.5 | 2467.7 | 289.27 | 2335.3 | 2624.6 | 0.9441 | 6.8234 | 7.7675 |
| 40 | 75.86 | 0.001026 | 3.9933 | 317.58 | 2158.8 | 2476.3 | 317.62 | 2318.4 | 2636.1 | 1.0261 | 6.6430 | 7.6691 |
| 50 | 81.32 | 0.001030 | 3.2403 | 340.49 | 2142.7 | 2483.2 | 340.54 | 2304.7 | 2645.2 | 1.0912 | 6.5019 | 7.5931 |
| 75 | 91.76 | 0.001037 | 2.2172 | 384.36 | 2111.8 | 2496.1 | 384.44 | 2278.0 | 2662.4 | 1.2132 | 6.2426 | 7.4558 |
| 100 | 99.61 | 0.001043 | 1.6941 | 417.40 | 2088.2 | 2505.6 | 417.51 | 2257.5 | 2675.0 | 1.3028 | 6.0562 | 7.3589 |
| 101.325 | 99.97 | 0.001043 | 1.6734 | 418.95 | 2087.0 | 2506.0 | 419.06 | 2256.5 | 2675.6 | 1.3069 | 6.0476 | 7.3545 |
| 125 | 105.97 | 0.001048 | 1.3750 | 444.23 | 2068.8 | 2513.0 | 444.36 | 2240.6 | 2684.9 | 1.3741 | 5.9100 | 7.2841 |
| 150 | 111.35 | 0.001053 | 1.1594 | 466.97 | 2052.3 | 2519.2 | 467.13 | 2226.0 | 2693.1 | 1.4337 | 5.7894 | 7.2231 |
| 175 | 116.04 | 0.001057 | 1.0037 | 486.82 | 2037.7 | 2524.5 | 487.01 | 2213.1 | 2700.2 | 1.4850 | 5.6865 | 7.1716 |
| 200 | 120.21 | 0.001061 | 0.88578 | 504.50 | 2024.6 | 2529.1 | 504.71 | 2201.6 | 2706.3 | 1.5302 | 5.5968 | 7.1270 |
| 225 | 123.97 | 0.001064 | 0.79329 | 520.47 | 2012.7 | 2533.2 | 520.71 | 2191.0 | 2711.7 | 1.5706 | 5.5171 | 7.0877 |
| 250 | 127.41 | 0.001067 | 0.71873 | 535.08 | 2001.8 | 2536.8 | 535.35 | 2181.2 | 2716.5 | 1.6072 | 5.4453 | 7.0525 |
| 275 | 130.58 | 0.001070 | 0.65732 | 548.57 | 1991.6 | 2540.1 | 548.86 | 2172.0 | 2720.9 | 1.6408 | 5.3800 | 7.0207 |
| 300 | 133.52 | 0.001073 | 0.60582 | 561.11 | 1982.1 | 2543.2 | 561.43 | 2163.5 | 2724.9 | 1.6717 | 5.3200 | 6.9917 |
| 325 | 136.27 | 0.001076 | 0.56199 | 572.84 | 1973.1 | 2545.9 | 573.19 | 2155.4 | 2728.6 | 1.7005 | 5.2645 | 6.9650 |
| 350 | 138.86 | 0.001079 | 0.52422 | 583.89 | 1964.6 | 2548.5 | 584.26 | 2147.7 | 2732.0 | 1.7274 | 5.2128 | 6.9402 |
| 375 | 141.30 | 0.001081 | 0.49133 | 594.32 | 1956.6 | 2550.9 | 594.73 | 2140.4 | 2735.1 | 1.7526 | 5.1645 | 6.9171 |
| 400 | 143.61 | 0.001084 | 0.46242 | 604.22 | 1948.9 | 2553.1 | 604.66 | 2133.4 | 2738.1 | 1.7765 | 5.1191 | 6.8955 |
| 450 | 147.90 | 0.001088 | 0.41392 | 622.65 | 1934.5 | 2557.1 | 623.14 | 2120.3 | 2743.4 | 1.8205 | 5.0356 | 6.8561 |
| 500 | 151.83 | 0.001093 | 0.37483 | 639.54 | 1921.2 | 2560.7 | 640.09 | 2108.0 | 2748.1 | 1.8604 | 4.9603 | 6.8207 |
| 550 | 155.46 | 0.001097 | 0.34261 | 655.16 | 1908.8 | 2563.9 | 655.77 | 2096.6 | 2752.4 | 1.8970 | 4.8916 | 6.7886 |
| 600 | 158.83 | 0.001101 | 0.31560 | 669.72 | 1897.1 | 2566.8 | 670.38 | 2085.8 | 2756.2 | 1.9308 | 4.8285 | 6.7593 |
| 650 | 161.98 | 0.001104 | 0.29260 | 683.37 | 1886.1 | 2569.4 | 684.08 | 2075.5 | 2759.6 | 1.9623 | 4.7699 | 6.7322 |
| 700 | 164.95 | 0.001108 | 0.27278 | 696.23 | 1875.6 | 2571.8 | 697.00 | 2065.8 | 2762.8 | 1.9918 | 4.7153 | 6.7071 |
| 750 | 167.75 | 0.001111 | 0.25552 | 708.40 | 1865.6 | 2574.0 | 709.24 | 2056.4 | 2765.7 | 2.0195 | 4.6642 | 6.6837 |

## TABLE A–5

Saturated water—Pressure table (*Concluded*)

| Press., P kPa | Sat. temp., $T_{sat}$ °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, $s_g$ |
| 800 | 170.41 | 0.001115 | 0.24035 | 719.97 | 1856.1 | 2576.0 | 720.87 | 2047.5 | 2768.3 | 2.0457 | 4.6160 | 6.6616 |
| 850 | 172.94 | 0.001118 | 0.22690 | 731.00 | 1846.9 | 2577.9 | 731.95 | 2038.8 | 2770.8 | 2.0705 | 4.5705 | 6.6409 |
| 900 | 175.35 | 0.001121 | 0.21489 | 741.55 | 1838.1 | 2579.6 | 742.56 | 2030.5 | 2773.0 | 2.0941 | 4.5273 | 6.6213 |
| 950 | 177.66 | 0.001124 | 0.20411 | 751.67 | 1829.6 | 2581.3 | 752.74 | 2022.4 | 2775.2 | 2.1166 | 4.4862 | 6.6027 |
| 1000 | 179.88 | 0.001127 | 0.19436 | 761.39 | 1821.4 | 2582.8 | 762.51 | 2014.6 | 2777.1 | 2.1381 | 4.4470 | 6.5850 |
| 1100 | 184.06 | 0.001133 | 0.17745 | 779.78 | 1805.7 | 2585.5 | 781.03 | 1999.6 | 2780.7 | 2.1785 | 4.3735 | 6.5520 |
| 1200 | 187.96 | 0.001138 | 0.16326 | 796.96 | 1790.9 | 2587.8 | 798.33 | 1985.4 | 2783.8 | 2.2159 | 4.3058 | 6.5217 |
| 1300 | 191.60 | 0.001144 | 0.15119 | 813.10 | 1776.8 | 2589.9 | 814.59 | 1971.9 | 2786.5 | 2.2508 | 4.2428 | 6.4936 |
| 1400 | 195.04 | 0.001149 | 0.14078 | 828.35 | 1763.4 | 2591.8 | 829.96 | 1958.9 | 2788.9 | 2.2835 | 4.1840 | 6.4675 |
| 1500 | 198.29 | 0.001154 | 0.13171 | 842.82 | 1750.6 | 2593.4 | 844.55 | 1946.4 | 2791.0 | 2.3143 | 4.1287 | 6.4430 |
| 1750 | 205.72 | 0.001166 | 0.11344 | 876.12 | 1720.6 | 2596.7 | 878.16 | 1917.1 | 2795.2 | 2.3844 | 4.0033 | 6.3877 |
| 2000 | 212.38 | 0.001177 | 0.099587 | 906.12 | 1693.0 | 2599.1 | 908.47 | 1889.8 | 2798.3 | 2.4467 | 3.8923 | 6.3390 |
| 2250 | 218.41 | 0.001187 | 0.088717 | 933.54 | 1667.3 | 2600.9 | 936.21 | 1864.3 | 2800.5 | 2.5029 | 3.7926 | 6.2954 |
| 2500 | 223.95 | 0.001197 | 0.079952 | 958.87 | 1643.2 | 2602.1 | 961.87 | 1840.1 | 2801.9 | 2.5542 | 3.7016 | 6.2558 |
| 3000 | 233.85 | 0.001217 | 0.066667 | 1004.6 | 1598.5 | 2603.2 | 1008.3 | 1794.9 | 2803.2 | 2.6454 | 3.5402 | 6.1856 |
| 3500 | 242.56 | 0.001235 | 0.057061 | 1045.4 | 1557.6 | 2603.0 | 1049.7 | 1753.0 | 2802.7 | 2.7253 | 3.3991 | 6.1244 |
| 4000 | 250.35 | 0.001252 | 0.049779 | 1082.4 | 1519.3 | 2601.7 | 1087.4 | 1713.5 | 2800.8 | 2.7966 | 3.2731 | 6.0696 |
| 5000 | 263.94 | 0.001286 | 0.039448 | 1148.1 | 1448.9 | 2597.0 | 1154.5 | 1639.7 | 2794.2 | 2.9207 | 3.0530 | 5.9737 |
| 6000 | 275.59 | 0.001319 | 0.032449 | 1205.8 | 1384.1 | 2589.9 | 1213.8 | 1570.9 | 2784.6 | 3.0275 | 2.8627 | 5.8902 |
| 7000 | 285.83 | 0.001352 | 0.027378 | 1258.0 | 1323.0 | 2581.0 | 1267.5 | 1505.2 | 2772.6 | 3.1220 | 2.6927 | 5.8148 |
| 8000 | 295.01 | 0.001384 | 0.023525 | 1306.0 | 1264.5 | 2570.5 | 1317.1 | 1441.6 | 2758.7 | 3.2077 | 2.5373 | 5.7450 |
| 9000 | 303.35 | 0.001418 | 0.020489 | 1350.9 | 1207.6 | 2558.5 | 1363.7 | 1379.3 | 2742.9 | 3.2866 | 2.3925 | 5.6791 |
| 10,000 | 311.00 | 0.001452 | 0.018028 | 1393.3 | 1151.8 | 2545.2 | 1407.8 | 1317.6 | 2725.5 | 3.3603 | 2.2556 | 5.6159 |
| 11,000 | 318.08 | 0.001488 | 0.015988 | 1433.9 | 1096.6 | 2530.4 | 1450.2 | 1256.1 | 2706.3 | 3.4299 | 2.1245 | 5.5544 |
| 12,000 | 324.68 | 0.001526 | 0.014264 | 1473.0 | 1041.3 | 2514.3 | 1491.3 | 1194.1 | 2685.4 | 3.4964 | 1.9975 | 5.4939 |
| 13,000 | 330.85 | 0.001566 | 0.012781 | 1511.0 | 985.5 | 2496.6 | 1531.4 | 1131.3 | 2662.7 | 3.5606 | 1.8730 | 5.4336 |
| 14,000 | 336.67 | 0.001610 | 0.011487 | 1548.4 | 928.7 | 2477.1 | 1571.0 | 1067.0 | 2637.9 | 3.6232 | 1.7497 | 5.3728 |
| 15,000 | 342.16 | 0.001657 | 0.010341 | 1585.5 | 870.3 | 2455.7 | 1610.3 | 1000.5 | 2610.8 | 3.6848 | 1.6261 | 5.3108 |
| 16,000 | 347.36 | 0.001710 | 0.009312 | 1622.6 | 809.4 | 2432.0 | 1649.9 | 931.1 | 2581.0 | 3.7461 | 1.5005 | 5.2466 |
| 17,000 | 352.29 | 0.001770 | 0.008374 | 1660.2 | 745.1 | 2405.4 | 1690.3 | 857.4 | 2547.7 | 3.8082 | 1.3709 | 5.1791 |
| 18,000 | 356.99 | 0.001840 | 0.007504 | 1699.1 | 675.9 | 2375.0 | 1732.2 | 777.8 | 2510.0 | 3.8720 | 1.2343 | 5.1064 |
| 19,000 | 361.47 | 0.001926 | 0.006677 | 1740.3 | 598.9 | 2339.2 | 1776.8 | 689.2 | 2466.0 | 3.9396 | 1.0860 | 5.0256 |
| 20,000 | 365.75 | 0.002038 | 0.005862 | 1785.8 | 509.0 | 2294.8 | 1826.6 | 585.5 | 2412.1 | 4.0146 | 0.9164 | 4.9310 |
| 21,000 | 369.83 | 0.002207 | 0.004994 | 1841.6 | 391.9 | 2233.5 | 1888.0 | 450.4 | 2338.4 | 4.1071 | 0.7005 | 4.8076 |
| 22,000 | 373.71 | 0.002703 | 0.003644 | 1951.7 | 140.8 | 2092.4 | 2011.1 | 161.5 | 2172.6 | 4.2942 | 0.2496 | 4.5439 |
| 22,064 | 373.95 | 0.003106 | 0.003106 | 2015.7 | 0 | 2015.7 | 2084.3 | 0 | 2084.3 | 4.4070 | 0 | 4.4070 |

## TABLE A–6

Superheated water

| 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 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | P = 0.01 MPa (45.81°C)* | | | | P = 0.05 MPa (81.32°C) | | | | P = 0.10 MPa (99.61°C) | | | |
| Sat.† | 14.670 | 2437.2 | 2583.9 | 8.1488 | 3.2403 | 2483.2 | 2645.2 | 7.5931 | 1.6941 | 2505.6 | 2675.0 | 7.3589 |
| 50 | 14.867 | 2443.3 | 2592.0 | 8.1741 | | | | | | | | |
| 100 | 17.196 | 2515.5 | 2687.5 | 8.4489 | 3.4187 | 2511.5 | 2682.4 | 7.6953 | 1.6959 | 2506.2 | 2675.8 | 7.3611 |
| 150 | 19.513 | 2587.9 | 2783.0 | 8.6893 | 3.8897 | 2585.7 | 2780.2 | 7.9413 | 1.9367 | 2582.9 | 2776.6 | 7.6148 |
| 200 | 21.826 | 2661.4 | 2879.6 | 8.9049 | 4.3562 | 2660.0 | 2877.8 | 8.1592 | 2.1724 | 2658.2 | 2875.5 | 7.8356 |
| 250 | 24.136 | 2736.1 | 2977.5 | 9.1015 | 4.8206 | 2735.1 | 2976.2 | 8.3568 | 2.4062 | 2733.9 | 2974.5 | 8.0346 |
| 300 | 26.446 | 2812.3 | 3076.7 | 9.2827 | 5.2841 | 2811.6 | 3075.8 | 8.5387 | 2.6389 | 2810.7 | 3074.5 | 8.2172 |
| 400 | 31.063 | 2969.3 | 3280.0 | 9.6094 | 6.2094 | 2968.9 | 3279.3 | 8.8659 | 3.1027 | 2968.3 | 3278.6 | 8.5452 |
| 500 | 35.680 | 3132.9 | 3489.7 | 9.8998 | 7.1338 | 3132.6 | 3489.3 | 9.1566 | 3.5655 | 3132.2 | 3488.7 | 8.8362 |
| 600 | 40.296 | 3303.3 | 3706.3 | 10.1631 | 8.0577 | 3303.1 | 3706.0 | 9.4201 | 4.0279 | 3302.8 | 3705.6 | 9.0999 |
| 700 | 44.911 | 3480.8 | 3929.9 | 10.4056 | 8.9813 | 3480.6 | 3929.7 | 9.6626 | 4.4900 | 3480.4 | 3929.4 | 9.3424 |
| 800 | 49.527 | 3665.4 | 4160.6 | 10.6312 | 9.9047 | 3665.2 | 4160.4 | 9.8883 | 4.9519 | 3665.0 | 4160.2 | 9.5682 |
| 900 | 54.143 | 3856.9 | 4398.3 | 10.8429 | 10.8280 | 3856.8 | 4398.2 | 10.1000 | 5.4137 | 3856.7 | 4398.0 | 9.7800 |
| 1000 | 58.758 | 4055.3 | 4642.8 | 11.0429 | 11.7513 | 4055.2 | 4642.7 | 10.3000 | 5.8755 | 4055.0 | 4642.6 | 9.9800 |
| 1100 | 63.373 | 4260.0 | 4893.8 | 11.2326 | 12.6745 | 4259.9 | 4893.7 | 10.4897 | 6.3372 | 4259.8 | 4893.6 | 10.1698 |
| 1200 | 67.989 | 4470.9 | 5150.8 | 11.4132 | 13.5977 | 4470.8 | 5150.7 | 10.6704 | 6.7988 | 4470.7 | 5150.6 | 10.3504 |
| 1300 | 72.604 | 4687.4 | 5413.4 | 11.5857 | 14.5209 | 4687.3 | 5413.3 | 10.8429 | 7.2605 | 4687.2 | 5413.3 | 10.5229 |
| | P = 0.20 MPa (120.21°C) | | | | P = 0.30 MPa (133.52°C) | | | | P = 0.40 MPa (143.61°C) | | | |
| Sat. | 0.88578 | 2529.1 | 2706.3 | 7.1270 | 0.60582 | 2543.2 | 2724.9 | 6.9917 | 0.46242 | 2553.1 | 2738.1 | 6.8955 |
| 150 | 0.95986 | 2577.1 | 2769.1 | 7.2810 | 0.63402 | 2571.0 | 2761.2 | 7.0792 | 0.47088 | 2564.4 | 2752.8 | 6.9306 |
| 200 | 1.08049 | 2654.6 | 2870.7 | 7.5081 | 0.71643 | 2651.0 | 2865.9 | 7.3132 | 0.53434 | 2647.2 | 2860.9 | 7.1723 |
| 250 | 1.19890 | 2731.4 | 2971.2 | 7.7100 | 0.79645 | 2728.9 | 2967.9 | 7.5180 | 0.59520 | 2726.4 | 2964.5 | 7.3804 |
| 300 | 1.31623 | 2808.8 | 3072.1 | 7.8941 | 0.87535 | 2807.0 | 3069.6 | 7.7037 | 0.65489 | 2805.1 | 3067.1 | 7.5677 |
| 400 | 1.54934 | 2967.2 | 3277.0 | 8.2236 | 1.03155 | 2966.0 | 3275.5 | 8.0347 | 0.77265 | 2964.9 | 3273.9 | 7.9003 |
| 500 | 1.78142 | 3131.4 | 3487.7 | 8.5153 | 1.18672 | 3130.6 | 3486.6 | 8.3271 | 0.88936 | 3129.8 | 3485.5 | 8.1933 |
| 600 | 2.01302 | 3302.2 | 3704.8 | 8.7793 | 1.34139 | 3301.6 | 3704.0 | 8.5915 | 1.00558 | 3301.0 | 3703.3 | 8.4580 |
| 700 | 2.24434 | 3479.9 | 3928.8 | 9.0221 | 1.49580 | 3479.5 | 3928.2 | 8.8345 | 1.12152 | 3479.0 | 3927.6 | 8.7012 |
| 800 | 2.47550 | 3664.7 | 4159.8 | 9.2479 | 1.65004 | 3664.3 | 4159.3 | 9.0605 | 1.23730 | 3663.9 | 4158.9 | 8.9274 |
| 900 | 2.70656 | 3856.3 | 4397.7 | 9.4598 | 1.80417 | 3856.0 | 4397.3 | 9.2725 | 1.35298 | 3855.7 | 4396.9 | 9.1394 |
| 1000 | 2.93755 | 4054.8 | 4642.3 | 9.6599 | 1.95824 | 4054.5 | 4642.0 | 9.4726 | 1.46859 | 4054.3 | 4641.7 | 9.3396 |
| 1100 | 3.16848 | 4259.6 | 4893.3 | 9.8497 | 2.11226 | 4259.4 | 4893.1 | 9.6624 | 1.58414 | 4259.2 | 4892.9 | 9.5295 |
| 1200 | 3.39938 | 4470.5 | 5150.4 | 10.0304 | 2.26624 | 4470.3 | 5150.2 | 9.8431 | 1.69966 | 4470.2 | 5150.0 | 9.7102 |
| 1300 | 3.63026 | 4687.1 | 5413.1 | 10.2029 | 2.42019 | 4686.9 | 5413.0 | 10.0157 | 1.81516 | 4686.7 | 5412.8 | 9.8828 |
| | P = 0.50 MPa (151.83°C) | | | | P = 0.60 MPa (158.83°C) | | | | P = 0.80 MPa (170.41°C) | | | |
| Sat. | 0.37483 | 2560.7 | 2748.1 | 6.8207 | 0.31560 | 2566.8 | 2756.2 | 6.7593 | 0.24035 | 2576.0 | 2768.3 | 6.6616 |
| 200 | 0.42503 | 2643.3 | 2855.8 | 7.0610 | 0.35212 | 2639.4 | 2850.6 | 6.9683 | 0.26088 | 2631.1 | 2839.8 | 6.8177 |
| 250 | 0.47443 | 2723.8 | 2961.0 | 7.2725 | 0.39390 | 2721.2 | 2957.6 | 7.1833 | 0.29321 | 2715.9 | 2950.4 | 7.0402 |
| 300 | 0.52261 | 2803.3 | 3064.6 | 7.4614 | 0.43442 | 2801.4 | 3062.0 | 7.3740 | 0.32416 | 2797.5 | 3056.9 | 7.2345 |
| 350 | 0.57015 | 2883.0 | 3168.1 | 7.6346 | 0.47428 | 2881.6 | 3166.1 | 7.5481 | 0.35442 | 2878.6 | 3162.2 | 7.4107 |
| 400 | 0.61731 | 2963.7 | 3272.4 | 7.7956 | 0.51374 | 2962.5 | 3270.8 | 7.7097 | 0.38429 | 2960.2 | 3267.7 | 7.5735 |
| 500 | 0.71095 | 3129.0 | 3484.5 | 8.0893 | 0.59200 | 3128.2 | 3483.4 | 8.0041 | 0.44332 | 3126.6 | 3481.3 | 7.8692 |
| 600 | 0.80409 | 3300.4 | 3702.5 | 8.3544 | 0.66976 | 3299.8 | 3701.7 | 8.2695 | 0.50186 | 3298.7 | 3700.1 | 8.1354 |
| 700 | 0.89696 | 3478.6 | 3927.0 | 8.5978 | 0.74725 | 3478.1 | 3926.4 | 8.5132 | 0.56011 | 3477.2 | 3925.3 | 8.3794 |
| 800 | 0.98966 | 3663.6 | 4158.4 | 8.8240 | 0.82457 | 3663.2 | 4157.9 | 8.7395 | 0.61820 | 3662.5 | 4157.0 | 8.6061 |
| 900 | 1.08227 | 3855.4 | 4396.6 | 9.0362 | 0.90179 | 3855.1 | 4396.2 | 8.9518 | 0.67619 | 3854.5 | 4395.5 | 8.8185 |
| 1000 | 1.17480 | 4054.0 | 4641.4 | 9.2364 | 0.97893 | 4053.8 | 4641.1 | 9.1521 | 0.73411 | 4053.3 | 4640.5 | 9.0189 |
| 1100 | 1.26728 | 4259.0 | 4892.6 | 9.4263 | 1.05603 | 4258.8 | 4892.4 | 9.3420 | 0.79197 | 4258.3 | 4891.9 | 9.2090 |
| 1200 | 1.35972 | 4470.0 | 5149.8 | 9.6071 | 1.13309 | 4469.8 | 5149.6 | 9.5229 | 0.84980 | 4469.4 | 5149.3 | 9.3898 |
| 1300 | 1.45214 | 4686.6 | 5412.6 | 9.7797 | 1.21012 | 4686.4 | 5412.5 | 9.6955 | 0.90761 | 4686.1 | 5412.2 | 9.5625 |

*The temperature in parentheses is the saturation temperature at the specified pressure.
† Properties of saturated vapor at the specified pressure.

## TABLE A–6

Superheated water (*Concluded*)

| T | v | u | h | s | v | u | h | s | v | u | h | s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| °C | m³/kg | kJ/kg | kJ/kg | kJ/kg·K | m³/kg | kJ/kg | kJ/kg | kJ/kg·K | m³/kg | kJ/kg | kJ/kg | kJ/kg·K |
| | P = 1.00 MPa (179.88°C) | | | | P = 1.20 MPa (187.96°C) | | | | P = 1.40 MPa (195.04°C) | | | |
| Sat. | 0.19437 | 2582.8 | 2777.1 | 6.5850 | 0.16326 | 2587.8 | 2783.8 | 6.5217 | 0.14078 | 2591.8 | 2788.9 | 6.4675 |
| 200 | 0.20602 | 2622.3 | 2828.3 | 6.6956 | 0.16934 | 2612.9 | 2816.1 | 6.5909 | 0.14303 | 2602.7 | 2803.0 | 6.4975 |
| 250 | 0.23275 | 2710.4 | 2943.1 | 6.9265 | 0.19241 | 2704.7 | 2935.6 | 6.8313 | 0.16356 | 2698.9 | 2927.9 | 6.7488 |
| 300 | 0.25799 | 2793.7 | 3051.6 | 7.1246 | 0.21386 | 2789.7 | 3046.3 | 7.0335 | 0.18233 | 2785.7 | 3040.9 | 6.9553 |
| 350 | 0.28250 | 2875.7 | 3158.2 | 7.3029 | 0.23455 | 2872.7 | 3154.2 | 7.2139 | 0.20029 | 2869.7 | 3150.1 | 7.1379 |
| 400 | 0.30661 | 2957.9 | 3264.5 | 7.4670 | 0.25482 | 2955.5 | 3261.3 | 7.3793 | 0.21782 | 2953.1 | 3258.1 | 7.3046 |
| 500 | 0.35411 | 3125.0 | 3479.1 | 7.7642 | 0.29464 | 3123.4 | 3477.0 | 7.6779 | 0.25216 | 3121.8 | 3474.8 | 7.6047 |
| 600 | 0.40111 | 3297.5 | 3698.6 | 8.0311 | 0.33395 | 3296.3 | 3697.0 | 7.9456 | 0.28597 | 3295.1 | 3695.5 | 7.8730 |
| 700 | 0.44783 | 3476.3 | 3924.1 | 8.2755 | 0.37297 | 3475.3 | 3922.9 | 8.1904 | 0.31951 | 3474.4 | 3921.7 | 8.1183 |
| 800 | 0.49438 | 3661.7 | 4156.1 | 8.5024 | 0.41184 | 3661.0 | 4155.2 | 8.4176 | 0.35288 | 3660.3 | 4154.3 | 8.3458 |
| 900 | 0.54083 | 3853.9 | 4394.8 | 8.7150 | 0.45059 | 3853.3 | 4394.0 | 8.6303 | 0.38614 | 3852.7 | 4393.3 | 8.5587 |
| 1000 | 0.58721 | 4052.7 | 4640.0 | 8.9155 | 0.48928 | 4052.2 | 4639.4 | 8.8310 | 0.41933 | 4051.7 | 4638.8 | 8.7595 |
| 1100 | 0.63354 | 4257.9 | 4891.4 | 9.1057 | 0.52792 | 4257.5 | 4891.0 | 9.0212 | 0.45247 | 4257.0 | 4890.5 | 8.9497 |
| 1200 | 0.67983 | 4469.0 | 5148.9 | 9.2866 | 0.56652 | 4468.7 | 5148.5 | 9.2022 | 0.48558 | 4468.3 | 5148.1 | 9.1308 |
| 1300 | 0.72610 | 4685.8 | 5411.9 | 9.4593 | 0.60509 | 4685.5 | 5411.6 | 9.3750 | 0.51866 | 4685.1 | 5411.3 | 9.3036 |
| | P = 1.60 MPa (201.37°C) | | | | P = 1.80 MPa (207.11°C) | | | | P = 2.00 MPa (212.38°C) | | | |
| Sat. | 0.12374 | 2594.8 | 2792.8 | 6.4200 | 0.11037 | 2597.3 | 2795.9 | 6.3775 | 0.09959 | 2599.1 | 2798.3 | 6.3390 |
| 225 | 0.13293 | 2645.1 | 2857.8 | 6.5537 | 0.11678 | 2637.0 | 2847.2 | 6.4825 | 0.10381 | 2628.5 | 2836.1 | 6.4160 |
| 250 | 0.14190 | 2692.9 | 2919.9 | 6.6753 | 0.12502 | 2686.7 | 2911.7 | 6.6088 | 0.11150 | 2680.3 | 2903.3 | 6.5475 |
| 300 | 0.15866 | 2781.6 | 3035.4 | 6.8864 | 0.14025 | 2777.4 | 3029.9 | 6.8246 | 0.12551 | 2773.2 | 3024.2 | 6.7684 |
| 350 | 0.17459 | 2866.6 | 3146.0 | 7.0713 | 0.15460 | 2863.6 | 3141.9 | 7.0120 | 0.13860 | 2860.5 | 3137.7 | 6.9583 |
| 400 | 0.19007 | 2950.8 | 3254.9 | 7.2394 | 0.16849 | 2948.3 | 3251.6 | 7.1814 | 0.15122 | 2945.9 | 3248.4 | 7.1292 |
| 500 | 0.22029 | 3120.1 | 3472.6 | 7.5410 | 0.19551 | 3118.5 | 3470.4 | 7.4845 | 0.17568 | 3116.9 | 3468.3 | 7.4337 |
| 600 | 0.24999 | 3293.9 | 3693.9 | 7.8101 | 0.22200 | 3292.7 | 3692.3 | 7.7543 | 0.19962 | 3291.5 | 3690.7 | 7.7043 |
| 700 | 0.27941 | 3473.5 | 3920.5 | 8.0558 | 0.24822 | 3472.6 | 3919.4 | 8.0005 | 0.22326 | 3471.7 | 3918.2 | 7.9509 |
| 800 | 0.30865 | 3659.5 | 4153.4 | 8.2834 | 0.27426 | 3658.8 | 4152.4 | 8.2284 | 0.24674 | 3658.0 | 4151.5 | 8.1791 |
| 900 | 0.33780 | 3852.1 | 4392.6 | 8.4965 | 0.30020 | 3851.5 | 4391.9 | 8.4417 | 0.27012 | 3850.9 | 4391.1 | 8.3925 |
| 1000 | 0.36687 | 4051.2 | 4638.2 | 8.6974 | 0.32606 | 4050.7 | 4637.6 | 8.6427 | 0.29342 | 4050.2 | 4637.1 | 8.5936 |
| 1100 | 0.39589 | 4256.6 | 4890.0 | 8.8878 | 0.35188 | 4256.2 | 4889.6 | 8.8331 | 0.31667 | 4255.7 | 4889.1 | 8.7842 |
| 1200 | 0.42488 | 4467.9 | 5147.7 | 9.0689 | 0.37766 | 4467.6 | 5147.3 | 9.0143 | 0.33989 | 4467.2 | 5147.0 | 8.9654 |
| 1300 | 0.45383 | 4684.8 | 5410.9 | 9.2418 | 0.40341 | 4684.5 | 5410.6 | 9.1872 | 0.36308 | 4684.2 | 5410.3 | 9.1384 |
| | P = 2.50 MPa (223.95°C) | | | | P = 3.00 MPa (233.85°C) | | | | P = 3.50 MPa (242.56°C) | | | |
| Sat. | 0.07995 | 2602.1 | 2801.9 | 6.2558 | 0.06667 | 2603.2 | 2803.2 | 6.1856 | 0.05706 | 2603.0 | 2802.7 | 6.1244 |
| 225 | 0.08026 | 2604.8 | 2805.5 | 6.2629 | | | | | | | | |
| 250 | 0.08705 | 2663.3 | 2880.9 | 6.4107 | 0.07063 | 2644.7 | 2856.5 | 6.2893 | 0.05876 | 2624.0 | 2829.7 | 6.1764 |
| 300 | 0.09894 | 2762.2 | 3009.6 | 6.6459 | 0.08118 | 2750.8 | 2994.3 | 6.5412 | 0.06845 | 2738.8 | 2978.4 | 6.4484 |
| 350 | 0.10979 | 2852.5 | 3127.0 | 6.8424 | 0.09056 | 2844.4 | 3116.1 | 6.7450 | 0.07680 | 2836.0 | 3104.9 | 6.6601 |
| 400 | 0.12012 | 2939.8 | 3240.1 | 7.0170 | 0.09938 | 2933.6 | 3231.7 | 6.9235 | 0.08456 | 2927.2 | 3223.2 | 6.8428 |
| 450 | 0.13015 | 3026.2 | 3351.6 | 7.1768 | 0.10789 | 3021.2 | 3344.9 | 7.0856 | 0.09198 | 3016.1 | 3338.1 | 7.0074 |
| 500 | 0.13999 | 3112.8 | 3462.8 | 7.3254 | 0.11620 | 3108.6 | 3457.2 | 7.2359 | 0.09919 | 3104.5 | 3451.7 | 7.1593 |
| 600 | 0.15931 | 3288.5 | 3686.8 | 7.5979 | 0.13245 | 3285.5 | 3682.8 | 7.5103 | 0.11325 | 3282.5 | 3678.9 | 7.4357 |
| 700 | 0.17835 | 3469.3 | 3915.2 | 7.8455 | 0.14841 | 3467.0 | 3912.2 | 7.7590 | 0.12702 | 3464.7 | 3909.3 | 7.6855 |
| 800 | 0.19722 | 3656.2 | 4149.2 | 8.0744 | 0.16420 | 3654.3 | 4146.9 | 7.9885 | 0.14061 | 3652.5 | 4144.6 | 7.9156 |
| 900 | 0.21597 | 3849.4 | 4389.3 | 8.2882 | 0.17988 | 3847.9 | 4387.5 | 8.2028 | 0.15410 | 3846.4 | 4385.7 | 8.1304 |
| 1000 | 0.23466 | 4049.0 | 4635.6 | 8.4897 | 0.19549 | 4047.7 | 4634.2 | 8.4045 | 0.16751 | 4046.4 | 4632.7 | 8.3324 |
| 1100 | 0.25330 | 4254.7 | 4887.9 | 8.6804 | 0.21105 | 4253.6 | 4886.7 | 8.5955 | 0.18087 | 4252.5 | 4885.6 | 8.5236 |
| 1200 | 0.27190 | 4466.3 | 5146.0 | 8.8618 | 0.22658 | 4465.3 | 5145.1 | 8.7771 | 0.19420 | 4464.4 | 5144.1 | 8.7053 |
| 1300 | 0.29048 | 4683.4 | 5409.5 | 9.0349 | 0.24207 | 4682.6 | 5408.8 | 8.9502 | 0.20750 | 4681.8 | 5408.0 | 8.8786 |

## TABLE A–6

Superheated water (*Continued*)

| T<br>°C | v<br>m³/kg | u<br>kJ/kg | h<br>kJ/kg | s<br>kJ/kg·K | v<br>m³/kg | u<br>kJ/kg | h<br>kJ/kg | s<br>kJ/kg·K | v<br>m³/kg | u<br>kJ/kg | h<br>kJ/kg | s<br>kJ/kg·K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *P* = 4.0 MPa (250.35°C) | | | | *P* = 4.5 MPa (257.44°C) | | | | *P* = 5.0 MPa (263.94°C) | | | |
| Sat. | 0.04978 | 2601.7 | 2800.8 | 6.0696 | 0.04406 | 2599.7 | 2798.0 | 6.0198 | 0.03945 | 2597.0 | 2794.2 | 5.9737 |
| 275 | 0.05461 | 2668.9 | 2887.3 | 6.2312 | 0.04733 | 2651.4 | 2864.4 | 6.1429 | 0.04144 | 2632.3 | 2839.5 | 6.0571 |
| 300 | 0.05887 | 2726.2 | 2961.7 | 6.3639 | 0.05138 | 2713.0 | 2944.2 | 6.2854 | 0.04535 | 2699.0 | 2925.7 | 6.2111 |
| 350 | 0.06647 | 2827.4 | 3093.3 | 6.5843 | 0.05842 | 2818.6 | 3081.5 | 6.5153 | 0.05197 | 2809.5 | 3069.3 | 6.4516 |
| 400 | 0.07343 | 2920.8 | 3214.5 | 6.7714 | 0.06477 | 2914.2 | 3205.7 | 6.7071 | 0.05784 | 2907.5 | 3196.7 | 6.6483 |
| 450 | 0.08004 | 3011.0 | 3331.2 | 6.9386 | 0.07076 | 3005.8 | 3324.2 | 6.8770 | 0.06332 | 3000.6 | 3317.2 | 6.8210 |
| 500 | 0.08644 | 3100.3 | 3446.0 | 7.0922 | 0.07652 | 3096.0 | 3440.4 | 7.0323 | 0.06858 | 3091.8 | 3434.7 | 6.9781 |
| 600 | 0.09886 | 3279.4 | 3674.9 | 7.3706 | 0.08766 | 3276.4 | 3670.9 | 7.3127 | 0.07870 | 3273.3 | 3666.9 | 7.2605 |
| 700 | 0.11098 | 3462.4 | 3906.3 | 7.6214 | 0.09850 | 3460.0 | 3903.3 | 7.5647 | 0.08852 | 3457.7 | 3900.3 | 7.5136 |
| 800 | 0.12292 | 3650.6 | 4142.3 | 7.8523 | 0.10916 | 3648.8 | 4140.0 | 7.7962 | 0.09816 | 3646.9 | 4137.7 | 7.7458 |
| 900 | 0.13476 | 3844.8 | 4383.9 | 8.0675 | 0.11972 | 3843.3 | 4382.1 | 8.0118 | 0.10769 | 3841.8 | 4380.2 | 7.9619 |
| 1000 | 0.14653 | 4045.1 | 4631.2 | 8.2698 | 0.13020 | 4043.9 | 4629.8 | 8.2144 | 0.11715 | 4042.6 | 4628.3 | 8.1648 |
| 1100 | 0.15824 | 4251.4 | 4884.4 | 8.4612 | 0.14064 | 4250.4 | 4883.2 | 8.4060 | 0.12655 | 4249.3 | 4882.1 | 8.3566 |
| 1200 | 0.16992 | 4463.5 | 5143.2 | 8.6430 | 0.15103 | 4462.6 | 5142.2 | 8.5880 | 0.13592 | 4461.6 | 5141.3 | 8.5388 |
| 1300 | 0.18157 | 4680.9 | 5407.2 | 8.8164 | 0.16140 | 4680.1 | 5406.5 | 8.7616 | 0.14527 | 4679.3 | 5405.7 | 8.7124 |
| | *P* = 6.0 MPa (275.59°C) | | | | *P* = 7.0 MPa (285.83°C) | | | | *P* = 8.0 MPa (295.01°C) | | | |
| Sat. | 0.03245 | 2589.9 | 2784.6 | 5.8902 | 0.027378 | 2581.0 | 2772.6 | 5.8148 | 0.023525 | 2570.5 | 2758.7 | 5.7450 |
| 300 | 0.03619 | 2668.4 | 2885.6 | 6.0703 | 0.029492 | 2633.5 | 2839.9 | 5.9337 | 0.024279 | 2592.3 | 2786.5 | 5.7937 |
| 350 | 0.04225 | 2790.4 | 3043.9 | 6.3357 | 0.035262 | 2770.1 | 3016.9 | 6.2305 | 0.029975 | 2748.3 | 2988.1 | 6.1321 |
| 400 | 0.04742 | 2893.7 | 3178.3 | 6.5432 | 0.039958 | 2879.5 | 3159.2 | 6.4502 | 0.034344 | 2864.6 | 3139.4 | 6.3658 |
| 450 | 0.05217 | 2989.9 | 3302.9 | 6.7219 | 0.044187 | 2979.0 | 3288.3 | 6.6353 | 0.038194 | 2967.8 | 3273.3 | 6.5579 |
| 500 | 0.05667 | 3083.1 | 3423.1 | 6.8826 | 0.048157 | 3074.3 | 3411.4 | 6.8000 | 0.041767 | 3065.4 | 3399.5 | 6.7266 |
| 550 | 0.06102 | 3175.2 | 3541.3 | 7.0308 | 0.051966 | 3167.9 | 3531.6 | 6.9507 | 0.045172 | 3160.5 | 3521.8 | 6.8800 |
| 600 | 0.06527 | 3267.2 | 3658.8 | 7.1693 | 0.055665 | 3261.0 | 3650.6 | 7.0910 | 0.048463 | 3254.7 | 3642.4 | 7.0221 |
| 700 | 0.07355 | 3453.0 | 3894.3 | 7.4247 | 0.062850 | 3448.3 | 3888.3 | 7.3487 | 0.054829 | 3443.6 | 3882.2 | 7.2822 |
| 800 | 0.08165 | 3643.2 | 4133.1 | 7.6582 | 0.069856 | 3639.5 | 4128.5 | 7.5836 | 0.061011 | 3635.7 | 4123.8 | 7.5185 |
| 900 | 0.08964 | 3838.8 | 4376.6 | 7.8751 | 0.076750 | 3835.7 | 4373.0 | 7.8014 | 0.067082 | 3832.7 | 4369.3 | 7.7372 |
| 1000 | 0.09756 | 4040.1 | 4625.4 | 8.0786 | 0.083571 | 4037.5 | 4622.5 | 8.0055 | 0.073079 | 4035.0 | 4619.6 | 7.9419 |
| 1100 | 0.10543 | 4247.1 | 4879.7 | 8.2709 | 0.090341 | 4245.0 | 4877.4 | 8.1982 | 0.079025 | 4242.8 | 4875.0 | 8.1350 |
| 1200 | 0.11326 | 4459.8 | 5139.4 | 8.4534 | 0.097075 | 4457.9 | 5137.4 | 8.3810 | 0.084934 | 4456.1 | 5135.5 | 8.3181 |
| 1300 | 0.12107 | 4677.7 | 5404.1 | 8.6273 | 0.103781 | 4676.1 | 5402.6 | 8.5551 | 0.090817 | 4674.5 | 5401.0 | 8.4925 |
| | *P* = 9.0 MPa (303.35°C) | | | | *P* = 10.0 MPa (311.00°C) | | | | *P* = 12.5 MPa (327.81°C) | | | |
| Sat. | 0.020489 | 2558.5 | 2742.9 | 5.6791 | 0.018028 | 2545.2 | 2725.5 | 5.6159 | 0.013496 | 2505.6 | 2674.3 | 5.4638 |
| 325 | 0.023284 | 2647.6 | 2857.1 | 5.8738 | 0.019877 | 2611.6 | 2810.3 | 5.7596 | | | | |
| 350 | 0.025816 | 2725.0 | 2957.3 | 6.0380 | 0.022440 | 2699.6 | 2924.0 | 5.9460 | 0.016138 | 2624.9 | 2826.6 | 5.7130 |
| 400 | 0.029960 | 2849.2 | 3118.8 | 6.2876 | 0.026436 | 2833.1 | 3097.5 | 6.2141 | 0.020030 | 2789.6 | 3040.0 | 6.0433 |
| 450 | 0.033524 | 2956.3 | 3258.0 | 6.4872 | 0.029782 | 2944.5 | 3242.4 | 6.4219 | 0.023019 | 2913.7 | 3201.5 | 6.2749 |
| 500 | 0.036793 | 3056.3 | 3387.4 | 6.6603 | 0.032811 | 3047.0 | 3375.1 | 6.5995 | 0.025630 | 3023.2 | 3343.6 | 6.4651 |
| 550 | 0.039885 | 3153.0 | 3512.0 | 6.8164 | 0.035655 | 3145.4 | 3502.0 | 6.7585 | 0.028033 | 3126.1 | 3476.5 | 6.6317 |
| 600 | 0.042861 | 3248.4 | 3634.1 | 6.9605 | 0.038378 | 3242.0 | 3625.8 | 6.9045 | 0.030306 | 3225.8 | 3604.6 | 6.7828 |
| 650 | 0.045755 | 3343.4 | 3755.2 | 7.0954 | 0.041018 | 3338.0 | 3748.1 | 7.0408 | 0.032491 | 3324.1 | 3730.2 | 6.9227 |
| 700 | 0.048589 | 3438.8 | 3876.1 | 7.2229 | 0.043597 | 3434.0 | 3870.0 | 7.1693 | 0.034612 | 3422.0 | 3854.6 | 7.0540 |
| 800 | 0.054132 | 3632.0 | 4119.2 | 7.4606 | 0.048629 | 3628.2 | 4114.5 | 7.4085 | 0.038724 | 3618.8 | 4102.8 | 7.2967 |
| 900 | 0.059562 | 3829.6 | 4365.7 | 7.6802 | 0.053547 | 3826.5 | 4362.0 | 7.6290 | 0.042720 | 3818.9 | 4352.9 | 7.5195 |
| 1000 | 0.064919 | 4032.4 | 4616.7 | 7.8855 | 0.058391 | 4029.9 | 4613.8 | 7.8349 | 0.046641 | 4023.5 | 4606.5 | 7.7269 |
| 1100 | 0.070224 | 4240.7 | 4872.7 | 8.0791 | 0.063183 | 4238.5 | 4870.3 | 8.0289 | 0.050510 | 4233.1 | 4864.5 | 7.9220 |
| 1200 | 0.075492 | 4454.2 | 5133.6 | 8.2625 | 0.067938 | 4452.4 | 5131.7 | 8.2126 | 0.054342 | 4447.7 | 5127.0 | 8.1065 |
| 1300 | 0.080733 | 4672.9 | 5399.5 | 8.4371 | 0.072667 | 4671.3 | 5398.0 | 8.3874 | 0.058147 | 4667.3 | 5394.1 | 8.2819 |

## TABLE A–6

Superheated water (*Concluded*)

| T<br>°C | v<br>m³/kg | u<br>kJ/kg | h<br>kJ/kg | s<br>kJ/kg·K | v<br>m³/kg | u<br>kJ/kg | h<br>kJ/kg | s<br>kJ/kg·K | v<br>m³/kg | u<br>kJ/kg | h<br>kJ/kg | s<br>kJ/kg·K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *P* = 15.0 MPa (342.16°C) | | | | *P* = 17.5 MPa (354.67°C) | | | | *P* = 20.0 MPa (365.75°C) | | | |
| Sat. | 0.010341 | 2455.7 | 2610.8 | 5.3108 | 0.007932 | 2390.7 | 2529.5 | 5.1435 | 0.005862 | 2294.8 | 2412.1 | 4.9310 |
| 350 | 0.011481 | 2520.9 | 2693.1 | 5.4438 | | | | | | | | |
| 400 | 0.015671 | 2740.6 | 2975.7 | 5.8819 | 0.012463 | 2684.3 | 2902.4 | 5.7211 | 0.009950 | 2617.9 | 2816.9 | 5.5526 |
| 450 | 0.018477 | 2880.8 | 3157.9 | 6.1434 | 0.015204 | 2845.4 | 3111.4 | 6.0212 | 0.012721 | 2807.3 | 3061.7 | 5.9043 |
| 500 | 0.020828 | 2998.4 | 3310.8 | 6.3480 | 0.017385 | 2972.4 | 3276.7 | 6.2424 | 0.014793 | 2945.3 | 3241.2 | 6.1446 |
| 550 | 0.022945 | 3106.2 | 3450.4 | 6.5230 | 0.019305 | 3085.8 | 3423.6 | 6.4266 | 0.016571 | 3064.7 | 3396.2 | 6.3390 |
| 600 | 0.024921 | 3209.3 | 3583.1 | 6.6796 | 0.021073 | 3192.5 | 3561.3 | 6.5890 | 0.018185 | 3175.3 | 3539.0 | 6.5075 |
| 650 | 0.026804 | 3310.1 | 3712.1 | 6.8233 | 0.022742 | 3295.8 | 3693.8 | 6.7366 | 0.019695 | 3281.4 | 3675.3 | 6.6593 |
| 700 | 0.028621 | 3409.8 | 3839.1 | 6.9573 | 0.024342 | 3397.5 | 3823.5 | 6.8735 | 0.021134 | 3385.1 | 3807.8 | 6.7991 |
| 800 | 0.032121 | 3609.3 | 4091.1 | 7.2037 | 0.027405 | 3599.7 | 4079.3 | 7.1237 | 0.023870 | 3590.1 | 4067.5 | 7.0531 |
| 900 | 0.035503 | 3811.2 | 4343.7 | 7.4288 | 0.030348 | 3803.5 | 4334.6 | 7.3511 | 0.026484 | 3795.7 | 4325.4 | 7.2829 |
| 1000 | 0.038808 | 4017.1 | 4599.2 | 7.6378 | 0.033215 | 4010.7 | 4592.0 | 7.5616 | 0.029020 | 4004.3 | 4584.7 | 7.4950 |
| 1100 | 0.042062 | 4227.7 | 4858.6 | 7.8339 | 0.036029 | 4222.3 | 4852.8 | 7.7588 | 0.031504 | 4216.9 | 4847.0 | 7.6933 |
| 1200 | 0.045279 | 4443.1 | 5122.3 | 8.0192 | 0.038806 | 4438.5 | 5117.6 | 7.9449 | 0.033952 | 4433.8 | 5112.9 | 7.8802 |
| 1300 | 0.048469 | 4663.3 | 5390.3 | 8.1952 | 0.041556 | 4659.2 | 5386.5 | 8.1215 | 0.036371 | 4655.2 | 5382.7 | 8.0574 |
| | *P* = 25.0 MPa | | | | *P* = 30.0 MPa | | | | *P* = 35.0 MPa | | | |
| 375 | 0.001978 | 1799.9 | 1849.4 | 4.0345 | 0.001792 | 1738.1 | 1791.9 | 3.9313 | 0.001701 | 1702.8 | 1762.4 | 3.8724 |
| 400 | 0.006005 | 2428.5 | 2578.7 | 5.1400 | 0.002798 | 2068.9 | 2152.8 | 4.4758 | 0.002105 | 1914.9 | 1988.6 | 4.2144 |
| 425 | 0.007886 | 2607.8 | 2805.0 | 5.4708 | 0.005299 | 2452.9 | 2611.8 | 5.1473 | 0.003434 | 2253.3 | 2373.5 | 4.7751 |
| 450 | 0.009176 | 2721.2 | 2950.6 | 5.6759 | 0.006737 | 2618.9 | 2821.0 | 5.4422 | 0.004957 | 2497.5 | 2671.0 | 5.1946 |
| 500 | 0.011143 | 2887.3 | 3165.9 | 5.9643 | 0.008691 | 2824.0 | 3084.8 | 5.7956 | 0.006933 | 2755.3 | 2997.9 | 5.6331 |
| 550 | 0.012736 | 3020.8 | 3339.2 | 6.1816 | 0.010175 | 2974.5 | 3279.7 | 6.0403 | 0.008348 | 2925.8 | 3218.0 | 5.9093 |
| 600 | 0.014140 | 3140.0 | 3493.5 | 6.3637 | 0.011445 | 3103.4 | 3446.8 | 6.2373 | 0.009523 | 3065.6 | 3399.0 | 6.1229 |
| 650 | 0.015430 | 3251.9 | 3637.7 | 6.5243 | 0.012590 | 3221.7 | 3599.4 | 6.4074 | 0.010565 | 3190.9 | 3560.7 | 6.3030 |
| 700 | 0.016643 | 3359.9 | 3776.0 | 6.6702 | 0.013654 | 3334.3 | 3743.9 | 6.5599 | 0.011523 | 3308.3 | 3711.6 | 6.4623 |
| 800 | 0.018922 | 3570.7 | 4043.8 | 6.9322 | 0.015628 | 3551.2 | 4020.0 | 6.8301 | 0.013278 | 3531.6 | 3996.3 | 6.7409 |
| 900 | 0.021075 | 3780.2 | 4307.1 | 7.1668 | 0.017473 | 3764.6 | 4288.8 | 7.0695 | 0.014904 | 3749.0 | 4270.6 | 6.9853 |
| 1000 | 0.023150 | 3991.5 | 4570.2 | 7.3821 | 0.019240 | 3978.6 | 4555.8 | 7.2880 | 0.016450 | 3965.8 | 4541.5 | 7.2069 |
| 1100 | 0.025172 | 4206.1 | 4835.4 | 7.5825 | 0.020954 | 4195.2 | 4823.9 | 7.4906 | 0.017942 | 4184.4 | 4812.4 | 7.4118 |
| 1200 | 0.027157 | 4424.6 | 5103.5 | 7.7710 | 0.022630 | 4415.3 | 5094.2 | 7.6807 | 0.019398 | 4406.1 | 5085.0 | 7.6034 |
| 1300 | 0.029115 | 4647.2 | 5375.1 | 7.9494 | 0.024279 | 4639.2 | 5367.6 | 7.8602 | 0.020827 | 4631.2 | 5360.2 | 7.7841 |
| | *P* = 40.0 MPa | | | | *P* = 50.0 MPa | | | | *P* = 60.0 MPa | | | |
| 375 | 0.001641 | 1677.0 | 1742.6 | 3.8290 | 0.001560 | 1638.6 | 1716.6 | 3.7642 | 0.001503 | 1609.7 | 1699.9 | 3.7149 |
| 400 | 0.001911 | 1855.0 | 1931.4 | 4.1145 | 0.001731 | 1787.8 | 1874.4 | 4.0029 | 0.001633 | 1745.2 | 1843.2 | 3.9317 |
| 425 | 0.002538 | 2097.5 | 2199.0 | 4.5044 | 0.002009 | 1960.3 | 2060.7 | 4.2746 | 0.001816 | 1892.9 | 2001.8 | 4.1630 |
| 450 | 0.003692 | 2364.2 | 2511.8 | 4.9449 | 0.002487 | 2160.3 | 2284.7 | 4.5896 | 0.002086 | 2055.1 | 2180.2 | 4.4140 |
| 500 | 0.005623 | 2681.6 | 2906.5 | 5.4744 | 0.003890 | 2528.1 | 2722.6 | 5.1762 | 0.002952 | 2393.2 | 2570.3 | 4.9356 |
| 550 | 0.006985 | 2875.1 | 3154.4 | 5.7857 | 0.005118 | 2769.5 | 3025.4 | 5.5563 | 0.003955 | 2664.6 | 2901.9 | 5.3517 |
| 600 | 0.008089 | 3026.8 | 3350.4 | 6.0170 | 0.006108 | 2947.1 | 3252.6 | 5.8245 | 0.004833 | 2866.8 | 3156.8 | 5.6527 |
| 650 | 0.009053 | 3159.5 | 3521.6 | 6.2078 | 0.006957 | 3095.6 | 3443.5 | 6.0373 | 0.005591 | 3031.3 | 3366.8 | 5.8867 |
| 700 | 0.009930 | 3282.0 | 3679.2 | 6.3740 | 0.007717 | 3228.7 | 3614.6 | 6.2179 | 0.006265 | 3175.4 | 3551.3 | 6.0814 |
| 800 | 0.011521 | 3511.8 | 3972.6 | 6.6613 | 0.009073 | 3472.2 | 3925.8 | 6.5225 | 0.007456 | 3432.6 | 3880.0 | 6.4033 |
| 900 | 0.012980 | 3733.3 | 4252.5 | 6.9107 | 0.010296 | 3702.0 | 4216.8 | 6.7819 | 0.008519 | 3670.9 | 4182.1 | 6.6725 |
| 1000 | 0.014360 | 3952.9 | 4527.3 | 7.1355 | 0.011441 | 3927.4 | 4499.4 | 7.0131 | 0.009504 | 3902.0 | 4472.2 | 6.9099 |
| 1100 | 0.015686 | 4173.7 | 4801.1 | 7.3425 | 0.012534 | 4152.2 | 4778.9 | 7.2244 | 0.010439 | 4130.9 | 4757.3 | 7.1255 |
| 1200 | 0.016976 | 4396.9 | 5075.9 | 7.5357 | 0.013590 | 4378.6 | 5058.1 | 7.4207 | 0.011339 | 4360.5 | 5040.8 | 7.3248 |
| 1300 | 0.018239 | 4623.3 | 5352.8 | 7.7175 | 0.014620 | 4607.5 | 5338.5 | 7.6048 | 0.012213 | 4591.8 | 5324.5 | 7.5111 |

## TABLE A–7

Compressed liquid water

| 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 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *P* = 5 MPa (263.94°C) | | | | *P* = 10 MPa (311.00°C) | | | | *P* = 15 MPa (342.16°C) | | | |
| Sat. | 0.0012862 | 1148.1 | 1154.5 | 2.9207 | 0.0014522 | 1393.3 | 1407.9 | 3.3603 | 0.0016572 | 1585.5 | 1610.3 | 3.6848 |
| 0 | 0.0009977 | 0.04 | 5.03 | 0.0001 | 0.0009952 | 0.12 | 10.07 | 0.0003 | 0.0009928 | 0.18 | 15.07 | 0.0004 |
| 20 | 0.0009996 | 83.61 | 88.61 | 0.2954 | 0.0009973 | 83.31 | 93.28 | 0.2943 | 0.0009951 | 83.01 | 97.93 | 0.2932 |
| 40 | 0.0010057 | 166.92 | 171.95 | 0.5705 | 0.0010035 | 166.33 | 176.37 | 0.5685 | 0.0010013 | 165.75 | 180.77 | 0.5666 |
| 60 | 0.0010149 | 250.29 | 255.36 | 0.8287 | 0.0010127 | 249.43 | 259.55 | 0.8260 | 0.0010105 | 248.58 | 263.74 | 0.8234 |
| 80 | 0.0010267 | 333.82 | 338.96 | 1.0723 | 0.0010244 | 332.69 | 342.94 | 1.0691 | 0.0010221 | 331.59 | 346.92 | 1.0659 |
| 100 | 0.0010410 | 417.65 | 422.85 | 1.3034 | 0.0010385 | 416.23 | 426.62 | 1.2996 | 0.0010361 | 414.85 | 430.39 | 1.2958 |
| 120 | 0.0010576 | 501.91 | 507.19 | 1.5236 | 0.0010549 | 500.18 | 510.73 | 1.5191 | 0.0010522 | 498.50 | 514.28 | 1.5148 |
| 140 | 0.0010769 | 586.80 | 592.18 | 1.7344 | 0.0010738 | 584.72 | 595.45 | 1.7293 | 0.0010708 | 582.69 | 598.75 | 1.7243 |
| 160 | 0.0010988 | 672.55 | 678.04 | 1.9374 | 0.0010954 | 670.06 | 681.01 | 1.9316 | 0.0010920 | 667.63 | 684.01 | 1.9259 |
| 180 | 0.0011240 | 759.47 | 765.09 | 2.1338 | 0.0011200 | 756.48 | 767.68 | 2.1271 | 0.0011160 | 753.58 | 770.32 | 2.1206 |
| 200 | 0.0011531 | 847.92 | 853.68 | 2.3251 | 0.0011482 | 844.32 | 855.80 | 2.3174 | 0.0011435 | 840.84 | 858.00 | 2.3100 |
| 220 | 0.0011868 | 938.39 | 944.32 | 2.5127 | 0.0011809 | 934.01 | 945.82 | 2.5037 | 0.0011752 | 929.81 | 947.43 | 2.4951 |
| 240 | 0.0012268 | 1031.6 | 1037.7 | 2.6983 | 0.0012192 | 1026.2 | 1038.3 | 2.6876 | 0.0012121 | 1021.0 | 1039.2 | 2.6774 |
| 260 | 0.0012755 | 1128.5 | 1134.9 | 2.8841 | 0.0012653 | 1121.6 | 1134.3 | 2.8710 | 0.0012560 | 1115.1 | 1134.0 | 2.8586 |
| 280 | | | | | 0.0013226 | 1221.8 | 1235.0 | 3.0565 | 0.0013096 | 1213.4 | 1233.0 | 3.0410 |
| 300 | | | | | 0.0013980 | 1329.4 | 1343.3 | 3.2488 | 0.0013783 | 1317.6 | 1338.3 | 3.2279 |
| 320 | | | | | | | | | 0.0014733 | 1431.9 | 1454.0 | 3.4263 |
| 340 | | | | | | | | | 0.0016311 | 1567.9 | 1592.4 | 3.6555 |
| | *P* = 20 MPa (365.75°C) | | | | *P* = 30 MPa | | | | *P* = 50 MPa | | | |
| Sat. | 0.0020378 | 1785.8 | 1826.6 | 4.0146 | | | | | | | | |
| 0 | 0.0009904 | 0.23 | 20.03 | 0.0005 | 0.0009857 | 0.29 | 29.86 | 0.0003 | 0.0009767 | 0.29 | 49.13 | −0.0010 |
| 20 | 0.0009929 | 82.71 | 102.57 | 0.2921 | 0.0009886 | 82.11 | 111.77 | 0.2897 | 0.0009805 | 80.93 | 129.95 | 0.2845 |
| 40 | 0.0009992 | 165.17 | 185.16 | 0.5646 | 0.0009951 | 164.05 | 193.90 | 0.5607 | 0.0009872 | 161.90 | 211.25 | 0.5528 |
| 60 | 0.0010084 | 247.75 | 267.92 | 0.8208 | 0.0010042 | 246.14 | 276.26 | 0.8156 | 0.0009962 | 243.08 | 292.88 | 0.8055 |
| 80 | 0.0010199 | 330.50 | 350.90 | 1.0627 | 0.0010155 | 328.40 | 358.86 | 1.0564 | 0.0010072 | 324.42 | 374.78 | 1.0442 |
| 100 | 0.0010337 | 413.50 | 434.17 | 1.2920 | 0.0010290 | 410.87 | 441.74 | 1.2847 | 0.0010201 | 405.94 | 456.94 | 1.2705 |
| 120 | 0.0010496 | 496.85 | 517.84 | 1.5105 | 0.0010445 | 493.66 | 525.00 | 1.5020 | 0.0010349 | 487.69 | 539.43 | 1.4859 |
| 140 | 0.0010679 | 580.71 | 602.07 | 1.7194 | 0.0010623 | 576.90 | 608.76 | 1.7098 | 0.0010517 | 569.77 | 622.36 | 1.6916 |
| 160 | 0.0010886 | 665.28 | 687.05 | 1.9203 | 0.0010823 | 660.74 | 693.21 | 1.9094 | 0.0010704 | 652.33 | 705.85 | 1.8889 |
| 180 | 0.0011122 | 750.78 | 773.02 | 2.1143 | 0.0011049 | 745.40 | 778.55 | 2.1020 | 0.0010914 | 735.49 | 790.06 | 2.0790 |
| 200 | 0.0011390 | 837.49 | 860.27 | 2.3027 | 0.0011304 | 831.11 | 865.02 | 2.2888 | 0.0011149 | 819.45 | 875.19 | 2.2628 |
| 220 | 0.0011697 | 925.77 | 949.16 | 2.4867 | 0.0011595 | 918.15 | 952.93 | 2.4707 | 0.0011412 | 904.39 | 961.45 | 2.4414 |
| 240 | 0.0012053 | 1016.1 | 1040.2 | 2.6676 | 0.0011927 | 1006.9 | 1042.7 | 2.6491 | 0.0011708 | 990.55 | 1049.1 | 2.6156 |
| 260 | 0.0012472 | 1109.0 | 1134.0 | 2.8469 | 0.0012314 | 1097.8 | 1134.7 | 2.8250 | 0.0012044 | 1078.2 | 1138.4 | 2.7864 |
| 280 | 0.0012978 | 1205.6 | 1231.5 | 3.0265 | 0.0012770 | 1191.5 | 1229.8 | 3.0001 | 0.0012430 | 1167.7 | 1229.9 | 2.9547 |
| 300 | 0.0013611 | 1307.2 | 1334.4 | 3.2091 | 0.0013322 | 1288.9 | 1328.9 | 3.1761 | 0.0012879 | 1259.6 | 1324.0 | 3.1218 |
| 320 | 0.0014450 | 1416.6 | 1445.5 | 3.3996 | 0.0014014 | 1391.7 | 1433.7 | 3.3558 | 0.0013409 | 1354.3 | 1421.4 | 3.2888 |
| 340 | 0.0015693 | 1540.2 | 1571.6 | 3.6086 | 0.0014932 | 1502.4 | 1547.1 | 3.5438 | 0.0014049 | 1452.9 | 1523.1 | 3.4575 |
| 360 | 0.0018248 | 1703.6 | 1740.1 | 3.8787 | 0.0016276 | 1626.8 | 1675.6 | 3.7499 | 0.0014848 | 1556.5 | 1630.7 | 3.6301 |
| 380 | | | | | 0.0018729 | 1782.0 | 1838.2 | 4.0026 | 0.0015884 | 1667.1 | 1746.5 | 3.8102 |