Basics of Mechanical Engineering

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Module-I
Thermodynamics

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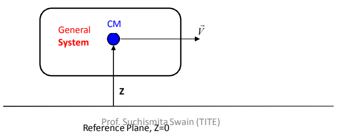
We will soon learn how to apply the first law of thermodynamics as the expression of the conservation of energy principle. But, first we study the ways in which energy may be transported across the boundary of a general thermodynamic system. For closed systems (fixed mass systems) energy can cross the boundaries of a closed system only in the form of heat or work. For open systems or control volumes energy can cross the control surface in the form of heat, work, and energy transported by the mass streams crossing the control surface. We now consider each of these modes of energy transport across the boundaries of the general thermodynamic system.

$\vec{V}$

Energy

Consider the system shown below moving with a velocity, $\vec{V}$ at an elevation *Z* relative to the reference plane.



The total energy *E* of a system is the sum of all forms of energy that can exist within the system such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear. The total energy of the system is normally thought of as the sum of the internal energy, kinetic energy, and potential energy. The internal energy *U* is that energy associated with the molecular structure of a system and the degree of the molecular activity (see Section 2-1 of text for more detail). The kinetic energy *KE* exists as a result of the system's motion relative to an external reference frame. When the system moves with velocity $\vec{V}$ the kinetic energy is expressed as

$$KE = m\frac{\vec{V}^2}{2} \qquad (kJ)$$

The energy that a system possesses as a result of its elevation in a gravitational field relative to the external reference frame is called potential energy *PE* and is expressed as

$$PE = mgZ \qquad (kJ)$$

where *g* is the gravitational acceleration and *z* is the elevation of the center of gravity of a system relative to the reference frame. The total energy of the system is expressed as

$$E = U + KE + PE \qquad (kJ)$$

or, on a unit mass basis,

$$e = \frac{E}{m} = \frac{U}{m} + \frac{KE}{m} + \frac{PE}{m} \qquad \left(\frac{kJ}{kg}\right)$$

$$= u + \frac{\vec{V}^2}{2} + gZ$$

where *e = E/m* is the specific stored energy, and *u = U/m* is the specific internal energy. The change in stored energy of a system is given by

$$\Delta E = \Delta U + \Delta KE + \Delta PE \qquad (kJ)$$

Most closed systems remain stationary during a process and, thus, experience no change in their kinetic and potential energies. The change in the stored energy is identical to the change in internal energy for stationary systems.

If $\Delta KE = \Delta PE = 0$,

$$\Delta E = \Delta U \qquad (kJ)$$

Energy Transport by Heat and Work and the Classical Sign Convention

Energy may cross the boundary of a closed system only by heat or work.

Energy transfer across a system boundary due solely to the temperature difference between a system and its surroundings is called heat.

Energy transferred across a system boundary that can be thought of as the energy expended to lift a weight is called work.

Heat and work are energy transport mechanisms between a system and its surroundings. The similarities between heat and work are as follows:

1. Both are recognized at the boundaries of a system as they cross the boundaries. They are both boundary phenomena.

2. Systems possess energy, but not heat or work.

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

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

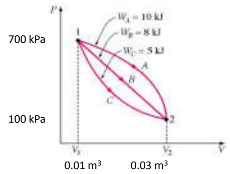
Since heat and work are path dependent functions, they have inexact differentials designated by the symbol δ. The differentials of heat and work are expressed as δQ and δW. The integral of the differentials of heat and work over the process path gives the amount of heat or work transfer that occurred at the system boundary during a process.

$$\int_{1,\,along\ path}^{2} \delta Q = Q_{12} \qquad (\text{not } \Delta Q)$$

$$\int_{1,\,along\ path}^{2} \delta W = W_{12} \qquad (\text{not } \Delta W)$$

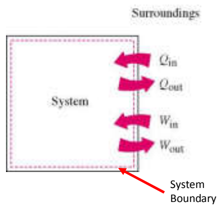
That is, the total heat transfer or work is obtained by following the process path and adding the differential amounts of heat (δQ) or work (δW) along the way. The integrals of δQ and δW are not $Q_2 – Q_1$ and $W_2 – W_1$, respectively, which are meaningless since both heat and work are not properties and systems do not possess heat or work at a state.

The following figure illustrates that properties (P, T, v, u, etc.) are point functions, that is, they depend only on the states. However, heat and work are path functions, that is, their magnitudes depend on the path followed.



A sign convention is required for heat and work energy transfers, and the classical thermodynamic sign convention is selected for these notes. According to the classical sign convention, heat transfer ***to*** a system and work ***done by*** a system are positive; heat transfer ***from*** a system and work a system are negative. The system shown below has heat supplied to it and work done by it.

In this study guide we will use the concept of net heat and net work.



Energy Transport by Heat

Recall that heat is energy in transition across the system boundary solely due to the temperature difference between the system and its surroundings. The net heat transferred to a system is defined as

$$Q_{net} = \sum Q_{in} - \sum Q_{out}$$

Here, Q_{in} and Q_{out} are the magnitudes of the heat transfer values. In most thermodynamics texts, the quantity Q is meant to be the net heat transferred to the system, Q_{net}. Since heat transfer is process dependent, the differential of heat transfer δQ is called inexact. We often think about the heat transfer per unit mass of the system, q.

Extra Problem

Explore what happens to T_{top} as you vary the convective heat transfer coefficient. On a night when the atmosphere is particularly still and cold and has a clear sky, why do fruit growers use fans to increase the air velocity in their fruit groves?

Energy Transfer by Work

Electrical Work

The rate of electrical work done by electrons crossing a system boundary is called electrical power and is given by the product of the voltage drop in volts and the current in amps.

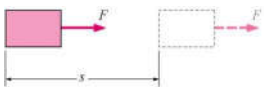
$$\dot{W}_e = V\,I \qquad (\text{W})$$

The amount of electrical work done in a time period is found by integrating the rate of electrical work over the time period.

$$W_e = \int_1^2 V\,I\,dt \qquad (\text{kJ})$$

Mechanical Forms of Work

Work is energy expended by a force acting through a distance. Thermodynamic work is defined as energy in transition across the system boundary and is done by a system if the sole effect external to the boundaries could have been the raising of a weight.



Mathematically, the differential of work is expressed as

$$\delta W = \vec{F}\cdot d\vec{s} = F\,ds\cos\Theta$$

here Θ is the angle between the force vector and the displacement vector.
As with the heat transfer, the Greek symbol δ means that work is a path-dependent function and has an inexact differential. If the angle between the force and the displacement is zero, the work done between two states is

$$W_{12} = \int_1^2 \delta W = \int_1^2 F\,ds$$

Work has the units of energy and is defined as force times displacement or newton times meter or joule (we will use kilojoules). Work per unit mass of a system is measured in kJ/kg.

Common Types of Mechanical Work Energy (See text for discussion of these topics)

- Shaft Work
- Spring Work
- Work done of Elastic Solid Bars
- Work Associated with the Stretching of a Liquid Film
- Work Done to Raise or to Accelerate a Body

Net Work Done By A System

The net work done by a system may be in two forms other work and boundary work. First, work may cross a system boundary in the form of a rotating shaft work, electrical work or other the work forms listed above. We will call these work forms “other” work, that is, work not associated with a moving boundary. In thermodynamics electrical energy is normally considered to be work energy rather than heat energy; however, the placement of the system boundary dictates whether to include electrical energy as work or heat. Second, the system may do work on its surroundings because of moving boundaries due to expansion or compression processes that a fluid may experience in a piston-cylinder device.

The net work done by a closed system is defined by

$$W_{net} = \left(\sum W_{out} - \sum W_{in}\right)_{other} + W_b$$

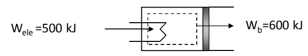
Here, W_{out} and Win are the magnitudes of the other work forms crossing the boundary. W_b is the work due to the moving boundary as would occur when a gas contained in a piston cylinder device expands and does work to move the piston. The boundary work will be positive or negative depending upon the process. Boundary work is discussed in detail in Chapter 4.

$$W_{net} = \left(W_{net}\right)_{other} + W_b$$

Several types of "other" work (shaft work, electrical work, etc.) are discussed in the text.

Example 2-3

A fluid contained in a piston-cylinder device receives 500 kJ of electrical work as the gas expands against the piston and does 600 kJ of boundary work on the piston. What is the net work done by the fluid?



$$W_{net} = \left(W_{net}\right)_{other} + W_b$$
$$W_{net} = \left(W_{out} - W_{in,ele}\right)_{other} + W_b$$
$$W_{net} = \left(0 - 500\,kJ\right) + 600\,kJ$$
$$W_{net} = 100\,kJ$$

The First Law of Thermodynamics

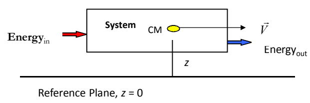
The first law of thermodynamics is known as the conservation of energy principle. It states that energy can be neither created nor destroyed; it can only change forms. Joule's experiments lead to the conclusion: For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process. A major consequence of the first law is the existence and definition of the property total energy E introduced earlier.

The First Law and the Conservation of Energy

The first law of thermodynamics is an expression of the conservation of energy principle.

Energy can cross the boundaries of a closed system in the form of heat or work. Energy may cross a system boundary (control surface) of an open system by heat, work and mass transfer.

A system moving relative to a reference plane is shown below where z is the elevation of the center of mass above the reference plane and $\vec{V}$ is the velocity of the center of mass.



For the system shown above, the **conservation of energy principle** or **the first law of thermodynamics** is expressed as

$$\begin{pmatrix}\textit{Total}\text{ energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\textit{Total}\text{ energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{The change in total}\\ \text{energy of the system}\end{pmatrix}$$

or

$$E_{in} - E_{out} = \Delta E_{system}$$

Normally the stored energy, or total energy, of a system is expressed as the sum of three separate energies. The **total energy of the system**, E_{system}, is given as

$$E = Internal\ energy + Kinetic\ energy + Potential\ energy$$
$$E = U + KE + PE$$

Recall that *U* is the sum of the energy contained within the molecules of the system other than the kinetic and potential energies of the system as a whole and is called the internal energy. The internal energy *U* is dependent on the state of the system and the mass of the system.

For a system moving relative to a reference plane, the kinetic energy *KE* and the potential energy *PE* are given by

$$KE = \int_{\vec{V}=0}^{\vec{V}} m\vec{V}\,d\vec{V} = \frac{m\vec{V}^2}{2}$$
$$PE = \int_{z=0}^{z} mg\,dz = mgz$$

The change in stored energy for the system is

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

Now the **conservation of energy principle,** or the **first law of thermodynamics for closed systems,** is written as

$$E_{in} - E_{out} = \Delta U + \Delta KE + \Delta PE$$

If the system does not move with a velocity and has no change in elevation, it is called a ***stationary system***, and the conservation of energy equation reduces to

$$E_{in} - E_{out} = \Delta U$$

Mechanisms of Energy Transfer, Ein and Eout

The mechanisms of energy transfer at a system boundary are: Heat, Work, mass flow. Only heat and work energy transfers occur at the boundary of a closed (fixed mass) system. Open systems or control volumes have energy transfer across the control surfaces by mass flow as well as heat and work.

1. Heat Transfer, Q: Heat is energy transfer caused by a temperature difference between the system and its surroundings. When added to a system heat transfer causes the energy of a system to increase and heat transfer from a system causes the energy to decrease. Q is zero for adiabatic systems.

2. Work, W: Work is energy transfer at a system boundary could have caused a weight to be raised. When added to a system, the energy of the system increases; and when done by a system, the energy of the system decreases. W is zero for systems having no work interactions at its boundaries.

3. Mass flow, m: As mass flows into a system, the energy of the system increases by the amount of energy carried with the mass into the system. Mass leaving the system carries energy with it, and the energy of the system decreases. Since no mass transfer occurs at the boundary of a closed system, energy transfer by mass is zero for closed systems.

The energy balance for a general system is

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

Expressed more compactly, the energy balance is

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

or on a rate form, as

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

For constant rates, the total quantities during the time interval Δt are related to the quantities per unit time as

$$Q = \dot{Q}\,\Delta t, \quad W = \dot{W}\,\Delta t, \quad \text{and} \quad \Delta E = \Delta \dot{E}\,\Delta t \quad (kJ)$$

The energy balance may be expressed on a per unit mass basis as

$$e_{in} - e_{out} = \Delta e_{system} \qquad (kJ/kg)$$

and in the differential forms as

$$\delta E_{in} - \delta E_{out} = \delta E_{system} \qquad (kJ)$$

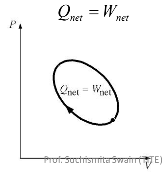
$$\delta e_{in} - \delta e_{out} = \delta e_{system} \qquad (kJ/kg)$$

First Law for a Cycle

A thermodynamic cycle is composed of processes that cause the working fluid to undergo a series of state changes through a process or a series of processes. These processes occur such that the final and initial states are identical and the change in internal energy of the working fluid is zero for whole numbers of cycles. Since thermodynamic cycles can be viewed as having heat and work (but not mass) crossing the cycle system boundary, the first law for a closed system operating in a thermodynamic cycle becomes

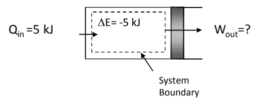
$$Q_{net} - W_{net} = \Delta E_{cycle}$$

$$Q_{net} = W_{net}$$



Example 2-4

A system receives 5 kJ of heat transfer and experiences a decrease in energy in the amount of 5 kJ. Determine the amount of work done by the system.



We apply the first law as

$$E_{in} - E_{out} = \Delta E_{system}$$
$$E_{in} = Q_{in} = 5\,kJ$$
$$E_{out} = W_{out}$$
$$\Delta E_{system} = -5\,kJ$$
$$E_{out} = E_{in} - \Delta E_{system}$$
$$W_{out} = \left[5 - (-5)\right] kJ$$
$$W_{out} = 10\,kJ$$

The work done by the system equals the energy input by heat plus the decrease in the energy of the working fluid.

Example 2-5

A steam power plant operates on a thermodynamic cycle in which water circulates through a boiler, turbine, condenser, pump, and back to the boiler. For each kilogram of steam (water) flowing through the cycle, the cycle receives 2000 kJ of heat in the boiler, rejects 1500 kJ of heat to the environment in the condenser, and receives 5 kJ of work in the cycle pump. Determine the work done by the steam in the turbine, in kJ/kg.

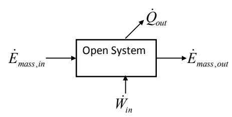
For a thermodynamic cycle, the first law becomes

$$Q_{net} - W_{net} = \Delta E_{cycle}$$
$$Q_{net} = W_{net}$$
$$Q_{in} - Q_{out} = W_{out} - W_{in}$$
$$W_{out} = Q_{in} - Q_{out} - W_{in}$$
$$\text{Let} \quad w = \frac{W}{m} \quad \text{and} \quad q = \frac{Q}{m}$$
$$w_{out} = q_{in} - q_{out} + w_{in}$$
$$w_{out} = (2000 - 1500 + 5)\,\frac{kJ}{kg}$$
$$w_{out} = 505\,\frac{kJ}{kg}$$

Example 2-6

Air flows into an open system and carries energy at the rate of 300 kW. As the air flows through the system it receives 600 kW of work and loses 100 kW of energy by heat transfer to the surroundings. If the system experiences no energy change as the air flows through it, how much energy does the air carry as it leaves the system, in kW?

System sketch:



Conservation of Energy:

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}$$
$$\dot{E}_{mass,in} + \dot{W}_{in} - \dot{E}_{mass,out} - \dot{Q}_{out} = \Delta \dot{E}_{system} = 0$$
$$\dot{E}_{mass,out} = \dot{E}_{mass,in} + \dot{W}_{in} - \dot{Q}_{out}$$
$$\dot{E}_{mass,out} = (300 + 600 - 100)\,kW = 800\,kW$$

Energy Conversion Efficiencies

A measure of performance for a device is its efficiency and is often given the symbol η. Efficiencies are expressed as follows:

$$\eta = \frac{\text{Desired Result}}{\text{Required Input}}$$

How will you measure your efficiency in this thermodynamics course?

Efficiency as the Measure of Performance of a Thermodynamic cycle

A system has completed a thermodynamic cycle when the working fluid undergoes a series of processes and then returns to its original state, so that the properties of the system at the end of the cycle are the same as at its beginning.

Thus, for whole numbers of cycles

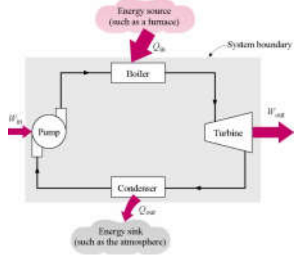
$$P_f = P_i,\ T_f = T_i,\ u_f = u_i,\ v_f = v_i,\ etc.$$

Heat Engine

A heat engine is a thermodynamic system operating in a thermodynamic cycle to which net heat is transferred and from which net work is delivered.

The system, or working fluid, undergoes a series of processes that constitute the heat engine cycle.

The following figure illustrates a steam power plant as a heat engine operating in a thermodynamic cycle.



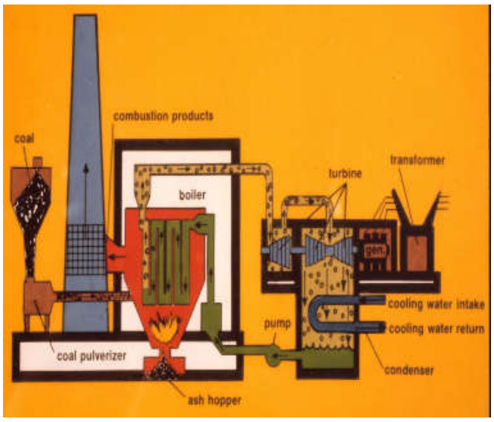


Photo courtesy of Progress Energy Carolinas, Inc.

Thermal Efficiency, ηth

The thermal efficiency is the index of performance of a work-producing device or a heat engine and is defined by the ratio of the net work output (the desired result) to the heat input (the cost or required input to obtain the desired result).

$$\eta_{th} = \frac{\text{Desired Result}}{\text{Required Input}}$$

For a heat engine the desired result is the net work done ($W_{out} - W_{in}$) and the input is the heat supplied to make the cycle operate Q_{in}. The thermal efficiency is always less than 1 or less than 100 percent.

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

where

$$W_{net,out} = W_{out} - W_{in}$$
$$Q_{in} \neq Q_{net}$$

Here, the use of the *in* and *out* subscripts means to use the magnitude (take the positive value) of either the work or heat transfer and let the minus sign in the net expression take care of the direction.

Example 2-7

In example 2-5 the steam power plant received 2000 kJ/kg of heat, 5 kJ/kg of pump work, and produced 505 kJ/kg of turbine work. Determine the thermal efficiency for this cycle.

We can write the thermal efficiency on a per unit mass basis as:

$$\eta_{th} = \frac{w_{net,out}}{q_{in}}$$
$$= \frac{w_{out} - w_{in}}{q_{in}} = \frac{(505-5)\frac{kJ}{kg}}{2000\frac{kJ}{kg}}$$
$$= 0.25 \quad \text{or} \quad 25\%$$

Combustion Efficiency

Consider the combustion of a fuel-air mixture as shown below.

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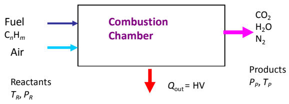

Fuels are usually composed of a compound or mixture containing carbon, C, and hydrogen, H_2. During a complete combustion process all of the carbon is converted to carbon dioxide and all of the hydrogen is converted to water. For stoichiometric combustion (theoretically correct amount of air is supplied for complete combustion) where both the reactants (fuel plus air) and the products (compounds formed during the combustion process) have the same temperatures, the heat transfer from the combustion process is called the heating value of the fuel.

The **lower heating value, LHV**, is the heating value when water appears as a gas in the products.

$$LHV = Q_{out} \ with \ H_2O_{vapor} \ in \ products$$

The lower heating value is often used as the measure of energy per kg of fuel supplied to the gas turbine engine because the exhaust gases have such a high temperature that the water formed is a vapor as it leaves the engine with other products of combustion.

The **higher heating value, HHV**, is the heating value when water appears as a liquid in the products.

$$HHV = Q_{out} \ with \ H_2O_{liquid} \ in \ products$$

The higher heating value is often used as the measure of energy per kg of fuel supplied to the steam power cycle because there are heat transfer processes within the cycle that absorb enough energy from the products of combustion that some of the water vapor formed during combustion will condense.

Combustion efficiency is the ratio of the actual heat transfer from the combustion process to the heating value of the fuel.

$$\eta_{combustion} = \frac{Q_{out}}{HV}$$

Combustion Efficiency

Combustion efficiency is the ratio of the actual heat transfer from the combustion process to the heating value of the fuel.

$$\eta_{combustion} = \frac{Q_{out}}{HV}$$

Example 2-8

A steam power plant receives 2000 kJ of heat per unit mass of steam flowing through the steam generator when the steam flow rate is 100 kg/s. If the fuel supplied to the combustion chamber of the steam generator has a higher heating value of 40,000 kJ/kg of fuel and the combustion efficiency is 85%, determine the required fuel flow rate, in kg/s.

$$\eta_{combustion} = \frac{Q_{out}}{HV} = \frac{\dot{m}_{steam} q_{out\,to\,steam}}{\dot{m}_{fuel} HHV}$$

$$\dot{m}_{fuel} = \frac{\dot{m}_{steam} q_{out\,to\,steam}}{\eta_{combustion} HHV}$$

$$\dot{m}_{fuel} = \frac{\left(100 \frac{kg_{steam}}{s}\right)\left(2000 \frac{kJ}{kg_{steam}}\right)}{(0.85)\left(40000 \frac{kJ}{kg_{fuel}}\right)}$$

$$\dot{m}_{fuel} = 5.88 \frac{kg_{fuel}}{s}$$

Generator Efficiency:

$$\eta_{generator} = \frac{\dot{W}_{electrical\,output}}{\dot{W}_{mechanical\,input}}$$

Power Plant Overall Efficiency:

$$\eta_{overall} = \left(\frac{\dot{Q}_{in,cycle}}{\dot{m}_{fuel} HHV_{fuel}}\right)\left(\frac{\dot{W}_{net,cycle}}{\dot{Q}_{in,cycle}}\right)\left(\frac{\dot{W}_{net,electrical\,output}}{\dot{W}_{net,cycle}}\right)$$

$$\eta_{overall} = \eta_{combustion}\eta_{thermal}\eta_{generator}$$

$$\eta_{overall} = \frac{\dot{W}_{net,electrical\,output}}{\dot{m}_{fuel} HHV_{fuel}}$$

Motor Efficiency:

$$\eta_{motor} = \frac{\dot{W}_{mechanical\,output}}{\dot{W}_{electrical\,input}}$$

Lighting Efficacy:

$$Lighting\ \ Efficacy = \frac{\text{Amount of Light in Lumens}}{\text{Watts of Electricity Consumed}}$$

Type of lighting	Efficacy, lumens/W
Ordinary Incandescent	6 - 20
Ordinary Fluorescent	40 - 60

Effectiveness of Conversion of Electrical or chemical Energy to Heat for Cooking, Called Efficacy of a Cooking Appliance:

$$Cooking\ \ Efficacy = \frac{\text{Useful Energy Transferred to Food}}{\text{Energy Consumed by Appliance}}$$

First Law applied to Closed System

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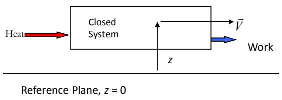
The first law of thermodynamics is an expression of the conservation of energy principle. Energy can cross the boundaries of a closed system in the form of heat or work. Energy transfer across a system boundary due solely to the temperature difference between a system and its surroundings is called heat.

Work energy can be thought of as the energy expended to lift a weight.

Closed System First Law

A closed system moving relative to a reference plane is shown below where z is the elevation of the center of mass above the reference plane and $\vec{V}$ is the velocity of the center of mass.



For the closed system shown above, the **conservation of energy principle** or **the first law of thermodynamics** is expressed as

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{The change in total}\\ \text{energy of the system}\end{pmatrix}$$

or

$$E_{in} - E_{out} = \Delta E_{system}$$

According to classical thermodynamics, we consider the energy added to be net heat transfer to the closed system and the energy leaving the closed system to be net work done by the closed system. So

$$Q_{net} - W_{net} = \Delta E_{system}$$

Where

$$Q_{net} = Q_{in} - Q_{out}$$
$$W_{net} = (W_{out} - W_{in})_{other} + W_b$$
$$W_b = \int_1^2 PdV$$

Normally the stored energy, or total energy, of a system is expressed as the sum of three separate energies. The **total energy of the system**, E_{system}, is given as

$$E = Internal\ energy + Kinetic\ energy + Potential\ energy$$
$$E = U + KE + PE$$

Recall that *U* is the sum of the energy contained within the molecules of the system other than the kinetic and potential energies of the system as a whole and is called the internal energy. The internal energy *U* is dependent on the state of the system and the mass of the system.

For a system moving relative to a reference plane, the kinetic energy *KE* and the potential energy *PE* are given by

$$KE = \int_{\vec{V}=0}^{\vec{V}} m\vec{V}\, d\vec{V} = \frac{m\vec{V}^2}{2}$$

$$PE = \int_{z=0}^{z} mg\, dz = mgz$$

The change in stored energy for the system is

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

Now the **conservation of energy principle,** or the **first law of thermodynamics for closed systems,** is written as

$$Q_{net} - W_{net} = \Delta U + \Delta KE + \Delta PE$$

If the system does not move with a velocity and has no change in elevation, the conservation of energy equation reduces to

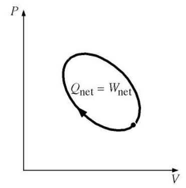
$$Q_{net} - W_{net} = \Delta U$$

We will find that this is the most commonly used form of the first law.

Closed System First Law for a Cycle

Since a thermodynamic cycle is composed of processes that cause the working fluid to undergo a series of state changes through a series of processes such that the final and initial states are identical, the change in internal energy of the working fluid is zero for whole numbers of cycles. The first law for a closed system operating in a thermodynamic cycle becomes

$$Q_{net} - W_{net} = \Delta U_{cycle}$$
$$Q_{net} = W_{net}$$



Example 4-1

Complete the table given below for a closed system under going a cycle.

Process	Q_{net} kJ	W_{net} kJ	$U_2 - U_1$ kJ
1-2	+5		-5
2-3	+20	+10	
3-1	-5		
Cycle			

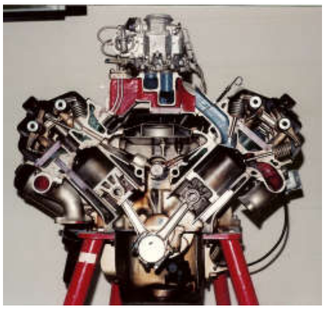
(Answer to above problem) Row 1: +10, Row 2: +10, Row 3: 0, -5
Row 4: +20, +20, 0

In the next section we will look at boundary work in detail.

Review the text material on other types of work such as shaft work, spring work, electrical work.

Closed system boundary work

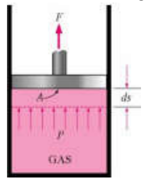
The piston-cylinders of the internal combustion engine shown below may be considered to operate as a closed system when the intake and exhaust valves are closed.



This internal combustion engine is an eight piston-cylinder device.

Boundary Work

Work is energy expended when a force acts through a displacement. Boundary work occurs because the mass of the substance contained within the system boundary causes a force, the pressure times the surface area, to act on the boundary surface and make it move. This is what happens when products of combustion, the "gas" in the figure below, of an internal combustion engine contained in a piston-cylinder device expands against the piston and forces the piston to move; thus, boundary work is done by the gas on the piston. Note the "gas" could also be a real fluid such as steam or refrigerant-134a.



Boundary work is then calculated from

$$W_b = \int_1^2 \delta W_b = \int_1^2 F\,ds = \int_1^2 \frac{F}{A} A\,ds$$
$$= \int_1^2 P\,dV$$

Since the work is process dependent, the differential of boundary work δW_b

$$\delta W_b = PdV$$

is called inexact. The above equation for W_b is valid for a quasi-equilibrium process and gives the maximum work done during expansion and the minimum work input during compression. In an expansion process the boundary work must overcome friction, push the atmospheric air out of the way, and rotate a crankshaft.

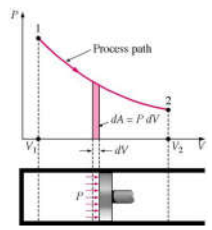
$$W_b = W_{friction} + W_{atm} + W_{crank}$$
$$= \int_1^2 (F_{friction} + P_{atm} A + F_{crank})ds$$

To calculate the boundary work, the process by which the system changed states must be known. Once the process is determined, the pressure-volume relationship for the process can be obtained and the integral in the boundary work equation can be performed. For each process we need to determine

$$P = f(V)$$

So as we work problems, we will be asking, "What is the pressure-volume relationship for the process?" Remember that this relation is really the force-displacement function for the process.

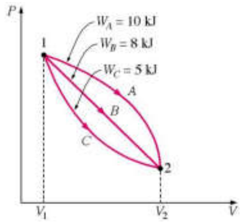
The boundary work is equal to the area under the process curve plotted on the pressure-volume diagram.



Note from the above figure:

P is the absolute pressure and is always positive.
When dV is positive, W_b is positive.
When dV is negative, W_b is negative.

Since the areas under different process curves on a *P-V* diagram are different, the boundary work for each process will be different. The next figure shows that each process gives a different value for the boundary work.



An example of negative classical thermodynamics boundary work is the work required to drive a compressor. The figure below shows a 7.5 horse power, two stage (two pistons) compressor with intercooling attached to an eighty gallon reservoir (see Chapter 7 for a discussion of this device).

The calculated boundary work W_{net} to compress the gas will be negative because the pistons do work on the air.

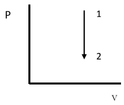
Of course, the actual work supplied by the motor W_{in} is negative of the calculated work.

Photo by M. Boles

Some Typical Processes

Constant volume process

If the volume is held constant, dV = 0, and the boundary work equation becomes

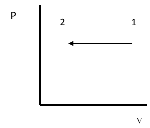


P-V diagram for *V* = constant

$$W_b = \int_1^2 PdV = 0$$

If the working fluid is an ideal gas, what will happen to the temperature of the gas during this constant volume process?

Constant pressure process



P-V DIAGRAM for *P* = CONSTANT

If the pressure is held constant, the boundary work equation becomes

$$W_b = \int_1^2 PdV = P\int_1^2 dV = P(V_2 - V_1)$$

For the constant pressure process shown above, is the boundary work positive or negative and why?

Constant temperature process, ideal gas

If the temperature of an ideal gas system is held constant, then the equation of state provides the pressure-volume relation

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

Then, the boundary work is

$$W_b = \int_1^2 PdV = \int_1^2 \frac{mRT}{V} dV$$
$$= mRT \ln\left(\frac{V_2}{V_1}\right)$$

Note: The above equation is the result of applying the ideal gas assumption for the equation of state. For real gases undergoing an isothermal (constant temperature) process, the integral in the boundary work equation would be done numerically.

The polytropic process

The polytropic process is one in which the pressure-volume relation is given as

$$PV^n = \text{constant}$$

The exponent n may have any value from minus infinity to plus infinity depending on the process. Some of the more common values are given below.

Process	**Exponent *n***
Constant pressure	0
Constant volume	∞
Isothermal & ideal gas	1
Adiabatic & ideal gas	$k = C_P/C_V$

Here, k is the ratio of the specific heat at constant pressure C_P to specific heat at constant volume C_V. The specific heats will be discussed later.

The boundary work done during the polytropic process is found by substituting the pressure-volume relation into the boundary work equation. The result is

$$W_b = \int_1^2 P dV = \int_1^2 \frac{Const}{V^n} dV$$

$$= \frac{P_2V_2 - P_1V_1}{1-n}, \ \text{n} \neq 1$$

$$= PV \ln\left(\frac{V_2}{V_1}\right), \ \text{n} = 1$$

Note: for the polytropic process the constant, ***Const*** = $P_1V_1 = P_2V_2$

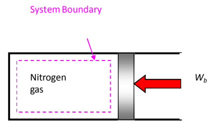
Notice that the result we obtained for an ideal gas undergoing a polytropic process when n = 1 is identical to that for an ideal gas undergoing the isothermal process.

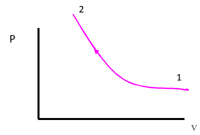
Example 4-2

Three kilograms of nitrogen gas at 27°C and 0.15 MPa are compressed isothermally to 0.3 MPa in a piston-cylinder device. Determine the minimum work of compression, in kJ.

__System__: Nitrogen contained in a colsed, piston-cylinder device.

__Process:__ Constant temperature





P-V DIAGRAM for *T* = CONSTANT

__Property Relation:__ Check the reduced temperature and pressure for nitrogen. The critical state properties are found in Table A-1.

$$T_{R1} = \frac{T_1}{T_{cr}} = \frac{(27+273)K}{126.2K} = 2.38 = T_{R2}$$

$$P_{R1} = \frac{P_1}{P_{cr}} = \frac{0.15MPa}{3.39MPa} = 0.044$$

$$P_{R2} = 2P_{R1} = 0.088$$

Since P_R<<1 and T>2T_{cr}, nitrogen is an ideal gas, and we use the ideal gas equation of state as the property relation.

$$PV = mRT$$

__Work Calculation:__

$$W_{net,12} = (W_{net})_{other,12} + W_{b,12}$$

$$W_{b,12} = \int_1^2 P dV = \int_1^2 \frac{mRT}{V} dV$$

$$= mRT \ln\left(\frac{V_2}{V_1}\right)$$

For an ideal gas in a closed system (mass = constant), we have

$$m_1 = m_2$$

$$\frac{P_1V_1}{RT_1} = \frac{P_2V_2}{RT_2}$$

Since the *R*'s cancel, we obtain the combined ideal gas equation. Since $T_2 = T_1$,

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

$$W_{b,12} = mRT \ln\left(\frac{P_1}{P_2}\right)$$

$$= (3\,kg)\left(0.2968\frac{kJ}{kg-K}\right)(300K)\ln\left(\frac{0.15\,MPa}{0.30\,MPa}\right)$$

$$= -184.5\,kJ$$

The net work is

$$W_{net,12} = 0 + W_{b,12} = -184.5\,kJ$$

On a per unit mass basis

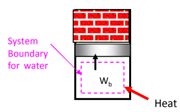
$$w_{net,12} = \frac{W_{net,12}}{m} = -61.5\frac{kJ}{kg}$$

The net work is negative because work is done **on** the system during the compression process. Thus, the work **done on** the system is 184.5 kJ, or 184.5 kJ of work energy is required to compress the nitrogen.

Example 4-3

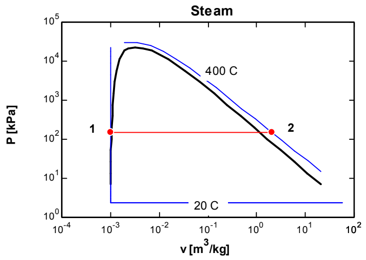
Water is placed in a piston-cylinder device at 20 °C, 0.1 MPa. Weights are placed on the piston to maintain a constant force on the water as it is heated to 400 °C. How much work does the water do on the piston?

__System__: The water contained in the piston-cylinder device



__Property Relation__: Steam tables

__Process__: Constant pressure



Work Calculation:

Since there is no W_{other} mentioned in the problem, the net work is

$$W_{net,12} = W_{b,12} = \int_1^2 PdV = P\int_1^2 dV = P(V_2 - V_1)$$

Since the mass of the water is unknown, we calculate the work per unit mass.

$$w_{b,12} = \frac{W_{b,12}}{m} = \frac{P(V_2 - V_1)}{m} = P(v_2 - v_1)$$

At T_1 = 20°C, P_{sat} = 2.339 kPa. Since P_1 > 2.339 kPa, state 1 is compressed liquid. Thus,

$v_1 \cong v_f$ at 20 °C = 0.001002 m³/ kg

At $P_2 = P_1$ = 0.1 MPa, $T_2 > T_{sat}$ at 0.1 MPa = 99.61°C.

So, state 2 is superheated. Using the superheated tables at 0.1 MPa, 400°C

$$w_{b,12} = P(v_2 - v_1) \qquad v_2 = 3.1027 \text{ m}^3/\text{kg}$$

$$= 0.1\, MPa(3.1027 - 0.001002)\frac{m^3}{kg}\frac{10^3 kPa}{MPa}\frac{kJ}{m^3 kPa}$$

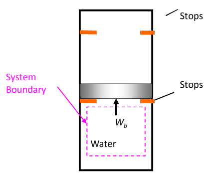
$$= 310.2\frac{kJ}{kg}$$

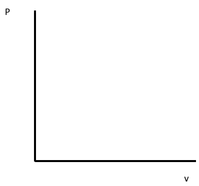
The water does work on the piston in the amount of 310.2 kJ/kg.

Example 4-4

One kilogram of water is contained in a piston-cylinder device at 100 °C. The piston rests on lower stops such that the volume occupied by the water is 0.835 m³. The cylinder is fitted with an upper set of stops. When the piston rests against the upper stops, the volume enclosed by the piston-cylinder device is 0.841 m³. A pressure of 200 kPa is required to support the piston. Heat is added to the water until the water exists as a saturated vapor. How much work does the water do on the piston?

System: The water contained in the piston-cylinder device





Property Relation: Steam tables

Process: Combination of constant volume and constant pressure processes to be shown on the *P-v* diagram with respect to the saturation lines as the problem is solved.

Work Calculation:

The specific volume at state 1 is $$v_1 = \frac{V_1}{m} = \frac{0.835\,\text{m}^3}{1\,\text{kg}} = 0.835\frac{\text{m}^3}{\text{kg}}$$

At T_1 = 100°C, $$v_f = 0.001044\frac{m^3}{kg} \qquad v_g = 1.6720\frac{m^3}{kg}$$

Therefore, $v_f < v_1 < v_g$ and state 1 is in the saturation region; so P_1 = 101.35 kPa. Show this state on the P-v diagram.

Now let's consider the processes for the water to reach the final state.

Process 1-2: The volume stays constant until the pressure increases to 200 kPa. Then the piston will move.

$$v_2 = v_1 = 0.835\frac{m^3}{kg}$$

Process 2-3: Piston lifts off the bottom stops while the pressure stays constant. Does the piston hit the upper stops before or after reaching the saturated vapor state?

Let's set $$v_3 = \frac{V_3}{m} = \frac{0.841 m^3}{1 kg} = 0.841\frac{m^3}{kg}$$

At $P_3 = P_2$ = 200 kPa $$v_f = 0.001061\frac{m^3}{kg} \qquad v_g = 0.88578\frac{m^3}{kg}$$

Thus, $v_f < v_3 < v_g$. So, the piston hits the upper stops before the water reaches the saturated vapor state. Now we have to consider a third process.

Process 3-4: With the piston against the upper stops, the volume remains constant during the final heating to the saturated vapor state and the pressure increases.

Because the volume is constant in process 3-to-4, $v_4 = v_3$ = 0.841 m³/kg and v_4 is a saturated vapor state. Interpolating in either the saturation pressure table or saturation temperature table at $v_4 = v_g$ gives

State 4:

$$\left.\begin{array}{l} P_4 = 211.3\,kPa \\ v_4 = v_g \end{array}\right\} \quad T_4 = 122°C$$

The net work for the heating process is (the "other" work is zero)

$$W_{net,14} = W_{b,14} = \int_1^4 PdV = \int_1^2 PdV + \int_2^3 PdV + \int_3^4 PdV$$

$$= 0 + mP(v_3 - v_2) + 0$$

$$= (1kg)(200kPa)(0.841 - 0.835)\frac{m^3}{kg}\frac{kJ}{m^3 kPa}$$

$$= 1.2\ kJ$$

Next in Example 4-5, we will apply the conservation of energy, or the first law of thermodynamics, to this process to determine the amount of heat transfer required.

Example 4-5

Find the required heat transfer to the water in Example 4-4.

Review the solution procedure of Example 4-4 and then apply the first law to the process.

Conservation of Energy:

$$E_{in} - E_{out} = \Delta E$$

$$Q_{net,14} - W_{net,14} = \Delta U_{14}$$

In Example 4-4 we found that

$$W_{net,14} = 1.2\ kJ$$

The heat transfer is obtained from the first law as

$$Q_{net,14} = W_{net,14} + \Delta U_{14}$$

where

$$\Delta U_{14} = U_4 - U_1 = m(u_4 - u_1)$$

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At state 1, T_1 = 100°C, v_1 = 0.835 m^3/kg and $v_f < v_1 < v_g$ at T_1. The quality at state 1 is

$$v_1 = v_f + x_1 v_{fg}$$

$$x_1 = \frac{v_1 - v_f}{v_{fg}} = \frac{0.835 - 0.001043}{1.6720 - 0.001043} = 0.499$$

$$u_1 = u_f + x_1 u_{fg}$$

$$= 419.06 + (0.499)(2087.0)$$

$$= 1460.5\,\frac{kJ}{kg}$$

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Because state 4 is a saturated vapor state and v_4 = 0.841 m^3/kg, interpolating in either the saturation pressure table or saturation temperature table at $v_4 = v_g$ gives

$$u_4 = 2531.48\,\frac{kJ}{kg}$$

Now

$$\Delta U_{14} = m(u_4 - u_1)$$

$$= (1\ kg)(2531.48 - 1460.5)\,\frac{kJ}{kg}$$

$$= 1071.0\ kJ$$

The heat transfer is

$$Q_{net,14} = W_{net,14} + \Delta U_{14}$$

$$= 1.2\ kJ + 1071.0\ kJ$$

$$= 1072.2\ kJ$$

Heat in the amount of 1072.42 kJ is added to the water.

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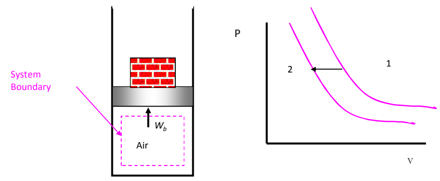
Example 4-6

Air undergoes a constant pressure cooling process in which the temperature decreases by 100°C. What is the magnitude and direction of the work for this process?

System:



Property Relation: Ideal gas law, $Pv = RT$

Process: Constant pressure

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Work Calculation: Neglecting the "other" work

$$W_{net,12} = 0 + W_{b,12} = \int_1^2 P dV = P(V_2 - V_1)$$

$$= mR(T_2 - T_1)$$

The work per unit mass is

$$w_{net,12} = \frac{W_{net,12}}{m} = R(T_2 - T_1)$$

$$= (0.287\,\frac{kJ}{kg \cdot K})(-100\,K) = -28.7\,\frac{kJ}{kg}$$

If we want to determine the required heat transfer for this process, we apply the first law as $Q_{net} - W_{net} = \Delta U$. To determine the internal energy change of the air, we now investigate how to find the internal energy change of an ideal gas.

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Specific Heats and Changes in Internal Energy and Enthalpy for Ideal Gases

Before the first law of thermodynamics can be applied to systems, ways to calculate the change in internal energy of the substance enclosed by the system boundary must be determined. For real substances like water, the property tables are used to find the internal energy change. For ideal gases the internal energy is found by knowing the specific heats. Physics defines the amount of energy needed to raise the temperature of a unit of mass of a substance one degree as the specific heat at constant volume C_V for a constant-volume process, and the specific heat at constant pressure C_P for a constant-pressure process. Recall that enthalpy h is the sum of the internal energy u and the pressure-volume product Pv.

$$h = u + Pv$$

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In thermodynamics, the specific heats are defined as

$$C_V = \left(\frac{\partial u}{\partial T}\right)_v \quad \text{and} \quad C_P = \left(\frac{\partial h}{\partial T}\right)_P$$

Simple Substance

The thermodynamic state of a simple, homogeneous substance is specified by giving any two independent, intensive properties. Let's consider the internal energy to be a function of *T* and *v* and the enthalpy to be a function of *T* and *P* as follows:

$$u = u(T, v) \quad \text{and} \quad h = h(T, P)$$

The total differential of *u* is

$$du = \left(\frac{\partial u}{\partial T}\right)_v dT + \left(\frac{\partial u}{\partial v}\right)_T dv$$

$$or$$

$$du = C_v\, dT + \left(\frac{\partial u}{\partial v}\right)_T dv$$

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The total differential of *h* is

$$dh = \left(\frac{\partial h}{\partial T}\right)_P dT + \left(\frac{\partial h}{\partial P}\right)_T dP$$

$$or$$

$$dh = C_P\, dT + \left(\frac{\partial h}{\partial P}\right)_T dP$$

Using thermodynamic relation theory, we could evaluate the remaining partial derivatives of *u* and h in terms of functions of *P*,*v*, and *T*. These functions depend upon the equation of state for the substance. Given the specific heat data and the equation of state for the substance, we can develop the property tables such as the steam tables.

Ideal Gases

For ideal gases, we use the thermodynamic function theory of Chapter 12 and the equation of state ($Pv = RT$) to show that *u*, *h*, C_V, and C_P are functions of temperature alone.

For example when total differential for $u = u(T,v)$ is written as above, the function theory of Chapter 12 shows that

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$$du = C_v\, dT + \left(\frac{\partial u}{\partial v}\right)_T dv$$

$$du = C_v\, dT + \left[T\left(\frac{\partial P}{\partial T}\right)_v - P\right]dv$$

Let's evaluate the following partial derivative for an ideal gas.

$$\left(\frac{\partial u}{\partial v}\right)_T = T\left(\frac{\partial P}{\partial T}\right)_v - P$$

For ideal gases

$$P = \frac{RT}{v}$$

$$\left(\frac{\partial P}{\partial T}\right)_v = \frac{R}{v}$$

$$\left(\frac{\partial u}{\partial v}\right)_T = T\frac{R}{v} - P = P - P = 0$$

1 May 2020 Prof. Suchismita Swain (TITE) 75

This result helps to show that the internal energy of an ideal gas does not depend upon specific volume. To completely show that internal energy of an ideal gas is independent of specific volume, we need to show that the specific heats of ideal gases are functions of temperature only. We will do this later in Chapter 12. A similar result that applies to the enthalpy function for ideal gases can be reviewed in Chapter 12.

Then for ideal gases,

$$C_V = C_V(T) \quad \text{and} \quad \left(\frac{\partial u}{\partial v}\right)_T \equiv 0$$

$$C_P = C_P(T) \quad \text{and} \quad \left(\frac{\partial h}{\partial P}\right)_T \equiv 0$$

The ideal gas specific heats are written in terms of ordinary differentials as

$$C_V = \left(\frac{du}{dT}\right)_{ideal\ gas}$$

$$C_P = \left(\frac{dh}{dT}\right)_{ideal\ gas}$$

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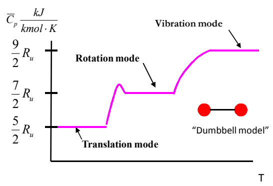
Using the simple "dumbbell model" for diatomic ideal gases, statistical thermodynamics predicts the molar specific heat at constant pressure as a function of temperature to look like the following

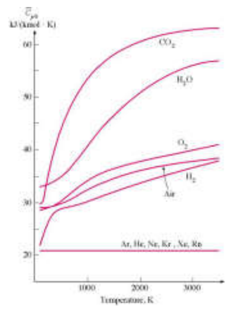


The following figure shows how the molar specific heats vary with temperature for selected ideal gases.

Read more about specific heats at

http://www.iun.edu/~cpanhd/C101webnotes/matter-and-energy/specificheat.html

1 May 2020 Prof. Suchismita Swain (TITE) 77



The differential changes in internal energy and enthalpy for ideal gases become

$$du = C_V\, dT$$

$$dh = C_P\, dT$$

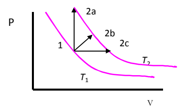
The change in internal energy and enthalpy of ideal gases can be expressed as

1 May 2020 Prof. Suchismita Swain (TITE) 78

$$\Delta u = u_2 - u_1 = \int_1^2 C_V(T)dT = C_{V,ave}(T_2 - T_1)$$

$$\Delta h = h_2 - h_1 = \int_1^2 C_P(T)dT = C_{P,ave}(T_2 - T_1)$$

where $C_{V,ave}$ and $C_{P,ave}$ are average or constant values of the specific heats over the temperature range. We will drop the **ave** subscript shortly.



P-V diagram for several processes for an ideal gas.

In the above figure an ideal gas undergoes three different process between the same two temperatures.

Process 1-2a: Constant volume
Process 1-2b: $P = a + bV$, a linear relationship
Process 1-2c: Constant pressure

These ideal gas processes have the same change in internal energy and enthalpy because the processes occur between the same temperature limits.

$$\Delta u_a = \Delta u_b = \Delta u_c = \int_1^2 C_V(T)dT$$

$$\Delta h_a = \Delta h_b = \Delta h_c = \int_1^2 C_P(T)dT$$

To find Δu and Δh we often use average, or constant, values of the specific heats. Some ways to determine these values are as follows:

1.The best average value (the one that gives the exact results)

See Table A-2(c) for variable specific data.

$$C_{v,ave} = \frac{\int_1^2 C_V(T)dT}{T_2 - T_1} \quad \text{and} \quad C_{P,ave} = \frac{\int_1^2 C_P(T)dT}{T_2 - T_1}$$

2.Good average values are

$$C_{v,ave} = \frac{C_V(T_2) + C_V(T_1)}{2} \quad C_{P,ave} = \frac{C_P(T_2) + C_P(T_1)}{2} \quad \text{and}$$

$$C_{v,ave} = C_V(T_{ave}) \quad C_{P,ave} = C_P(T_{ave})$$

where

$$T_{ave} = \frac{T_2 + T_1}{2}$$

3.Sometimes adequate (and most often used) values are the ones evaluated at 300 K and are given in Table A-2(a).

$$C_{v,ave} = C_V(300K) \quad \text{and} \quad C_{P,ave} = C_P(300K)$$

Let's take a second look at the definition of Δu and Δh for ideal gases. Just consider the enthalpy for now.

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

Let's perform the integral relative to a reference state where $h = h_{ref}$ at $T = T_{ref}$.

$$\Delta h = h_2 - h_1 = \int_{T_1}^{T_{ref}} C_P(T')dT' + \int_{T_{ref}}^{T_2} C_P(T')dT'$$

or

$$\Delta h = h_2 - h_1 = \int_{T_{ref}}^{T_2} C_P(T')dT' - \int_{T_{ref}}^{T_1} C_P(T')dT'$$

$$= (h_2 - h_{ref}) - (h_1 - h_{ref})$$

At any temperature, we can calculate the enthalpy relative to the reference state as

$$h - h_{ref} = \int_{T_{ref}}^{T} C_P(T')dT'$$

$$or$$

$$h = h_{ref} + \int_{T_{ref}}^{T} C_P(T')dT'$$

A similar result is found for the change in internal energy.

$$u = u_{ref} + \int_{T_{ref}}^{T} C_v(T')dT'$$

These last two relations form the basis of the air tables (Table A-17 on a mass basis) and the other ideal gas tables (Tables A-18 through A-25 on a mole basis). When you review Table A-17, you will find *h* and *u* as functions of *T* in K. Since the parameters P_r, v_r, and so, also found in Table A=17, apply to air only in a particular process, call isentropic, you should ignore these parameters until we study Chapter 7. The reference state for these tables is defined as

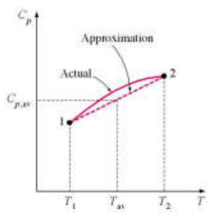
$$u_{ref} = 0 \text{ at } T_{ref} = 0K$$

$$h_{ref} = 0 \text{ at } T_{ref} = 0K$$

A partial listing of data similar to that found in Table A.17 is shown in the following figure.

AIR

T, K	u, kJ/kg	h, kJ/kg
0	0	0
.	.	.
300	214.17	300.19
310	221.25	310.24
.	.	.



In the analysis to follow, the "ave" notation is dropped. In most applications for ideal gases, the values of the specific heats at 300 K given in Table A-2 are adequate constants.

Exercise

Determine the average specific heat for air at 305 K.

$$C_{P,\,ave} =$$

(Answer: 1.005 kJ/kg-K, approximate the derivative of h with respect to T as differences)

Relation between C_P and C_V for Ideal Gases

Using the definition of enthalpy ($h = u + Pv$) and writing the differential of enthalpy, the relationship between the specific heats for ideal gases is

$$h = u + Pv$$

$$dh = du + d(RT)$$

$$C_P dT = C_V dT + RdT$$

$$C_P = C_V + R$$

where *R* is the particular gas constant. The specific heat ratio *k* (fluids texts often use γ instead of *k*) is defined as

$$k = \frac{C_P}{C_V}$$

Extra Problem

Show that

$$C_P = \frac{kR}{k-1} \quad \text{and} \quad C_V = \frac{R}{k-1}$$

Example 2-9

Two kilograms of air are heated from 300 to 500 K. Find the change in enthalpy by assuming

a. Empirical specific heat data from Table A-2(c).
b. Air tables from Table A-17.
c. Specific heat at the average temperature from Table A-2(c).
d. Use the 300 K value for the specific heat from Table A-2(a).

a.Table A-2(c) gives the molar specific heat at constant pressure for air as

$$\overline{C}_P = 28.11 + 0.1967x10^{-2}\,T \; + 0.4802x10^{-5}\,T^2 \text{ - } 1.966x10^{-9}\,T^3 \quad \frac{kJ}{kmol\text{ - }K}$$

The enthalpy change per unit mole is

$$\Delta\overline{h} = \overline{h}_2 - \overline{h}_1 = \int_1^2 \overline{C}_P(T)dT$$

$$= \int_{300K}^{500K}(28.11 + 0.1967x10^{-2}\,T \; + 0.4802x10^{-5}\,T^2 \text{ - } 1.966x10^{-9}\,T^3\,)dT$$

$$= (28.11T + \frac{0.1967x10^{-2}}{2}T^2 \; + \frac{0.4802x10^{-5}}{3}T^3 \text{ - } \frac{1.966x10^{-9}}{4}T^4\,)_{300K}^{500K}$$

$$= 5909.49\,\frac{kJ}{kmol}$$

$$\Delta h = \frac{\Delta\overline{h}}{M} = \frac{5909.49\,\frac{kJ}{kmol}}{28.97\,\frac{kg}{kmol}} = 203.9\,\frac{kJ}{kg}$$

$$\Delta H = m\Delta h = (2\;kg)(203.9\,\frac{kJ}{kg}) = 407.98\;kJ$$

b.Using the air tables, Table A-17, at T_1 = 300 K, h_1 = 300.19 kJ/kg and at T_2 = 500 K, h_2 = 503.02 kJ/kg

$$\Delta H = m\Delta h = (2\;kg)(503.02 - 300.19)\,\frac{kJ}{kg} = 405.66\;kJ$$

The results of parts a and b would be identical if Table A-17 had been based on the same specific heat function listed in Table A-2(c).

c.Let's use a constant specific heat at the average temperature.

T_{ave} = (300 + 500)K/2 = 400 K. At T_{ave} , T_{able} A-2 gives
C_p = 1.013 kJ/(kg·K).

For C_p = constant,

$$\Delta h = h_2 - h_1 = C_{P,ave}(T_2 - T_1)$$
$$= 1.013\,\frac{kJ}{kg\cdot K}(500 - 300)\;K$$
$$= 202.6\,\frac{kJ}{kg}$$

$$\Delta H = m\Delta h = (2\;kg)(202.6)\,\frac{kJ}{kg} = 405.2\;kJ$$

d.Using the 300 K value from Table A-2(a), C_P = 1.005 kJ/kg- K.

For C_P = constant,

$$\Delta h = h_2 - h_1 = C_P(T_2 - T_1)$$
$$= 1.005\,\frac{kJ}{kg\cdot K}(500 - 300)\;K = 201.0\,\frac{kJ}{kg}$$
$$\Delta H = m\Delta h = (2\;kg)(201.0)\,\frac{kJ}{kg} = 402.0\;kJ$$

Extra Problem

Find the change in internal energy for air between 300 K and 500 K, in kJ/kg.

The Systematic Thermodynamics Solution Procedure

When we apply a methodical solution procedure, thermodynamics problems are relatively easy to solve. Each thermodynamics problem is approached the same way as shown in the following, which is a modification of the procedure given in the text:

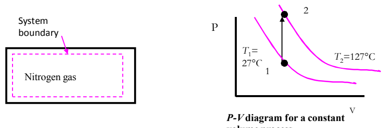
Thermodynamics Solution Method

1. Sketch the system and show energy interactions across the boundaries.
2. Determine the property relation. Is the working substance an ideal gas or a real substance? Begin to set up and fill in a property table.
3. Determine the process and sketch the process diagram. Continue to fill in the property table.
4. Apply conservation of mass and conservation of energy principles.
5. Bring in other information from the problem statement, called physical constraints, such as the volume doubles or the pressure is halved during the process.
6. Develop enough equations for the unknowns and solve.

Example 4-7

A tank contains nitrogen at 27°C. The temperature rises to 127°C by heat transfer to the system. Find the heat transfer and the ratio of the final pressure to the initial pressure.

<u>System</u>: Nitrogen in the tank.



***P-V* diagram for a constant volume process**

<u>**Property Relation**</u>: Nitrogen is an ideal gas. The ideal gas property relations apply. Let's assume constant specific heats. (You are encouraged to rework this problem using variable specific heat data.)

<u>**Process**</u>: Tanks are rigid vessels; therefore, the process is constant volume.

<u>**Conservation of Mass**</u>:

$$m_2 = m_1$$

Using the combined ideal gas equation of state,

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

Since *R* is the particular gas constant, and the process is constant volume,

$$V_2 = V_1$$

$$\frac{P_2}{P_1} = \frac{T_2}{T_1} = \frac{(127+273)K}{(27+273)K} = 1.333$$

Conservation of Energy:

The first law closed system is

$$E_{in} - E_{out} = \Delta E$$

$$Q_{net} - W_{net} = \Delta U$$

For nitrogen undergoing a constant volume process ($dV = 0$), the net work is ($W_{other} = 0$)

$$W_{net,12} = 0 + W_{b,12} = \int_1^2 P dV = 0$$

Using the ideal gas relations with $W_{net} = 0$, the first law becomes (constant specific heats)

$$Q_{net} - 0 = \Delta U = m\int_1^2 C_V dT = mC_V(T_2 - T_1)$$

The heat transfer per unit mass is

$$q_{net} = \frac{Q_{net}}{m} = C_V(T_2 - T_1)$$

$$= 0.743 \frac{kJ}{kg \cdot K}(127-27)K$$

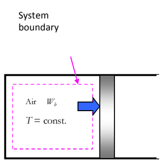
$$= 74.3 \frac{kJ}{kg}$$

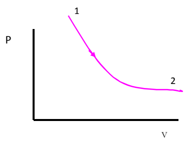
Example 4-8

Air is expanded isothermally at 100°C from 0.4 MPa to 0.1 MPa. Find the ratio of the final to the initial volume, the heat transfer, and work.

System: Air contained in a piston-cylinder device, a closed system

Process: Constant temperature





P-V diagram for *T*= constant

Property Relation: Assume air is an ideal gas and use the ideal gas property relations with constant specific heats.

$$PV = mRT$$

$$\Delta u = C_V(T_2 - T_1)$$

Conservation of Energy:

$$E_{in} - E_{out} = \Delta E$$

$$Q_{net} - W_{net} = \Delta U$$

The system mass is constant but is not given and cannot be calculated; therefore, let's find the work and heat transfer per unit mass.

Work Calculation:

$$W_{net,12} = (W_{net})_{other,12} + W_{b,12}$$

$$W_{b,12} = \int_1^2 P\,dV = \int_1^2 \frac{mRT}{V} dV$$

$$= mRT \ln\left(\frac{V_2}{V_1}\right)$$

Conservation of Mass: For an ideal gas in a closed system (mass = constant), we have

$$m_1 = m_2$$

$$\frac{P_1 V_1}{RT_1} = \frac{P_2 V_2}{RT_2}$$

Since the *R*'s cancel and $T_2 = T_1$

$$\frac{V_2}{V_1} = \frac{P_1}{P_2} = \frac{0.4\,MPa}{0.1\,MPa} = 4$$

Then the work expression per unit mass becomes

$$w_{b,12} = \frac{W_{b,12}}{m} = RT\ln\left(\frac{V_2}{V_1}\right)$$

$$w_{b,12} = \left(0.287\frac{kJ}{kg-K}\right)(100+273)K\,\ln(4)$$

$$= 148.4\frac{kJ}{kg}$$

The net work per unit mass is

$$w_{net,12} = 0 + w_{b,12} = 148.4\frac{kJ}{kg}$$

Now to continue with the conservation of energy to find the heat transfer. Since $T_2 = T_1$ = constant,

$$\Delta U_{12} = m\Delta u_{12} = mC_V(T_2 - T_1) = 0$$

So the heat transfer per unit mass is

$$q_{net} = \frac{Q_{net}}{m}$$
$$q_{net} - w_{net} = \Delta u = 0$$
$$q_{net} = w_{net}$$
$$= 148.4 \frac{kJ}{kg}$$

The heat transferred **to** the air during an isothermal expansion process equals the work **done**.

Examples Using Variable Specific Heats

Review the solutions in Chapter 4 to the ideal gas examples where the variable specific heat data are used to determine the changes in internal energy and enthalpy.

Extra Problem for You to Try:

An ideal gas, contained in a piston-cylinder device, undergoes a polytropic process in which the polytropic exponent *n* is equal to *k*, the ratio of specific heats. Show that this process is adiabatic. When we get to Chapter 7 you will find that this is an important ideal gas process.

Internal Energy and Enthalpy Changes of Solids and Liquids

We treat solids and liquids as incompressible substances. That is, we assume that the density or specific volume of the substance is essentially constant during a process. We can show that the specific heats of incompressible substances (see Chapter 12) are identical.

$$C_P = C_V = C \qquad \left(\frac{kJ}{kg \cdot K}\right)$$

The specific heats of incompressible substances depend only on temperature; therefore, we write the differential change in internal energy as

$$du = C_V\, dT = C dT$$

and assuming constant specific heats, the change in internal energy is

$$\Delta u = C\Delta T = C(T_2 - T_1)$$

Recall that enthalpy is defined as

$$h = u + Pv$$

The differential of enthalpy is

$$dh = du + Pdv + vdP$$

For incompressible substances, the differential enthalpy becomes

$$dv = 0$$
$$dh = du + Pd\cancel{v}^{0} + vdP$$
$$dh = du + vdP$$

Integrating, assuming constant specific heats

$$\Delta h = \Delta u + v\Delta P = C\Delta T + v\Delta P$$

For **solids** the specific volume is approximately zero; therefore,

$$\Delta h_{solid} = \Delta u_{solid} + \cancel{v}^{0}\Delta P$$
$$\Delta h_{solid} = \Delta u_{solid} \cong C\Delta T$$

For **liquids**, two special cases are encountered:

1.**Constant-pressure processes**, as in heaters ($\Delta P = 0$)

$$\Delta h_{liquid} = \Delta u_{liquid} \cong C\Delta T$$

2.**Constant-temperature processes,** as in pumps ($\Delta T = 0$)

$$\Delta h_{liquid} = \Delta u_{liquid} + v\Delta P \cong C\cancel{\Delta}^{0} T + v\Delta P$$
$$\Delta h_{liquid} = v\Delta P$$

We will derive this last expression for Δh again once we have discussed the first law for the open system in Chapter 5 and the second law of thermodynamics in Chapter 7.

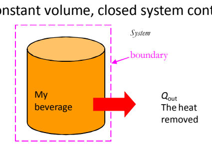
The specific heats of selected liquids and solids are given in Table A-3.

Example 4-8 Incompressible Liquid

A two-liter bottle of your favorite beverage has just been removed from the trunk of your car. The temperature of the beverage is 35°C, and you always drink your beverage at 10°C.

a. How much heat energy must be removed from your two liters of beverage?
b. You are having a party and need to cool 10 of these two-liter bottles in one-half hour. What rate of heat removal, in kW, is required? Assuming that your refrigerator can accomplish this and that electricity costs 10 cents per kW-hr, how much will it cost to cool these 10 bottles?

<u>**System:**</u> The liquid in the constant volume, closed system container



<u>**Property Relation:**</u> Incompressible liquid relations, let's assume that the beverage is mostly water and takes on the properties of liquid water. The specific volume is 0.001 m³/kg, C = 4.18 kJ/kg·K.

<u>**Process:**</u> Constant volume

$$V_2 = V_1$$

<u>**Conservation of Mass:**</u>

$$m_2 = m_1 = m$$
$$m = \frac{V}{v} = \frac{2\ L}{0.001\frac{m^3}{kg}}\left(\frac{m^3}{1000\ L}\right) = 2\ kg$$

<u>**Conservation of Energy:**</u>

The first law closed system is

$$E_{in} - E_{out} = \Delta E$$

Since the container is constant volume and there is no "other" work done on the container during the cooling process, we have

$$W_{net} = \left(W_{net}\right)_{other} + W_b = 0$$

The only energy crossing the boundary is the heat transfer leaving the container. Assuming the container to be stationary, the conservation of energy becomes

$$-E_{out} = \Delta E$$
$$-Q_{out} = \Delta U = mC\Delta T$$
$$-Q_{out} = (2\ kg)(4.18\frac{kJ}{kg \cdot K})(10-35)K$$
$$-Q_{out} = -209.2\ kJ$$
$$Q_{out} = 209.2\ kJ$$

The heat transfer rate to cool the 10 bottles in one-half hour is

$$\dot{Q}_{out} = \frac{(10 bottles)(209.2\frac{kJ}{bottle})}{0.5hr}\left(\frac{1hr}{3600s}\right)\left(\frac{kW}{\frac{kJ}{s}}\right)$$
$$= 1.162\ kW$$
$$Cost = (1.162\ kW)(0.5\ hr)\frac{\$0.10}{kW-hr}$$
$$= \$0.058$$

First Law Applied to Open System

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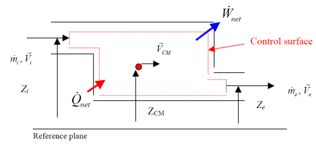
Conservation of Energy for Control volumes

The conservation of mass and the conservation of energy principles for open systems or control volumes apply to systems having mass crossing the system boundary or control surface. In addition to the heat transfer and work crossing the system boundaries, mass carries energy with it as it crosses the system boundaries. Thus, the mass and energy content of the open system may change when mass enters or leaves the control volume.



Typical control volume or open system

Thermodynamic processes involving control volumes can be considered in two groups: steady-flow processes and unsteady-flow processes. During a steady-flow process, the fluid flows through the control volume steadily, experiencing no change with time at a fixed position.

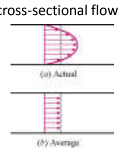
Let's review the concepts of mass flow rate and energy transport by mass.
One should study the development of the general conservation of mass presented in the text. Here we present an overview of the concepts important to successful problem solving techniques.

Mass Flow Rate

Mass flow through a cross-sectional area per unit time is called the mass flow rate $\dot{m}$. Note the dot over the mass symbol indicates a time rate of change. It is expressed as

$$\dot{m} = \int_A \rho \vec{V}_n dA$$

where $\vec{V}_n$ is the velocity normal to the cross-sectional flow area.



If the fluid density and velocity are constant over the flow cross-sectional area, the mass flow rate is

$$\dot{m} = \rho \vec{V}_{ave} A = \frac{\vec{V}_{ave} A}{v}$$

where ρ is the density, kg/m^3 (= 1/v), A is the cross-sectional area, m^2; and $\vec{V}_{ave}$ is the average fluid velocity normal to the area, m/s.

Example 5-1

Refrigerant-134a at 200 kPa, 40% quality, flows through a 1.1-cm inside diameter, *d*, tube with a velocity of 50 m/s. Find the mass flow rate of the refrigerant-134a.

At *P* = 200 kPa, *x* = 0.4 we determine the specific volume from

$$v = v_f + x v_{fg}$$
$$= 0.0007533 + 0.4(0.0999 - 0.0007533)$$
$$= 0.0404\frac{m^3}{kg}$$
$$\dot{m} = \frac{\vec{V}_{ave} A}{v} = \frac{\vec{V}_{ave}}{v}\frac{\pi d^2}{4}$$
$$= \frac{50\ m/s}{0.0404\ m^3/kg}\frac{\pi(0.011\ m)^2}{4}$$
$$= 0.117\frac{kg}{s}$$

The fluid volume flowing through a cross-section per unit time is called the volume flow rate . The volume flow rate is given by integrating the product of the velocity normal to the flow area and the differential flow area over the flow area. If the velocity over the flow area is a constant, the volume flow rate is given by (note we are dropping the "ave" subscript on the velocity)

$$\dot{V} = \vec{V}A \qquad (m^3/s)$$

The mass and volume flow rate are related by

$$\dot{m} = \rho\dot{V} = \frac{\dot{V}}{v} \qquad (kg/s)$$

Example 5-2

Air at 100 kPa, 50oC, flows through a pipe with a volume flow rate of 40 m^3/min. Find the mass flow rate through the pipe, in kg/s.

Assume air to be an ideal gas, so

$$v = \frac{RT}{P} = 0.287\frac{kJ}{kg\cdot K}\frac{(50+273)K}{100kPa}\frac{m^3 kPa}{kJ}$$
$$= 0.9270\frac{m^3}{kg}$$

$$\dot{m} = \frac{\dot{V}}{v} = \frac{40m^3/\min}{0.9270m^3/kg}\frac{1\min}{60s}$$
$$= 0.719\frac{kg}{s}$$

Conservation of Mass for General Control Volume

The conservation of mass principle for the open system or control volume is expressed as

$$\begin{bmatrix}\text{Sum of rate}\\ \text{of mass flowing}\\ \text{into control volume}\end{bmatrix} - \begin{bmatrix}\text{Sum of rate}\\ \text{of mass flowing}\\ \text{from control volume}\end{bmatrix} = \begin{bmatrix}\text{Time rate change}\\ \text{of mass inside}\\ \text{control volume}\end{bmatrix}$$

or

$$\sum\dot{m}_{in} - \sum\dot{m}_{out} = \Delta\dot{m}_{system} \qquad (kg/s)$$

Steady-State, Steady-Flow Processes

Most energy conversion devices operate steadily over long periods of time. The rates of heat transfer and work crossing the control surface are constant with time. The states of the mass streams crossing the control surface or boundary are constant with time. Under these conditions the mass and energy content of the control volume are constant with time.

$$\frac{dm_{CV}}{dt} = \Delta\dot{m}_{CV} = 0$$

Steady-state, Steady-Flow Conservation of Mass:

Since the mass of the control volume is constant with time during the steady-state, steady-flow process, the conservation of mass principle becomes

$$\begin{bmatrix}\text{Sum of rate}\\ \text{of mass flowing}\\ \text{into control volume}\end{bmatrix} = \begin{bmatrix}\text{Sum of rate}\\ \text{of mass flowing}\\ \text{from control volume}\end{bmatrix}$$

or

$$\sum\dot{m}_{in} = \sum\dot{m}_{out} \qquad (kg/s)$$

Special Case: Steady Flow of an Incompressible Fluid

The mass flow rate is related to volume flow rate and fluid density by

$$\dot{m} = \rho\dot{V}$$

For one entrance, one exit steady flow control volume, the mass flow rates are related by

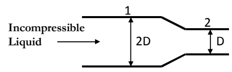
$$\dot{m}_{in} = \dot{m}_{out} \quad \text{(kg/s)}$$
$$\rho_{in}\dot{V}_{in} = \rho_{out}\dot{V}_{out}$$
$$\rho_{in} = \rho_{out} \quad \text{incompressible assumption}$$
$$\dot{V}_{in} = \dot{V}_{out}$$
$$\vec{V}_{in}A_{in} = \vec{V}_{out}A_{out}$$

Word of caution: This result applies only to incompressible fluids. Most thermodynamic systems deal with processes involving compressible fluids such as ideal gases, steam, and the refrigerants for which the above relation **will not apply**.

Example 5-3 Geometry Effects on Fluid Flow

An incompressible liquid flows through the pipe shown in the figure. The velocity at location 2 is

A) $\frac{1}{4}\vec{V}_1$ B) $\frac{1}{2}\vec{V}_1$ C) $2\vec{V}_1$ D) $4\vec{V}_1$



Solution:

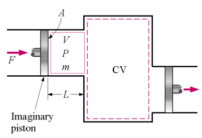
$$\dot{m} = \rho\dot{V}$$
$$\sum_{Inlets}\dot{m}_{in} = \sum_{Outlets}\dot{m}_{out}$$
$$\rho\dot{V}_1 = \rho\dot{V}_2$$
$$\dot{V}_1 = \dot{V}_2$$
$$A_1\vec{V}_1 = A_2\vec{V}_2$$
$$\vec{V}_2 = \frac{A_1}{A_2}\vec{V}_1 = \frac{\pi D_1^2/4}{\pi D_2^2/4}\vec{V}_1$$
$$\vec{V}_2 = \left(\frac{D_1}{D_2}\right)^2\vec{V}_1 = \left(\frac{2D}{D}\right)^2\vec{V}_1$$
$$\vec{V}_2 = 4\vec{V}_1$$

Answer: D

Flow work and the energy of a flowing fluid

Energy flows into and from the control volume with the mass. The energy required to push the mass into or out of the control volume is known as the flow work or flow energy.

The fluid up steam of the control surface acts as a piston to push a unit of mass into or out of the control volume. Consider the unit of mass entering the control volume shown below.



As the fluid upstream pushes mass across the control surface, work done on that unit of mass is

$$W_{flow} = FL = FL\frac{A}{A} = PV = Pmv$$
$$w_{flow} = \frac{W_{flow}}{m} = Pv$$

The term *Pv* is called the flow work done on the unit of mass as it crosses the control surface.

The total energy of flowing fluid

The total energy carried by a unit of mass as it crosses the control surface is the sum of the internal energy, flow work, potential energy, and kinetic energy.

$$\theta = u + Pv + \frac{\vec{V}^2}{2} + gz$$
$$= h + \frac{\vec{V}^2}{2} + gz$$

Here we have used the definition of enthalpy, ***h = u + Pv***.

Energy transport by mass

Amount of energy transport across a control surface:

$$E_{mass} = m\theta = m\left(h + \frac{\vec{V}^2}{2} + gz\right) \quad \text{(kJ)}$$

Rate of energy transport across a control surface:

$$\dot{E}_{mass} = \dot{m}\theta = \dot{m}\left(h + \frac{\vec{V}^2}{2} + gz\right) \quad (kW)$$

Conservation of Energy for General Control Volume

The conservation of energy principle for the control volume or open system has the same word definition as the first law for the closed system. Expressing the energy transfers on a rate basis, the control volume first law is

$$\begin{bmatrix}\text{Sum of rate}\\ \text{of energy flowing}\\ \text{into control volume}\end{bmatrix} - \begin{bmatrix}\text{Sum of rate}\\ \text{of energy flowing}\\ \text{from control volume}\end{bmatrix} = \begin{bmatrix}\text{Time rate change}\\ \text{of energy inside}\\ \text{control volume}\end{bmatrix}$$

or

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

Considering that energy flows into and from the control volume with the mass, energy enters because net heat is transferred to the control volume, and energy leaves because the control volume does net work on its surroundings, the open system, or control volume, the first law becomes

$$\dot{Q}_{net} + \sum \underbrace{\dot{m}_i\theta_i}_{\text{for each inlet}} - \dot{W}_{net} - \sum \underbrace{\dot{m}_e\theta_e}_{\text{for each exit}} = \frac{dE_{CV}}{dt} \quad (kW)$$

where θ is the energy per unit mass flowing into or from the control volume. The energy per unit mass, θ, flowing across the control surface that defines the control volume is composed of four terms: the internal energy, the kinetic energy, the potential energy, and the flow work.

The total energy carried by a unit of mass as it crosses the control surface is

$$\theta = u + Pv + \frac{\vec{V}^2}{2} + gz$$
$$= h + \frac{\vec{V}^2}{2} + gz$$
$$\dot{E}_{in} - \dot{E}_{out} = \Delta\dot{E}_{CV}$$
$$\dot{Q}_{net} + \underbrace{\sum \dot{m}_i\left(h_i + \frac{\vec{V}_i^2}{2} + gz_i\right)}_{\text{for each inlet}} - \dot{W}_{net} - \underbrace{\sum \dot{m}_e\left(h_e + \frac{\vec{V}_e^2}{2} + gz_e\right)}_{\text{for each exit}} = \Delta\dot{E}_{CV}$$

Where the time rate change of the energy of the control volume has been written as $\Delta\dot{E}_{CV}$

Steady-State, Steady-Flow Processes

Most energy conversion devices operate steadily over long periods of time. The rates of heat transfer and work crossing the control surface are constant with time. The states of the mass streams crossing the control surface or boundary are constant with time. Under these conditions the mass and energy content of the control volume are constant with time.

$$\frac{dm_{CV}}{dt} = \Delta\dot{m}_{CV} = 0$$
$$\frac{dE_{CV}}{dt} = \Delta\dot{E}_{CV} = 0$$

Steady-state, Steady-Flow Conservation of Mass:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (kg/s)$$

Steady-state, steady-flow conservation of energy

Since the energy of the control volume is constant with time during the steady-state, steady-flow process, the conservation of energy principle becomes

$$\begin{bmatrix}\text{Sum of rate}\\ \text{of energy flowing}\\ \text{into control volume}\end{bmatrix} = \begin{bmatrix}\text{Sum of rate}\\ \text{of energy flowing}\\ \text{from control volume}\end{bmatrix}$$

or

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

or

$$\underbrace{\dot{E}_{in}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}\\ \text{into the system}}} = \underbrace{\dot{E}_{out}}_{\substack{\text{Rate of energy transfer}\\ \text{by heat, work, and mass}\\ \text{from the system}}}$$

Considering that energy flows into and from the control volume with the mass, energy enters because heat is transferred to the control volume, and energy leaves because the control volume does work on its surroundings, the steady-state, steady-flow first law becomes

$$\dot{Q}_{in} + \dot{W}_{in} + \underbrace{\sum \dot{m}_i\left(h_i + \frac{\vec{V}_i^2}{2} + gz_i\right)}_{\text{for each inlet}} = \dot{Q}_{out} + \dot{W}_{out} + \underbrace{\sum \dot{m}_e\left(h_e + \frac{\vec{V}_e^2}{2} + gz_e\right)}_{\text{for each exit}}$$

Often this result is written as

$$\dot{Q}_{net} - \dot{W}_{net} = \underbrace{\sum \dot{m}_e\left(h_e + \frac{\vec{V}_e^2}{2} + gz_e\right)}_{\text{for each exit}} - \underbrace{\sum \dot{m}_i\left(h_i + \frac{\vec{V}_i^2}{2} + gz_i\right)}_{\text{for each inlet}}$$

where

$$\dot{Q}_{net} = \sum \dot{Q}_{in} - \sum \dot{Q}_{out}$$
$$\dot{W}_{net} = \sum \dot{W}_{out} - \sum \dot{W}_{in}$$

Steady-state, steady-flow for one entrance and one exit

A number of thermodynamic devices such as pumps, fans, compressors, turbines, nozzles, diffusers, and heaters operate with one entrance and one exit. The steady-state, steady-flow conservation of mass and first law of thermodynamics for these systems reduce to

$$\dot{m}_1 = \dot{m}_2 \quad (kg/s)$$
$$\frac{1}{v_1}\vec{V}_1 A_1 = \frac{1}{v_2}\vec{V}_2 A_2$$
$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2} + g(z_2 - z_1)\right] \quad (kW)$$

where the entrance to the control volume is state 1 and the exit is state 2 and $\dot{m}$ is the mass flow rate through the device.

When can we neglect the kinetic and potential energy terms in the first law?

Consider the kinetic and potential energies per unit mass.

$$ke = \frac{\vec{V}^2}{2}$$

$$\text{For } \vec{V} = 45\frac{m}{s} \quad ke = \frac{(45m/s)^2}{2}\frac{1kJ/kg}{1000m^2/s^2} = 1\frac{kJ}{kg}$$

$$\vec{V} = 140\frac{m}{s} \quad ke = \frac{(140m/s)^2}{2}\frac{1kJ/kg}{1000m^2/s^2} = 10\frac{kJ}{kg}$$

$$pe = gz$$

$$\text{For } z = 100m \quad pe = 9.8\frac{m}{s^2}100m\frac{1kJ/kg}{1000m^2/s^2} = 0.98\frac{kJ}{kg}$$

$$z = 1000m \quad pe = 9.8\frac{m}{s^2}1000m\frac{1kJ/kg}{1000m^2/s^2} = 9.8\frac{kJ}{kg}$$

When compared to the enthalpy of steam ($h \cong$ 2000 to 3000 kJ/kg) and the enthalpy of air ($h \cong$ 200 to 6000 kJ/kg), the kinetic and potential energies are often neglected.

When the kinetic and potential energies can be neglected, the conservation of energy equation becomes

$$\dot{Q} - \dot{W} = \dot{m}(h_2 - h_1) \qquad (kW)$$

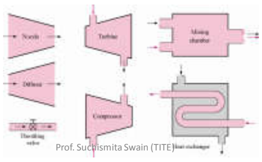
We often write this last result per unit mass flow as

$$q - w = (h_2 - h_1) \qquad (kJ/kg)$$

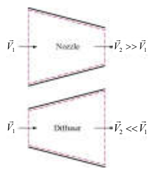
where $q = \frac{\dot{Q}}{\dot{m}}$ and $w = \frac{\dot{W}}{\dot{m}}$

Some Steady-Flow Engineering Devices

Below are some engineering devices that operate essentially as steady-state, steady-flow control volumes.



Nozzles and Diffusers



For flow through nozzles, the heat transfer, work, and potential energy are normally neglected, and nozzles have one entrance and one exit. The conservation of energy becomes

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

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

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

$$\dot{Q}_{net} + \underbrace{\sum \dot{m}_i\left(h_i + \frac{\vec{V}_i^2}{2} + gz_i\right)}_{\text{for each inlet}} = \dot{W}_{net} + \underbrace{\sum \dot{m}_e\left(h_e + \frac{\vec{V}_e^2}{2} + gz_e\right)}_{\text{for each exit}}$$

$$\dot{m}\left(h_1 + \frac{\vec{V}_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{\vec{V}_2^2}{2}\right)$$

Solving for $\vec{V}_2$

$$\vec{V}_2 = \sqrt{2(h_1 - h_2) + \vec{V}_1^2}$$

Example 5-4

Steam at 0.4 MPa, 300oC, enters an adiabatic nozzle with a low velocity and leaves at 0.2 MPa with a quality of 90%. Find the exit velocity, in m/s.

Control Volume: The nozzle

Property Relation: Steam tables

Process: Assume adiabatic, steady-flow

Conservation Principles:

Conservation of mass:

For one entrance, one exit, the conservation of mass becomes

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

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

Conservation of energy:

According to the sketched control volume, mass crosses the control surface, but no work or heat transfer crosses the control surface. Neglecting the potential energies, we have

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

$$\dot{m}\left(h_1 + \frac{\vec{V}_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{\vec{V}_2^2}{2}\right)$$

Neglecting the inlet kinetic energy, the exit velocity is

$$\vec{V}_2 = \sqrt{2(h_1 - h_2)}$$

Now, we need to find the enthalpies from the steam tables.

$$\left.\begin{matrix}\text{Superheated}\\ T_1 = 300^oC\\ P_1 = 0.4\,MPa\end{matrix}\right\} h_1 = 3067.1\frac{kJ}{kg} \qquad \left.\begin{matrix}\text{Saturated Mix.}\\ P_2 = 0.2\,MPa\\ x_2 = 0.90\end{matrix}\right\} h_2$$

At 0.2 MPa h_f = 504.7 kJ/kg and h_{fg} = 2201.6 kJ/kg.

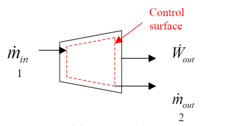
$$h_2 = h_f + x_2 h_{fg}$$

$$= 504.7 + (0.90)(2201.6) = 2486.1\frac{kJ}{kg}$$

$$\vec{V}_2 = \sqrt{2(3067.1 - 2486.1)\frac{kJ}{kg}\frac{1000\,m^2/s^2}{kJ/kg}}$$

$$= 1078.0\frac{m}{s}$$

Turbines



Turbine control volume

If we neglect the changes in kinetic and potential energies as fluid flows through an adiabatic turbine having one entrance and one exit, the conservation of mass and the steady-state, steady-flow first law becomes

$$\dot{m}_{in} = \dot{m}_{out}$$
$$\dot{m}_1 = \dot{m}_2 = \dot{m}$$
$$\dot{E}_{in} = \dot{E}_{out}$$
$$\dot{Q}_{net} + \sum \underbrace{\dot{m}_i\left(h_i + \frac{\vec{V}_i^2}{2} + gz_i\right)}_{\text{for each inlet}} = \dot{W}_{net} + \sum \underbrace{\dot{m}_e\left(h_e + \frac{\vec{V}_e^2}{2} + gz_e\right)}_{\text{for each exit}}$$
$$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{W}_{out}$$
$$\dot{W}_{out} = \dot{m}(h_1 - h_2)$$

Example 5-5

High pressure air at 1300 K flows into an aircraft gas turbine and undergoes a steady-state, steady-flow, adiabatic process to the turbine exit at 660 K. Calculate the work done per unit mass of air flowing through the turbine when

(a) Temperature-dependent data are used.
(b) $C_{p,\text{ave}}$ at the average temperature is used.
(c) C_p at 300 K is used.

Control Volume: The turbine.

Property Relation: Assume air is an ideal gas and use ideal gas relations.

Process: Steady-state, steady-flow, adiabatic process

Conservation Principles:

Conservation of mass:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$
$$\dot{m}_1 = \dot{m}_2 = \dot{m}$$

Conservation of energy:

$$\dot{Q}_{in} + \sum \underbrace{\dot{m}_i\left(h_i + \frac{\vec{V}_i^2}{2} + gz_i\right)}_{\text{for each inlet}} = \dot{W}_{out} + \sum \underbrace{\dot{m}_e\left(h_e + \frac{\vec{V}_e^2}{2} + gz_e\right)}_{\text{for each exit}}$$

According to the sketched control volume, mass and work cross the control surface. Neglecting kinetic and potential energies and noting the process is adiabatic, we have

$$0 + \dot{m}_1 h_1 = \dot{W}_{out} + \dot{m}_2 h_2$$
$$\dot{W}_{out} = \dot{m}(h_1 - h_2)$$

The work done by the air per unit mass flow is

$$w_{out} = \frac{\dot{W}_{out}}{\dot{m}} = h_1 - h_2$$

Notice that the work done by a fluid flowing through a turbine is equal to the enthalpy decrease of the fluid.

(a) Using the air tables, Table A-17
at T_1 = 1300 K, h_1 = 1395.97 kJ/kg
at T_2 = 660 K, h_2 = 670.47 kJ/kg

$$w_{out} = h_1 - h_2$$
$$= (1395.97 - 670.47)\frac{kJ}{kg}$$
$$= 725.5\frac{kJ}{kg}$$

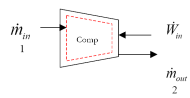
(b) Using Table A-2(c) at T_{ave} = 980 K, $C_{p,\,ave}$ = 1.138 kJ/kg·K

$$w_{out} = h_1 - h_2 = C_{p,ave}(T_1 - T_2)$$
$$= 1.138\frac{kJ}{kg \cdot K}(1300 - 660)K$$
$$= 728.3\frac{kJ}{kg}$$

(c) Using Table A-2(a) at T = 300 K, Cp = 1.005 kJ/kg ·K

$$w_{out} = h_1 - h_2 = C_p(T_1 - T_2)$$
$$= 1.005\frac{kJ}{kg \cdot K}(1300 - 660)K$$
$$= 643.2\frac{kJ}{kg}$$

Compressors and fans



Steady-Flow Compressor

Compressors and fans are essentially the same devices. However, compressors operate over larger pressure ratios than fans. If we neglect the changes in kinetic and potential energies as fluid flows through an adiabatic compressor having one entrance and one exit, the steady-state, steady-flow first law or the conservation of energy equation becomes

$$\dot{Q}_{net} + \sum \underbrace{\dot{m}_i\left(h_i + \frac{\vec{V}_i^2}{2} + gz_i\right)}_{\text{for each inlet}} = \dot{W}_{net} + \sum \underbrace{\dot{m}_e\left(h_e + \frac{\vec{V}_e^2}{2} + gz_e\right)}_{\text{for each exit}}$$
$$-\dot{W}_{net} = \dot{m}(h_2 - h_1)$$
$$-(-\dot{W}_{in}) = \dot{m}(h_2 - h_1)$$
$$\dot{W}_{in} = \dot{m}(h_2 - h_1)$$

Example 5-6

Nitrogen gas is compressed in a steady-state, steady-flow, adiabatic process from 0.1 MPa, 25oC. During the compression process the temperature becomes 125oC. If the mass flow rate is 0.2 kg/s, determine the work done on the nitrogen, in kW.

Control Volume: The compressor (see the compressor sketched above)

Property Relation: Assume nitrogen is an ideal gas and use ideal gas relations

Process: Adiabatic, steady-flow

Conservation Principles:

Conservation of mass:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$
$$\dot{m}_1 = \dot{m}_2 = \dot{m}$$

Conservation of energy:

$$\dot{Q}_{net} + \sum \underbrace{\dot{m}_i\left(h_i + \frac{\vec{V}_i^2}{2} + gz_i\right)}_{\text{for each inlet}} = \dot{W}_{net} + \sum \underbrace{\dot{m}_e\left(h_e + \frac{\vec{V}_e^2}{2} + gz_e\right)}_{\text{for each exit}}$$

According to the sketched control volume, mass and work cross the control surface. Neglecting kinetic and potential energies and noting the process is adiabatic, we have for one entrance and one exit

$$0 + \dot{m}_1(h_1 + 0 + 0) = (-\dot{W}_{in}) + \dot{m}_2(h_2 + 0 + 0)$$
$$\dot{W}_{in} = \dot{m}(h_2 - h_1)$$

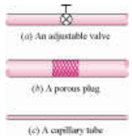
The work done ***on*** the nitrogen is related to the enthalpy rise of the nitrogen as it flows through the compressor. The work done on the nitrogen per unit mass flow is

$$w_{in} = \frac{\dot{W}_{in}}{\dot{m}} = h_2 - h_1$$

Assuming constant specific heats at 300 K from Table A-2(a), we write the work as

$$\begin{aligned} w_{in} &= C_p (T_2 - T_1) \\ &= 1.039 \frac{kJ}{kg \cdot K}(125 - 25)K \\ &= 103.9 \frac{kJ}{kg} \\ \dot{W}_{in} &= \dot{m}\, w_{in} = 0.2 \frac{kg}{s}\left(103.9 \frac{kJ}{kg}\right) \\ &= 20.78 \frac{kJ}{s} = 20.78\ kW \end{aligned}$$

Throttling devices



Consider fluid flowing through a one-entrance, one-exit porous plug. The fluid experiences a pressure drop as it flows through the plug. No net work is done by the fluid. Assume the process is adiabatic and that the kinetic and potential energies are neglected; then the conservation of mass and energy equations become

$$\dot{m}_i = \dot{m}_e$$

$$\dot{Q}_{net} + \underbrace{\sum \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + g z_i \right)}_{\text{for each inlet}} = \dot{W}_{net} + \underbrace{\sum \dot{m}_e \left(h_e + \frac{\vec{V}_e^2}{2} + g z_e \right)}_{\text{for each exit}}$$

$$\dot{m}_i h_i = \dot{m}_e h_e$$

$$h_i = h_e$$

This process is called a throttling process. What happens when an ideal gas is throttled?

$$h_i = h_e$$

$$h_e - h_i = 0$$

$$\int_i^e C_p(T)dT = 0$$

$$or$$

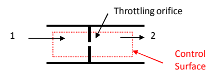
$$T_e = T_i$$

When throttling an ideal gas, the temperature does not change. We will see later in Chapter 11 that the throttling process is an important process in the refrigeration cycle.

A throttling device may be used to determine the enthalpy of saturated steam. The steam is throttled from the pressure in the pipe to ambient pressure in the calorimeter. The pressure drop is sufficient to superheat the steam in the calorimeter. Thus, the temperature and pressure in the calorimeter will specify the enthalpy of the steam in the pipe.

Example 5-7

One way to determine the quality of saturated steam is to throttle the steam to a low enough pressure that it exists as a superheated vapor. Saturated steam at 0.4 MPa is throttled to 0.1 MPa, 100°C. Determine the quality of the steam at 0.4 MPa.



Control Volume: The throttle

Property Relation: The steam tables

Process: Steady-state, steady-flow, no work, no heat transfer, neglect kinetic and potential energies, one entrance, one exit

Conservation Principles:

Conservation of mass:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

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

Conservation of energy:

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

$$\dot{Q}_{net} + \underbrace{\sum \dot{m}_i \left(h_i + \frac{\vec{V}_i^2}{2} + g z_i \right)}_{\text{for each inlet}} = \dot{W}_{net} + \underbrace{\sum \dot{m}_e \left(h_e + \frac{\vec{V}_e^2}{2} + g z_e \right)}_{\text{for each exit}}$$

According to the sketched control volume, mass crosses the control surface. Neglecting kinetic and potential energies and noting the process is adiabatic with no work, we have for one entrance and one exit

$$0 + \dot{m}_1 (h_1 + 0 + 0) = 0 + \dot{m}_2 (h_2 + 0 + 0)$$

$$\dot{m}_1 h_1 = \dot{m}_2 h_2$$

$$h_1 = h_2$$

$$\left. \begin{aligned} T_2 &= 100^\circ C \\ P_2 &= 0.1 MPa \end{aligned} \right\} h_2 = 2675.8 \frac{kJ}{kg}$$

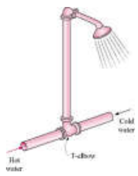
Therefore,

$$\begin{aligned} h_1 = h_2 &= 2675.8 \frac{kJ}{kg} \\ &= \left(h_f + x_1 h_{fg} \right)_{@P_1 = 0.4 MPa} \end{aligned}$$

$$\begin{aligned} x_1 &= \frac{h_1 - h_f}{h_{fg}} \\ &= \frac{2675.8 - 604.66}{2133.4} \\ &= 0.971 \end{aligned}$$

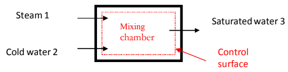
Mixing chambers

The mixing of two fluids occurs frequently in engineering applications. The section where the mixing process takes place is called a mixing chamber. The ordinary shower is an example of a mixing chamber.



Example 5-8

Steam at 0.2 MPa, 300oC, enters a mixing chamber and is mixed with cold water at 20oC, 0.2 MPa, to produce 20 kg/s of saturated liquid water at 0.2 MPa. What are the required steam and cold water flow rates?



Control Volume: The mixing chamber

Property Relation: Steam tables

Process: Assume steady-flow, adiabatic mixing, with no work

Conservation Principles:

Conservation of mass:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$
$$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$$
$$\dot{m}_2 = \dot{m}_3 - \dot{m}_1$$

Conservation of energy:

$$\dot{E}_{in} = \dot{E}_{out}$$
$$\dot{Q}_{net} + \underbrace{\sum \dot{m}_i\left(h_i + \frac{\vec{V}_i^2}{2} + gz_i\right)}_{\text{for each inlet}} = \dot{W}_{net} + \underbrace{\sum \dot{m}_e\left(h_e + \frac{\vec{V}_e^2}{2} + gz_e\right)}_{\text{for each exit}}$$

According to the sketched control volume, mass crosses the control surface. Neglecting kinetic and potential energies and noting the process is adiabatic with no work, we have for two entrances and one exit

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$
$$\dot{m}_1 h_1 + (\dot{m}_3 - \dot{m}_1) h_2 = \dot{m}_3 h_3$$
$$\dot{m}_1 (h_1 - h_2) = \dot{m}_3 (h_3 - h_2)$$
$$\dot{m}_1 = \dot{m}_3 \frac{(h_3 - h_2)}{(h_1 - h_2)}$$

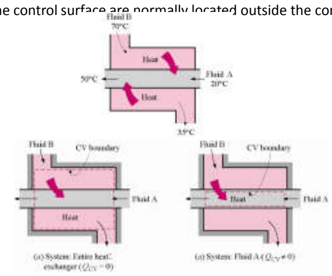
Now, we use the steam tables to find the enthalpies:

$$\left.\begin{array}{l} T_1 = 300^\circ C \\ P_1 = 0.2\,MPa \end{array}\right\} h_1 = 3072.1 \frac{kJ}{kg}$$

$$\left.\begin{array}{l} T_2 = 20^\circ C \\ P_2 = 0.2\,MPa \end{array}\right\} h_2 \approx h_{f\,@\,20^\circ C} = 83.91 \frac{kJ}{kg}$$
$$\left.\begin{array}{l} P_3 = 0.2\,MPa \\ Sat.\,liquid \end{array}\right\} h_3 = h_{f\,@\,0.2\,MPa} = 504.7 \frac{kJ}{kg}$$
$$\dot{m}_1 = \dot{m}_3 \frac{(h_3 - h_2)}{(h_1 - h_2)}$$
$$= 20 \frac{kg}{s} \frac{(504.7 - 83.91) kJ/kg}{(3072.1 - 83.91) kJ/kg}$$
$$= 2.82 \frac{kg}{s}$$
$$\dot{m}_2 = \dot{m}_3 - \dot{m}_1$$
$$= (20 - 2.82) \frac{kg}{s}$$
$$= 17.18 \frac{kg}{s}$$

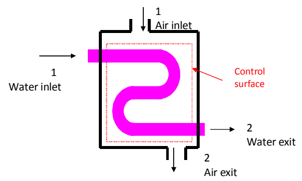
Heat exchangers

Heat exchangers are normally well-insulated devices that allow energy exchange between hot and cold fluids without mixing the fluids. The pumps, fans, and blowers causing the fluids to flow across the control surface are normally located outside the control surface.



Example 5-9

Air is heated in a heat exchanger by hot water. The water enters the heat exchanger at 45oC and experiences a 20oC drop in temperature. As the air passes through the heat exchanger, its temperature is increased by 25oC. Determine the ratio of mass flow rate of the air to mass flow rate of the water.



Control Volume: The heat exchanger

Property Relation: Air: ideal gas relations
Water: steam tables or incompressible liquid results

Process: Assume adiabatic, steady-flow

Conservation Principles:

Conservation of mass:

$$\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{system} \overset{0\,(steady)}{} \quad (kg/s)$$

For two entrances, two exits, the conservation of mass becomes

$$\dot{m}_{in} = \dot{m}_{out}$$
$$\dot{m}_{air,1} + \dot{m}_{w,1} = \dot{m}_{air,2} + \dot{m}_{w,2}$$

For two fluid streams that exchange energy but do not mix, it is better to conserve the mass for the fluid streams separately.

$$\dot{m}_{air,1} = \dot{m}_{air,2} = \dot{m}_{air}$$
$$\dot{m}_{w,1} = \dot{m}_{w,2} = \dot{m}_{w}$$

Conservation of energy:

According to the sketched control volume, mass crosses the control surface, but no work or heat transfer crosses the control surface. Neglecting the kinetic and potential energies, we have for steady-flo

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

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

$$\dot{m}_{air,1} h_{air,1} + \dot{m}_{w,1} h_{w,1} = \dot{m}_{air,2} h_{air,2} + \dot{m}_{w,2} h_{w,2}$$

$$\dot{m}_{air}(h_{air,1} - h_{air,2}) = \dot{m}_{w}(h_{w,2} - h_{w,1})$$

$$\frac{\dot{m}_{air}}{\dot{m}_{w}} = \frac{(h_{w,2} - h_{w,1})}{(h_{air,1} - h_{air,2})}$$

We assume that the air has constant specific heats at 300 K, Table A-2(a) (we don't know the actual temperatures, just the temperature difference). Because we know the initial and final temperatures for the water, we can use either the incompressible fluid result or the steam tables for its properties.

Using the incompressible fluid approach for the water, Table A-3, $C_{p,w}$ = 4.18 kJ/kg·K.

$$\frac{\dot{m}_{air}}{\dot{m}_{w}} = \frac{C_{p,w}(T_{w,2} - T_{w,1})}{C_{p,air}(T_{air,1} - T_{air,2})}$$

$$= \frac{4.18 \dfrac{kJ}{kg_w \cdot K}(-20\,K)}{1.005 \dfrac{kJ}{kg_{air} \cdot K}(-25\,K)}$$

$$= 3.33 \frac{kg_{air}/s}{kg_w/s}$$

A second solution to this problem is obtained by determining the heat transfer rate from the hot water and noting that this is the heat transfer rate to the air. Considering each fluid separately for steady-flow, one entrance, and one exit, and neglecting the kinetic and potential energies, the first law, or conservation of energy, equations become

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

$$air: \quad \dot{m}_{air,1} h_{air,1} + \dot{Q}_{in,air} = \dot{m}_{air,2} h_{air,2}$$

$$water: \quad \dot{m}_{w,1} h_{w,1} = \dot{Q}_{out,w} + \dot{m}_{w,2} h_{w,2}$$

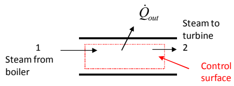
$$\dot{Q}_{in,air} = \dot{Q}_{out,w}$$

Pipe and duct flow

The flow of fluids through pipes and ducts is often a steady-state, steady-flow process. We normally neglect the kinetic and potential energies; however, depending on the flow situation, the work and heat transfer may or may not be zero.

Example 5-10

In a simple steam power plant, steam leaves a boiler at 3 MPa, 600oC, and enters a turbine at 2 MPa, 500oC. Determine the in-line heat transfer from the steam per kilogram mass flowing in the pipe between the boiler and the turbine.



<u>**Control Volume:**</u> Pipe section in which the heat loss occurs.

<u>**Property Relation:**</u> Steam tables

<u>**Process:**</u> Steady-flow

<u>**Conservation Principles:**</u>

Conservation of mass:

$$\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{system}^{\nearrow 0(\text{steady})} \quad (kg/s)$$

For one entrance, one exit, the conservation of mass becomes

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

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

Conservation of energy:

According to the sketched control volume, heat transfer and mass cross the control surface, but no work crosses the control surface. Neglecting the kinetic and potential energies, we have for steady-flow

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

We determine the heat transfer rate per unit mass of flowing steam as

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{Q}_{out}$$

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

$$q_{out} = \frac{\dot{Q}_{out}}{\dot{m}} = h_1 - h_2$$

We use the steam tables to determine the enthalpies at the two states as

$$\left.\begin{array}{l} T_1 = 600^{\circ}C \\ P_1 = 3\,MPa \end{array}\right\} h_1 = 3682.8 \frac{kJ}{kg}$$

$$\left.\begin{array}{l} T_2 = 500^{\circ}C \\ P_2 = 2\,MPa \end{array}\right\} h_2 = 3468.3 \frac{kJ}{kg}$$

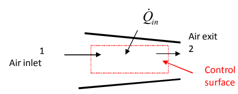
$$q_{out} = h_1 - h_2$$

$$= (3682.8 - 3468.3)\frac{kJ}{kg}$$

$$= 214.5 \frac{kJ}{kg}$$

Example 5-11

Air at 100oC, 0.15 MPa, 40 m/s, flows through a converging duct with a mass flow rate of 0.2 kg/s. The air leaves the duct at 0.1 MPa, 113.6 m/s. The exit-to-inlet duct area ratio is 0.5. Find the required rate of heat transfer to the air when no work is done by the air.



<u>**Control Volume:**</u> The converging duct

<u>**Property Relation:**</u> Assume air is an ideal gas and use ideal gas relations

<u>**Process:**</u> Steady-flow

<u>**Conservation Principles:**</u>

Conservation of mass:

$$\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{system}^{\nearrow 0(\text{steady})} \quad (kg/s)$$

For one entrance, one exit, the conservation of mass becomes

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

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

Conservation of energy:

According to the sketched control volume, heat transfer and mass cross the control surface, but no work crosses the control surface. Here keep the kinetic energy and still neglect the potential energies, we have for steady-state, steady-flow process

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

$$\dot{m}_1\left(h_1 + \frac{\vec{V}_1^2}{2}\right) + \dot{Q}_{in} = \dot{m}_2\left(h_2 + \frac{\vec{V}_2^2}{2}\right)$$

$$\dot{Q}_{in} = \dot{m}\left((h_2 - h_1) + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2}\right)$$

In the first law equation, the following are known: P_1, T_1 (and h_1), $\vec{V}_1$, $\vec{V}_2$, $\dot{m}$, and A_2/A_1. The unknowns are $\dot{Q}_{in}$, and h_2 (or T_2). We use the first law and the conservation of mass equation to solve for the two unknowns.

$$\dot{m}_1 = \dot{m}_2 \qquad (kg/s)$$

$$\frac{1}{v_1}\vec{V}_1 A_1 = \frac{1}{v_2}\vec{V}_2 A_2$$

$$\vec{V}_1 A_1 \frac{P_1}{RT_1} = \vec{V}_2 A_2 \frac{P_2}{RT_2}$$

Solving for T_2

$$T_2 = T_1 \frac{P_2}{P_1}\frac{A_2}{A_1}\frac{\vec{V}_2}{\vec{V}_1}$$
$$= (100+273)K\left(\frac{0.1\,MPa}{0.15\,MPa}\right)(0.5)\left(\frac{113.6\,m/s}{40\,m/s}\right)$$
$$= 353.1\,K$$

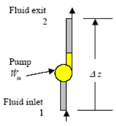
Assuming C_p = constant, $h_2 - h_1 = C_p(T_2 - T_1)$

$$\dot{Q}_{in} = \dot{m}\left(C_p(T_2 - T_1) + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2}\right)$$
$$= 0.2\frac{kg}{s}(1.005\frac{kJ}{kg \cdot K}(353.1 - 373)K$$
$$+ \frac{(113.6^2 - 40^2)m^2/s^2}{2}\frac{kJ/kg}{1000 m^2/s^2})$$
$$= -2.87\frac{kJ}{s} = -2.87\,kW$$

Looks like we made the wrong assumption for the direction of the heat transfer. The heat is really leaving the flow duct. (What type of device is this anyway?)

$$\dot{Q}_{out} = -\dot{Q}_{in} = 2.87\,kW$$

Liquid pumps



Liquid flow through a pump

The work required when pumping an incompressible liquid in an adiabatic steady-state, steady-flow process is given by

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2} + g(z_2 - z_1)\right] \quad (kW)$$

The enthalpy difference can be written as

$$h_2 - h_1 = (u_2 - u_1) + \left[(Pv)_2 - (Pv)_1\right]$$

For incompressible liquids we assume that the density and specific volume are constant. The pumping process for an incompressible liquid is essentially isothermal, and the internal energy change is approximately zero (we will see this more clearly after introducing the second law). Thus, the enthalpy difference reduces to the difference in the pressure-specific volume products. Since $v_2 = v_1 = v$ the work input to the pump becomes

$$-\dot{W} = \dot{m}\left[v(P_2 - P_1) + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2} + g(z_2 - z_1)\right] \quad (kW)$$

$\dot{W}$ is the net work done by the control volume, and it is noted that work is input to the pump; so, $\dot{W} = -\dot{W}_{in,\,pump}$

If we neglect the changes in kinetic and potential energies, the pump work becomes

$$-(-\dot{W}_{in,\,pump}) = \dot{m}\left[v(P_2 - P_1)\right] \quad (kW)$$
$$\dot{W}_{in,\,pump} = \dot{m}\left[v(P_2 - P_1)\right]$$

We use this result to calculate the work supplied to boiler feedwater pumps in steam power plants.

If we apply the above energy balance to a pipe section that has no pump ($\dot{W} = 0$), we obtain.

$$-\dot{W} = \dot{m}\left[v(P_2 - P_1) + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2} + g(z_2 - z_1)\right] \quad (kW)$$
$$0 = \dot{m}\left[v(P_2 - P_1) + \frac{\vec{V}_2^2 - \vec{V}_1^2}{2} + g(z_2 - z_1)\right]$$
$$v = \frac{1}{\rho}$$
$$\frac{P_2}{\rho} + \frac{\vec{V}_2^2}{2g} + z_2 = \frac{P_1}{\rho} + \frac{\vec{V}_1^2}{2g} + z_1$$

This last equation is the famous Bernoulli's equation for frictionless, incompressible fluid flow through a pipe.

Uniform-State, Uniform-Flow Problems

During unsteady energy transfer to or from open systems or control volumes, the system may have a change in the stored energy and mass. Several unsteady thermodynamic problems may be treated as uniform-state, uniform-flow problems. The assumptions for uniform-state, uniform-flow are

- The process takes place over a specified time period.
- The state of the mass within the control volume is uniform at any instant of time but may vary with time.
- The state of mass crossing the control surface is uniform and steady. The mass flow may be different at different control surface locations.

To find the amount of mass crossing the control surface at a given location, we integrate the mass flow rate over the time period.

$$Inlets:\ m_i = \int_0^t \dot{m}_i\,dt \quad Exits:\ m_e = \int_0^t \dot{m}_e\,dt$$

The change in mass of the control volume in the time period is

$$(m_2 u_2 - m_1 u_1)_{CV} = \int_0^t \left.\frac{dU}{dt}\right|_{CV} dt$$

The uniform-state, uniform-flow conservation of mass becomes

$$\sum m_i - \sum m_e = (m_2 - m_1)_{CV}$$

The change in internal energy for the control volume during the time period is

$$Q = \int_0^t \dot{Q}\,dt \quad and \quad W = \int_0^t \dot{W}\,dt$$

The energy crossing the control surface with the mass in the time period is

$$\sum m_j \theta_j = \int_0^t \dot{m}_j \left(h_j + \frac{\vec{V}_j^2}{2} + gz_j \right) dt$$

where

j =i, for inlets
e, for exits

The first law for uniform-state, uniform-flow becomes

$$E_{in} - E_{out} = \Delta E_{CV}$$

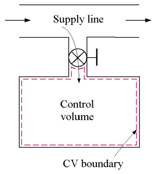
$$Q - W = \sum m_e \left(h_e + \frac{\vec{V}_e^2}{2} + gz_e \right) - \sum m_i \left(h_i + \frac{\vec{V}_i^2}{2} + gz_i \right) + (m_2 e_2 - m_1 e_1)_{CV}$$

When the kinetic and potential energy changes associated with the control volume and the fluid streams are negligible, it simplifies to

$$Q - W = \sum m_e h_e - \sum m_i h_i + (m_2 u_2 - m_1 u_1)_{CV} \qquad (kJ)$$

Example 5-12

Consider an evacuated, insulated, rigid tank connected through a closed valve to a high-pressure line. The valve is opened and the tank is filled with the fluid in the line. If the fluid is an ideal gas, determine the final temperature in the tank when the tank pressure equals that of the line.



Control Volume: The tank

Property Relation: Ideal gas relations

Process: Assume uniform-state, uniform-flow

Conservation Principles:

Conservation of mass:

$$\sum m_i - \sum m_e = (m_2 - m_1)_{CV}$$

Or, for one entrance, no exit, and initial mass of zero, this becomes

$$m_i = (m_2)_{CV}$$

Conservation of energy:

For an insulated tank *Q* is zero and for a rigid tank with no shaft work *W* is zero. For a one-inlet mass stream and no-exit mass stream and neglecting changes in kinetic and potential energies, the uniform-state, uniform-flow conservation of energy reduces to

$$Q - W = \sum m_e h_e - \sum m_i h_i + (m_2 u_2 - m_1 u_1)_{CV} \qquad (kJ)$$

$$0 = -m_i h_i + (m_2 u_2)_{CV}$$

or

$$m_i h_i = (m_2 u_2)_{CV}$$
$$h_i = u_2$$
$$u_i + P_i v_i = u_2$$
$$u_2 - u_i = P_i v_i$$
$$C_v (T_2 - T_i) = P_i v_i$$

$$C_v (T_2 - T_i) = RT_i$$

$$T_2 = \frac{C_v + R}{C_v} T_i = \frac{C_p}{C_v} T_i$$

$$= kT_i$$

If the fluid is air, *k* = 1.4 and the absolute temperature in the tank at the final state is 40 percent higher than the fluid absolute temperature in the supply line. The internal energy in the full tank differs from the internal energy of the supply line by the amount of flow work done to push the fluid from the line into the tank.

Extra Assignment

Rework the above problem for a 10 m^3 tank initially open to the atmosphere at 25oC and being filled from an air supply line at 90 psig, 25oC, until the pressure inside the tank is 70 psig.

The Second Law of Thermodynamics

By:

Prof. Suchismita Swain
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The second law of thermodynamics states that processes occur in a certain direction, not in just any direction. Physical processes in nature can proceed toward equilibrium spontaneously:

Water flows down a waterfall.
Gases expand from a high pressure to a low pressure.
Heat flows from a high temperature to a low temperature.

Once it has taken place, a spontaneous process can be reversed, but it will not reverse itself spontaneously. Some external inputs, energy, must be expended to reverse the process. As it falls down the waterfall, water can be collected in a water wheel, cause a shaft to rotate, coil a rope onto the shaft, and lift a weight. So the energy of the falling water is captured as potential energy increase in the weight, and the first law of thermodynamics is satisfied. However, there are losses associated with this process (friction). Allowing the weight to fall, causing the shaft to rotate in the opposite direction, will not pump all of the water back up the waterfall.

Spontaneous processes can proceed only in a particular direction. The first law of thermodynamics gives no information about direction; it states only that when one form of energy is converted into another, identical quantities of energy are involved regardless of the feasibility of the process. We know by experience that heat flows spontaneously from a high temperature to a low temperature. But heat flowing from a low temperature to a higher temperature with no expenditure of energy to cause the process to take place would not violate the first law.

The first law is concerned with the conversion of energy from one form to another. Joule's experiments showed that energy in the form of heat could not be completely converted into work; however, work energy can be completely converted into heat energy. Evidently heat and work are not completely interchangeable forms of energy. Furthermore, when energy is transferred from one form to another, there is often a degradation of the supplied energy into a less "useful" form. We shall see that it is the second law of thermodynamics that controls the direction processes may take and how much heat is converted into work. A process will not occur unless it satisfies both the first and the second laws of thermodynamics.

Some Definitions

To express the second law in a workable form, we need the following definitions.

Heat (thermal) reservoir

A heat reservoir is a sufficiently large system in stable equilibrium to which and from which finite amounts of heat can be transferred without any change in its temperature.

A high temperature heat reservoir from which heat is transferred is sometimes called a heat source. A low temperature heat reservoir to which heat is transferred is sometimes called a heat sink.

Work reservoir

A work reservoir is a sufficiently large system in stable equilibrium to which and from which finite amounts of work can be transferred adiabatically without any change in its pressure.

Thermodynamic cycle

A system has completed a thermodynamic cycle when the system undergoes a series of processes and then returns to its original state, so that the properties of the system at the end of the cycle are the same as at its beginning.
Thus, for whole numbers of cycles

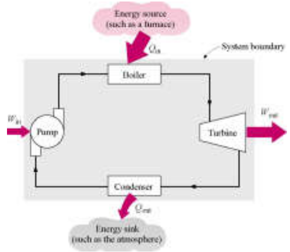
$$P_f = P_i,\ T_f = T_i,\ u_f = u_i,\ v_f = v_i,\ etc.$$

Heat Engine

A heat engine is a thermodynamic system operating in a thermodynamic cycle to which net heat is transferred and from which net work is delivered.

The system, or working fluid, undergoes a series of processes that constitute the heat engine cycle.

The following figure illustrates a steam power plant as a heat engine operating in a thermodynamic cycle.



The next slide gives another overview of a steam power plant. Heat transfer from the products of combustion of the fuel in air is supplied the pressurized water in the boiler or steam generator. The high pressure, high temperature steam expands in the turbine to produce shaft work which drives the generator and the pump. The steam leaves the turbine at a low pressure and is condensed to a liquid in the condenser. The liquid water is pumped to the boiler pressure and flows into the boiler to be heated again, and the cycle is complete.

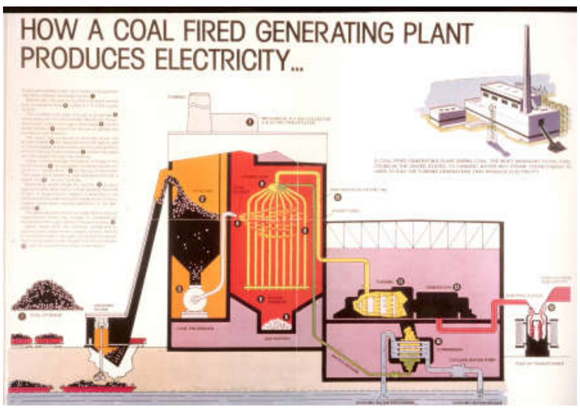


Photo courtesy of Progress Energy Carolinas, Inc.

Thermal Efficiency, η_{th}

The thermal efficiency is the index of performance of a work-producing device or a heat engine and is defined by the ratio of the net work output (the desired result) to the heat input (the costs to obtain the desired result).

$$\eta_{th} = \frac{\text{Desired Result}}{\text{Required Input}}$$

For a heat engine the desired result is the net work done and the input is the heat supplied to make the cycle operate. The thermal efficiency is always less than 1 or less than 100 percent.

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

where

$$W_{net,out} = W_{out} - W_{in}$$

$$Q_{in} \neq Q_{net}$$

Here the use of the *in* and *out* subscripts means to use the magnitude (take the positive value) of either the work or heat transfer and let the minus sign in the net expression take care of the direction.

Now apply the first law to the cyclic heat engine.

$$Q_{net,in} - W_{net,out} = \Delta U^{\nearrow 0 \text{ (Cyclic)}}$$

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

$$W_{net,out} = Q_{in} - Q_{out}$$

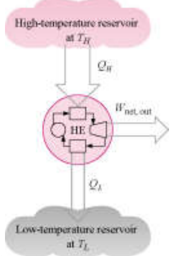
The cycle thermal efficiency may be written as

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

Cyclic devices such as heat engines, refrigerators, and heat pumps often operate between a high-temperature reservoir at temperature T_H and a low-temperature reservoir at temperature T_L.

The thermal efficiency of the above device becomes

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



Example 6-1

A steam power plant produces 50 MW of net work while burning fuel to produce 150 MW of heat energy at the high temperature. Determine the cycle thermal efficiency and the heat rejected by the cycle to the surroundings.

$$\eta_{th} = \frac{W_{net,out}}{Q_H} = \frac{50\ MW}{150\ MW} = 0.333 \quad \text{or} \quad 33.3\%$$

$$W_{net,out} = Q_H - Q_L$$

$$Q_L = Q_H - W_{net,out} = 150\ MW - 50\ MW = 100\ MW$$

Heat Pump

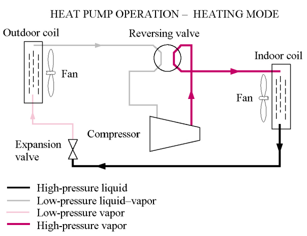
A heat pump is a thermodynamic system operating in a thermodynamic cycle that removes heat from a low-temperature body and delivers heat to a high-temperature body. To accomplish this energy transfer, the heat pump receives external energy in the form of work or heat from the surroundings.

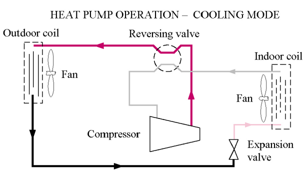
While the name "heat pump" is the thermodynamic term used to describe a cyclic device that allows the transfer of heat energy from a low temperature to a higher temperature, we use the terms "refrigerator" and "heat pump" to apply to particular devices. Here a refrigerator is a device that operates on a thermodynamic cycle and extracts heat from a low-temperature medium. The heat pump also operates on a thermodynamic cycle but rejects heat to the high-temperature medium.

The following figure illustrates a refrigerator as a heat pump operating in a thermodynamic cycle.

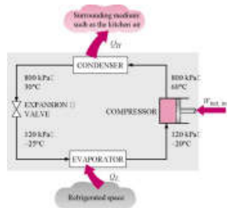
Heat Pump Systems

A typical heat pump system is shown here. In the heating mode high pressure vapor refrigerant is sent to the indoor heat exchanger coil. The refrigerant gives up its energy to the inside air and condenses to a liquid. The liquid is throttled to a low pressure and temperature to the outdoor coil and receives energy from the from the outside air. The refrigerant vaporizes, enters the compressor to be compressed to the high pressure, and the cycle is completed.





Read more about heat pump systems used for heating and cooling the US Government website listed below.



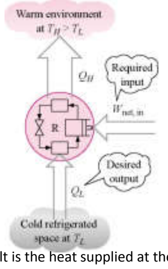
http://www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12610

Coefficient of Performance, COP

The index of performance of a refrigerator or heat pump is expressed in terms of the coefficient of performance, COP, the ratio of desired result to input. This measure of performance may be larger than 1, and we want the COP to be as large as possible.

$$COP = \frac{\text{Desired Result}}{\text{Required Input}}$$

For the heat pump acting like a refrigerator or an air conditioner, the primary function of the device is the transfer of heat *from* the low- temperature system.



For the refrigerator the desired result is the heat supplied at the low temperature and the input is the net work into the device to make the cycle operate.

$$COP_R = \frac{Q_L}{W_{net,in}}$$

Now apply the first law to the cyclic refrigerator.

$$(Q_L - Q_H) - (0 - W_{in}) = \Delta U_{cycle} = 0$$

$$W_{in} = W_{net,in} = Q_H - Q_L$$

and the coefficient of performance becomes

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

For the device acting like a "heat pump," the primary function of the device is the transfer of heat to the high-temperature system. The coefficient of performance for a heat pump is

$$COP_{HP} = \frac{Q_H}{W_{net,in}} = \frac{Q_H}{Q_H - Q_L}$$

Note, under the same operating conditions the COP_{HP} and COP_R are related by

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

Heat Pump and Air Conditioner Ratings

Heat pumps and air conditioners are rated using the SEER system. SEER is the seasonal adjusted energy efficiency (bad term for HP and A/C devices) rating. The SEER rating is the amount of heating (cooling) on a seasonal basis in Btu/hr per unit rate of power expended in watts, W.

The heat transfer rate is often given in terms of tons of heating or cooling. One ton equals 12,000 Btu/hr = 211 kJ/min.

A discussion on how to maintain the SEER rating of heat pumps and air conditioners may be found at
http://www.advancedenergy.org/buildings/knowledge_library/heating_and_cooling/seer_facts_bulletin.pdf

Second Law Statements

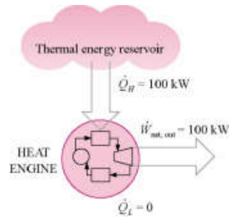
The following two statements of the second law of thermodynamics are based on the definitions of the heat engines and heat pumps.

Kelvin-Planck statement of the second law

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.

The Kelvin-Planck statement of the second law of thermodynamics states that no heat engine can produce a net amount of work while exchanging heat with a single reservoir only. In other words, the maximum possible efficiency is less than 100 percent.

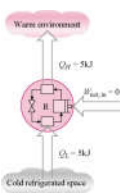
η_{th} **< 100%**



Heat engine that violates the Kelvin-Planck statement of the second law

Clausius statement of the second law

The Clausius statement of the second law states that 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.



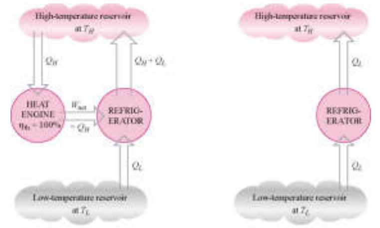
Heat pump that violates the Clausius statement of the second law

Or energy from the surroundings in the form of work or heat has to be expended to force heat to flow from a low-temperature medium to a high-temperature medium.

Thus, the COP of a refrigerator or heat pump must be less than infinity.

$$COP < \infty$$

A violation of either the Kelvin-Planck or Clausius statements of the second law implies a violation of the other. Assume that the heat engine shown below is violating the Kelvin-Planck statement by absorbing heat from a single reservoir and producing an equal amount of work *W*. The output of the engine drives a heat pump that transfers an amount of heat Q_L from the low-temperature thermal reservoir and an amount of heat $Q_H + Q_L$ to the high-temperature thermal reservoir. The combination of the heat engine and refrigerator in the left figure acts like a heat pump that transfers heat Q_L from the low-temperature reservoir without any external energy input. This is a violation of the Clausius statement of the second law.



(a) A refrigerator which is powered by a 100% efficient heat engine

(b) The equivalent refrigerator

Perpetual-Motion Machines

Any device that violates the first or second law of thermodynamics is called a perpetual-motion machine. If the device violates the first law, it is a perpetual-motion machine of the first kind. If the device violates the second law, it is a perpetual-motion machine of the second kind.

Reversible Processes

A reversible process is a quasi-equilibrium, or quasi-static, process with a more restrictive requirement.

Internally reversible process

The internally reversible process is a quasi-equilibrium process, which, once having taken place, can be reversed and in so doing leave no change in the system. This says nothing about what happens to the surroundings about the system.

Totally or externally reversible process

The externally reversible process is a quasi-equilibrium process, which, once having taken place, can be reversed and in so doing leave no change in the system or surroundings.

Irreversible Process

An irreversible process is a process that is not reversible.

All real processes are irreversible. Irreversible processes occur because of the following:

- Friction
- Unrestrained expansion of gases
- Heat transfer through a finite temperature difference
- Mixing of two different substances
- Hysteresis effects
- I^2R losses in electrical circuits
- Any deviation from a quasi-static process

The Carnot Cycle

French military engineer Nicolas Sadi Carnot (1769-1832) was among the first to study the principles of the second law of thermodynamics. Carnot was the first to introduce the concept of cyclic operation and devised a reversible cycle that is composed of four reversible processes, two isothermal and two adiabatic.

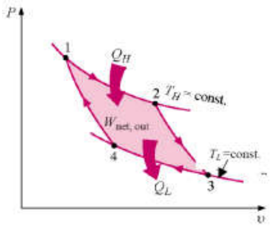
The Carnot Cycle

Process 1-2:Reversible isothermal heat addition at high temperature, $T_H > T_L$, to the working fluid in a piston-cylinder device that does some boundary work.

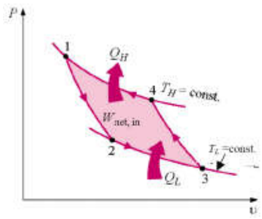
Process 2-3:Reversible adiabatic expansion during which the system does work as the working fluid temperature decreases from T_H to T_L.

Process 3-4:The system is brought in contact with a heat reservoir at $T_L < T_H$ and a reversible isothermal heat exchange takes place while work of compression is done on the system.

Process 4-1:A reversible adiabatic compression process increases the working fluid temperature from T_L to T_H



P-v diagram for Carnot heat engine



P-v diagram for Carnot refrigerator

You may have observed that power cycles operate in the clockwise direction when plotted on a process diagram. The Carnot cycle may be reversed, in which it operates as a refrigerator. The refrigeration cycle operates in the counterclockwise direction.

Carnot Principles

The second law of thermodynamics puts limits on the operation of cyclic devices as expressed by the Kelvin-Planck and Clausius statements. A heat engine cannot operate by exchanging heat with a single heat reservoir, and a refrigerator cannot operate without net work input from an external source.

Consider heat engines operating between two fixed temperature reservoirs at $T_H > T_L$. We draw two conclusions about the thermal efficiency of reversible and irreversible heat engines, known as the Carnot principles.

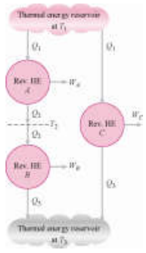
(a)The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

$$\eta_{th} < \eta_{th,\, Carnot}$$

(b) The efficiencies of all reversible heat engines operating between the same two constant-temperature heat reservoirs have the same efficiency.

As the result of the above, Lord Kelvin in 1848 used energy as a thermodynamic property to define temperature and devised a temperature scale that is independent of the thermodynamic substance.

The following is Lord Kelvin's Carnot heat engine arrangement.



Since the thermal efficiency in general is

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

For the Carnot engine, this can be written as

$$\eta_{th} = g(T_L, T_H) = 1 - f(T_L, T_H)$$

Considering engines A, B, and C

$$\frac{Q_1}{Q_3} = \frac{Q_1}{Q_2}\frac{Q_2}{Q_3}$$

This looks like

$$f(T_1,T_3) = f(T_1,T_2) f(T_2,T_3)$$

One way to define the *f* function is

$$f(T_1,T_3) = \frac{\theta(T_2)}{\theta(T_1)}\frac{\theta(T_3)}{\theta(T_2)} = \frac{\theta(T_3)}{\theta(T_1)}$$

The simplest form of θ is the absolute temperature itself.

$$f(T_1,T_3) = \frac{T_3}{T_1}$$

The Carnot thermal efficiency becomes

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

This is the maximum possible efficiency of a heat engine operating between two heat reservoirs at temperatures T_H and T_L. Note that the temperatures are absolute temperatures.

These statements form the basis for establishing an absolute temperature scale, also called the Kelvin scale, related to the heat transfers between a reversible device and the high- and low-temperature heat reservoirs by

$$\frac{Q_L}{Q_H} = \frac{T_L}{T_H}$$

Then the Q_H/Q_L ratio can be replaced by T_H/T_L for reversible devices, where T_H and T_L are the absolute temperatures of the high- and low-temperature heat reservoirs, respectively. This result is only valid for heat exchange across a heat engine operating between two constant temperature heat reservoirs. These results do not apply when the heat exchange is occurring with heat sources and sinks that do not have constant temperature.

The thermal efficiencies of actual and reversible heat engines operating between the same temperature limits compare as follows:

$$\eta_{th} \begin{cases} < \eta_{th,\,rev} & \text{irreversible heat engine} \\ = \eta_{th,\,rev} & \text{reversible heat engine} \\ > \eta_{th,\,rev} & \text{impossible heat engine} \end{cases}$$

Reversed Carnot Device Coefficient of Performance

If the Carnot device is caused to operate in the reversed cycle, the reversible heat pump is created. The COP of reversible refrigerators and heat pumps are given in a similar manner to that of the Carnot heat engine as

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

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

Again, these are the maximum possible COPs for a refrigerator or a heat pump operating between the temperature limits of T_H and T_L.

The coefficients of performance of actual and reversible (such as Carnot) refrigerators operating between the same temperature limits compare as follows:

$$COP_R \begin{cases} < COP_{R,\,rev} & \text{irreversible refrigerator} \\ = COP_{R,\,rev} & \text{reversible refrigerator} \\ > COP_{R,\,rev} & \text{impossible refrigerator} \end{cases}$$

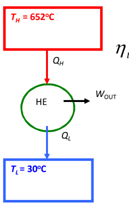
A similar relation can be obtained for heat pumps by replacing all values of COP_R by COP_{HP} in the above relation.

Example 6-2

A Carnot heat engine receives 500 kJ of heat per cycle from a high-temperature heat reservoir at 652°C and rejects heat to a low-temperature heat reservoir at 30°C. Determine

(a) The thermal efficiency of this Carnot engine.
(b) The amount of heat rejected to the low-temperature heat reservoir.

a.



$$\eta_{th,\,rev} = 1 - \frac{T_L}{T_H} = 1 - \frac{(30+273)K}{(652+273)K} = 0.672 \quad or \quad 67.2\%$$

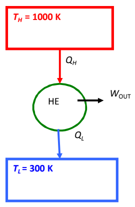
b.

$$\frac{Q_L}{Q_H} = \frac{T_L}{T_H} = \frac{(30+273)K}{(652+273)K} = 0.328$$

$$Q_L = 500\,kJ(0.328) = 164\,kJ$$

Example 6-3

An inventor claims to have invented a heat engine that develops a thermal efficiency of 80 percent when operating between two heat reservoirs at 1000 K and 300 K. Evaluate his claim.

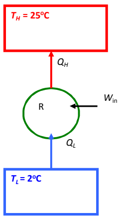


$$\eta_{th,\,rev} = 1 - \frac{T_L}{T_H} = 1 - \frac{300K}{1000K} = 0.70 \quad or \quad 70\%$$

The claim is false since no heat engine may be more efficient than a Carnot engine operating between the heat reservoirs.

Example 6-4

An inventor claims to have developed a refrigerator that maintains the refrigerated space at 2°C while operating in a room where the temperature is 25°C and has a COP of 13.5. Is there any truth to his claim?

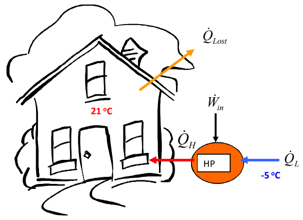


$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{T_L}{T_H - T_L} = \frac{(2+273)K}{(25-2)K} = 11.96$$

The claim is false since no refrigerator may have a COP larger than the COP for the reversed Carnot device.

Example 6-5

A heat pump is to be used to heat a building during the winter. The building is to be maintained at 21°C at all times. The building is estimated to be losing heat at a rate of 135,000 kJ/h when the outside temperature drops to -5°C. Determine the minimum power required to drive the heat pump unit for this outside temperature.



The heat lost by the building has to be supplied by the heat pump.

$$\dot{Q}_H = \dot{Q}_{Lost} = 135000\frac{kJ}{h}$$

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{Q}_H - \dot{Q}_L} = \frac{T_H}{T_H - T_L} = \frac{(21+273)K}{(21-(-5))K} = 11.31$$

Using the basic definition of the COP

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,in}}$$

$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{135{,}000\,kJ/h}{11.31}\,\frac{1h}{3600s}\,\frac{1kW}{kJ/s} = 3.316\,kW$$

(d) Repeat the constant specific heat calculation assuming C_p is a constant at the average of the specific heats for the temperatures. Then C_p = 1.054 kJ/kg·K (see Table A-2(b)).

$$s_2 - s_1 = C_{p,av}\ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1} = 1.054\frac{kJ}{kg\cdot K}\ln\left(\frac{800K}{400K}\right) - 0.1889\frac{kJ}{kg\cdot K}\ln\left(\frac{2000kPa}{50kPa}\right) = +0.0337\frac{kJ}{kg\cdot K}$$

We observe that the 300 K data give completely incorrect results here.

If the compression process is adiabatic, why is Δs positive for this process?

Entropy

By:

Prof. Suchismita Swain (TITE Khorda)

Entropy and the Clausius Inequality

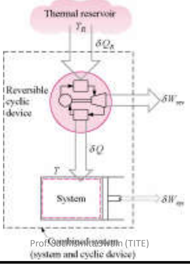
The second law of thermodynamics leads to the definition of a new property called entropy, a quantitative measure of microscopic disorder for a system. Entropy is a measure of energy that is no longer available to perform useful work within the current environment.

For more information and animations illustrating this topic visit the Animation Library developed by Professor S. Bhattacharjee, San Diego State University, at this link.

test.sdsu.edu/testhome/vtAnimations/index.html

To obtain the working definition of entropy and, thus, the second law, let's derive the Clausius inequality.

Consider a heat reservoir giving up heat to a reversible heat engine, which in turn gives up heat to a piston-cylinder device as shown below.



We apply the first law on an incremental basis to the combined system composed of the heat engine and the system.

$$E_{in} - E_{out} = \Delta E_c$$

$$\delta Q_R - (\delta W_{rev} + \delta W_{sys}) = dE_c$$

where E_c is the energy of the combined system. Let W_c be the work done by the combined system. Then the first law becomes

$$\delta W_c = \delta W_{rev} + \delta W_{sys}$$

$$\delta Q_R - \delta W_c = dE_c$$

If we assume that the engine is totally reversible, then

$$\frac{\delta Q_R}{T_R} = \frac{\delta Q}{T}$$

$$\delta Q_R = T_R \frac{\delta Q}{T}$$

The total net work done by the combined system becomes

$$\delta W_c = T_R \frac{\delta Q}{T} - dE_c$$

Now the total work done is found by taking the cyclic integral of the incremental work.

$$W_c = T_R \oint \frac{\delta Q}{T} - \oint dE_c$$

If the system, as well as the heat engine, is required to undergo a cycle, then

$$\oint dE_c = 0$$

and the total net work becomes

$$W_c = T_R \oint \frac{\delta Q}{T}$$

If W_c is positive, we have a cyclic device exchanging energy with a single heat reservoir and producing an equivalent amount of work; thus, the Kelvin-Planck statement of the second law is violated. But W_c can be zero (no work done) or negative (work is done on the combined system) and not violate the Kelvin-Planck statement of the second law. Therefore, since $T_R > 0$ (absolute temperature), we conclude

$$W_c = T_R \oint \frac{\delta Q}{T} \le 0$$

or

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

Here Q is the net heat added *to* the system, Q_{net}.

$$\oint \frac{\delta Q_{net}}{T} \le 0$$

This equation is called the Clausius inequality. The equality holds for the reversible process and the inequality holds for the irreversible process.

Example 7-1

For a particular power plant, the heat added and rejected both occur at constant temperature and no other processes experience any heat transfer. The heat is added in the amount of 3150 kJ at 440°C and is rejected in the amount of 1950 kJ at 20°C. Is the Clausius inequality satisfied and is the cycle reversible or irreversible?

$$\oint \frac{\delta Q_{net}}{T} \le 0$$

$$\int \left(\frac{\delta Q_{net}}{T}\right)_{in} + \int \left(\frac{\delta Q_{net}}{T}\right)_{out} \le 0$$

$$\left(\frac{Q_{net}}{T}\right)_{in} + \left(\frac{Q_{net}}{T}\right)_{out} \le 0$$

$$\left(\frac{Q_{in}}{T_{in}}\right) + \left(\frac{-Q_{out}}{T_{out}}\right) \le 0$$

$$\left(\frac{3150\,kJ}{(440+273)K}\right) + \left(\frac{-1950\,kJ}{(20+273)K}\right) \le 0$$

$$(4.418 - 6.655)\frac{kJ}{K} \le 0$$

$$-2.237\frac{kJ}{K} \le 0$$

Calculate the net work, cycle efficiency, and Carnot efficiency based on T_H and T_L for this cycle.

$$W_{net} = Q_{in} - Q_{out} = (3150 - 1950)\,kJ = 1200\,kJ$$

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{1200\,kJ}{3150\,kJ} = 0.381 \;\; or \;\; 38.1\%$$

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H} = 1 - \frac{(20+273)\,K}{(440+273)\,K} = 0.589 \;\; or \;\; 58.9\%$$

The Clausius inequality is satisfied. Since the inequality is less than zero, the cycle has at least one irreversible process and the cycle is irreversible.

Example 7-2

For a particular power plant, the heat added and rejected both occur at constant temperature; no other processes experience any heat transfer. The heat is added in the amount of 3150 kJ at 440°C and is rejected in the amount of 1294.46 kJ at 20°C. Is the Clausius inequality satisfied and is the cycle reversible or irreversible?

$$\oint \frac{\delta Q_{net}}{T} \le 0$$

$$\int \left(\frac{\delta Q_{net}}{T}\right)_{in} + \int \left(\frac{\delta Q_{net}}{T}\right)_{out} \le 0$$

$$\left(\frac{Q_{in}}{T_{in}}\right) + \left(\frac{-Q_{out}}{T_{out}}\right) \le 0$$

$$\left(\frac{3150\,kJ}{(440+273)K}\right) + \left(\frac{-1294.46\,kJ}{(20+273)K}\right) \le 0$$

$$(4.418 - 4.418)\frac{kJ}{K} = 0$$

The Clausius inequality is satisfied. Since the cyclic integral is equal to zero, the cycle is made of reversible processes. What cycle can this be?

Calculate the net work and cycle efficiency for this cycle.

$$W_{net} = Q_{in} - Q_{out} = (3150 - 1294.46)\,kJ = 1855.4\,kJ$$

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{1855.54\,kJ}{3150\,kJ} = 0.589 \;\; or \;\; 58.9\%$$

Definition of Entropy

Let's take another look at the quantity

$$\oint \frac{\delta Q_{net}}{T} \le 0$$

If no irreversibilities occur within the system as well as the reversible cyclic device, then the cycle undergone by the combined system will be inter-nally reversible. As such, it can be reversed. In the reversed cycle case, all the quantities will have the same magnitude but the opposite sign. Therefore, the work W_C, which could not be a positive quantity in the regular case, cannot be a negative quantity in the reversed case. Then it follows that

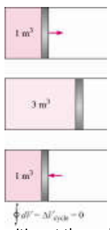
$W_{C,int\,rev} = 0$ since it cannot be a positive or negative quantity, and therefore

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

for internally reversible cycles. Thus we conclude that *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, let us examine this last equation more closely. Here 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 below.



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

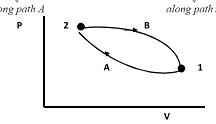
$$\oint (dV) = 0$$

We see that the cyclic integral of a property is zero. A quantity whose cyclic integral is zero depends only on the *state* and not on the process path; thus it is a property. Therefore the quantity $(\delta Q_{net}/T)_{int\,rev}$ must be a property.

In-class Example

Consider the cycle shown below composed of two reversible processes A and B. Apply the Clausius inequality for this cycle. What do you conclude about these two integrals?

$$\underbrace{\int_1^2 \left(\frac{\delta Q_{net}}{T} \right)_{\text{int rev}}}_{along\ path\ A} \quad and \quad \underbrace{\int_1^2 \left(\frac{\delta Q_{net}}{T} \right)_{\text{int rev}}}_{along\ path\ B}$$



A cycle composed of two reversible processes.

Apply the Clausius inequality for the cycle made of two internally reversible processes:

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

You should find:

$$\underbrace{\int_1^2 \left(\frac{\delta Q_{net}}{T} \right)_{\text{int rev}}}_{along\ path\ A} = \underbrace{\int_1^2 \left(\frac{\delta Q_{net}}{T} \right)_{\text{int rev}}}_{along\ path\ B}$$

Since the quantity $(\delta Q_{net}/T)_{int\,rev}$ is independent of the path and must be a property, we call this property the entropy *S*.

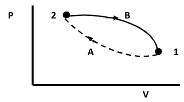
The entropy change occurring during a process is related to the heat transfer and the temperature of the system. The entropy is given the symbol S (kJ/K), and the specific entropy is *s* (kJ/kg·*K).*

The entropy change during a reversible process, sometimes called an internally reversible process, is defined as

$$dS = \left. \frac{\delta Q_{net}}{T} \right|_{\text{int rev}}$$

$$S_2 - S_1 = \int_1^2 \left. \frac{\delta Q_{net}}{T} \right|_{\text{int rev}}$$

Consider the cycle 1-A-2-B-1, shown below, where process A is arbitrary that is, it can be either reversible or irreversible, and process B is internally reversible.



A cycle composed of reversible and irreversible processes.

$$\oint \left(\frac{\delta Q_{net}}{T} \right)_{\text{int rev}} \le 0$$

$$\underbrace{\int_1^2 \frac{\delta Q_{net}}{T}}_{along\ A} + \underbrace{\int_2^1 \left(\frac{\delta Q_{net}}{T} \right)_{\text{int rev}}}_{along\ B} \le 0$$

The integral along the internally reversible path, process B, is the entropy change $S_1 - S_2$. Therefore,

$$\int_1^2 \frac{\delta Q_{net}}{T} + S_1 - S_2 \le 0$$

or

$$S_2 - S_1 \geq \int_1^2 \frac{\delta Q_{net}}{T}$$

In general the entropy change during a process is defined as

$$dS \geq \frac{\delta Q_{net}}{T}$$

where = holds for the internally reversible process
> holds for the irreversible process

Consider the effect of heat transfer on entropy for the internally reversible case.

$$dS = \frac{\delta Q_{net}}{T}$$

Which temperature *T* is this one? If

$$\delta Q_{net} > 0, \quad then \quad dS > 0$$
$$\delta Q_{net} = 0, \quad then \quad dS = 0$$
$$\delta Q_{net} < 0, \quad then \quad dS < 0$$

This last result shows why we have kept the subscript *net* on the heat transfer *Q*. It is important for you to recognize that *Q* has a sign depending on the direction of heat transfer. The *net* subscript is to remind us that *Q* is positive when added to a system and negative when leaving a system. Thus, the entropy change of the system will have the same sign as the heat transfer in a reversible process.

From the above, we see that for a reversible, adiabatic process

$$dS = 0$$
$$S_2 = S_1$$

The *reversible, adiabatic process* is called an *isentropic process*.

Entropy change is caused by heat transfer and irreversibilities. Heat transfer to a system increases the entropy; heat transfer from a system decreases it. The effect of irreversibilities is always to increase the entropy. In fact, a process in which the heat transfer is out of the system may be so irreversible that the actual entropy change is positive. Friction is one source of irreversibilities in a system.

The entropy change during a process is obtained by integrating the *dS* equation over the process:

$$\Delta S_{sys} = S_2 - S_1 \geq \int_1^2 \frac{\delta Q_{net}}{T} \qquad \left(\frac{kJ}{K}\right)$$

Here, the inequality is to remind us that the entropy change of a system during an irreversible process is always greater than $\int_1^2 \delta Q / T$ d 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 as S_{gen}.

We can remove the inequality by noting the following

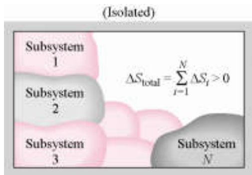
$$\Delta S_{sys} = S_2 - S_1 = \int_1^2 \frac{\delta Q_{net}}{T} + S_{gen} \qquad \left(\frac{kJ}{K}\right)$$

S_{gen} is always a positive quantity or zero. Its value depends upon the process and thus it is **not** a property. S_{gen} is zero for an internally reversible process.

The integral $\int_1^2 \delta Q / T$ performed by applying the first law to the process to obtain the heat transfer as a function of the temperature. The integration is not easy to perform, in general.

Definition of Second Law of Thermodynamics

Now consider an isolated system composed of several subsystems exchanging energy among themselves. Since the isolated system has no energy transfer across its system boundary, the heat transfer across the system boundary is zero.



Applying the definition of entropy to the isolated system

$$\Delta S_{isolated} \geq \int_1^2 \frac{\delta Q_{net}}{T} \quad \text{0, adiabatic}$$

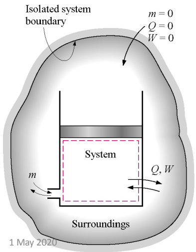
The total entropy change for the isolated system is

$$\Delta S_{isolated} \geq 0$$

This equation is the working definition of the second law of thermodynamics. The second law, known as the principle of increase of entropy, is stated as

The total entropy change of an isolated system during a process always increases or, in the limiting case of a reversible process, remains constant.

Now consider a general system exchanging mass as well as energy with its surroundings.



$$S_{gen} = \Delta S_{total} = \Delta S_{sys} + \sum \Delta S_{surr} \geq 0$$

where = holds for the totally reversible process
> holds for the irreversible process

Thus, the entropy generated or the total entropy change (sometimes called the entropy change of the universe or net entropy change) due to the process of this isolated system is positive (for actual processes) or zero (for reversible processes). The total entropy change for a process is the amount of entropy generated during that process (S_{gen}), and it is equal to the sum of the entropy changes of the system and the surroundings. The entropy changes of the important system (closed system or control volume) and its surroundings do not both have to be positive. The entropy for a given system (important or surroundings) may decrease during a process, but the ***sum*** of the entropy changes of the system and its surroundings for an isolated system can never decrease.

Entropy change is caused by heat transfer and irreversibilities. Heat transfer to a system increases the entropy, and heat transfer from a system decreases it. The effect of irreversibilities is always to increase the entropy.

The increase in entropy principle can be summarized as follows:

$$S_{gen} = \Delta S_{Total} \begin{cases} > 0 & \text{Irreversible processes} \\ = 0 & \text{Reversible processes} \\ < 0 & \text{Impossible processes} \end{cases}$$

Some Remarks about Entropy

1. Processes can occur in a certain direction only, not in just any direction, such that $S_{gen} \geq 0$.
2. Entropy is a nonconserved property, and there is no such thing as the conservation of entropy principle. The entropy of the universe is continuously increasing.
3. The performance of engineering systems is degraded by the presence of irreversibilities, and entropy generation is a measure of the magnitudes of the irreversibilities present during that process.

Heat Transfer as the Area under a *T-S* Curve

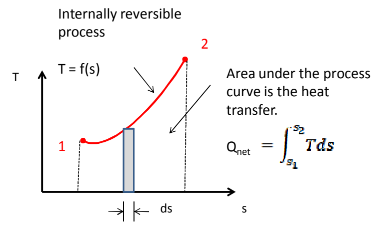
For the reversible process, the equation for *dS* implies that

$$dS = \frac{\delta Q_{net}}{T}$$

$$\delta Q_{net} = TdS$$

or the incremental heat transfer in a process is the product of the temperature and the differential of the entropy, the differential area under the process curve plotted on the *T-S* diagram.

The process curve shown here is appropriate for either a constant volume or a constant pressure process. The constant volume process has a steeper slope on the T-s diagram than does the constant pressure process.



In the above figure, the heat transfer in an internally reversible process is shown as the area under the process curve plotted on the T-S diagram.

$$Q_{net} = \int_1^2 TdS$$

Isothermal, Reversible Process

For an isothermal, reversible process, the temperature is constant and the integral to find the entropy change is readily performed. If the system has a constant temperature, T_0, the entropy change becomes

$$\Delta S = S_2 - S_1 = \int_1^2 \frac{\delta Q_{net}}{T} = \frac{Q_{net}}{T_0}$$

For a process occurring over a varying temperature, the entropy change must be found by integration over the process.

Example: We have shown that the incremental heat transfer to an ideal gas in a closed system undergoing a constant volume process with constant specific heats is

$$\delta Q_{net} = dU = mCvdT$$

Then for this process,

$$\Delta S = \int_{T_1}^{T_2} \frac{mC_v dT}{T} = mC_v \ln\left(\frac{T_2}{T_1}\right)$$

Caution: The change in entropy will depend upon the working fluid and the process.

Adiabatic, Reversible (Isentropic) Process

For an adiabatic process, one in which there is no heat transfer, the entropy change is

$$\Delta S = S_2 - S_1 \geq \int_1^2 \frac{\delta Q_{net}}{T} \quad \text{0, adiabatic}$$

$$\Delta S = S_2 - S_1 \geq 0$$

If the process is adiabatic and reversible, the equality holds and the entropy change is

$$\Delta S = S_2 - S_1 = 0$$

$$S_2 = S_1$$

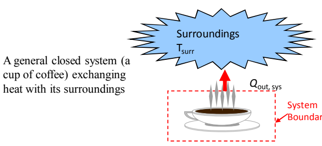
or on a per unit mass basis

$$s = \frac{S}{m}$$

$$s_2 = s_1$$

The *adiabatic, reversible process is a constant entropy process and is called isentropic*. As will be shown later for an ideal gas, the adiabatic, reversible process is the same as the polytropic process where the polytropic exponent $n = k = C_p/C_v$.

The principle of increase of entropy for a closed system exchanging heat with its surroundings at a constant temperature T_{surr} is found by using the equation for the entropy generated for an isolated system.



$$S_{gen} = \Delta S_{total} = \Delta S_{sys} + \sum \Delta S_{surr} \geq 0$$

$$\Delta S_{sys} = (S_2 - S_1)_{sys}$$

$$\sum \Delta S_{surr} = \frac{Q_{net,surr}}{T_{surr}}$$

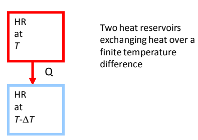
$$S_{gen} = \Delta S_{total} = m(s_2 - s_1)_{sys} + \frac{Q_{net,surr}}{T_{surr}} \geq 0$$

where

$$Q_{net,surr} = -Q_{net,sys} = -(0 - Q_{out,sys}) = Q_{out,sys}$$

Effect of Heat Transfer on Entropy

Let's apply the second law to the following situation. Consider the transfer of heat from a heat reservoir at temperature *T* to a heat reservoir at temperature *T* - Δ*T* > 0 where Δ*T* > 0, as shown below.



The second law for the isolated system composed of the two heat reservoirs is

$$S_{gen} = \Delta S_{total} = \Delta S_{sys} + \sum \Delta S_{surr} \geq 0$$
$$S_{gen} = \Delta S_{total} = \Delta S_{HR@T} + \Delta S_{HR@T-\Delta T}$$

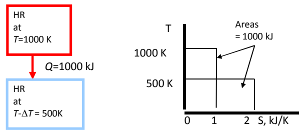
In general, if the heat reservoirs are internally reversible

$$\Delta S_{sys} = \int_1^2 \frac{\delta Q_{net}}{T}$$
$$\Delta S_{HR@T} = \frac{-Q}{T}$$
$$\Delta S_{HR@T-\Delta T} = \frac{+Q}{T-\Delta T}$$
$$S_{gen} = \Delta S_{Total} = \frac{-Q}{T} + \frac{+Q}{T-\Delta T}$$
$$S_{gen} = \Delta S_{Total} = \frac{Q}{T}\left[\frac{\Delta T}{(T-\Delta T)}\right]$$

Now as $\Delta T \to 0$, $S_{gen} \to 0$ and the process becomes totally reversible. Therefore, for reversible heat transfer ΔT must be small. As ΔT gets large, *S*gen increases and the process becomes irreversible.

Example 7-3

Find the total entropy change, or entropy generation, for the transfer of 1000 kJ of heat energy from a heat reservoir at 1000 K to a heat reservoir at 500 K.



The second law for the isolated system is

$$S_{gen} = \Delta S_{Total} = \frac{-Q}{T} + \frac{+Q}{T-\Delta T}$$
$$= \frac{-1000kJ}{1000K} + \frac{1000kJ}{500K}$$
$$= (-1+2)\frac{kJ}{K}$$
$$= 1\frac{kJ}{K}$$

What happens when the low-temperature reservoir is at 750 K?

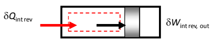
The effect of decreasing the ΔT for heat transfer is to reduce the entropy generation or total entropy change of the universe due to the isolated system and the irreversibilities associated with the heat transfer process.

Third Law of Thermodynamics

The third law of thermodynamics states that the entropy of a pure crystalline substance at absolute zero temperature is zero. This law provides an absolute reference point for the determination of entropy. The entropy determined relative to this point is called absolute entropy.

Entropy as a Property

Entropy is a property, and it can be expressed in terms of more familiar properties (*P,v,T*) through the *Tds* relations. These relations come from the analysis of a reversible closed system that does boundary work and has heat added. Writing the first law for the closed system in differential form on a per unit mass basis



System used to find expressions for *ds*

$$\delta Q_{\text{int rev}} - \delta W_{\text{int rev, out}} = dU$$
$$\delta Q_{\text{int rev}} = T\,dS$$
$$\delta W_{\text{int rev, out}} = P\,dV$$
$$T\,dS - P\,dV = dU$$

On a unit mass basis we obtain the first *Tds* equation, or Gibbs equation, as

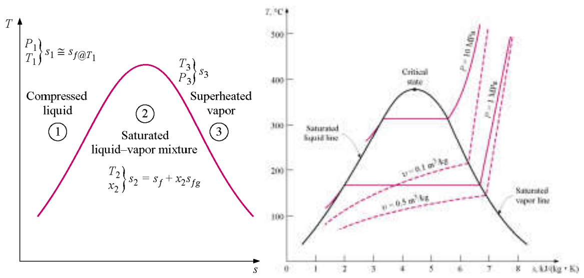
$$Tds = du + Pdv$$

Recall that the enthalpy is related to the internal energy by *h = u + Pv*. Using this relation in the above equation, the second *Tds* equation is

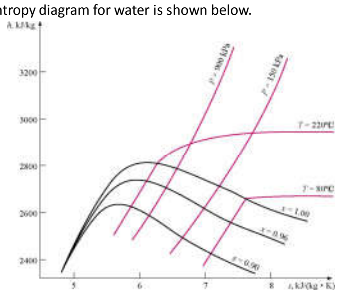
$$T\,ds = dh - v\,dP$$

These last two relations have many uses in thermodynamics and serve as the starting point in developing entropy-change relations for processes. The successful use of *Tds* relations depends on the availability of property relations. Such relations do not exist in an easily used form for a general pure substance but are available for incompressible substances (liquids, solids) and ideal gases. So, for the general pure substance, such as water and the refrigerants, we must resort to property tables to find values of entropy and entropy changes.

The temperature-entropy diagram for water is shown below.



The enthalpy-entropy diagram for water is shown below.



Shown above are the temperature-entropy and enthalpy-entropy diagrams for water. The *h-s* diagram, called the Mollier diagram, is a useful aid in solving steam power plant problems where heat transfer and work may be expressed as enthalpy changes for steady-flow constant pressure and isentropic processes, respectively.

Example 7-4

Find the entropy and/or temperature of steam at the following states:

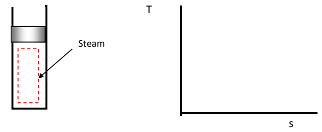
P	T	Region	s kJ/(kg K)
5 MPa	120°C		
1 MPa	50°C		
1.8 MPa	400°C		
40 kPa		Quality, x = 0.9	
40 kPa			7.1794

(Answers are on the last page of Chapter 7.)

Example 7-5

Determine the entropy change of water contained in a closed system as it changes phase from saturated liquid to saturated vapor when the pressure is 0.1 MPa and constant. Why is the entropy change positive for this process?

System: The water contained in the system (a piston-cylinder device)



Property Relation: Steam tables

Process and Process Diagram: Constant pressure (sketch the process relative to the saturation lines)

Conservation Principles: Using the definition of entropy change, the entropy change of the water per mass is

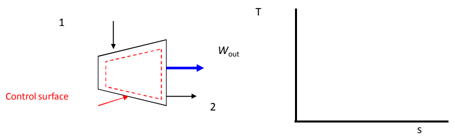
$$\Delta s = s_2 - s_1 = s_g - s_f = s_{fg}$$
$$= 6.0562 \frac{kJ}{kg \cdot K}$$

The entropy change is positive because: (Heat is added to the water.)

Example 7-6

Steam at 1 MPa, 600°C, expands in a turbine to 0.01 MPa. If the process is isentropic, find the final temperature, the final enthalpy of the steam, and the turbine work.

System: The control volume formed by the turbine



Property Relation: Steam tables

Process and Process Diagram: Isentropic (sketch the process relative to the saturation lines on the *T-s* diagram)

Conservation Principles:

Assume: steady-state, steady-flow, one entrance, one exit, neglect KE and PE

Conservation of mass:

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

First Law or conservation of energy:

The process is isentropic and thus adiabatic and reversible; therefore Q = 0. The conservation of energy becomes

$$\dot{E}_{in} = \dot{E}_{out}$$
$$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{W}_{out}$$

Since the mass flow rates in and out are equal, solve for the work done per unit mass

$$\dot{E}_{in} = \dot{E}_{out}$$
$$\dot{W}_{out} = \dot{m}_1 h_1 - \dot{m}_2 h_2$$
$$= \dot{m}(h_1 - h_2)$$
$$w = \frac{\dot{W}_{out}}{\dot{m}} = h_1 - h_2$$

Now, let's go to the steam tables to find the h's.

$$\left.\begin{matrix} P_1 = 1 MPa \\ T_1 = 600^o C \end{matrix}\right\} \left\{\begin{matrix} h_1 = 3698.6 \frac{kJ}{kg} \\ s_1 = 8.0311 \frac{kJ}{kg \cdot K} \end{matrix}\right.$$

The process is isentropic, therefore; $s_2 = s_1$ = 8.0311 kJ/(kg K)
At P_2 = 0.01 MPa, s_f = 0.6492 kJ/kg·K, and s_g = 8.1488 kJ/(kg K);
thus, $s_f < s_2 < s_g$.

State 2 is in the saturation region, and the quality is needed to specify the state.

State 2 is in the saturation region, and the quality is needed to specify the state.

$$s_2 = s_f + x_2 s_{fg}$$
$$x_2 = \frac{s_2 - s_f}{s_{fg}}$$
$$= \frac{8.0311 - 0.6492}{7.4996} = 0.984$$

Since state 2 is in the two-phase region, $T_2 = T_{sat\ at\ P2}$ = 45.81°C.

$$h_2 = h_f + x_2 h_{fg}$$
$$= 191.8 + (0.984)(2392.1)$$
$$= 2545.6 \frac{kJ}{kg}$$

$$w = h_1 - h_2$$
$$= (3698.6 - 2545.6) \frac{kJ}{kg}$$
$$= 1153 \frac{kJ}{kg}$$

Entropy Change and Isentropic Processes

The *entropy-change* and *isentropic relations* for a process can be sum-marized as follows:

1. *Pure substances:*
   Any process: $\Delta s = s_2 - s_1$ (kJ/kg·K)
   Isentropic process: $s_2 = s_1$
2. Incompressible substances (Liquids and Solids):

$$ds = \frac{du}{T} + \frac{P}{T}dv$$

The change in internal energy and volume for an incompressible substance is

$$du = C\,dT$$
$$dv \cong 0$$

The entropy change now becomes

$$ds = \frac{C\,dT}{T} + 0$$
$$\Delta s = \int_1^2 \frac{C(T)\,dT}{T}$$

If the specific heat for the incompressible substance is constant, then the entropy change is

Any process: $s_2 - s_1 = C_{av}\ln\frac{T_2}{T_1}$ (kJ/kg·K)

Isentropic process: $T_2 = T_1$

3. *Ideal gases:*
   a. Constant specific heats (approximate treatment):
   Any process: (can you fill in the steps?)

$$s_2 - s_1 = C_{v,av}\ln\frac{T_2}{T_1} + R\ln\frac{v_2}{v_1} \quad \text{(kJ/kg·K)}$$

and (can you fill in the steps?)

$$s_2 - s_1 = C_{p,av}\ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1} \quad \text{(kJ/kg·K)}$$

Or, on a unit-mole basis,

$$\bar{s}_2 - \bar{s}_1 = \bar{C}_{v,av}\ln\frac{T_2}{T_1} + R_u\ln\frac{v_2}{v_1} \quad \text{(kJ/kmol·K)}$$

and

$$\bar{s}_2 - \bar{s}_1 = \bar{C}_{p,av}\ln\frac{T_2}{T_1} - R_u\ln\frac{P_2}{P_1} \quad \text{(kJ/kmol·K)}$$

Isentropic process:

(Can you fill in the steps here?) $\left(\frac{T_2}{T_1}\right)_{s=const.} = \left(\frac{v_1}{v_2}\right)^{k-1}$

$$\left(\frac{T_2}{T_1}\right)_{s=const.} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} \qquad \left(\frac{P_2}{P_1}\right)_{s=const.} = \left(\frac{v_1}{v_2}\right)^{k}$$

For an isentropic process this last result looks like Pv^k = constant which is the polytropic process equation Pv^n = con-stant with $n = k = C_p/C_v$.

b. Variable specific heats (exact treatment):

From $Tds = dh - vdP$, we obtain

$$\Delta s = \int_1^2 \frac{C_p(T)}{T}dT - R\ln\frac{P_2}{P_1}$$

The first term can be integrated relative to a reference state at temperature T_{ref}.

$$\int_1^2 \frac{C_p(T)}{T}dT = \int_{T_1}^{T_{ref}} \frac{C_p(T)}{T}dT + \int_{T_{ref}}^{T_2} \frac{C_p(T)}{T}dT$$
$$= \int_{T_{ref}}^{T_2} \frac{C_p(T)}{T}dT - \int_{T_{ref}}^{T_1} \frac{C_p(T)}{T}dT$$

The integrals on the right-hand side of the above equation are called the standard state entropies, s^o, at state 1, T_1, and state 2, T_2; so is a function of temperature only.

$$s_1^o = \int_{T_{ref}}^{T_1} \frac{C_p(T)}{T}dT$$
$$s_2^o = \int_{T_{ref}}^{T_2} \frac{C_p(T)}{T}dT$$

Therefore, for any process:

$$s_2 - s_1 = s_2^o - s_1^o - R\ln\frac{P_2}{P_1} \quad \text{(kJ/kg·K)}$$

or

$$\bar{s}_2 - \bar{s}_1 = \bar{s}_2^o - \bar{s}_1^o - R_u\ln\frac{P_2}{P_1} \quad \text{(kJ/kmol·K)}$$

The standard state entropies are found in Tables A-17 for air on a mass basis and Tables A-18 through A-25 for other gases on a mole basis. When using this variable specific heat approach to finding the entropy change for an ideal gas, remember to include the pressure term along with the standard state entropy terms--the tables don’t warn you to do this.

Isentropic process: $\Delta s = 0$

$$s_2^o = s_1^o + R\ln\frac{P_2}{P_1} \quad \text{(kJ/kg·K)}$$

If we are given T_1, P_1, and P_2, we find s^o_1 at T_1, calculate s^o_2, and then determine from the tables T_2, u_2, and h_2.

When air undergoes an isentropic process when variable specific heat data are required, there is another approach to finding the properties at the end of the isentropic process. Consider the entropy change written as

$$\Delta s = \int_1^2 \frac{C_p(T)}{T}dT - R\ln\frac{P_2}{P_1}$$

Letting $T_1 = T_{ref}$, $P_1 = P_{ref}$ = 1atm, $T_2 = T$, $P_2 = P$, and setting the entropy change equal to zero yield

$$\left(\frac{P}{P_{ref}}\right)_{s=const} = EXP\left(\frac{1}{R}\int_{T_{ref}}^{T}\frac{C_p(T')}{T'}dT'\right)$$

We define the relative pressure P_r as the above pressure ratio. P_r is the pressure ratio necessary to have an isentropic process between the reference temperature and the actual temperature and is a function of the actual temperature. This parameter is a function of temperature only and is found in the air tables, Table A-17. The relative pressure is not available for other gases in this text.

$$(P_r)_{s=const} = EXP\left(\frac{1}{R}\int_{T_{ref}}^{T}\frac{C_p(T')}{T'}dT'\right)$$

The ratio of pressures in an isentropic process is related to the ratio of relative pressures.

$$\left(\frac{P_2}{P_1}\right)_{s=const.} = \left(\frac{P_2/P_{ref}}{P_1/P_{ref}}\right)_{s=const.} = \frac{P_{r2}}{P_{r1}}$$

There is a second approach to finding data at the end of an ideal gas isentropic process when variable specific heat data are required. Consider the following entropy change equation set equal to zero.

From $Tds = du + Pdv$, we obtain for ideal gases

$$\Delta s = \int_1^2 \frac{C_v(T)}{T}dT + R\ln\frac{v_2}{v_1}$$

Letting $T_1 = T_{ref}$, $v_1 = v_{ref}$, $T_2 = T$, $v_2 = v$, and setting the entropy change equal to zero yield

$$\left(\frac{v}{v_{ref}}\right)_{s=const} = EXP\left(-\frac{1}{R}\int_{T_{ref}}^{T}\frac{C_v(T')}{T'}dT'\right)$$

We define the relative volume v_r as the above volume ratio. v_r is the volume ratio necessary to have an isentropic process between the reference temperature and the actual temperature and is a function of the actual temperature. This parameter is a function of temperature only and is found in the air tables, Table A-17. The relative volume is not available for other gases in this text.

$$(v_r)_{s=const} = EXP\left(-\frac{1}{R}\int_{T_{ref}}^{T}\frac{C_v(T')}{T'}dT'\right)$$

$$\left(\frac{v_2}{v_1}\right)_{s=const.} = \left(\frac{v_2/v_{ref}}{v_1/v_{ref}}\right)_{s=const.} = \frac{v_{r2}}{v_{r1}}$$

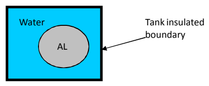
Extra Assignment

For an ideal gas having constant specific heats and undergoing a polytropic process in a closed system, Pv^n = constant, with $n = k$, find the heat transfer by applying the first law. Based on the above discussion of isentropic processes, explain your answer. Compare your results to this problem to a similar extra assignment problem in Chapter 4.

Example 7-7

Aluminum at 100°C is placed in a large, insulated tank having 10 kg of water at a temperature of 30°C. If the mass of the aluminum is 0.5 kg, find the final equilibrium temperature of the aluminum and water, the entropy change of the aluminum and the water, and the total entropy change of the universe because of this process. Before we work the problem, what do you think the answers ought to be? Are entropy changes going to be positive or negative? What about the entropy generated as the process takes place?

<u>**System:**</u> Closed system including the aluminum and water.



<u>**Property Relation:**</u> ?

<u>**Process:**</u> Constant volume, adiabatic, no work energy exchange between the aluminum and water.

<u>**Conservation Principles:**</u>

Apply the first law, closed system to the aluminum-water system.

$$Q - W = \Delta U_{system}$$

$$0 - 0 = \Delta U_{water} + \Delta U_{AL}$$

Using the solid and incompressible liquid relations, we have

$$m_{water}C_{water}(T_2 - T_1)_{water} + m_{AL}C_{AL}(T_2 - T_1)_{AL} = 0$$

But at equilibrium, $T_{2,AL} = T_{2,water} = \underline{T_2}$

$$T_2 = \frac{m_{water}C_{water}(T_1)_{water} + m_{AL}C_{AL}(T_1)_{AL}}{m_{water}C_{water} + m_{AL}C_{AL}}$$

$$= \frac{10kg_{water}(4.18kJ/kg_{water}\cdot K)(303K) + 0.5kg_{AL}(0.941kJ/kg_{AL}\cdot K)(373K)}{10kg_{water}(4.18kJ/kg_{water}\cdot K) + 0.5kg_{AL}(0.941kJ/kg_{AL}\cdot K)}$$

$$= 303.8K$$

The second law gives the entropy production, or total entropy change of the universe, as

$$S_{gen} = \Delta S_{total} = \Delta S_{water} + \Delta S_{AL} \geq 0$$

Using the entropy change equation for solids and liquids,

$$\Delta S_{AL} = m_{AL}C_{AL}\ln\frac{T_2}{T_{1,AL}}$$

$$= 0.5kg(0.941\frac{kJ}{kg\cdot K})\ln\left(\frac{303.8K}{(100+273)K}\right)$$

$$= -0.0966\frac{kJ}{K}$$

$$\Delta S_{water} = m_{water}C_{water}\ln\frac{T_2}{T_{1,water}}$$

$$= 10kg(4.177\frac{kJ}{kg\cdot K})\ln\left(\frac{303.8K}{(30+273)K}\right)$$

$$= +0.1101\frac{kJ}{K}$$

Why is ΔS_{AL} negative? Why is ΔS_{water} positive?

$$S_{gen} = \Delta S_{total} = \Delta S_{water} + \Delta S_{AL}$$

$$= (0.1101 - 0.0966)\frac{kJ}{K}$$

$$= +0.0135\frac{kJ}{K}$$

Why is S_{gen} or ΔS_{Total} positive?

Example 7-8

Carbon dioxide initially at 50 kPa, 400 K, undergoes a process in a closed system until its pressure and temperature are 2 MPa and 800 K, respectively. Assuming ideal gas behavior, find the entropy change of the carbon dioxide by first assuming constant specific heats and then assuming variable specific heats. Compare your results with the real gas data obtained from the EES software.

(a) Assume the Table A-2(a) data at 300 K are adequate; then C_p = 0.846 kJ/kg·K and R = 0.1889 kJ/kg-K.

$$s_2 - s_1 = C_{p,av} \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}$$
$$= 0.846\frac{kJ}{kg\cdot K}\ln\left(\frac{800K}{400K}\right) - 0.1889\frac{kJ}{kg\cdot K}\ln\left(\frac{2000kPa}{50kPa}\right)$$
$$= -0.1104\frac{kJ}{kg\cdot K}$$

(b) For variable specific heat data, use the carbon dioxide data from Table A-20.

$$s_2 - s_1 = \left(\frac{\bar{s}^o_{T_2} - \bar{s}^o_{T_1}}{M_{CO_2}}\right) - R\ln\frac{P_2}{P_1}$$
$$= \left(\frac{(257.408 - 225.225)kJ/kmol\cdot K}{44kg/kmol}\right) - 0.1889\frac{kJ}{kg\cdot K}\ln\left(\frac{2000kPa}{50kPa}\right)$$
$$= +0.0346\frac{kJ}{kg\cdot K}$$

(c) Using EES for carbon dioxide as a real gas:

```
Deltas=ENTROPY(CarbonDioxide,T=800,P=2000)-
    ENTROPY(CarbonDioxide,T=400,P=50)
    = +0.03452 kJ/kg·K
```


(d) Repeat the constant specific heat calculation assuming C_p is a constant at the average of the specific heats for the temperatures. Then C_p = 1.054 kJ/kg·K (see Table A-2(b)).

$$s_2 - s_1 = C_{p,av} \ln\frac{T_2}{T_1} - R\ln\frac{P_2}{P_1}$$
$$= 1.054\frac{kJ}{kg\cdot K}\ln\left(\frac{800K}{400K}\right) - 0.1889\frac{kJ}{kg\cdot K}\ln\left(\frac{2000kPa}{50kPa}\right)$$
$$= +0.0337\frac{kJ}{kg\cdot K}$$

We observe that the 300 K data give completely incorrect results here.

If the compression process is adiabatic, why is Δs positive for this process?

Module-II

BME

By:

Prof. Suchismita Swain

TITE, Khurda

Thermal Power plant

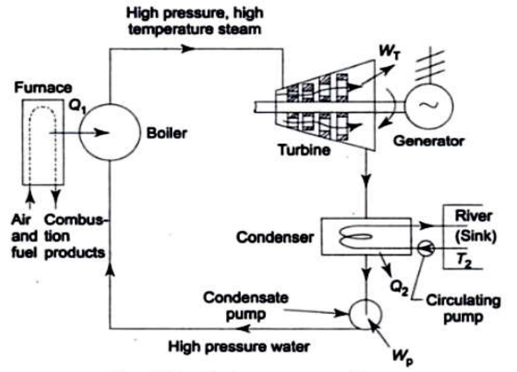


Fig. 12.1 *Simple steam power plant*

Principle of Operation of Thermal Power Plants

- Thermal power plant operate on the principle of Rankine thermodynamic cycle
- The Rankine cycle is an idealized **thermodynamic cycle** of a heat engine that converts heat into mechanical work. The heat is supplied externally to a closed loop, which usually uses water as the working fluid
- thermodynamic cycle in which there is net heat transfer to the system and a net work transfer from the system.
- Power generation from coal can be estimated by means of its calorific value kCal/kg or kJ/kg.

Principle of steam power plant

Working fluid cycle steam power plant is a closed cycle, which uses the same fluid repeatedly. First, the water is filled into the boiler to fill the entire surface area of heat transfer. In the boiler water is heated by the hot gases of combustion fuel with air so that turned into vapor phase.

- Steam produced by boiler with pressure and temperature are directed to do work on the turbine to produce mechanical power in the form of rotation.
- The former steam out of the turbine, and then flowed into the condenser to be cooled with cooling water that turned to water. Condensate water is then used again as boiler feed water. Thus the cycle goes on and repeats.

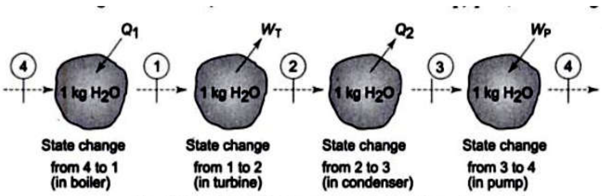


Fig. 12.2 *One kg H_2O executing a heat engine cycle*

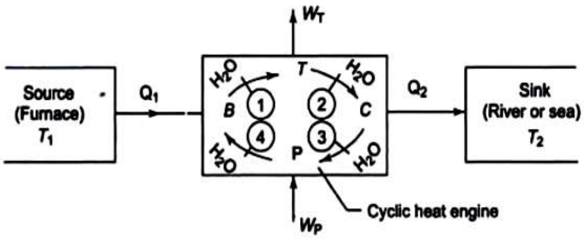


Fig. 12.3 *Cyclic heat engine with water as the working fluid*

$$\sum_{\text{cycle}} Q_{\text{net}} = \sum_{\text{cycle}} W_{\text{net}}$$

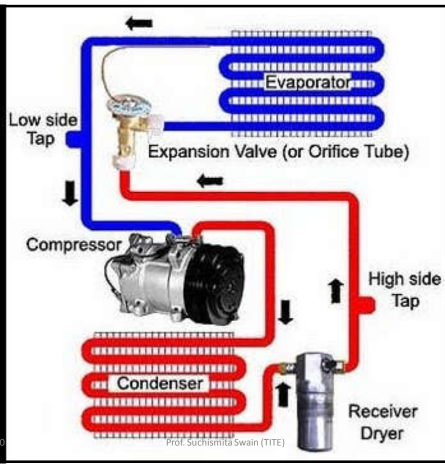
or
$$Q_1 - Q_2 = W_T - W_P$$

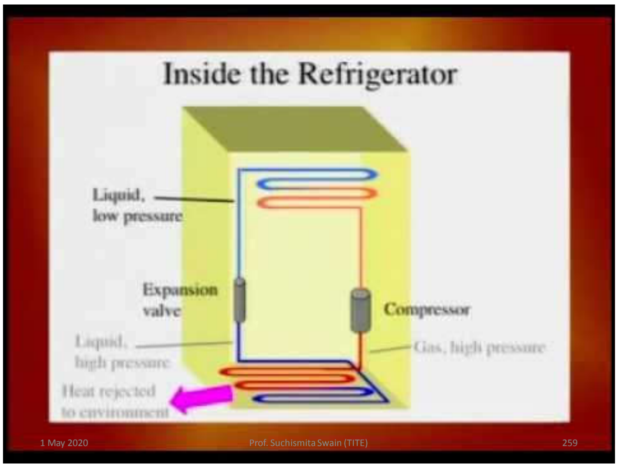
where Q_1 = heat transferred to the working fluid (kJ/kg)
Q_2 = heat rejected from the working fluid (kJ/kg)
W_T = work transferred from the working fluid (kJ/kg)
W_P = work transferred into the working fluid (kJ/kg)

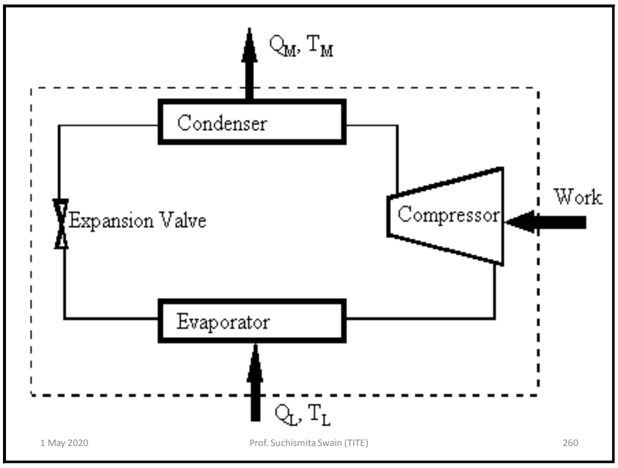
The efficiency of the vapour power cycle would be given by

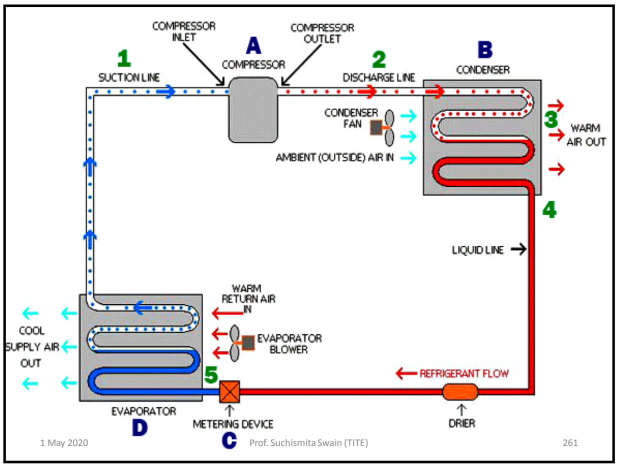
$$\eta_{\text{cycle}} = \frac{W_{\text{net}}}{Q_1} = \frac{W_T - W_P}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$
$$= 1 - \frac{Q_2}{Q_1}$$

Refrigerator





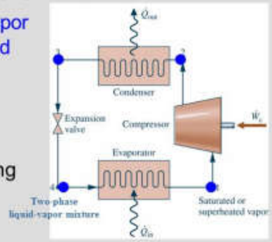




The Vapor-Compression Refrigeration Cycle

- The processes of this cycle are

Process 4-1: two-phase liquid-vapor mixture of refrigerant is evaporated through heat transfer from the refrigerated space.
Process 1-2: vapor refrigerant is compressed to a relatively high temperature and pressure requiring work input.
Process 2-3: vapor refrigerant condenses to liquid through heat transfer to the cooler surroundings.
Process 3-4: liquid refrigerant expands to the evaporator pressure.



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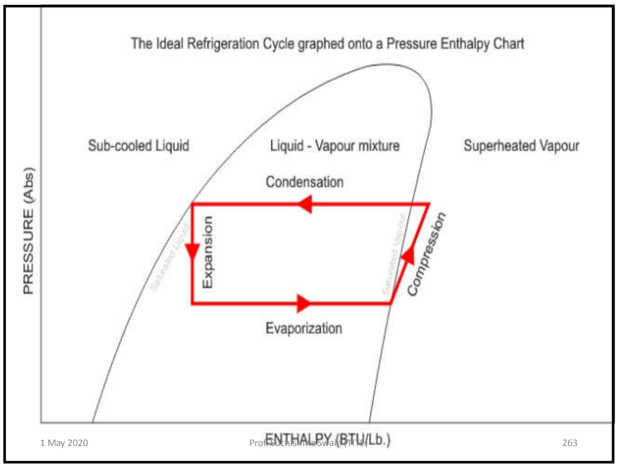

The performance of refrigerators and heat pumps is expressed in terms of *coefficient of performance* (COP), defined as

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{net,in}}$$

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{net,in}}$$

Both COP_R and COP_{HP} can be larger than 1. Under the same operating conditions, the COPs are related by

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

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The Vapor-Compression Refrigeration Cycle

► Performance parameters

Coefficient of Performance (COP)

$$\beta = \frac{\dot{Q}_{in}/\dot{m}}{\dot{W}_c/\dot{m}} = \frac{h_1 - h_4}{h_2 - h_1} \quad \textbf{(Eq. 10.7)}$$

Carnot Coefficient of Performance

$$\beta_{max} = \frac{T_C}{T_H - T_C} \quad \textbf{(Eq. 10.1)}$$

This equation represents the maximum theoretical coefficient of performance of any refrigeration cycle operating between cold and hot regions at T_C and T_H, respectively.

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Applications of Refrigeration

- In chemical industries, for separating and liquefying the gases.
- In manufacturing and storing ice.
- For the preservation of perishable food items in cold storages.
- For cooling water.
- For controlling humidity of air manufacture and heat treatment of steels.
- For chilling the oil to remove wax in oil refineries.
- For the preservation of tablets and medicines in pharmaceutical industries.
- For the preservation of blood tissues etc.,
- For comfort air conditioning the hospitals, theatres, etc.,

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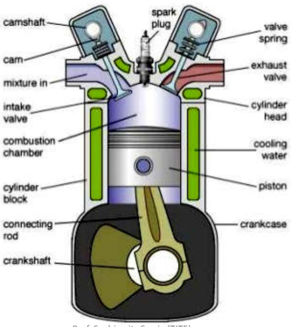
Internal Combustion Engines



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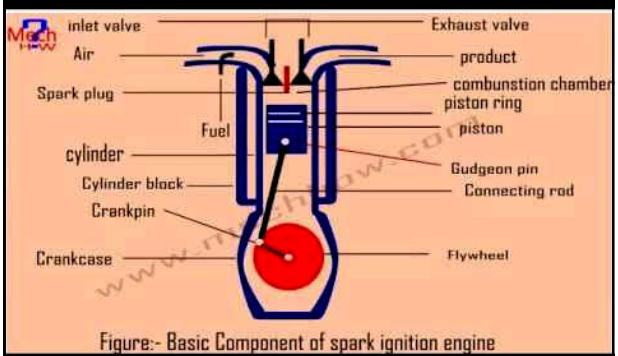

Figure:- Basic Component of spark ignition engine

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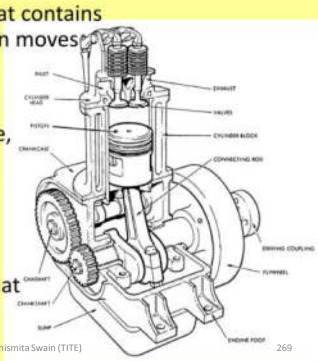
COMPONENTS OF I.C ENGINE

- Cylinder Block
  - Part of engine frame that contains cylinders in which piston moves
  - Supports liners & head
- Cylinder Head
  - Serves to admit, confine, and release fuel/air
  - Cover to cylinder block
  - Supports valve train
- Crankcase
  - Engine frame section that houses the crankshaft



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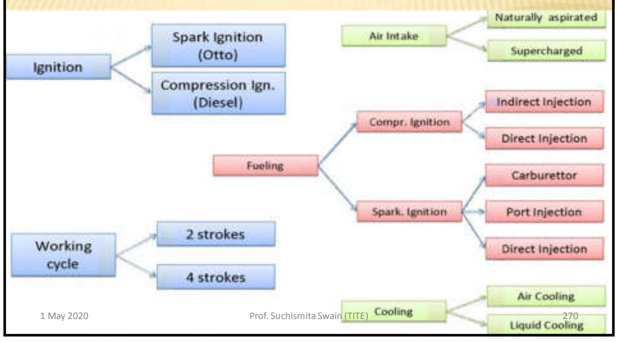
CLASSIFICATION OF INTERNAL-COMBUSTION ENGINE-



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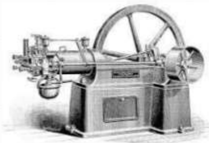
WHAT IS 2S & 4S ?

- A **two-stroke petrol engine** is an internal combustion engine that completes the process cycle in one revolution of the crankshaft. Thus, one power stroke is obtained in each revolution of the crank shaft.
- A **four stroke diesel engine** is an internal combustion engine that completes the process cycle in two revolution of the crank shaft. Thus, one power stroke is obtained in each two revolutions of the crank shaft.

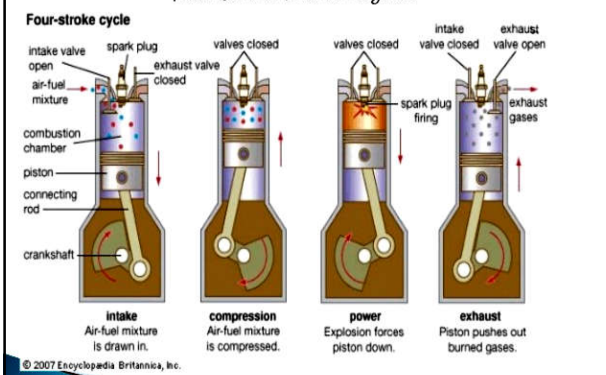
History

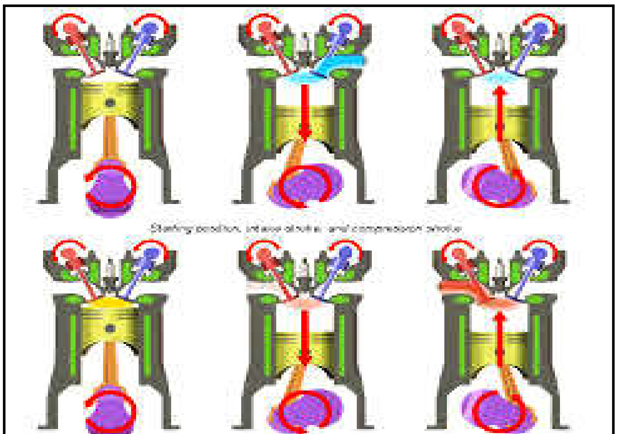
The first person to build a working four-stroke engine, a stationary engine using a coal gas-air mixture for fuel (a gas engine), was German engineer Dr. Nikolaus Otto. This is why the four-stroke principle today is commonly known as the Otto cycle and four-stroke engines using spark plugs often are called Otto engines.

Otto Cycle: Dr. Nicolaus Otto -1876

Four stroke Petrol Engine





FOUR STROKE ENGINE

- Four stroke cycle engine s is working at completed four stroke of the piston or two revoluation of the crank shaft it is called as four stroke engine
- It is two types of valves is presented these are
  - Inlet valve
  - Exhaust valve
- Four stroke petrol engine working at the four types of stroke
  - Suction stroke
  - Compression stroke
  - Power stroke or expansion stroke
  - Exhaust stroke

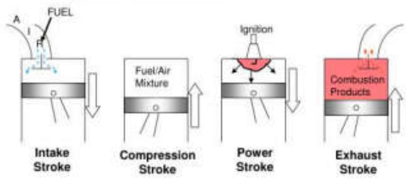
Four Stroke SI Engine

Stroke 1: Fuel-air mixture introduced into cylinder through intake valve

Stroke 2: Fuel-air mixture compressed

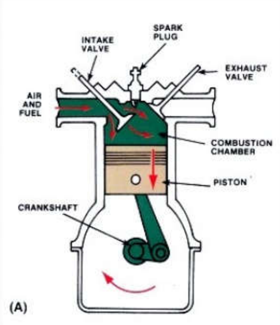
Stroke 3: Combustion (~constant volume) occurs and product gases expand doing work

Stroke 4: Product gases pushed out of the cylinder through the exhaust valve



Intake Stroke

- Intake valve opens.
- Piston moves down, ½ turn of crankshaft.
- A vacuum is created in the cylinder.
- Atmospheric pressure pushes the air/fuel mixture into the cylinder.



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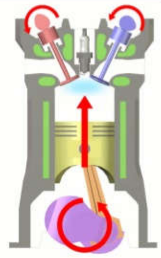
COMPRESSION STROKE

- Intake valve closed
- Exhaust valve closed
- Piston go to BDC to TDC
- Air-fuel mixture compressed in to the cylinder



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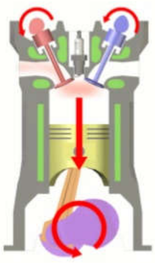
POWER STROKE

- Intake valve closed
- Exhaust valve closed
- Air-fuel mixture burn into the combustion chamber
- Piston go to TDC to BDC



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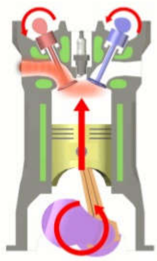
EXHAUST STROKE

- Intake valve closed
- Exhaust valve open
- Piston go to BDC to TDC
- Exhaust gas out through the exhaust valve



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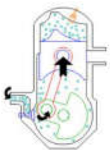
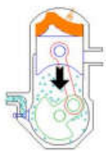
Working Priciple of 2 Stroke Spark Ignition Engine

Intake
The fuel/air mixture is first drawn into the crankcase by the vacuum that is created during the upward stroke of the piston. The illustrated engine features a poppet intake valve; however, many engines use a rotary value incorporated into the crankshaft.



Crankcase compression
During the downward stroke, the poppet valve is forced closed by the increased crankcase pressure. The fuel mixture is then compressed in the crankcase during the remainder of the stroke.



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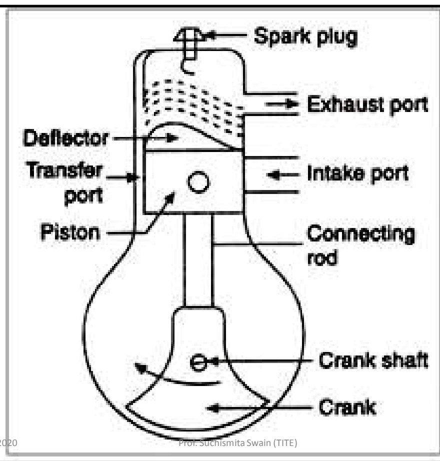

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Two Stroke Cycle Petrol Engine

- The principle of two-stroke cycle petrol engine is shown in Figure . Its two strokes are described as follows:

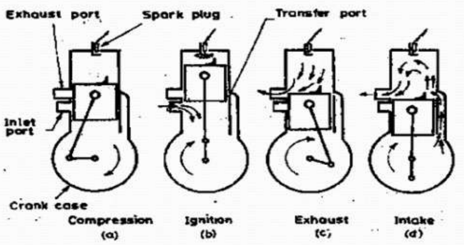

Figure: 7 Working of Two stroke Petrol Engine

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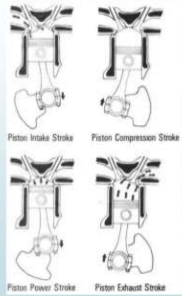
2 Stoke Engines

- Everything a 4 stroke engine does in 2 revolutions a 2 stroke engine does in 1 revolution of the crankshaft.

How to identify 2 stroke engine from outside:

- Exhaust port in center of cylinder
- Small crankcase



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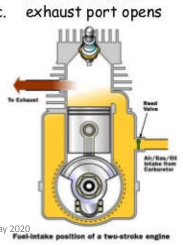
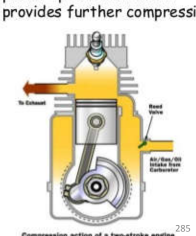
Internal Combustion Engines – two stroke -

1. Power / Exhaust
   a. ignition
   b. piston moves downward compressing fuel-air mixture in the crankcase
   c. exhaust port opens

2. Intake / Compression
   a. inlet port opens
   b. compressed fuel-air mixture rushes into the cylinder
   c. piston upward movement provides further compression



Fuel-intake position of a two-stroke engine



Compression action of a two-stroke engine

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Advantages of 2S-petrol engine

- The power developed will be nearly twice that of four-stroke engine of same dimension and operating at the same speed.
- The work required to overcome the friction of the exhaust and suction strokes is saved.
- Low weight.
- Construction is simple.

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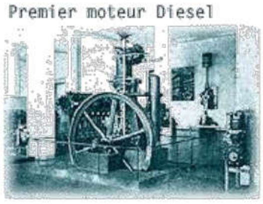
4-Stroke Diesel Engine

Rudolf Christian Karl Diesel (March 18, 1858 – September 29, 1913) was a German inventor and mechanical engineer, famous for the invention of the 4-stroke diesel engine.



Diesel Engine - Dr. Rudolph Diesel -1895

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BRIEF INTRODUCTION

- A diesel engine is an internal combustion engine.
- It uses the heat of compression to initiate ignition to burn the fuel that has been injected into the combustion chamber.
- The engine was developed by German inventor Rudolf Diesel in 1893.
- The engine works on the principle of diesel cycle

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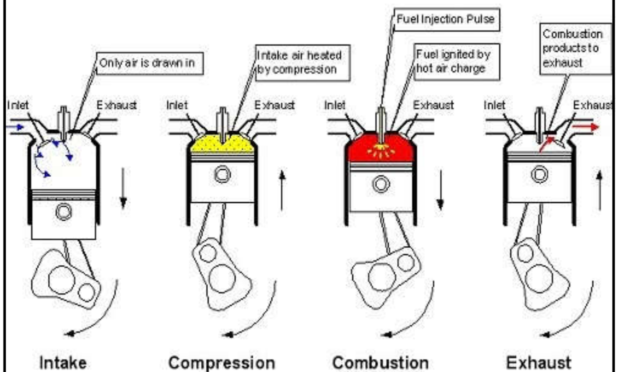
4-stroke Compression-ignition (Diesel) Engine Cycle



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The 4 Stroke COMBUSTION CYCLE

•The Diesel Engine 4 Stroke cycle consists of four distinct stages carried out whilst the engine Crank Shaft does two complete turns (or as we say, two revolutions).

•The Cams rotate once every two turns of the Crank Shaft, i.e. once per complete 4 stroke cycle.

•A 'stroke' is a movement of the Piston from one end of the Cylinder to the other end.

1st Stroke - **INDUCTION**. Fresh air is drawn into the Cylinder through the open Inlet Valve by the Piston descending. The Inlet Valve closes when the Piston reaches bottom of Cylinder, trapping the fresh air in the Cylinder.

2nd Stroke - **COMPRESSION**. The Air is squeezed as the Piston rises, reaching about 40 bar pressure. The air gets very hot (about 700° C) because of the work done to it by the Piston. Diesel fuel is started to be Injected into the Cylinder as the Piston gets near to the top.

3rd Stroke - **POWER**. Fuel is injected into the Cylinder for a short while as the Piston is near the top. The fuel spray ignites and burns in the hot air, creating even higher pressures and temperatures in the cylinder. The pressure of the hot gases push the Piston down, delivering power to the crank-shaft and fly wheel.

4th Stroke - **EXHAUST**. The Exhaust Valve opens and the rising Piston pushes the burnt gases out of the Cylinder. When the Piston gets near the top the Exhaust Valve closes and the Inlet Valve opens, ready to draw fresh air in again. 290

Two Stroke Diesel Engine

Two stroke engine is first described by Du gal Clerk in 1878.In two stroke engine one cycle is completed in every revolution of crankshaft.

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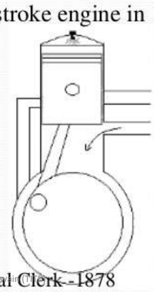
2-Stroke Diesel Engine

Sir **Dugald Clerk** KBE, FRS (1854, Glasgow – 1932, Ewhurst, Surrey) was a Scottish engineer who designed the world's first successful two-stroke engine in 1878 and patented it in England in 1881.



1 May 2020 2-Cycle Engine, Du gal Clerk -1878 292

Comparison of Petrol and Diesel Engines

PETROL ENGINE	DIESEL ENGINE
1. Works on Otto Cycle	1. Works on Diesel Cycle
2. Fuel-air mixture is admitted during suction stroke	2. Fuel is injected at the end of compression stroke
3. Spark ignition	3. Compression ignition
4. Low compression ratios (6 to 10)	4. High compression ratios (10 to 20)
5. Lower engine efficiency	5. Higher engine efficiency
6. Higher fuel consumption	6. Lower fuel consumption
7. Lower engine vibrations and noise	7. Higher engine vibrations and noise
8. High running cost	8. Low running cost
9. Light duty application	9. Heavy duty application

12 1 May 2020 Prof. Suchismita Swain (TITE) 293

Difference between 4-Stroke Engine & 2-Stroke Engine

4-Stroke Engine	2-Stroke Engine
One cycle completed in every 2 revolution of crankshaft	One cycle completed in every revolution of crankshaft
More moving parts	Less moving parts
More maintenance	Less maintenance
Heavy in weight	Light in weight
More expensive	Less expensive

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WHAT IS AIR COMPRESSORS?

- **COMPRESSOR** :
  "The machine which takes in air or any other gas at low pressure and compresses it to high pressure are called compressors."

The compressor used for increasing the pressure is called "air compressor."

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Introduction to compressors

- The machine which takes in air or any other gas at low pressure and compresses it to high pressure is called compressor. The compressor is power consuming machine in which mechanical work is converted into pressure energy of fluid. They are also considered as reversed heat engine.

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Types of Air Compressors

1. Reciprocating or Piston Compressors
2. Rotary Sliding Vane Compressors
3. Rotary Screw Compressors
4. Centrifugal Compressors

Phone: 508-230-7118
Email: info@compressorworld.com
COMPRESSORWORLD THE ONLINE AIR COMPRESSOR SUPERSTORE

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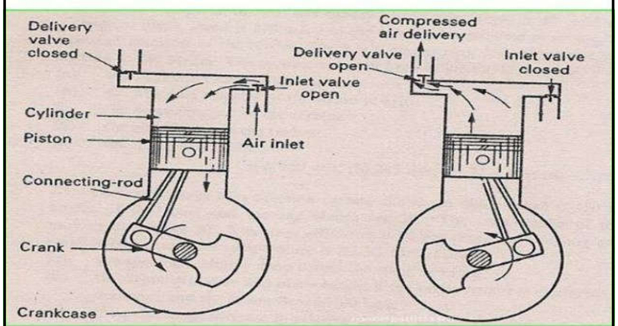
Reciprocating Compressor



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Single stage Reciprocating Air compressors

- When piston starts moving downwards, the pressure inside the cylinder falls below atmospheric pressure that opens suction valve.
- The pressure of the air in the cylinder rises during compression and at the end of compression, delivery valve opens and discharges the compressed air into the receiver tank.

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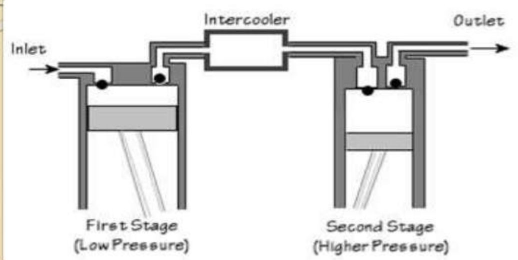
Reciprocating Compressor Types

- Single–Stage Reciprocating Compressor
  - Compression is done in single stage or by single cylinder only and it is used for generation of low pressure air.
- Double–stage Reciprocating Compressor
  - It is a compressor that produces highly pressurised air and mostly it is used nowadays in heavy duty mechanical devices.

Two stage- reciprocating air compressor



ADVANTAGES

- Reciprocating compressors are cheaper, it costs about half the rotary compressors.
- Low installation and service cost as it have low maintenance points.
- **Ideal for light use** - For smaller jobs, reciprocating air compressors are more efficient and more affordable. If you need a compressor for your home workshop, this is the way to go.
- **Durable** - Reciprocating air compressors tend to be very sturdy and reliable. They are able to withstand harsh environments.

Advantages of multi-stage compression

- The work done in compressing the air is reduced, thus power can be saved.
- Prevents mechanical problems as the air temperature is controlled.
- The suction and delivery valves remain in cleaner condition as the temperature and vaporization of lubricating oil is less
- The machine is smaller and better balanced
- Effects from moisture can be handled better, by draining at each stage
- Compression approaches near isothermal

MODULE-3

By:

Prof. Suchismita Swain

Asst. Proff.(ME)

TITE-Bhubaneswar

Power Transmission

- The following are the major types of power transmission devices

(a) Belt drive (b) Rope drive

(c) Chain drive (d) Gear drive

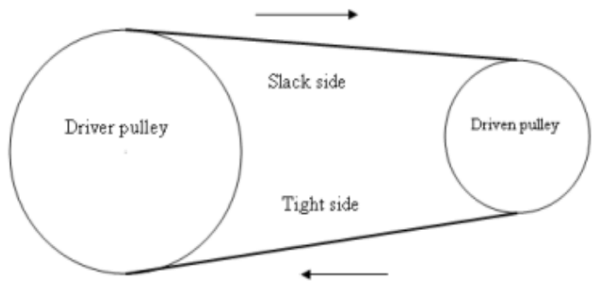
Belt Drive:

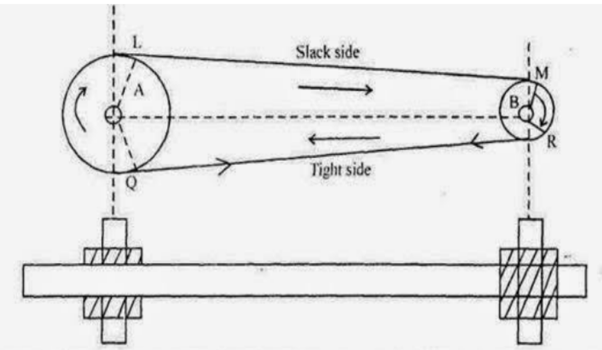
- This type of drive is used when the power is to be transmitted from one shaft to other which is at a distance.
- Pulleys are mounted on the driver and driven shafts and an endless belt are fitted tightly over these pulleys.

➢The frictional resistance between these pulleys and belt is the reason for the power transmission, which depends on the velocity of belt, tension of the belt and arc of contact of the belt in the smaller pulley.

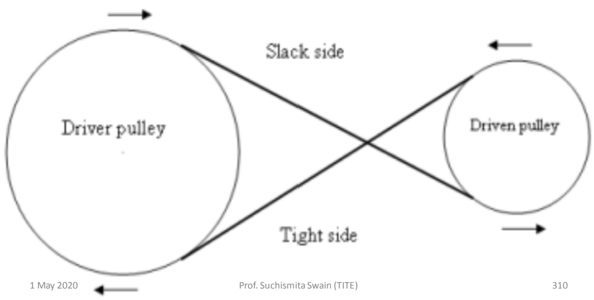
Types of Belt drive:

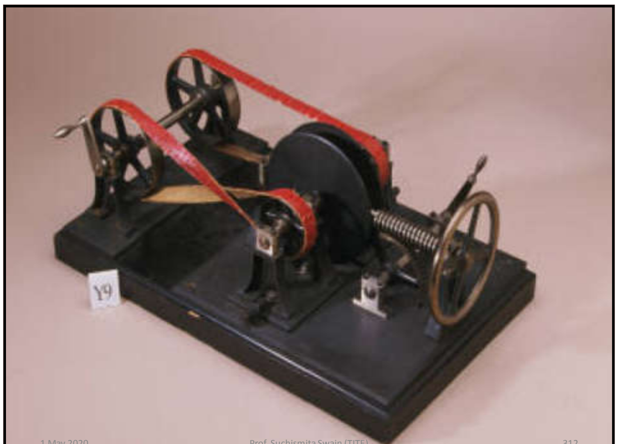
(a) Open belt drive: For parallel shafts and to be rotated in the same direction as that of the driver shaft. The driver pulley pulls the belt from one side and delivers it to the other side. The tension in the former side will be larger and hence called tight side and the other side is called slack side.





- **(b) Crossed belt drive:** When the driven shaft is to be rotated in the opposite direction as that of the driver shaft, the belt is to be arranged in a crossed manner.





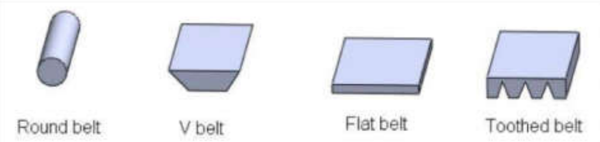
Types of Belts

- There are mainly 3-types of belts.

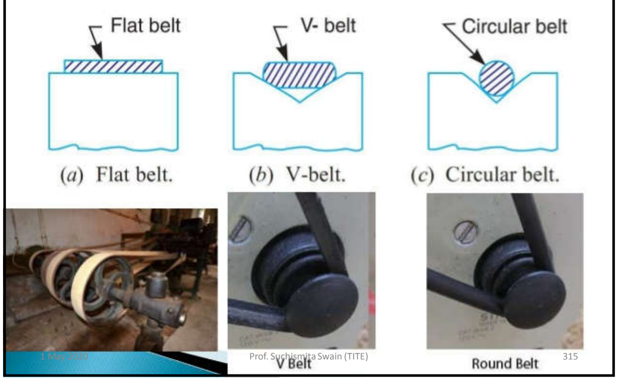
(a) Flat belt: It is mostly used in factories and workshops, where a moderate amount of power is to be transmitted, when the two pulleys are not more than 8 m apart.

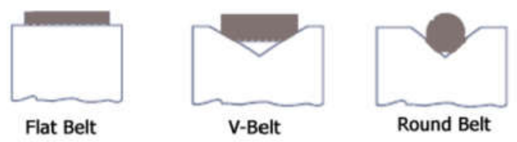
(b) V-belt: It is used in factories and workshops, where comparatively large amount of power is to be transmitted, when the two pulleys are very near to each other.

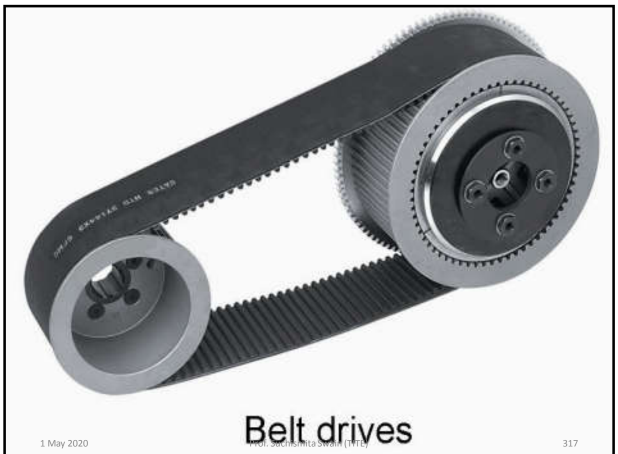
(c) Circular (round) belt: It is used in factories and workshops, where a great amount of power is to be transmitted from one pulley to another, when the pulleys are more than 8m apart.



Belt Type

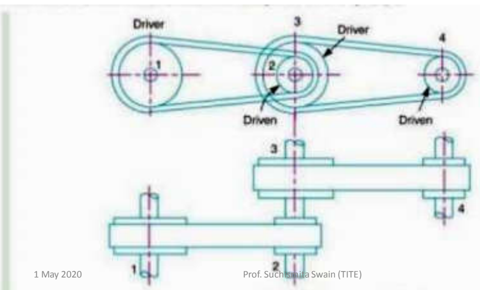






Compound Belt Drive

- A compound belt drive is used when power is transmitted from one shaft to another through a no. Of pulleys and the velocity ratio is high

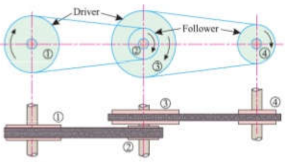


Compound belt drive

Let d_1, d_2, d_3, d_4, and N_1, N_2, N_3, N_4 = diameters and speeds for pulleys 1, 2, 3 and 4.

We know that velocity ratio of pulleys 1 and 2,

$$VR_1 = \frac{N_2}{N_1} = \frac{d_1}{d_2} \quad \text{---------------} \quad (1)$$



Similarly, velocity ratio of pulleys 3 and 4,

$$VR_2 = \frac{N_4}{N_3} = \frac{d_3}{d_4} \quad \text{---------------} \quad (2)$$

Multiplying the above equations

$$VR_1 \times VR_2 = \frac{N_2 \times N_4}{N_1 \times N_3} = \frac{d_1 \times d_3}{d_2 \times d_4} \quad \text{---------------} \quad (3)$$

Since $N_2=N_3$, therefore velocity ratio of compound belt drive

$$VR = VR_1 \times VR_2 = \frac{N_4}{N_1} = \frac{d_1 \times d_3}{d_2 \times d_4} \quad \text{---------------} \quad (4)$$

$$VR = \frac{Speed\ of\ last\ follower}{Speed\ of\ first\ driver} = \frac{product\ of\ diameters\ of\ drivers}{product\ of\ diameters\ of\ followers}$$

Slip of belt

- Some times the frictional grip between belt and pulley becomes insufficient, this may cause some forward motion of the driver without carrying the belt with it. This may also cause some forward motion of the belt without carrying the driven pulley with it. This is called **slip** of the belt.
- It is generally expressed as a percentage.
- The result of slip is to reduce the velocity ratio of the system.

Creep of Belt

- When the belt passes from the slack side, a certain portion of the belt extends and it contracts again when the belt passes from the tight side to slack side. Due to these changes of length, there is a relative motion between the belt and the pulley. This relative motion is called **creep**.
- The total effect of creep is to reduce the speed of the driven pulley.

- Creep is due to elastic property of belt, where as the conventional slip is due to insufficient frictional grip between the belt and pulley.
- The effect of both is to reduce speed ratio hence reduce the power transmission.

- Explain briefly about Slip and creep of a belt in belt drive. **[2 marks] [BPUT-1st sem.-2016]**

ROPE DRIVE

- Ropes are used when considerable power is to be transmitted over long distances.
- Ropes are placed in grooves provided in the pulley.
- The groove angle varies from 40 to 60 degree, but is generally 45degree
- Wire ropes are made up of wires, which are twisted together to form a strand.
- A no. of strands twisted together to form a rope.
- Ropes are designated by specifying the no. of strands and no. of wires on it. Eg: 6*19

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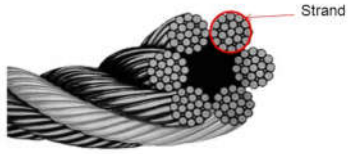
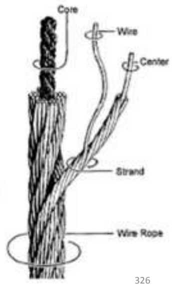
Wire Ropes

Wire rope consists of multiple wires or strands, helically wound or laid about an axis.

Wires, strands and cores are independent- that interact with each other during service.





Wire ropes are designed in different steel grades, finishes and a variety of constructions to attain the best balance of strength, abrasion resistance, crush resistance, bending fatigue resistance and corrosion resistance for each application.

Advantages of Rope drives

- Smooth and silent
- Less weight
- Shock resistant
- Longer life.

Gear Drives

- Slipping of a belt or rope is a common phenomenon, in the transmission of power.
- The effect of slipping is to reduce the velocity ratio of the system.
- In precision machines, in which a definite velocity ratio is of importance like in watch, the only positive drive is by means of gears or toothed wheels.
- Toothed wheel is the gear for transmitting power between two shafts, which are very closer.

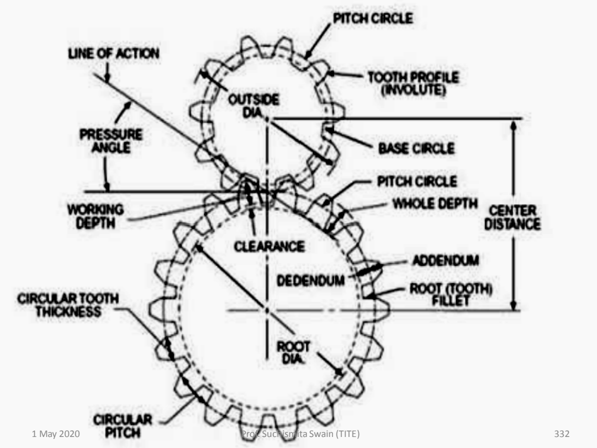
- The teeth of the gear mounted on the shaft meshes each other during rotation.
- Gears are manufactured either by milling, by casting or by hobbing.

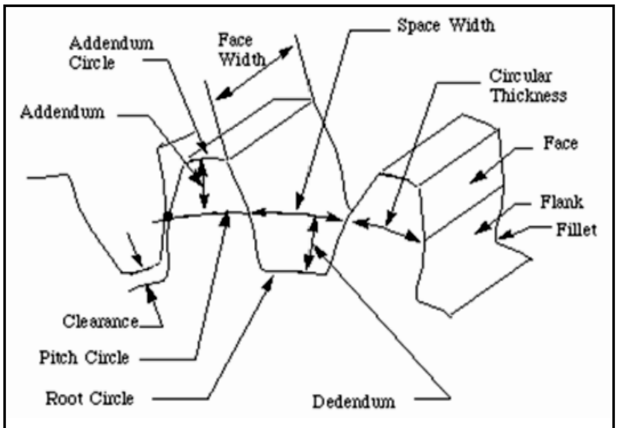
ADVANTAGES OF GEAR DRIVES

It transmits exact velocity ratio.
Transmits large power.
High efficiency.
Reliable service.
Compact layout.

DISADVANTAGES OF GEAR DRIVES

The manufacture of gears require special tools and equipments.
The error in cutting teeth may cause vibrations and noise during operations.





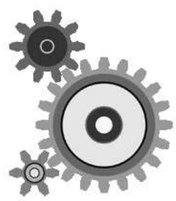
Internal and External Gear

Internal Gear

- An internal gear is one with the teeth formed on the inner surface of a cylinder or cone.

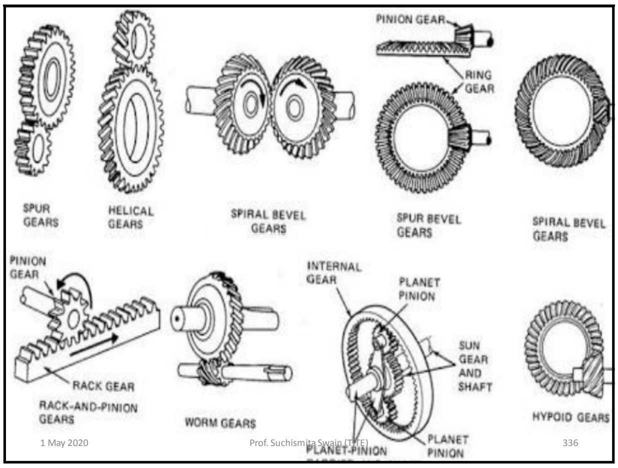
External Gear

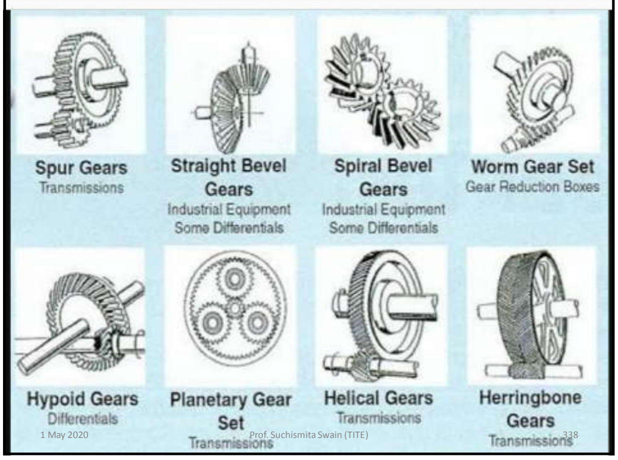
- An external gear is one with the teeth formed on the outer surface of a cylinder or cone.



Classification of Gears

- ***According to the position of axes of the shafts.***
  - Spur gears – parallel shafts – most common
  - Bevel gears – perpendicular shafts
  - Worm gears - perpendicular overlapping shafts
  - Rack and pinion gears – convert circular motion to linear motion
- According to the type of gearing
- ***According to the position of teeth on the gear surface.***





Gear Ratio

- A gear ratio is the ratio used to determine the angular speed and torque of a geared system.

Number of driven teeth : Number of driver teeth

Also written as:

$$\frac{\textit{Driven teeth}}{\textit{Driver teeth}}$$

- If a set of gears has a driver and driven gearof the same size. The gear ratio would be 1:1.
- This causes a change in the direction of the motion with no change to speed or torque.

BME-2016-1st Semester-10marks

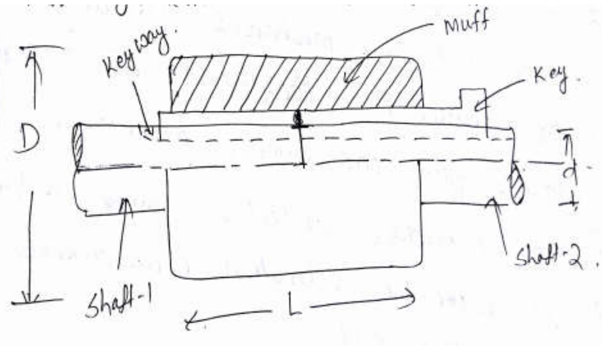
Two parallel shafts are connected with the help of two gears, one gear on each shaft. The no. of teeth on one gear is 38 and the speed of the shaft is 420 rpm. If the speed ratio is equal to 3 and circular pitch of the gear is 25mm, then find:

(i) No. of teeth and speed of other shaft.

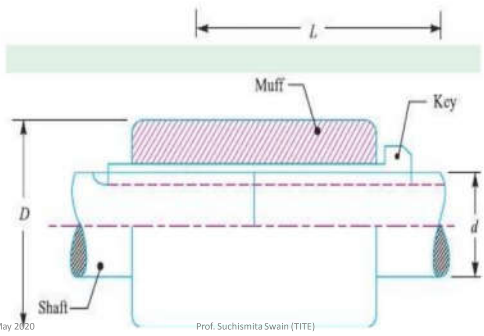
(ii) Centre distance between two shafts.

COUPLING

- A coupling is a device used to connect two shafts together at their ends for transmitting power. Coupling do not normally allow disconnection of shafts during operation.
- The primary purpose of coupling is to join two pieces of rotating equipment while permitting some degree of misalignment or end movement or both.



a. Sleeve or Muff-coupling



Uses

- To transfer power from one end to another. Ex.: motor transfers power to pump through coupling.
- To provide the connection of shafts of units that are manufactured separately such as a motor and generator and to provide for disconnection for repair or alterations.
- To provide misalignment of the shafts or to introduce mechanical flexibility.
- To reduce the transmission of shock loads from one shafts to another
- To introduce protection against overload

Types of Coupling

- **Rigid Coupling:** It is used to connect two shafts which are perfectly aligned. Following types of rigid coupling are important.

a) Sleeve or muff coupling.

b) Clamp or split-muff or compression coupling

c) Flange coupling.

- **Flexible Coupling:** It is used to connect two shafts having both lateral and angular misalignment. Following are the types.

a) Bushed pin type coupling

b) Universal coupling

c) Oldham coupling.

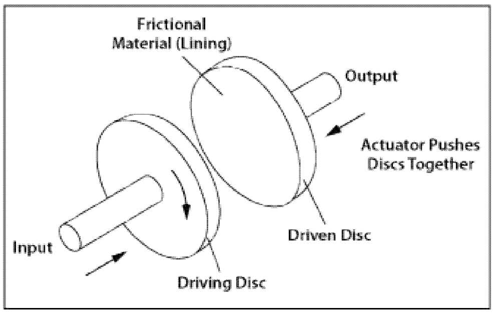
CLUTCH

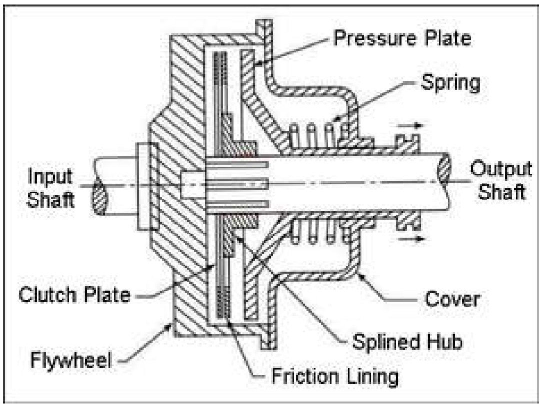
- Transmission is the mechanism which is used to transfer the power developed by engine to the wheels of an automobile.
- The transmission system of an automobile includes clutch, gearbox, propeller shaft axle and wheels etc.
- Clutch is used to engage or disengage the engine to the transmission or gearbox.
- When the clutch is in engaged position, the engine power or rotary motion of engine crank shaft is transmitted to gear box and then to wheels.

- When clutch is disengaged, the engine power does not reach to gear box or to wheels although the engine is running.
- Clutch is also used to allow shifting or changing of gears when vehicle is running.
- For shifting gears clutch is first disengaged then gear is shifted and then clutch is engaged.
- Clutch has to be disengaged to stop the vehicle, if the vehicle is not in neutral gear.

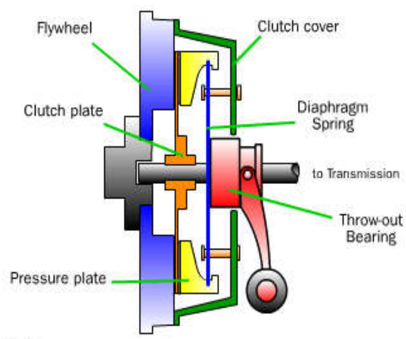
Principle of Clutch

- It operates on the principle of friction.
- When two surfaces are brought in contact and are held against each other due to friction between them, they can be used to transmit power. If one is rotated the other one also rotates.
- One surface is connected to engine and other to the transmission system of automobile.
- Hence clutch is nothing but a combination of two friction surfaces.





Clutch Engaged



Main parts of a Clutch

(a) A driving member:

- It consists of a flywheel, which is mounted on the engine crankshaft.
- The flywheel is bolted to a cover which carries pressure plate, pressure springs and releasing levers.

(b) A driven member:

- It consists of a disc plate called clutch plate.
- The clutch is free to slide on the splines of the clutch shaft.

- It carries friction materials on both of its surfaces.
- When the clutch plate is gripped between the flywheel and the pressure plate, it rotates the clutch shaft through splines.

(c) An operating member:

- The operating member consists of a pedal or lever which can be pressed to disengage the driving and driven plate.

Types of clutch

(a) Friction clutch:

- Single plate clutch
- Multi plate clutch (Dry or Wet)
- Cone clutch

(b) Centrifugal clutch

(c) semi-centrifugal clutch

(d) Hydraulic clutch

(e) Positive clutch

(f) Vacuum clutch

(g) Electromagnetic clutch.

- Explain the function of a clutch and different types of clutch with their relative advantages and disadvantages. [10 marks] **[BPUT-1st sem.-2017]**

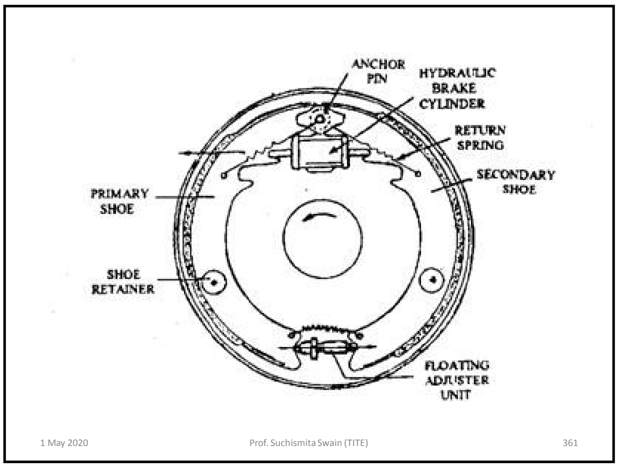
Brakes

- A brake is a mechanical device that retards motion by absorbing energy from a moving system.
- It is used for slowing or stopping a moving vehicle, wheel, axle or to prevent its motion by means of friction.

Types

(a) Drum Brakes:

- In drum brakes, the brake lining is adhered to the external surface of a curved bracket called shoes.
- The most common configuration includes, two shoes mounted inside a drum of a plate. A cylinder presses the shoes onto the insides of the drum to initiate deceleration.
- A drum brake that presses on the outside of the drum is called a **clasp brake**.
- A double clasp brake applies braking pressure to both inside and outside of the drum


ANCHOR PIN
HYDRAULIC BRAKE CYLINDER
RETURN SPRING
SECONDARY SHOE
PRIMARY SHOE
SHOE RETAINER
FLOATING ADJUSTER UNIT
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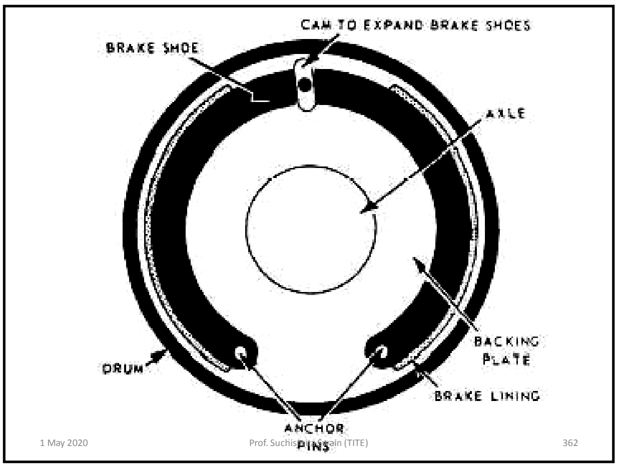
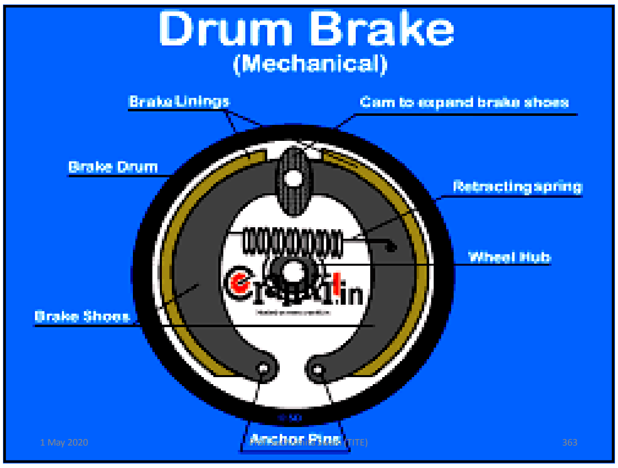
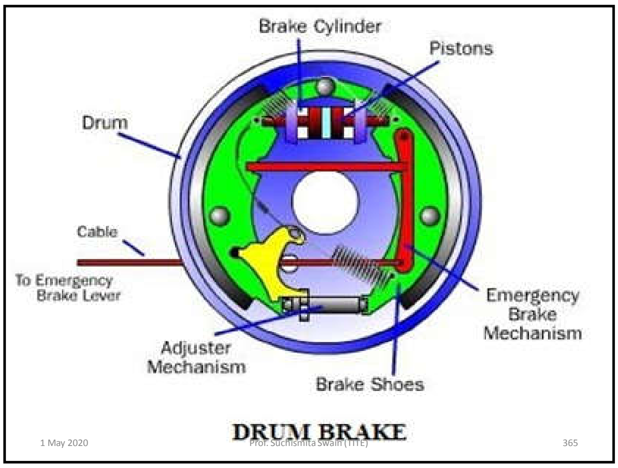
361


CAM TO EXPAND BRAKE SHOES
BRAKE SHOE
AXLE
BACKING PLATE
DRUM
BRAKE LINING
ANCHOR PINS
1 May 2020
362


Drum Brake
(Mechanical)
Brake Linings
Cam to expand brake shoes
Brake Drum
Retracting spring
Wheel Hub
Brake Shoes
Anchor Pins
1 May 2020
363


Brake Cylinder
Pistons
Drum
Cable
To Emergency Brake Lever
Emergency Brake Mechanism
Adjuster Mechanism
Brake Shoes
DRUM BRAKE
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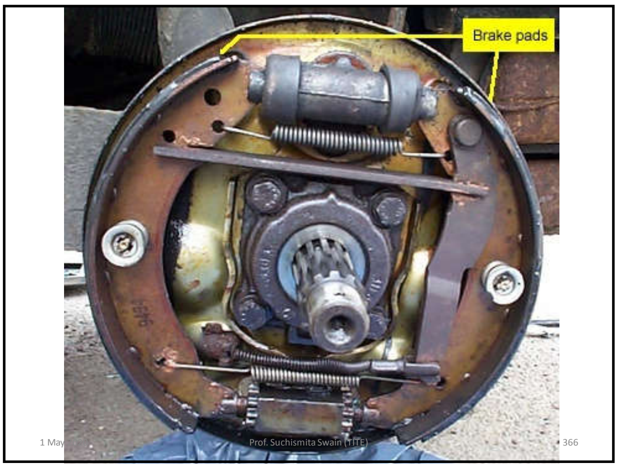
365


Brake pads
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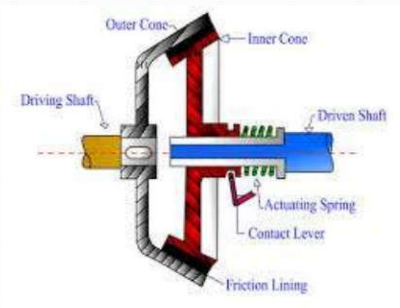
366

(b) Cone Brakes:

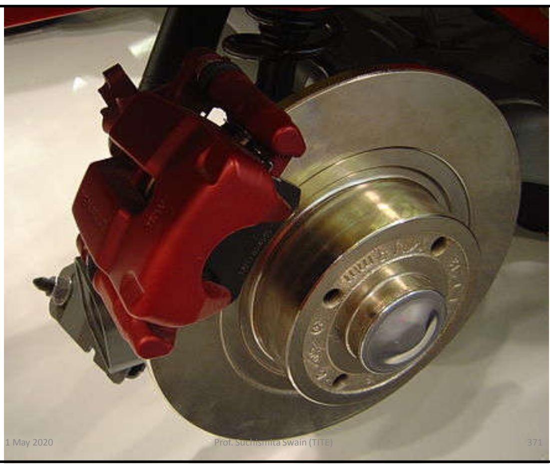
- This is a type of drum brake where the drum and shoe are mating sections of conical frustums.
- The shoe (cone) is outfitted with brake lining and pressed into the drum (cup) to apply friction.
- The advantage is increased surface area, less force required for disengage and hence quicker deceleration.

Cone clutch

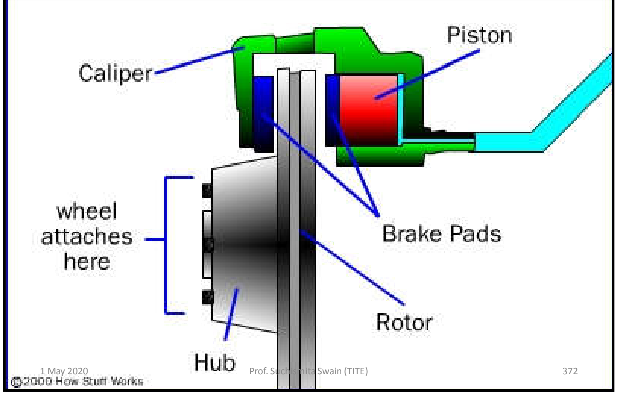


(c) Disc Brakes:

- It utilise a metal disc, also called a rotor, that is connected to the axle.
- The rotor spins between a calliper, which pushes a lining material outfitted on a brake pad against the rotor surface.

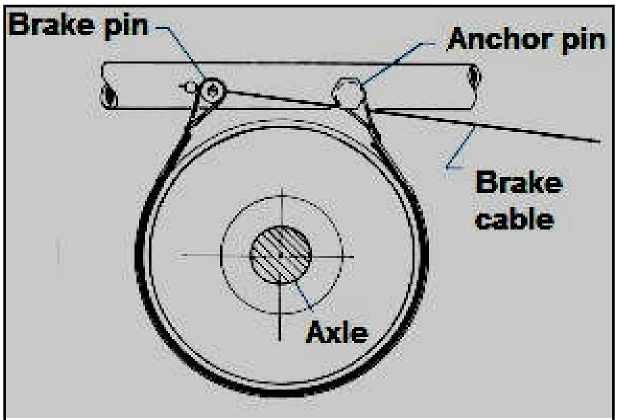


How a Disc Brake Works



(d) Band Brakes:

- Band brakes tighten a ribbon of high friction material around a pulley attached to the rotating axle.
- They are often employed on bicycles. If the pull on the band is in the direction of axle rotation the brake is self-energizing.
- Differential band brakes attach both ends of the brakes ribbon to the lever to supply braking power for bi-directional shafts.



Band Brake

- Classify the brake on basis of mode of operation. **[5 marks]** **[BPUT-1st sem.-2017]**

INTRODUCTION TO ROBOTICS

By:
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Asst.Prof.(ME)
TITE, Khurda

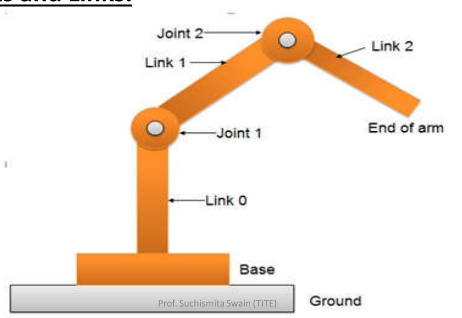
INTRODUCTION

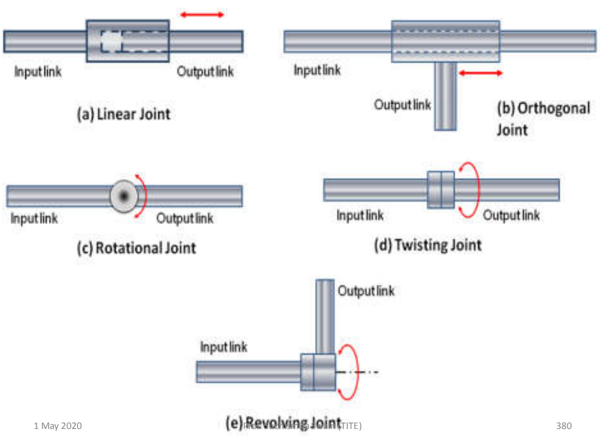
- An industrial robot is a general-purpose, programmable machine. It possesses some anthropomorphic characteristics, i.e. human-like characteristics that resemble the human physical structure. The robots also respond to sensory signals in a manner that is similar to humans.
- Robots are good substitutes to the human beings in hazardous or uncomfortable work environments.
- A robot performs its work cycle with a consistency and repeatability which is difficult for human beings to attain over a long period of continuous working.

- Robots can be reprogrammed. When the production run of the current task is completed, a robot can be reprogrammed and equipped with the necessary tooling to perform an altogether different task.
- Robots can be connected to the computer systems and other robotics systems. Nowadays robots can be controlled with wire-less control technologies. This has enhanced the productivity and efficiency of automation industry.

Robot anatomy and related attributes

Joints and Links:





a) Linear joint (type L joint)

The relative movement between the input link and the output link is a translational sliding motion, with the axes of the two links being parallel.

b) Orthogonal joint (type U joint)

This is also a translational sliding motion, but the input and output links are perpendicular to each other during the move.

c) Rotational joint (type R joint)

This type provides rotational relative motion, with the axis of rotation perpendicular to the axes of the input and output links.

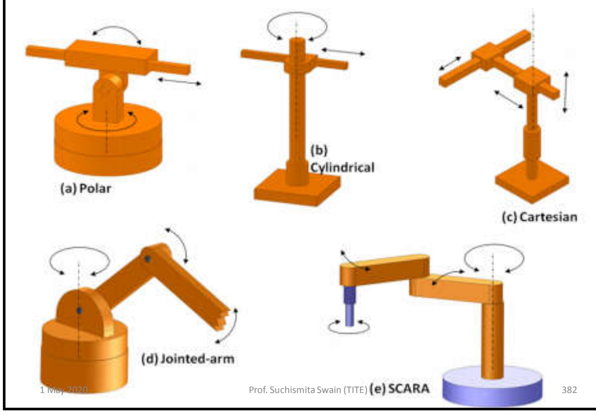
d) Twisting joint (type T joint)

This joint also involves rotary motion, but the axis or rotation is parallel to the axes of the two links.

e) Revolving joint (type V-joint, V from the "v" in revolving)

In this type, axis of input link is parallel to the axis of rotation of the joint. However the axis of the output link is perpendicular to the axis of rotation.

Common Robot Configurations



a. Polar configuration

It consists of a sliding arm L-joint, actuated relative to the body, which rotates around both a vertical axis (T-joint), and horizontal axis (R-joint).

b. Cylindrical configuration

It consists of a vertical column. An arm assembly is moved up or down relative to the vertical column. The arm can be moved in and out relative to the axis of the column. Common configuration is to use a T-joint to rotate the column about its axis. An L-joint is used to move the arm assembly vertically along the column, while an O-joint is used to achieve radial movement of the arm.

c. Cartesian co-ordinate robot

It is also known as rectilinear robot and x-y-z robot. It consists of three sliding joints, two of which are orthogonal O-joints.

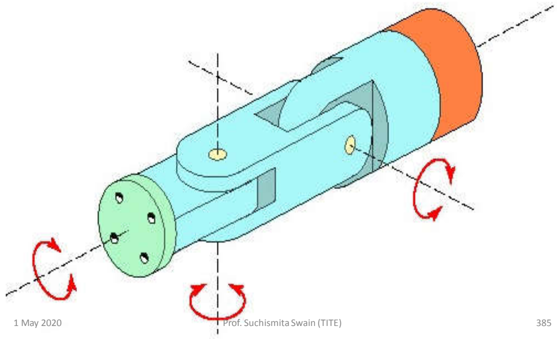
d. Jointed-arm robot

It is similar to the configuration of a human arm. It consists of a vertical column that swivels about the base using a T-joint. Shoulder joint (R-joint) is located at the top of the column. The output link is an elbow joint (another R joint).

e. SCARA

Its full form is 'Selective Compliance Assembly Robot Arm'. It is similar in construction to the jointer-arm robot, except the shoulder and elbow rotational axes are vertical. It means that the arm is very rigid in the vertical direction, but compliant in the horizontal direction.

Robotic wrist joint



- Robot wrist assemblies consist of either two or three degrees-of-freedom. A typical three-degree-of-freedom wrist joint is depicted in Figure 7.5.4. The roll joint is accomplished by use of a T-joint. The pitch joint is achieved by recourse to an R-joint. And the yaw joint, a right-and-left motion, is gained by deploying a second R-joint.

MODULE-4

By:

Prof. Suchismita Swain

(TITE, Khorda)

Power Transmission

- The following are the major types of power transmission devices

(a) Belt drive (b) Rope drive

(c) Chain drive (d) Gear drive

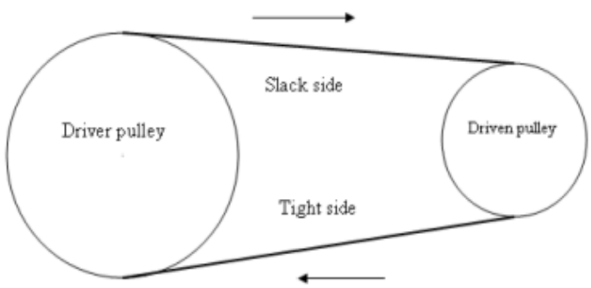
Belt Drive:

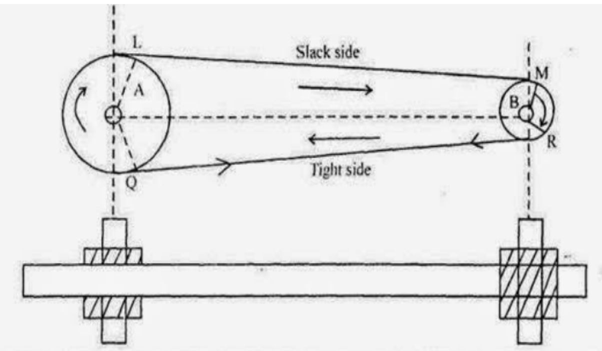
- This type of drive is used when the power is to be transmitted from one shaft to other which is at a distance.
- Pulleys are mounted on the driver and driven shafts and an endless belt are fitted tightly over these pulleys.

- The frictional resistance between these pulleys and belt is the reason for the power transmission, which depends on the velocity of belt, tension of the belt and arc of contact of the belt in the smaller pulley.

Types of Belt drive:

(a) Open belt drive: For parallel shafts and to be rotated in the same direction as that of the driver shaft. The driver pulley pulls the belt from one side and delivers it to the other side. The tension in the former side will be larger and hence called tight side and the other side is called slack side.





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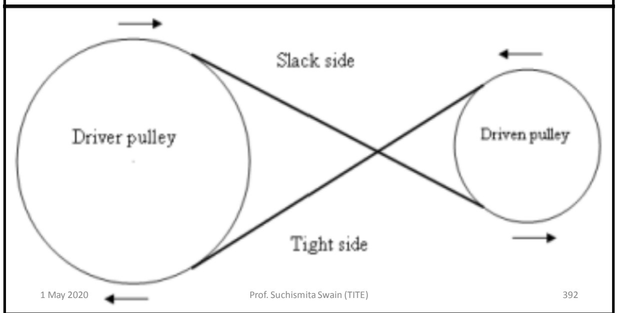
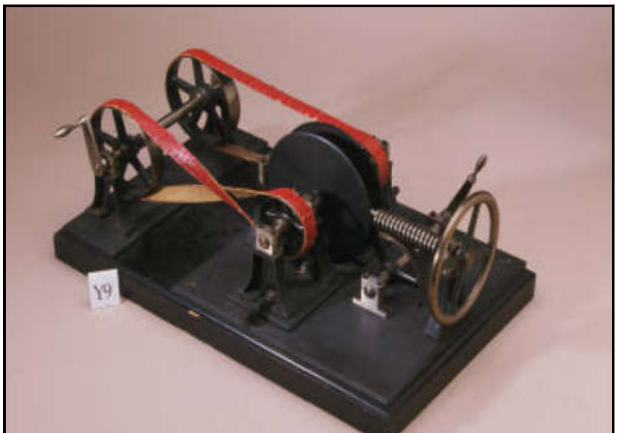
- **(b) <u>Crossed belt drive:</u>** When the driven shaft is to be rotated in the opposite direction as that of the driver shaft, the belt is to be arranged in a crossed manner.



1 May 2020 Prof. Suchismita Swain (TITE) 392

1 May 2020 Prof. Suchismita Swain (TITE) 393



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<u>Types of Belts</u>

- There are mainly 3-types of belts.

(a) Flat belt: It is mostly used in factories and workshops, where a <u>moderate amount of power</u> is to be transmitted, when the two pulleys are not more than 8 m apart.

(b) V-belt: It is used in factories and workshops, where <u>comparatively large amount of power</u> is to be transmitted, when the two pulleys are very near to each other.

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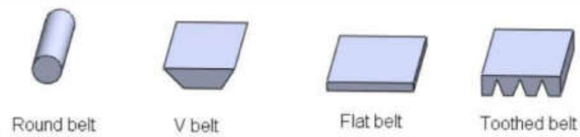
(c) Circular (round) belt: It is used in factories and workshops, where a great amount of power is to be transmitted from one pulley to another, when the pulleys are more than 8m apart.



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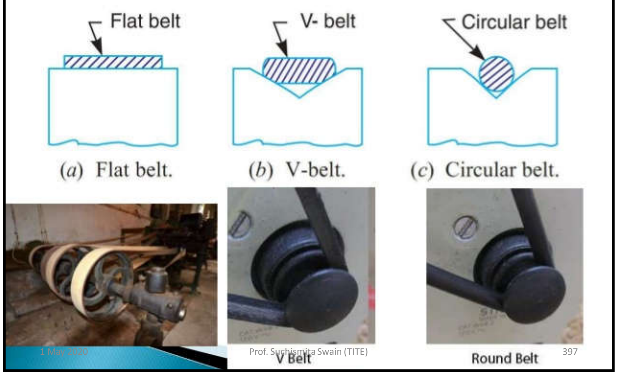
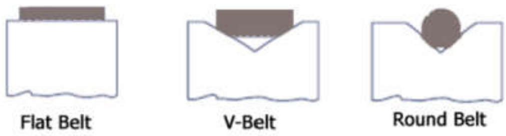
Belt Type

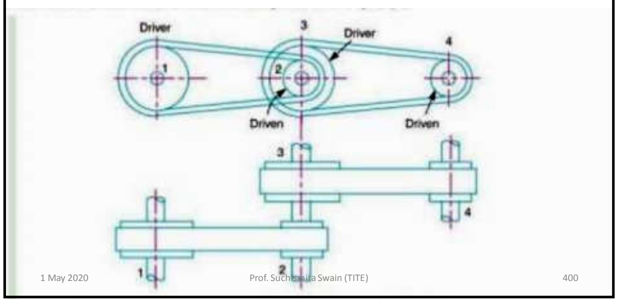




Belt drives

Compound Belt Drive

- A compound belt drive is used when power is transmitted from one shaft to another through a no. Of pulleys and the velocity ratio is high



Compound belt drive

Let d_1, d_2, d_3, d_4, and N_1, N_2, N_3, N_4 = diameters and speeds for pulleys 1, 2, 3 and 4.

We know that velocity ratio of pulleys 1 and 2,

$$VR_1 = \frac{N_2}{N_1} = \frac{d_1}{d_2} \quad \text{----------------} \quad (1)$$

Similarly, velocity ratio of pulleys 3 and 4,

$$VR_2 = \frac{N_4}{N_3} = \frac{d_3}{d_4} \quad \text{----------------} \quad (2)$$

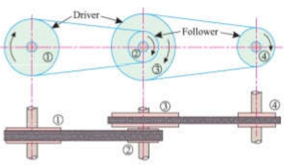
Multiplying the above equations

$$VR_1 \times VR_2 = \frac{N_2 \times N_4}{N_1 \times N_3} = \frac{d_1 \times d_3}{d_2 \times d_4} \quad \text{----------------} \quad (3)$$

Since $N_2 = N_3$, therefore velocity ratio of compound belt drive

$$VR = VR_1 \times VR_2 = \frac{N_4}{N_1} = \frac{d_1 \times d_3}{d_2 \times d_4} \quad \text{----------------} \quad (4)$$

$$VR = \frac{Speed\ of\ last\ follower}{Speed\ of\ first\ driver} = \frac{product\ of\ diameters\ of\ drivers}{product\ of\ diameters\ of\ followers}$$



Slip of belt

- Some times the frictional grip between belt and pulley becomes insufficient, this may cause some forward motion of the driver without carrying the belt with it. This may also cause some forward motion of the belt without carrying the driven pulley with it. This is called **slip** of the belt.
- It is generally expressed as a percentage.
- The result of slip is to reduce the velocity ratio of the system.

Creep of Belt

- When the belt passes from the slack side, a certain portion of the belt extends and it contracts again when the belt passes from the tight side to slack side. Due to these changes of length, there is a relative motion between the belt and the pulley. This relative motion is called **creep**.
- The total effect of creep is to reduce the speed of the driven pulley.

- Creep is due to elastic property of belt, where as the conventional slip is due to insufficient frictional grip between the belt and pulley.
- The effect of both is to reduce speed ratio hence reduce the power transmission.

- Explain briefly about Slip and creep of a belt in belt drive. **[2 marks]** **[BPUT-1st sem.-2016]**

ROPE DRIVE

- Ropes are used when considerable power is to be transmitted over long distances.
- Ropes are placed in grooves provided in the pulley.
- The groove angle varies from 40 to 60 degree, but is generally 45degree
- Wire ropes are made up of wires, which are twisted together to form a strand.
- A no. of strands twisted together to form a rope.
- Ropes are designated by specifying the no. of strands and no. of wires on it. Eg: 6*19

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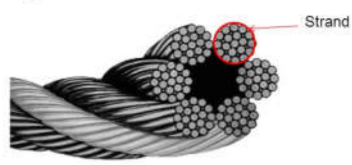
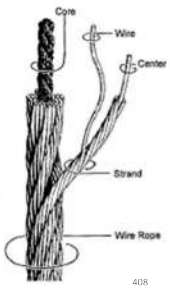
Wire Ropes

Wire rope consists of multiple wires or strands, helically wound or laid about an axis.

Wires, strands and cores are independent- that interact with each other during service.





Wire ropes are designed in different steel grades, finishes and a variety of constructions to attain the best balance of strength, abrasion resistance, crush resistance, bending fatigue resistance and corrosion resistance for each application.

Advantages of Rope drives

- Smooth and silent
- Less weight
- Shock resistant
- Longer life.

Gear Drives

- Slipping of a belt or rope is a common phenomenon, in the transmission of power.
- The effect of slipping is to reduce the velocity ratio of the system.
- In precision machines, in which a definite velocity ratio is of importance like in watch, the only positive drive is by means of gears or toothed wheels.
- Toothed wheel is the gear for transmitting power between two shafts, which are very closer.

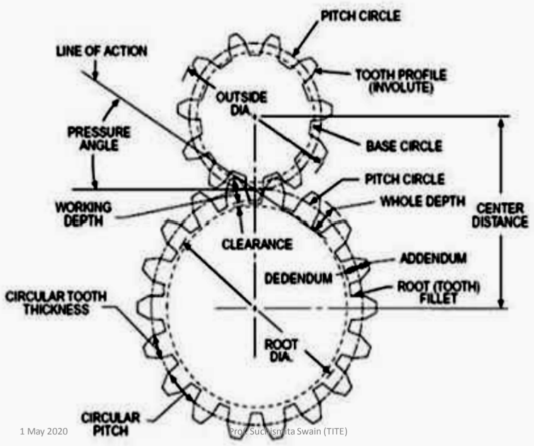
- The teeth of the gear mounted on the shaft meshes each other during rotation.
- Gears are manufactured either by milling, by casting or by hobbing.

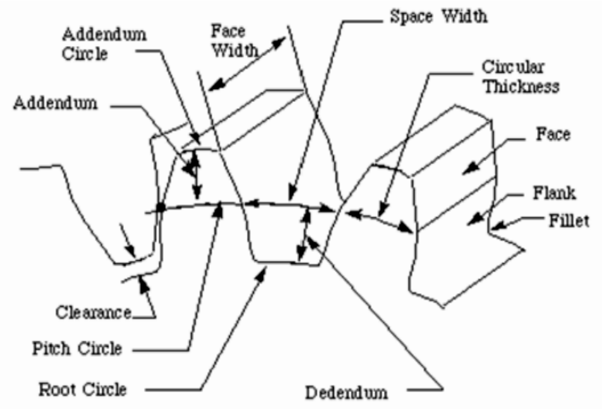
ADVANTAGES OF GEAR DRIVES

It transmits exact velocity ratio.
Transmits large power.
High efficiency.
Reliable service.
Compact layout.

DISADVANTAGES OF GEAR DRIVES

The manufacture of gears require special tools and equipments.
The error in cutting teeth may cause vibrations and noise during operations.





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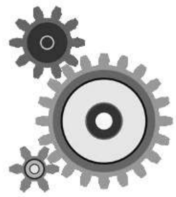
Internal and External Gear

Internal Gear

- An internal gear is one with the teeth formed on the inner surface of a cylinder or cone.

External Gear

- An external gear is one with the teeth formed on the outer surface of a cylinder or cone.



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Classification of Gears

- *According to the position of axes of the shafts.*
  - Spur gears – parallel shafts – most common
  - Bevel gears – perpendicular shafts
  - Worm gears - perpendicular overlapping shafts
  - Rack and pinion gears – convert circular motion to linear motion
- According to the type of gearing
- *According to the position of teeth on the gear surface.*

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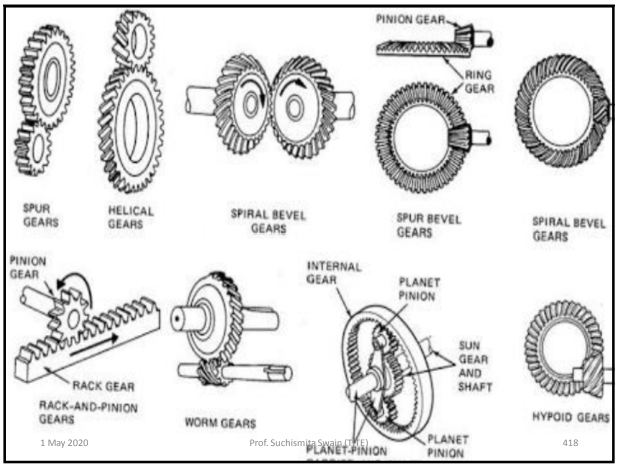

1 May 2020 Prof. Suchismita Swain (TITE) 418

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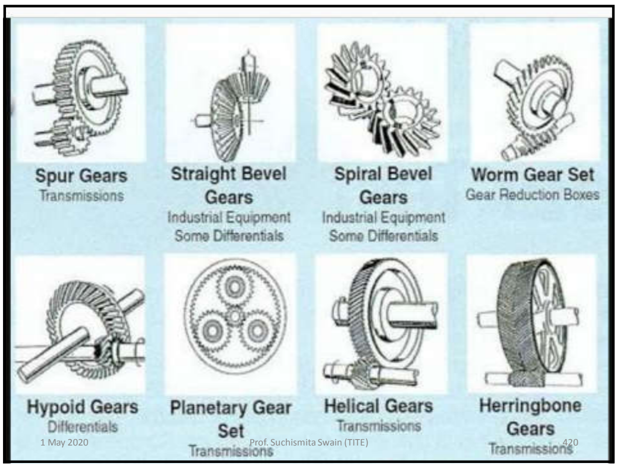

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Gear Ratio

- A gear ratio is the ratio used to determine the angular speed and torque of a geared system.

Number of driven teeth : Number of driver teeth

Also written as:

$$\frac{\textbf{Driven teeth}}{\textbf{Driver teeth}}$$

- If a set of gears has a driver and driven gearof the same size. The gear ratio would be 1:1.
- This causes a change in the direction of the motion with no change to speed or torque.

BME-2016-1st Semester-10marks

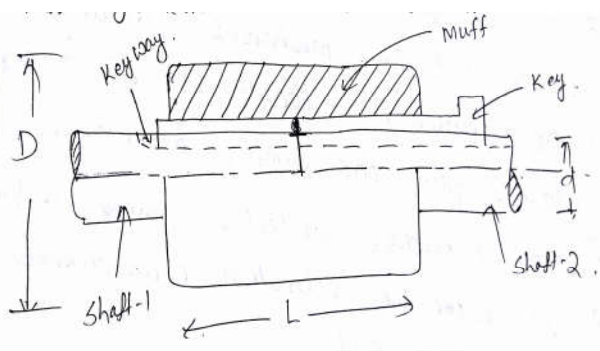
Two parallel shafts are connected with the help of two gears, one gear on each shaft. The no. of teeth on one gear is 38 and the speed of the shaft is 420 rpm. If the speed ratio is equal to 3 and circular pitch of the gear is 25mm, then find:

(i) No. of teeth and speed of other shaft.

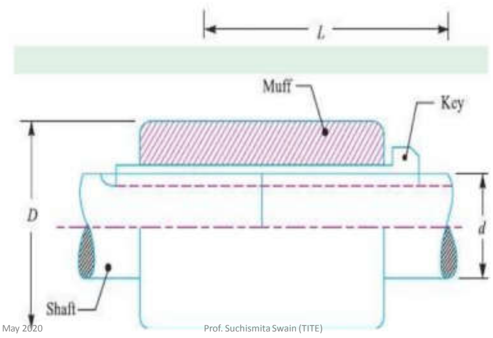
(ii) Centre distance between two shafts.

COUPLING

- A coupling is a device used to connect two shafts together at their ends for transmitting power. Coupling do not normally allow disconnection of shafts during operation.
- The primary purpose of coupling is to join two pieces of rotating equipment while permitting some degree of misalignment or end movement or both.



a. Sleeve or Muff-coupling



Uses

- To transfer power from one end to another. Ex.: motor transfers power to pump through coupling.
- To provide the connection of shafts of units that are manufactured separately such as a motor and generator and to provide for disconnection for repair or alterations.
- To provide misalignment of the shafts or to introduce mechanical flexibility.
- To reduce the transmission of shock loads from one shafts to another
- To introduce protection against overload

Types of Coupling

- **Rigid Coupling:** It is used to connect two shafts which are perfectly aligned. Following types of rigid coupling are important.

a) Sleeve or muff coupling.
b) Clamp or split-muff or compression coupling
c) Flange coupling.

- **Flexible Coupling:** It is used to connect two shafts having both lateral and angular misalignment. Following are the types.

a) Bushed pin type coupling
b) Universal coupling
c) Oldham coupling.

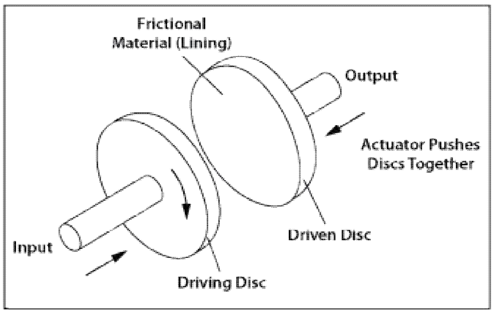
CLUTCH

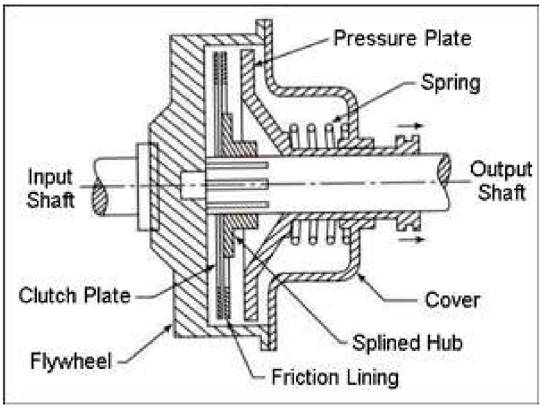
- Transmission is the mechanism which is used to transfer the power developed by engine to the wheels of an automobile.
- The transmission system of an automobile includes clutch, gearbox, propeller shaft axle and wheels etc.
- Clutch is used to engage or disengage the engine to the transmission or gearbox.
- When the clutch is in engaged position, the engine power or rotary motion of engine crank shaft is transmitted to gear box and then to wheels.

- When clutch is disengaged, the engine power does not reach to gear box or to wheels although the engine is running.
- Clutch is also used to allow shifting or changing of gears when vehicle is running.
- For shifting gears clutch is first disengaged then gear is shifted and then clutch is engaged.
- Clutch has to be disengaged to stop the vehicle, if the vehicle is not in neutral gear.

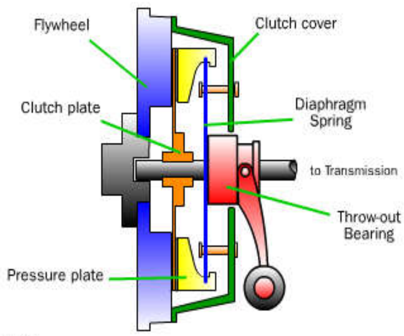
Principle of Clutch

- It operates on the principle of friction.
- When two surfaces are brought in contact and are held against each other due to friction between them, they can be used to transmit power. If one is rotated the other one also rotates.
- One surface is connected to engine and other to the transmission system of automobile.
- Hence clutch is nothing but a combination of two friction surfaces.





Clutch Engaged



Main parts of a Clutch

(a) A driving member:

- It consists of a flywheel, which is mounted on the engine crankshaft.
- The flywheel is bolted to a cover which carries pressure plate, pressure springs and releasing levers.

(b) A driven member:

- It consists of a disc plate called clutch plate.
- The clutch is free to slide on the splines of the clutch shaft.

- It carries friction materials on both of its surfaces.
- When the clutch plate is gripped between the flywheel and the pressure plate, it rotates the clutch shaft through splines.

(c) An operating member:

- The operating member consists of a pedal or lever which can be pressed to disengage the driving and driven plate.

Types of clutch

(a) Friction clutch:
- Single plate clutch
- Multi plate clutch (Dry or Wet)
- Cone clutch

(b) Centrifugal clutch
(c) semi-centrifugal clutch
(d) Hydraulic clutch
(e) Positive clutch
(f) Vacuum clutch
(g) Electromagnetic clutch.

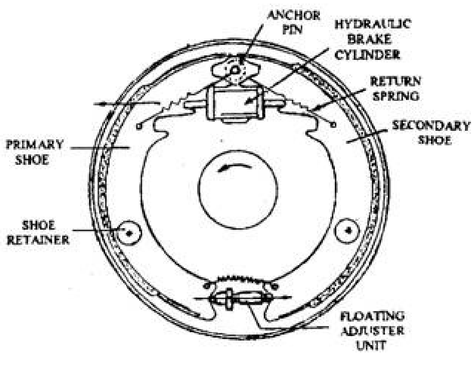
- Explain the function of a clutch and different types of clutch with their relative advantages and disadvantages. [10 marks] **[BPUT-1st sem.-2017]**

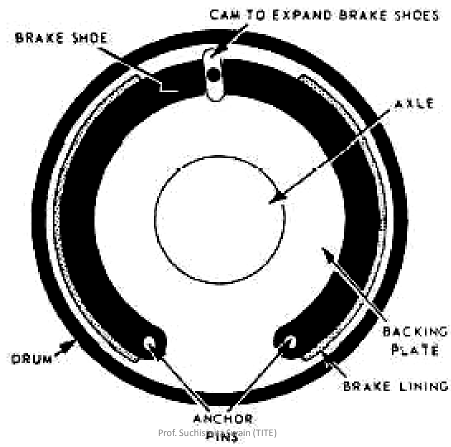
Brakes

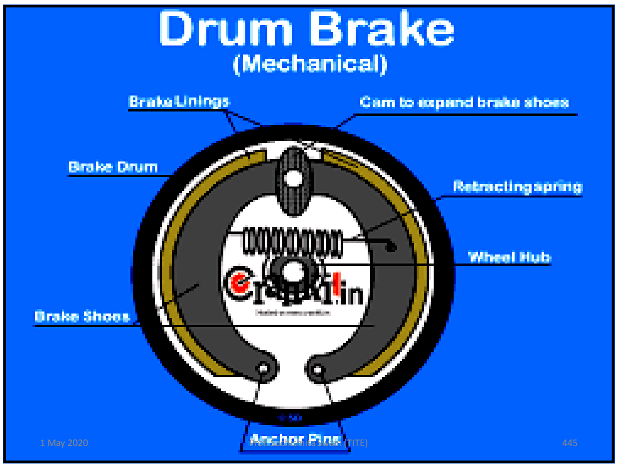
- A brake is a mechanical device that retards motion by absorbing energy from a moving system.
- It is used for slowing or stopping a moving vehicle, wheel, axle or to prevent its motion by means of friction.

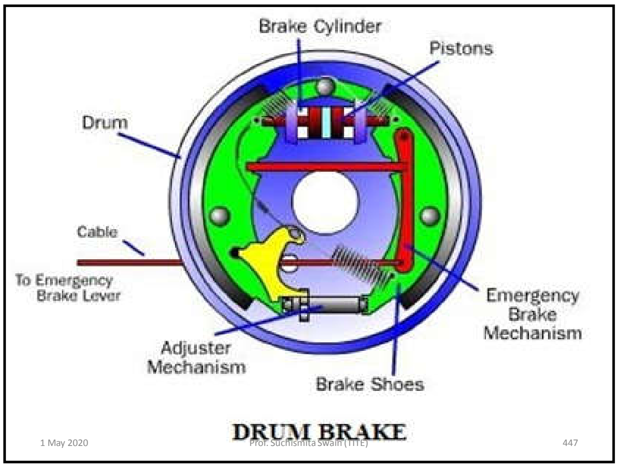
Types

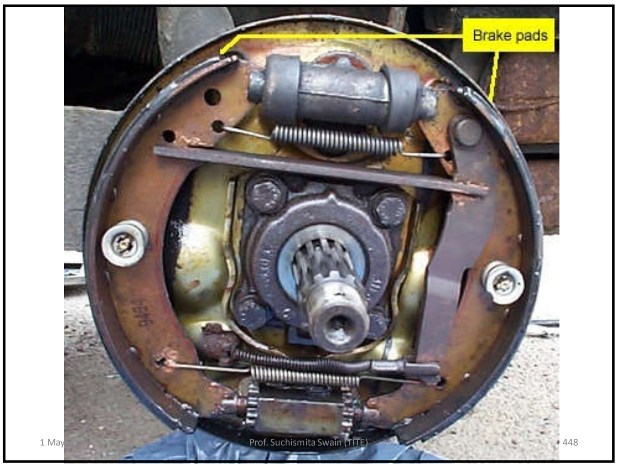
(a) Drum Brakes:
- In drum brakes, the brake lining is adhered to the external surface of a curved bracket called shoes.
- The most common configuration includes, two shoes mounted inside a drum of a plate. A cylinder presses the shoes onto the insides of the drum to initiate deceleration.
- A drum brake that presses on the outside of the drum is called a **clasp brake**.
- A double clasp brake applies braking pressure to both inside and outside of the drum









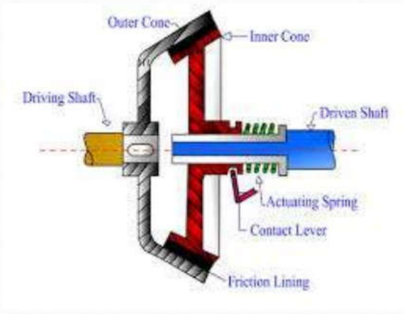


(b) Cone Brakes:

- This is a type of drum brake where the drum and shoe are mating sections of conical frustums.
- The shoe (cone) is outfitted with brake lining and pressed into the drum (cup) to apply friction.
- The advantage is increased surface area, less force required for disengage and hence quicker deceleration.

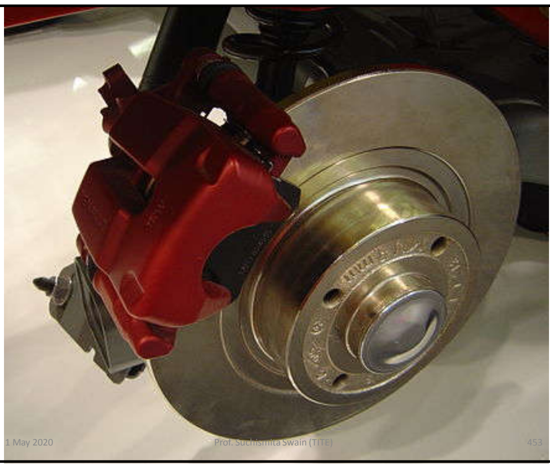
1 May 2020 Prof. Suchismita Swain (TITE) 450

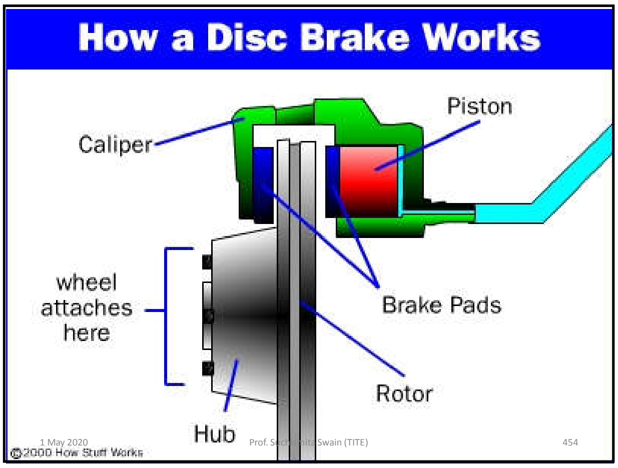
Cone clutch



(c) Disc Brakes:

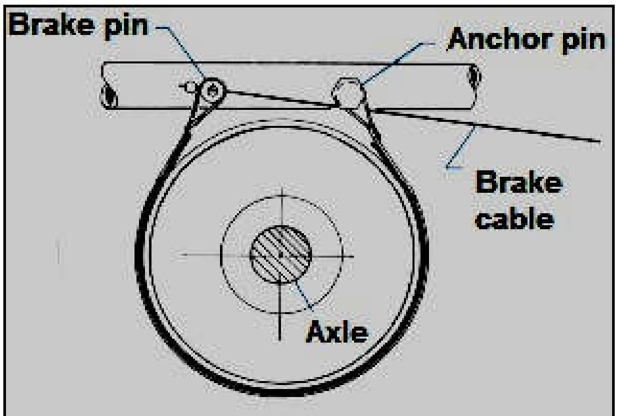
- It utilise a metal disc, also called a rotor, that is connected to the axle.
- The rotor spins between a calliper, which pushes a lining material outfitted on a brake pad against the rotor surface.





(d) Band Brakes:

- Band brakes tighten a ribbon of high friction material around a pulley attached to the rotating axle.
- They are often employed on bicycles. If the pull on the band is in the direction of axle rotation the brake is self-energizing.
- Differential band brakes attach both ends of the brakes ribbon to the lever to supply braking power for bi-directional shafts.



Band Brake

- Classify the brake on basis of mode of operation. **[5 marks]** **[BPUT-1st sem.-2017]**

Mechanical Measurements

Pressure Measurement:

Pressure is measured by following methods,

(i) By Manometers.

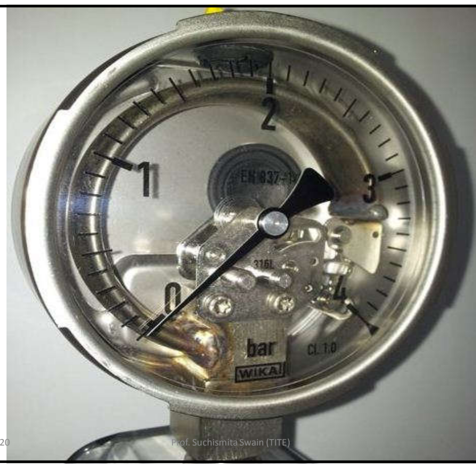
(ii) By Bourdon tube pressure gauge.

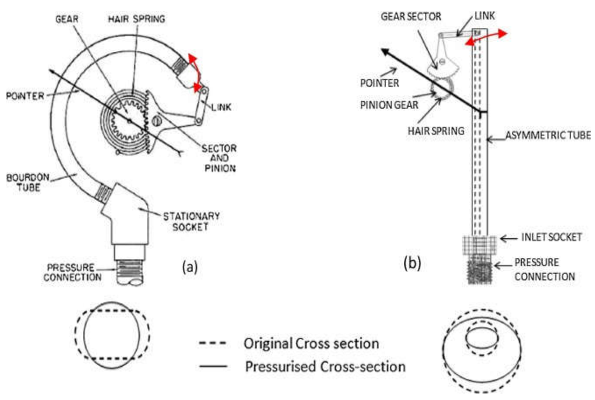
❖ Manometers we have discussed earlier.

Bourdon Tube Pressure Gauge

- It is known for its very high range of differential pressure.
- The bourdon tube pressure gauge used today have an elliptical cross-section and the tube is bent into a C-shape of an arc length of about 270 degrees.
- When the pressure input is given to the socket, the other end is sealed by a tip. This tip is connected to a segmental lever.

- As the fluid pressure enters the bourdon tube, it tries to expand its arc by converting the elliptical cross-section into circular as pressure increases.
- The deflection of the free end is amplified with the help of a pointer. The pointer indicates the values on a pre-calibrated scale.





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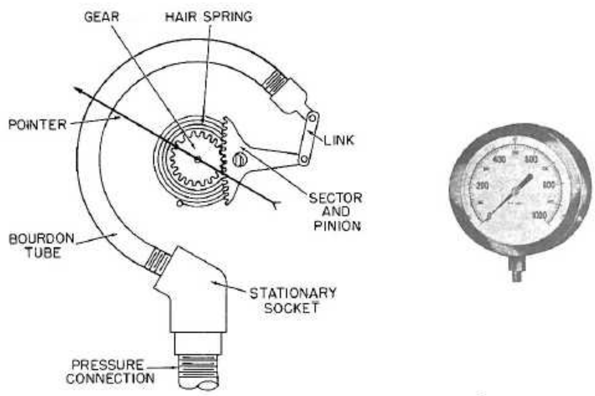

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What is a thermocouple ?

- A thermocouple is a temperature-measuring device consisting of two dissimilar conductors that contact each other at one or more spots.
- A thermocouple comprises of at least two metals joined together to form two junctions. One is connected to the body whose temperature is to be measured-this is the hot or measuring junction.
- The other junction is connected to a body of known temperature; this is the cold or reference junction. Therefore the thermocouple measures unknown temperature of the body with reference to the known temperature of the other body.

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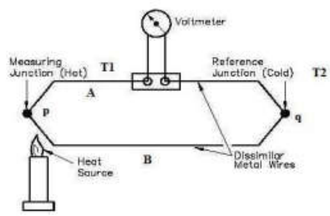

Thermocouple Circuit

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How does it work ?

- when any conductor is subjected to temperature, it will generate a voltage. This is now known as the thermoelectric effect or Seebeck effect.
- Any attempt to measure this voltage necessarily involves connecting another conductor to the "hot" end. This additional conductor experiences the same temperature gradient and also develops a voltage.
- The magnitude of the effect depends on the metal in use, and so a nonzero voltage will be measured if two dissimilar metals are used. After carefully calibrating the temperature-voltage dependence for a given pair of metals, these metals can be used as a thermometer.

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Where are they used ?

- Thermocouples are a widely used as temperature sensors for measurement, control and can also convert a temperature into electricity.
- Thermocouples are widely used in research and industry; applications include temperature measurement for furnaces, gas turbine exhaust, diesel engines, and other industrial processes.
- Thermocouples are also used in homes & offices as temperature sensors in thermostats and also in flame sensors for fire detection.

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Working principle.

- The working principle of thermocouple is based on three effects discovered by Seebeck, Peltier and Thomson. They are as follows:
- 1) **Seebeck effect:** The Seebeck effect states that when two different or unlike metals are joined together at two junctions, an electromotive force (emf) is generated at the two junctions. The amount of emf generated is different for different combinations of the metals.
- 2) **Peltier effect:** when two dissimilar metals are joined together to form two junctions, emf is generated within the circuit due to the different temperatures of the two junctions of the circuit.

- 3) **Thomson effect:** when two unlike metals are joined together forming two junctions, the potential exists within the circuit due to temperature gradient along the entire length of the conductors within the circuit.
- In most of the cases the emf suggested by the Thomson effect is very small and it can be neglected by making proper selection of the metals. The Peltier effect plays a prominent role in the working principle of the thermocouple.

PITOT TUBE

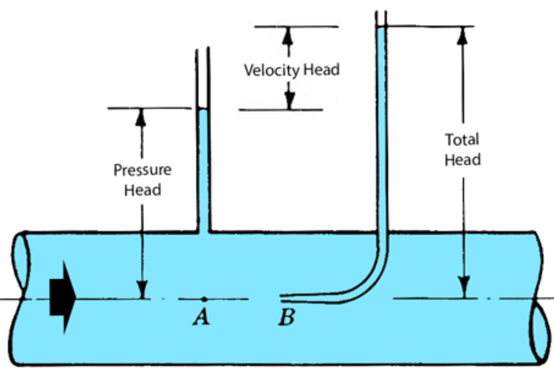
Introduction

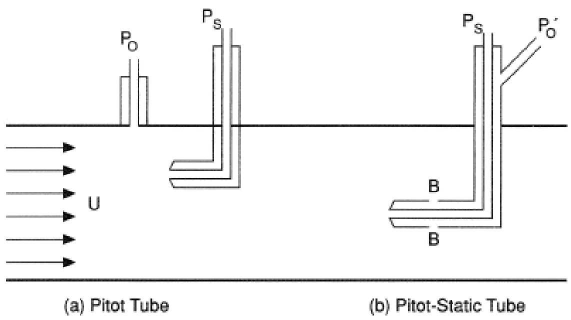
- A **pitot tube** is a pressure measurement instrument used to measure fluid flow velocity. The pitot tube was invented by the French engineer Henri Pitot in the early 18th century and was modified to its modern form in the mid-19th century by French scientist Henry Darcy. It is widely used to determine the airspeed of an aircraft, water speed of a boat, and to measure liquid, air and gas velocities in industrial applications. The pitot tube is used to measure the local velocity at a given point in the flow stream and not the average velocity in the pipe or conduit.

Pitot tube and Pitot-Static Tube

Working principle of Pitot tube

- "If the velocity of flow at a point becomes zero, the pressure is increased there due to the conversion of the kinetic energy into pressure energy."
- The point at which the velocity of flow becomes zero is called stagnant point.
- The pressure at stagnant point is called total pressure or head or stagnation pressure.





1 May 2020 Prof. Suchismita Swain (TITE) 475

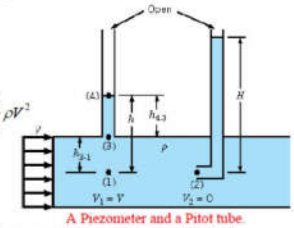
PITOT TUBE IN THE PIPE-(method1)

Two piezometers

for ideal flow

$$p_2 = p_1 + \frac{1}{2}\rho V_1^2 \Rightarrow \rho g H = \rho g h + \frac{1}{2}\rho V^2$$

$$\Rightarrow V = \sqrt{2g(H-h)}$$



To account for **real fluid** effects, the equation can be modified into

$$V = C_v\sqrt{2g(H-h)},$$

where is the coefficient of velocity to be determined empirically.

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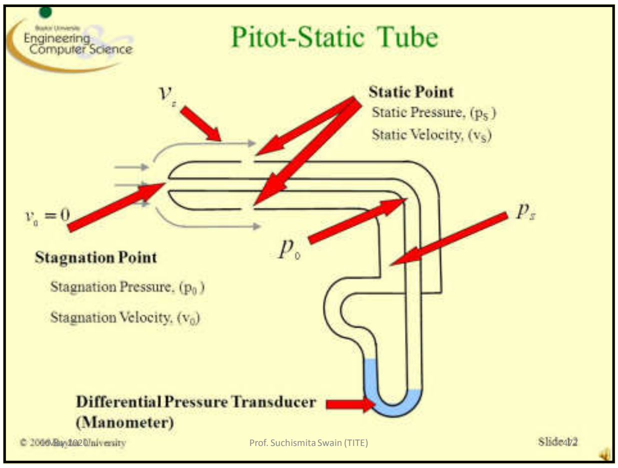

Flow Measurements

Advantages of Pitot tube:

- Simple & low cost device
- No appreciable pressure loss
- Easy installation
- Useful in measuring flow velocities

Limitations of Pitot tube:

- Not suitable for measuring low velocities i.e. below 5 m/s
- Sensitive to misalignment of the probe with respect to free stream velocity.
- Not suitable for measuring highly fluctuating velocities.
- Not commonly used in industrial applications as numerous Pitot tube traverses are required for velocity distribution data which is quite tedious & time consuming.

Contents provided in this presentation are for reference purpose & the detailed theory to be read/written from respective text book/Class Notes

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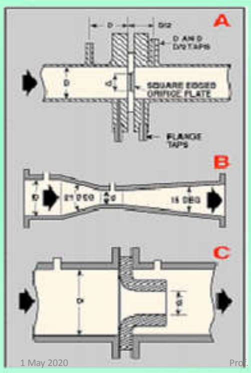
Obstruction Meters



- Orifice Meters
- Venturi Meters
- Flow Nozzles

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Orifice meter

- It is also known as Pipe orifice & Orifice plate.
- It may be installed in pipeline with a minimum of trouble and expense.
- Pipe orifice is a device used for measuring the rate of flow of a fluid through a pipe.
- It consists of a thin,circular plate with a hole in it.

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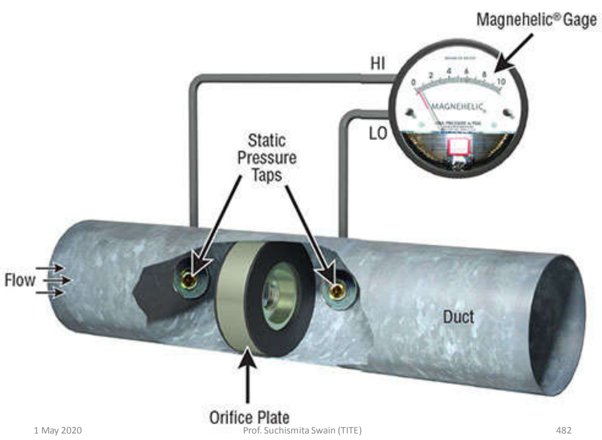
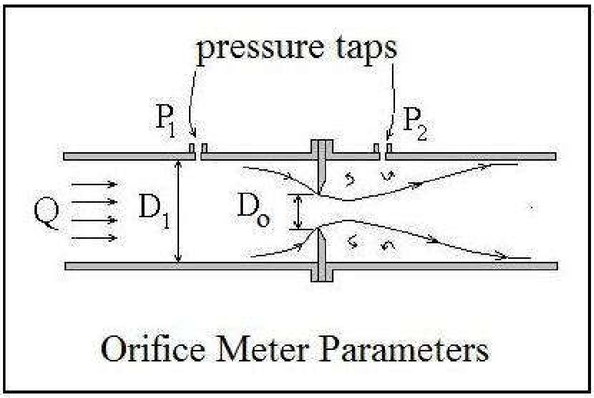
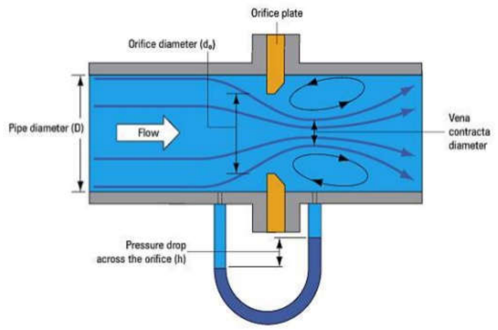
Working

- Orifice meter is device used to determine the rate of flow through pipe.
- It consist of flat circular plate which has a sharp edged circular hole called orifice.
- It is fixed concentric to pipe.
- The orifice diameter is generally kept half of the diameter of the pipe.
- It is based on the same principle as explained in venturimeter.
- The value of Cd varies between 0.60 to 0.65.
- It is a economical and less space is requred for fitting.





ORIFICE PLATE



Venturi meter

Introduction :

- A venturi meter is a variable head meter which is used for measuring the flow rate of a fluid through a pipe.
- In this meter, the fluid is gradually accelerated to a throat and then gradually retarded in a diverging section where the flow expand through the pipe size.
- The large portion of kinetic energy is thus recovered.

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Venturimeter

It is a device, which is used for measuring the rate of flow of fluid through a pipe.

It consists of an

- **Inlet section followed by**
- **Convergent section**
- **A cylindrical throat and**
- **A gradually divergent cone.**

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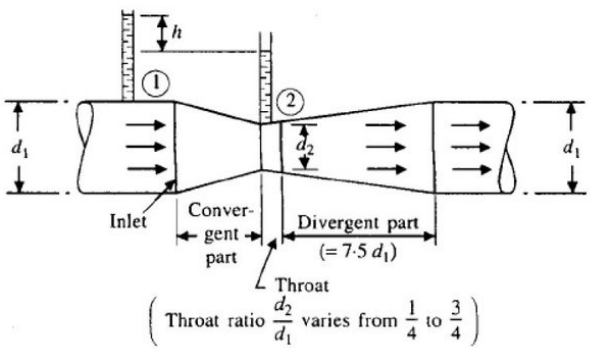

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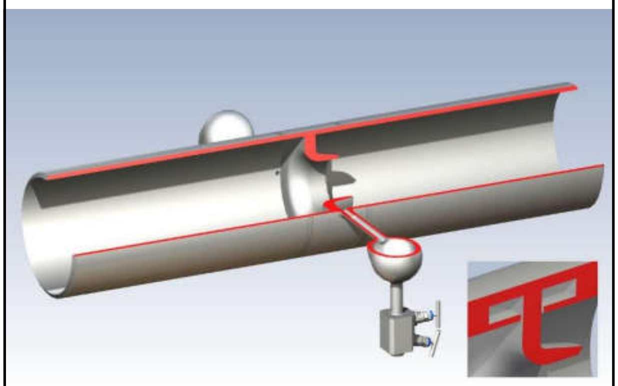
25

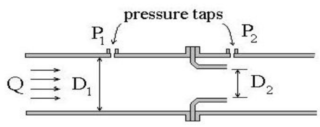
ADVANTAGES

1. Less chances of getting clogged with sediments.
2. Coefficient of discharge is high.
3. Its behaviour can be predicted perfectly.
4. Can be installed vertically, horizontally or inclinded.

Disadvantages of venturi meter

1. It is expansive and bulky.
2. It occupies considerable space.
3. Relatively complex in construction.
4. Used only for permanent installations.
5. It cannot be altered once it is installed.





Flow Nozzle Meter Parameters

Flow Measurements

Nozzle Flow meter Features:

- Offers all the advantages of venturimeter but to a lesser extent
- Occupies less space
- Nozzle is difficult to install and the installation is limited to small to moderate pipe sizes

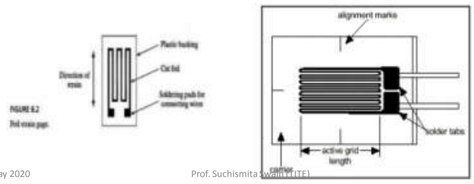
Orifice Flow meter Features:

- Simple geometry, so cost is low
- Easy to install
- Takes almost no space
- Susceptible to inaccuracies due to erosion, corrosion, clogging etc.
- Suffers from a head loss of the order of 30-40%

Contents provided in this presentation are for reference purpose & the detailed theory to be read/written from respective text book/Class Notes

STRAIN GAUGE

- The strain gauge is a passive, resistive transducer which converts the mechanical elongation and compression into a resistance change.
- This change in resistance takes place due to variation in length and cross sectional area of the gauge wire, when an external force acts on it.



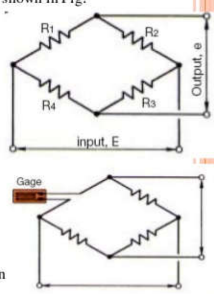
What's the Wheatstone Bridge?

- Wheatstone bridge is an electric circuit suitable for detection of minute resistance changes, therefore used to measure resistance changes of a strain gage
- The bridge is configured by combining four resistors as shown in Fig.
- Initially R1=R2=R3=R4, in this condition no output voltage is there, **e=0**
- When one of the Resistances is replaced by strain Gauge attached to the object whose strain is to be measured and load is applied, then there is small change in the resistance of gauge, hence some output voltage is there which can be related to strain as

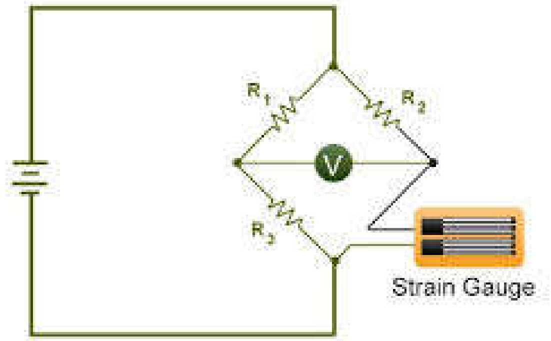
$$e = \frac{1}{4} \cdot \frac{\Delta R}{R} \cdot E$$

From this, strain can be easily determined using the relation

$$e = \frac{1}{4} \cdot K \cdot \varepsilon \cdot E$$



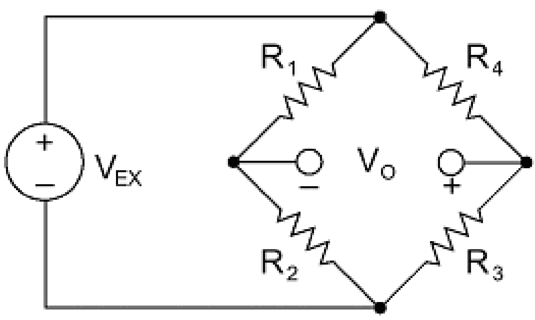
Quarter-bridge Strain Gauge Circuit

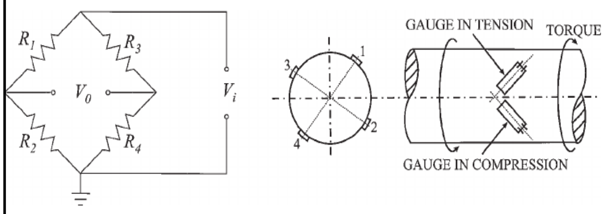


Strain Measurement

- The amount of deformation a material experiences due to an applied force is called strain.
- Strain is defined as the ratio of the change in length of a material to the original length.
- Strain can be positive (tensile) due to elongation or negative (compressive) due to contraction.

- When a material is compressed in one direction, the tendency to expand in the other two directions perpendicular to this force is known as the Poisson effect.
- Poisson's ratio, is the measure of this effect and is defined as the –ve ratio of strain in the transverse direction to the strain in the axial direction.
- The strain can be measured with a strain gauge.





- A strain gauge's electrical resistance varies in proportion to the amount of strain in the device.
- The most widely used strain gauge is the bonded metallic strain gauge.
- The metallic strain gauge consists of a very fine wire or metallic foil arranged in a grid pattern.
- The strain experienced by the test specimen is transferred directly to the strain gauge, which responds with a linear change in electrical resistance.

- Gauge Factor (GF) is the ratio of the fractional change in electrical resistance to the fractional change in length or strain.
- GF = (δR/R)/(δL/L) = (δR/R)/ε

  GF is fixed by vendor.

  So by measuring, (δR/R), we can measure the value of ε.
- Strain gauge configurations are based on the concept of a Wheatstone bridge.
- The general Wheatstone bridge, is a network of four resistance arms with an excitations voltage, V_{ex}, that is applied across the bridge.

- The Wheatstone bridge is the electrical equivalent of two parallel voltage divider circuits.
- R_1 and R_2 compose one voltage divider circuit and R_4 and R_3 compose the second voltage divider circuit.
- The output of a Wheatstone bridge ,V_o is measured between the middle nodes of the two voltage dividers.

$$V_o = \left(\frac{R_3}{R_3+R_4} - \frac{R_2}{R_1+R_2}\right) \times V_{Ex}$$

From this equation

$$\frac{R_1}{R_2} = \frac{R_4}{R_3}$$

When $V_o = 0$

- Under this condition, the bridge is said to be balanced.
- Any change in resistance in any arm of the bridge results in a non-zero output voltage.

- Therefore, if you replace R_4 with an active strain gauge, any changes in the strain gauge resistance unbalance the bridge and produce a non-zero output voltage that is a function of strain.

Force and Torque Measurement

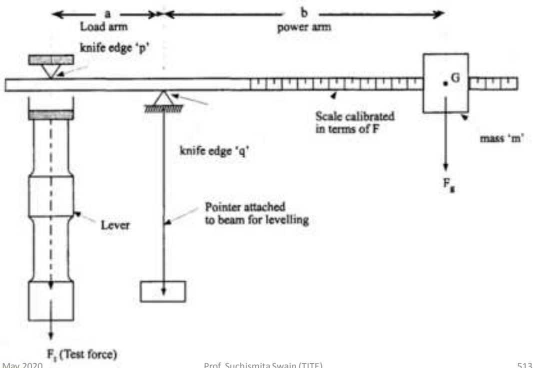
- Force is defined as the reaction between the two bodies or components.
- The reaction can be either tensile force(pull) or it can be compressive force (push)
- Measurement of force can be done by any two methods.

➢ **Direct Method:** This involves a direct comparison with a known gravitational force on a standard mass. Ex.: Physical balance.

➢ **Indirect Method**: This involves the measurement of effect of force on a body.

Ex.: Force is calculated from acceleration due to gravity and the mass of the components.

Unequal arm balance:



Unequal arm balance:

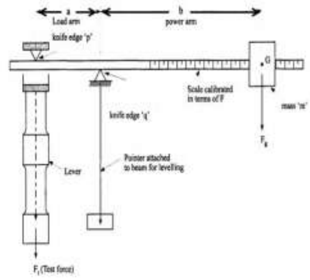
For balance of moments,

$F_t * a = F_g * b$

or test force,

$F_t = F_g * (b / a)$

Therefore, the test force is proportional to the distance 'b' of the mass from the pivot.

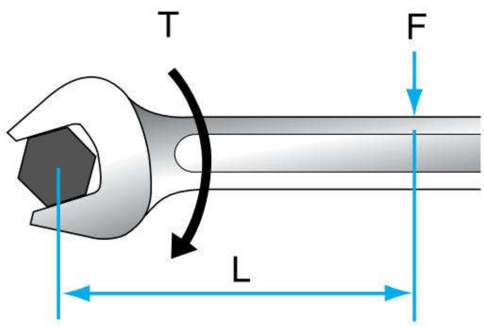


Torque Measurement

- Force that causes twisting or turning moment is called torque.

Ex.: Force generated by an i.c.engine to turn a vehicle's drive or shaft.

- Torque measuring devices are called as dynamometers.
- Torque measurement is usually associated with determination of mechanical power.
- The power is required either to operate a machine or power is developed by the machine.

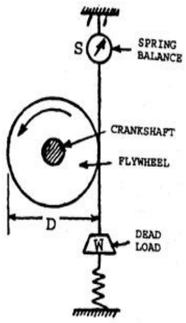


Torque T = F (Force) × L (Length)

- Power = $\frac{2\pi NT}{60}\ Watt = T.\omega$

Where N = Speed in rpm

T = Torque applied



$$\text{b.p.} = \frac{2\pi NT}{60{,}000}, \text{ kW}$$

where N is rpm of crankshaft or engine

T is the torque or resisting torque in the dynamometer, Nm

Resisting torque, $T = (W - S)D/2$, Nm

where W = dead load applied, N

S = spring tension, N

D = diameter of flywheel, N

If there is no missing cycle, then,

$n = N/2$ for single acting, four-stroke engine

$= N$ for single acting, two-stroke engine

$= N$ for double acting, four-stroke engine

$= 2N$ for double acting two-stroke engine.