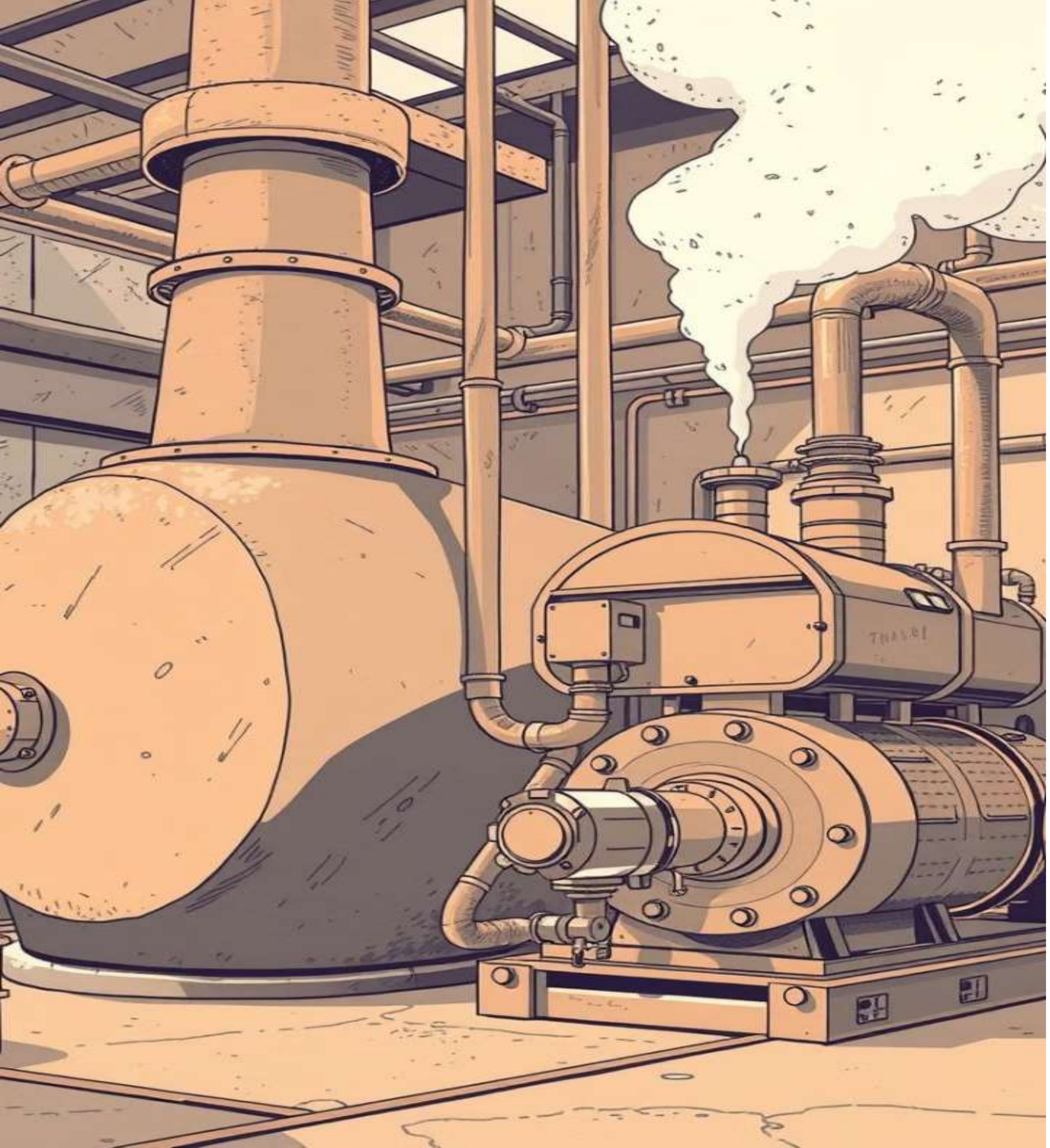


Lecture

on

Engineering Thermodynamics

Prepared by

Anisul Islam

Lecturer

Department of Mechanical Engineering (UGV)

Engineering Thermodynamics

Course Code: 0715-2103	Credits: 03
	CIE Marks: 90
Exam Hours: 03	SEE Marks: 60
CLO1	After Completing this Course a Student will be able to Define and differentiate between key thermodynamic concepts like system, surroundings, boundary, state, process, and cycle.
CLO2	After Completing this Course a Student will be able to Explain the Zeroth, First, Second, and Third Laws of Thermodynamics and their applications in engineering systems.
CLO3	After Completing this Course a Student will be able to Apply the concepts of work, heat, and energy to analyze various thermodynamic processes.
CLO4	After Completing this Course a Student will be able to Analyze the working principles of various power cycles, including Carnot, Rankine, Otto, and Diesel cycles.
CLO5	After Completing this Course a Student will be able to Calculate the thermal efficiency and work output of power cycles.
CLO6	After Completing this Course a Student will be able to Evaluate the factors affecting the performance of gas turbine and Steam Turbine systems.

S. L	Content of Course	Hrs	CLOs
1	System, Surroundings, Types of Boundaries, Specific Heat, Sensible heat, Enthalpy, Entropy, Internal Energy, Intensive, Extensive Property and difference, Isochoric Process, Reversible and Irreversible Process, Isobaric Process, Adiabatic Process, Isothermal Process, Polytropic Process, laws of Thermodynamics,	8	CLO 1, CLO 2
2	Heat Pump, Heat Engine, Refrigerator and their differences, Carnot Cycle (PV and TS diagram with Efficiency), Otto Cycle (PV and TS diagram with Efficiency), Ericson and Stirling Cycle (PV and TS diagram with Efficiency), Diesel Cycle (PV and TS diagram with Efficiency)	4	CLO 3, CLO 4
3	Rankine Cycle (PV and TS diagram with Efficiency), Rankine Cycle with Reheat and Regeneration and intercooling, Bryton Cycle (PV and TS diagram with Efficiency), Difference between Steam and Gas Turbine, Combined Cycle (PV & TS diagram), Difference between SI and CI, Difference between Two stroke and Four Stroke Cycle,	6	CLO 5, CLO 6
4	Refrigeration Effect, COP, TOR, Refrigerant, Vapor Compression Refrigeration System, Calorific Value Types, Bomb Calorimeter, Problem Solving on Calculation of Amount of Fuel (by Air and Mass)	2	CLO 7, CLO 8
5	Boiler Types, Construction and Working Principle, Boiler Draught, Problem Solving, Boiler Mountings and accessories	4	CLO 7, CLO 8
6	IC Engine, Classification, Components, Cycle, Performance, Valve Timing Diagram	8	CLO 3, CLO 4

Reference Books:

- Engineering Thermodynamics- P K Nag
- A Textbook of Thermal Engineering- R.S Khurmi
- Engineering Thermodynamics- Work and Heat Transfer- R.K Rajput

ASSESSMENT PATTERN

CIE- Continuous Internal Evaluation (90 Marks)

Bloom's Category Marks (out of 90)	Tests (45)	Assignments(10)	Class Test (20)	Quiz (5)	External Participation in Curricular/Co-Curricular Activities (10)
Remember	5		10	05	
Understand	5	05	10		
Apply	10				10
Analyze	15				
Evaluate	10				
Create		05			

SEE- Semester End Examination (60 Marks)

Bloom's Category	Test
Remember	10
Understand	10
Apply	10
Analyze	10
Evaluate	10
Create	10

Course Plan Specifying Content, CLOs, Teaching Learning Strategy and Assessment Strategy

Week	Topics	Teaching Learning Strategy	Assessment Strategy	Corresponding CLOs
1	System, Surroundings, Types of Boundaries, Specific Heat, Sensible heat Enthalpy, Entropy, Internal Energy Intensive, Extensive Property and difference ,	Lecture, Oral Presentation, PPT	Quiz, Written exam, CT	CLO 1
2	Isobaric Process, Adiabatic Process Isothermal Process, Polytropic Process	Lecture, Oral Presentation, PPT	Assignment, Quiz, Written exam	CLO 1
3	zeroth law and 1st law of Thermodynamics	Lecture, Oral Presentation, PPT	Quiz, Written exam, CT	CLO 2
4	2nd and 3rd Law of Thermodynamics	Lecture, Oral Presentation, PPT	Quiz, Written exam, CT	CLO 2

	Course Plan Specifying Content, CLOs, Teaching Learning Strategy and Assessment Strategy			
Week	Topics	Teaching Learning Strategy	Written exam	Corresponding CLOs
5	Heat Pump, Heat Engine, Refrigerator and their differences Carnot Cycle (PV and TS diagram with Efficiency)	Lecture, Oral Presentation, Video Presentation, PPT	Assignment, Written exam, Quiz, CT	CLO 3, CLO 4
6	Otto Cycle (PV and TS diagram with Efficiency) Ericson and Stirling Cycle (PV and TS diagram with Efficiency), Diesel Cycle (PV and TS diagram with Efficiency)	Lecture, Oral Presentation, Video Presentation, PPT	Assignment, Quiz, Written exam, CT	CLO 3, CLO 4
7	Rankine Cycle (PV and TS	Lecture, Oral		

Week	Topics	Teaching Learning Strategy	Assessment Strategy	Corresponding CLOs
8	Bryton Cycle (PV and TS diagram with Efficiency)	Lecture, Oral Presentation, Video Presentation, PPT	Quiz, Written exam, CT	CLO 5, CLO 6, CLO 4
9	Bryton Cycle Improvement (PV and TS diagram with Efficiency)	Lecture, Oral Presentation, Video Presentation, PPT	Assignment, Quiz, Written exam, CT	CLO 4, CLO 5
10				

11	Boiler Classification, components	Lecture, Oral Presentation, Video Presentation, PPT	Assignment, Quiz, Written exam, CT	CLO 7
12	Boiler Mountings and accessories, Boiler Draught, Problem Solving	Lecture, Oral Presentation, Video Presentation, PPT	Quiz, Written exam, CT	CLO 7
13	IC Engine (Components and Classification)	Lecture, Oral Presentation, Video Presentation, PPT	Assignment, Quiz, Written exam, CT	CLO 7, CLO 8
14	IC Engine (Cycle and Efficiency, Performance)	Lecture, Oral Presentation, Video Presentation, PPT	Quiz, Written exam	CLO 3, CLO 4
15	IC Engine (Two stroke and Four Stroke Engine, Petrol and Diesel engine)	Lecture, Oral Presentation, Video Presentation, PPT	Quiz, Written exam, CT	CLO 3, CLO 4
16		Lecture, Oral	Quiz, Written exam, CT	CLO 3, CLO 4

Week -1

Lecture

on

Basic Thermodynamics Concept and Applications

(12-25)

THERMODYNAMICS AND ENERGY

- **Thermodynamics**: The science of *energy.*
- **Energy**: The ability to cause changes.
- The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).
- **Conservation of energy principle**: During an interaction, energy can change from one form to another but the total amount of energy remains constant.
- Energy cannot be created or destroyed.
- **The first law of thermodynamics**: An expression of the conservation of energy principle.
- The first law asserts that *energy* is a thermodynamic property.

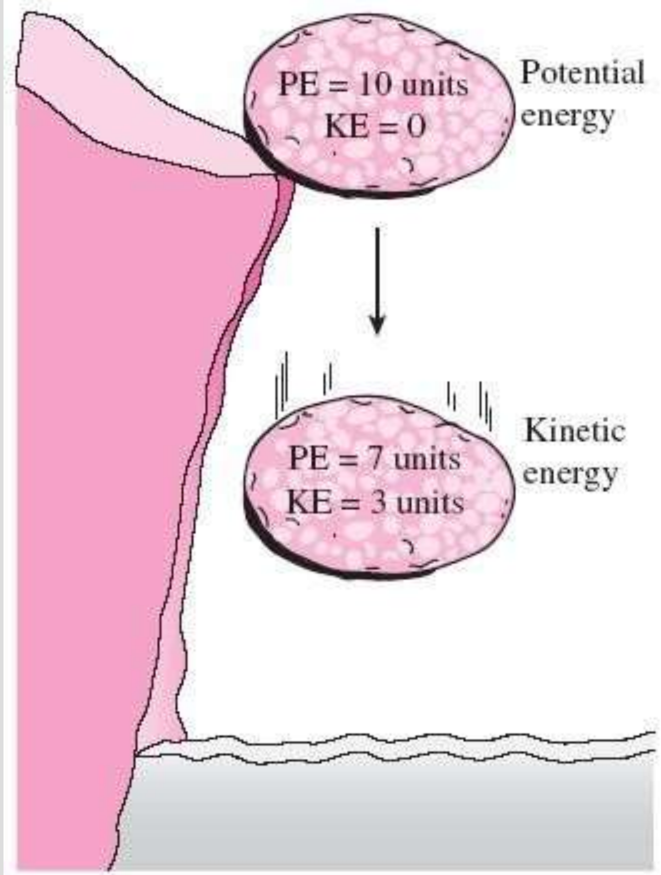


FIGURE 1–1
Energy cannot be created or destroyed; it can only change forms (the first law).

- **The second law of thermodynamics:** It asserts that energy has *quality* as well as *quantity*, and actual processes occur in the direction of decreasing quality of energy.
- **Classical thermodynamics**: A macroscopic approach to the study of thermodynamics that does not require a knowledge of the behavior of individual particles.
- It provides a direct and easy way to the solution of engineering problems and it is used in this text.
- **Statistical thermodynamics**: A microscopic approach, based on the average behavior of large groups of individual particles.
- It is used in this text only in the supporting role.

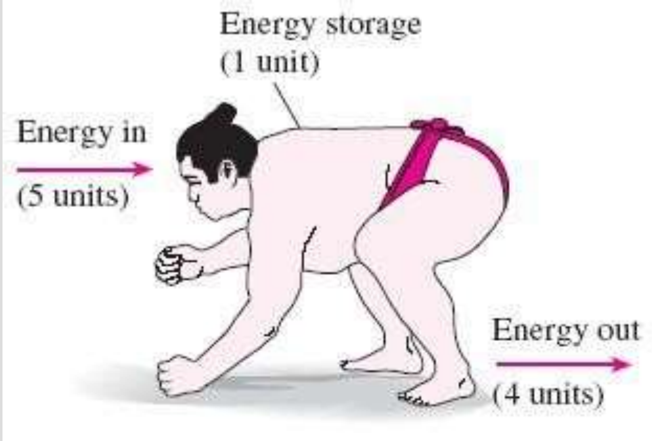


FIGURE 1–2
Conservation of energy principle for the human body.

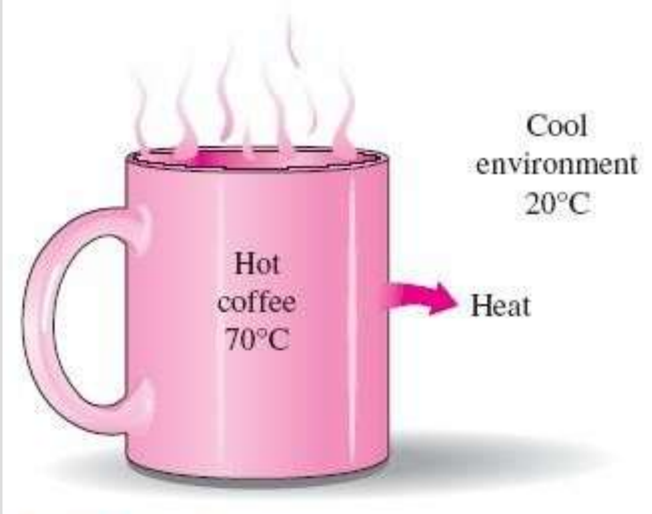


FIGURE 1–3
Heat flows in the direction of decreasing temperature.

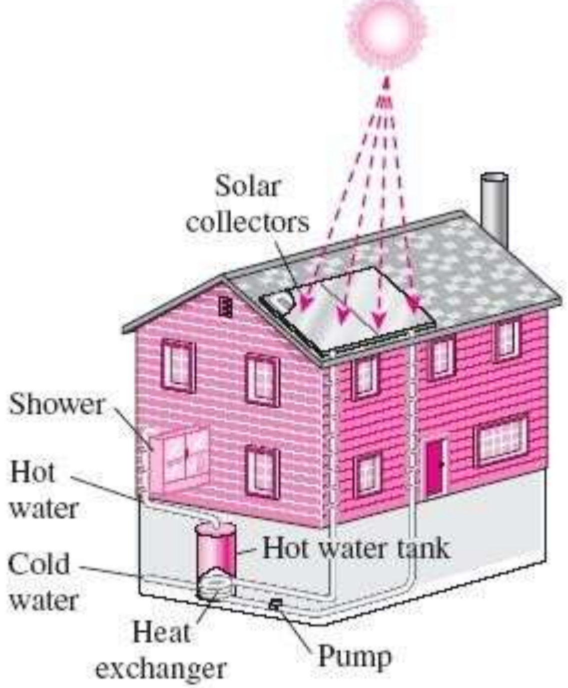


FIGURE 1–4

The design of many engineering systems, such as this solar hot water system, involves thermodynamics.

Refrigeration systems

Boats

Aircraft and spacecraft

Power plants

All activities in nature involve some interaction between energy and matter; thus, it is hard to imagine an area that does not relate to thermodynamics in some manner.

Human body

Cars

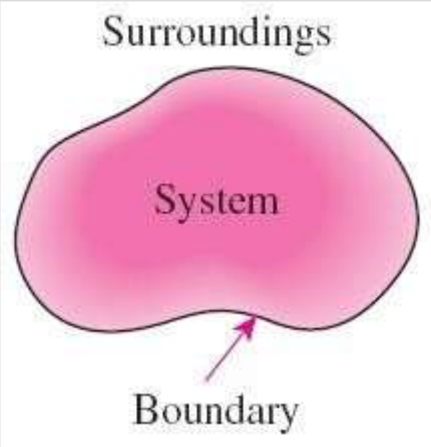
Wind turbines

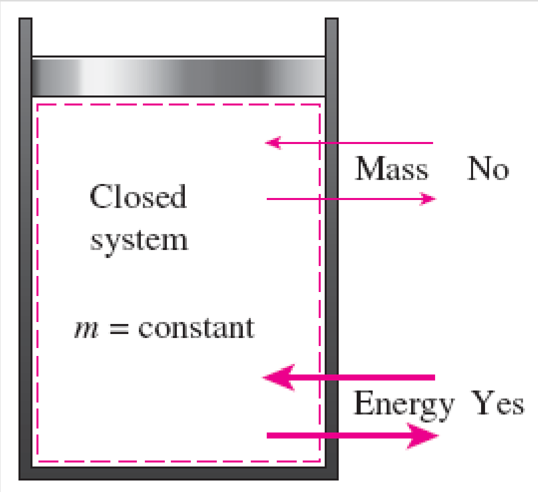
Air conditioning systems

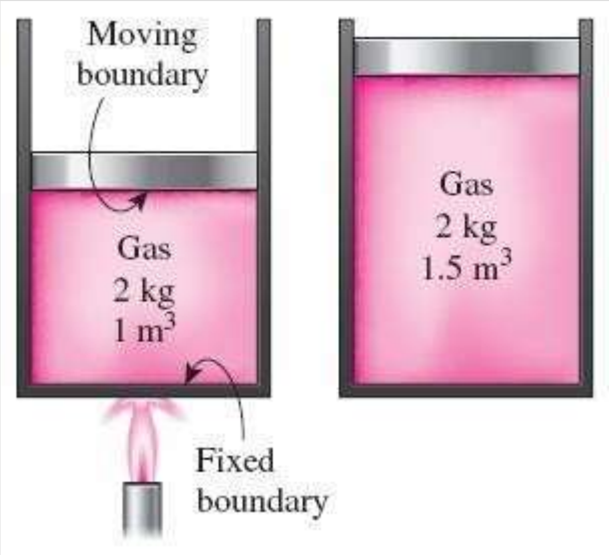
Industrial applications

SYSTEMS AND CONTROL VOLUMES

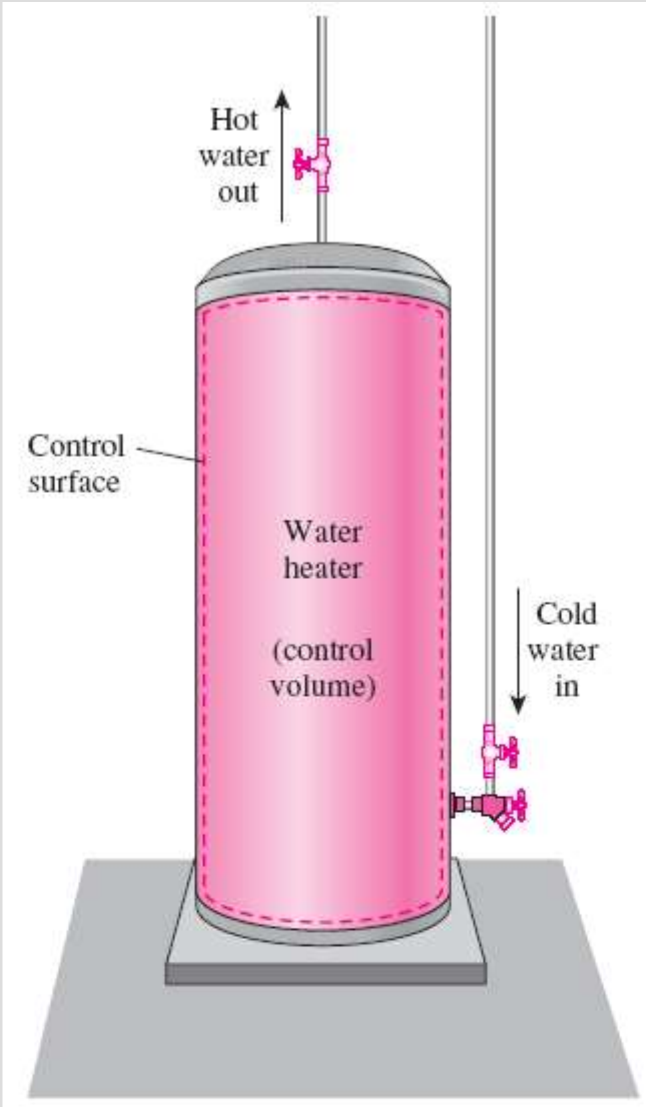
- **System**: A quantity of matter or a region in space chosen for study.
- **Surroundings**: The mass or region outside the system
- **Boundary**: The real or imaginary surface that separates the system from its surroundings.
- The boundary of a system can be *fixed* or *movable.*
- Systems may be considered to be *closed* or *open.*
- **Closed system (Control mass):** A fixed amount of mass, and no mass can cross its boundary

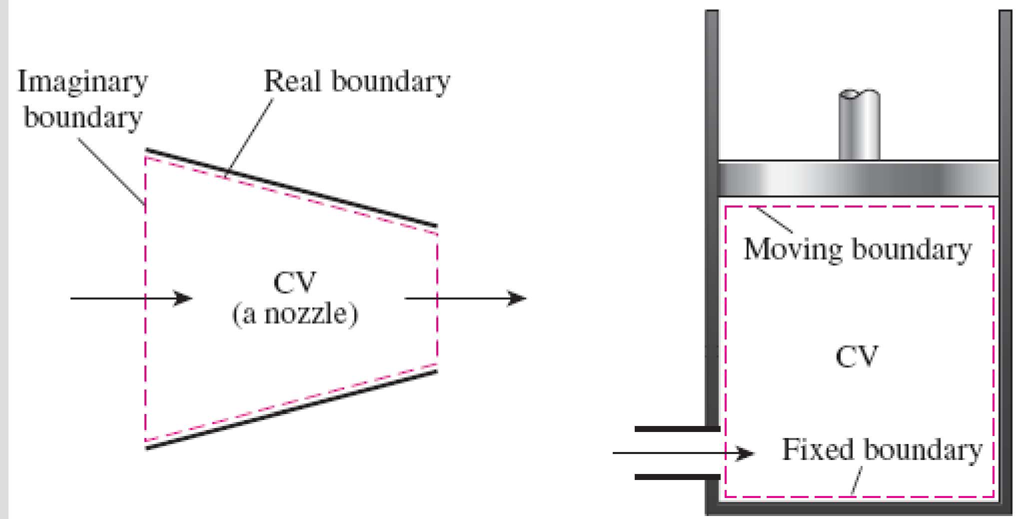






- Both mass and energy can cross the boundary of a control volume.
- **Control surface**: The boundaries of a control volume. It can be real or imaginary.





(*a*) A control volume with real and imaginary boundaries

(*b*) A control volume with fixed and moving boundaries

FIGURE 1–22
A control volume can involve fixed, moving, real, and imaginary boundaries.

system.

- Some familiar properties are pressure *P*, temperature *T*, volume *V*, and mass *m*.
- Properties are considered to be either *intensive* or *extensive*.
- **Intensive properties:** Those that are independent of the mass of a system, such as temperature, pressure, and density.
- **Extensive properties:** Those whose values depend on the size—or extent—of the system.
- **Specific properties:** Extensive properties per unit mass.

$(v = V/m)$ $(e = E/m)$

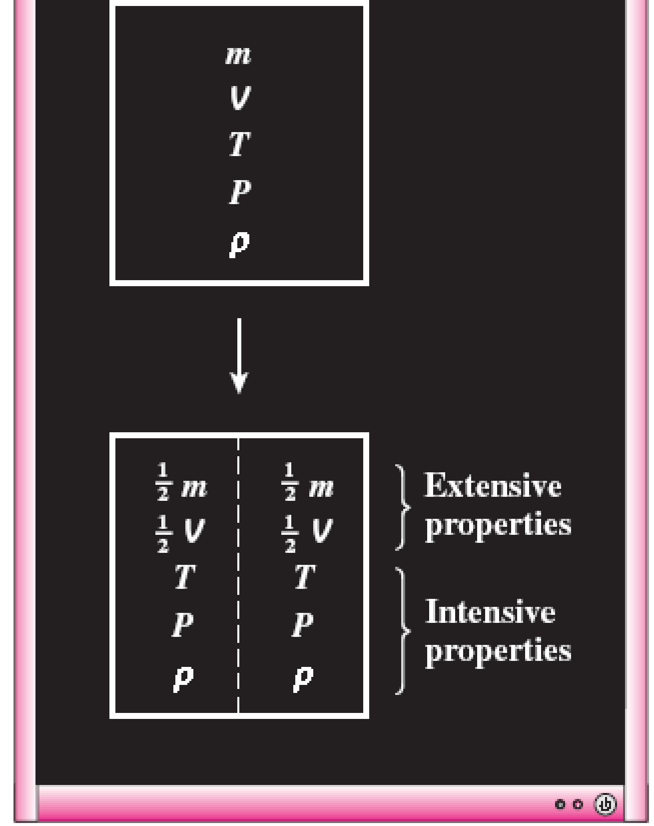


FIGURE 1–24
Criterion to differentiate intensive and extensive properties.

$$\rho = \frac{m}{V} \quad (\text{kg/m}^3)$$

substance to the density of some standard substance at a specified temperature (usually water at 4°C).

$$SG = \frac{\rho}{\rho_{H_2O}}$$

Specific volume

$$v = \frac{V}{m} = \frac{1}{\rho}$$

Specific weight: The weight of a unit volume of a substance.

$$\gamma_s = \rho g \qquad (\text{N/m}^3)$$

$V = 12\ \text{m}^3$

$m = 3\ \text{kg}$

↓

$\rho = 0.25\ \text{kg/m}^3$

$v = \frac{1}{\rho} = 4\ \text{m}^3/\text{kg}$

Density is mass per unit volume; specific volume is volume per unit mass.

TABLE 1–3

Specific gravities of some substances at 0°C

Substance	SG
Water	1.0
Blood	1.05
Seawater	1.025
Gasoline	0.7
Ethyl alcohol	0.79
Mercury	13.6
Wood	0.3–0.9
Gold	19.2
Bones	1.7–2.0
Ice	0.92
Air (at 1 atm)	0.0013

- **Equilibrium**: A state of balance.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- **Thermal equilibrium**: If the temperature is the same throughout the entire system.
- **Mechanical equilibrium:** If there is no change in pressure at any point of the system with time.
- **Phase equilibrium:** If a system involves two phases and when the mass of each phase reaches an equilibrium level and stays there.
- **Chemical equilibrium:** If the chemical composition of a system does not change with time, that is, no chemical reactions occur.

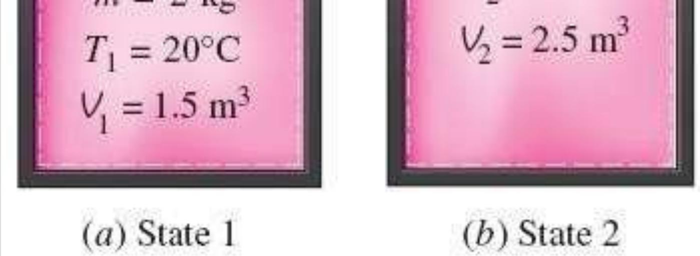


FIGURE 1–27
A system at two different states.

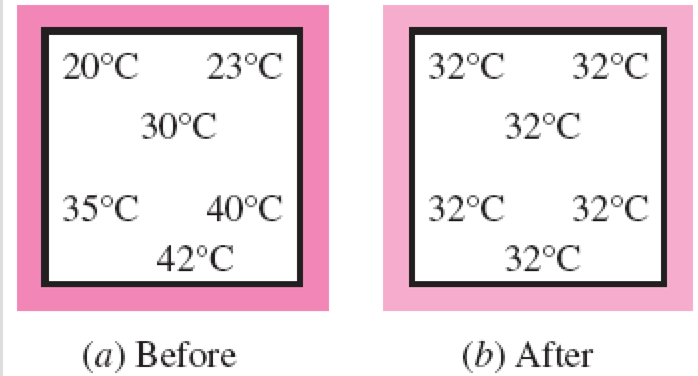


FIGURE 1–28
A closed system reaching thermal equilibrium.

system is given by the **state postulate**:

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

- **Simple compressible system:** If a system involves no electrical, magnetic, gravitational, motion, and surface tension effects.

The state of nitrogen is fixed by two independent, intensive properties.

To describe a process completely, one should specify the initial and final states, as well as the path it follows, and the interactions with the surroundings.

Quasistatic or quasi-equilibrium process: When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times.

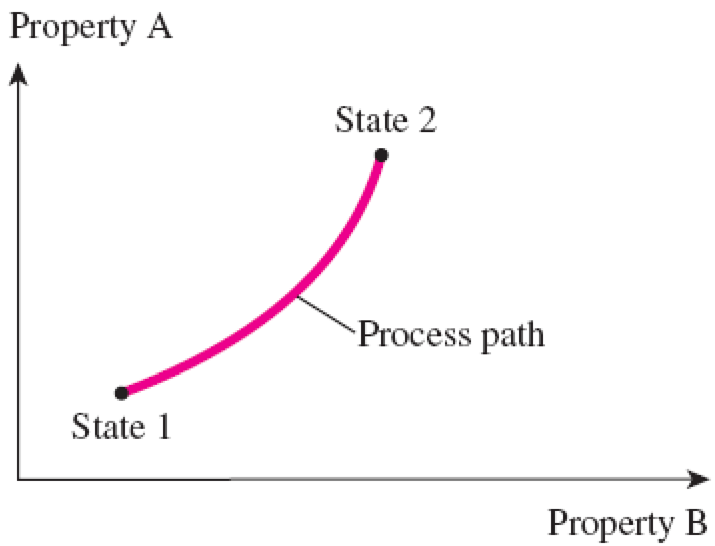


FIGURE 1–30
A process between states 1 and 2 and the process path.

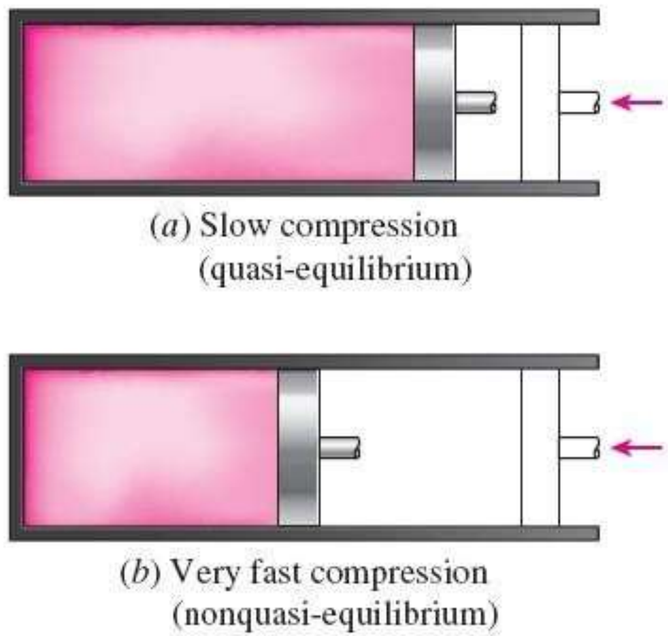


FIGURE 1–31
Quasi-equilibrium and nonquasi-equilibrium compression processes.

- Some common properties that are used as coordinates are temperature *T*, pressure *P*, and volume *V* (or specific volume *v*).
- The prefix *iso-* is often used to designate a process for which a particular property remains constant.
- **Isothermal process**: A process during which the temperature *T* remains constant.
- **Isobaric process**: A process during which the pressure *P* remains constant.
- **Isochoric (or isometric) process**: A process during which the specific volume *v* remains constant.
- **Cycle**: A process during which the initial and final states are identical.

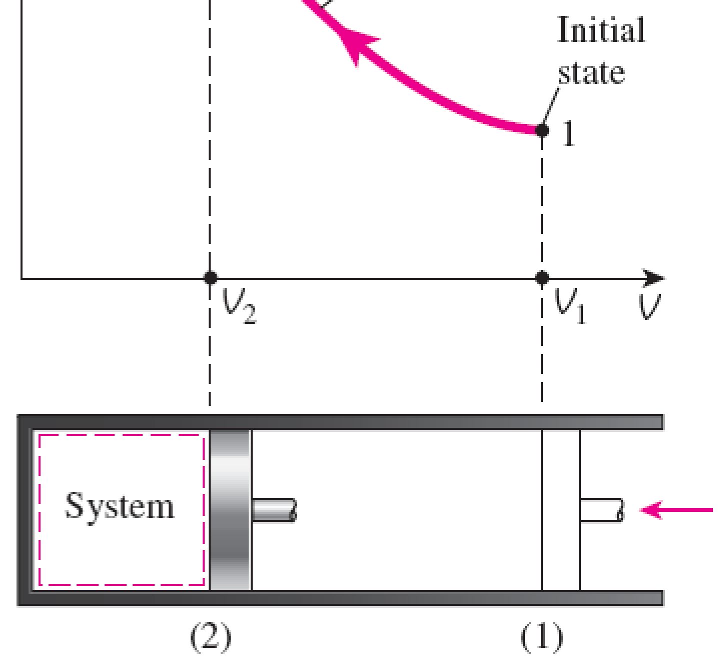
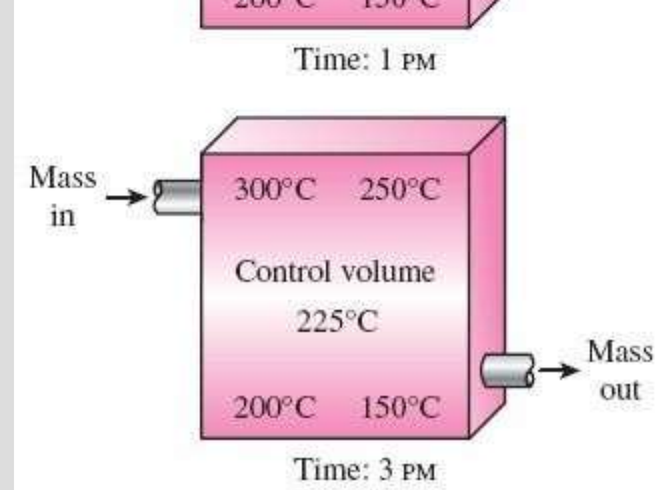


FIGURE 1–32
The *P*-*V* diagram of a compression process.

unsteady, or *transient*.

- A large number of engineering devices operate for long periods of time under the same conditions, and they are classified as *steady-flow devices*.
- **Steady-flow process**: A process during which a fluid flows through a control volume steadily.
- Steady-flow conditions can be closely approximated by devices that are intended for continuous operation such as turbines, pumps, boilers, condensers, and heat exchangers or power plants or refrigeration systems.

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



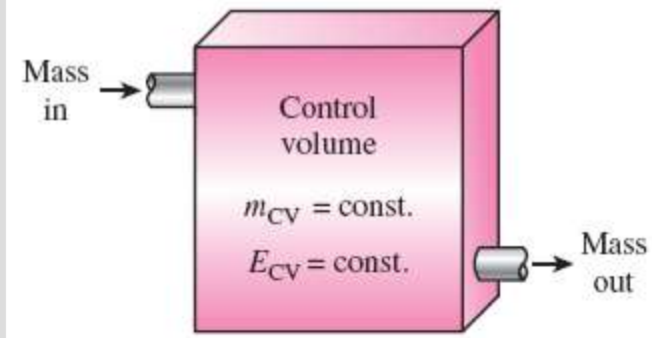


FIGURE 1–34
Under steady-flow conditions, the mass and energy contents of a control volume remain constant.

- **The zeroth law of thermodynamics:** If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- By replacing the third body with a thermometer, the zeroth law can be restated as *two bodies are in thermal equilibrium if both have the same temperature reading even if they are not in contact*.

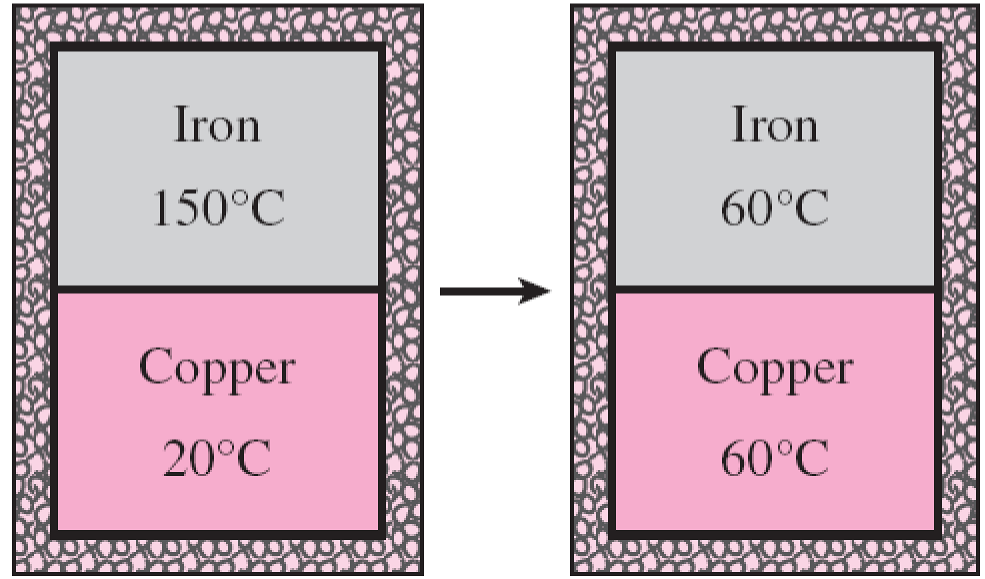


FIGURE 1–35
Two bodies reaching thermal equilibrium after being brought into contact in an isolated enclosure.

Week -2

Lecture

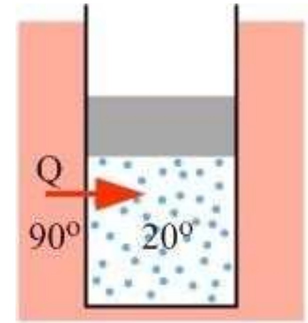
on

Thermodynamic Process
(27-36)

EXPLORATION 15.1 – Adding heat to a cylinder

Figure 15.1: A cylinder sealed with a piston that can move up or down without friction. The cylinder is initially at room temperature, 20°C.

A cylinder of ideal gas, as in Figure 15.1, is sealed with a piston that can move up or down without friction. The top of the piston is exposed to the atmosphere. The ideal gas in the cylinder is initially at room temperature, 20°C. The cylinder is then placed in a water bath that is maintained at a constant temperature of 90°C.



Step 1 – ***Describe qualitatively what happens to this gas system when it is placed in the water bath.***
Because the temperature of the gas in the cylinder is lower than that of the water bath, heat will be transferred from the water into the gas. This is shown in Figure 15.2. This transfer of energy will continue until the gas in the cylinder reaches 90°C, the same temperature as the water bath. At that point, thermal equilibrium will be reached and the energy transfer will stop.

Figure 15.2: When the cylinder is placed in a water bath that is maintained at a temperature higher than the gas, heat is naturally transferred from the water bath into the cylinder until thermal equilibrium is reached.

Step 2 – ***Describe what happens to the energy transferred as heat from the water bath to the ideal gas.*** Increasing the temperature of the gas means increasing the internal energy of the gas. Thus, some of the heat *Q* transferred to the gas causes a change in internal energy, ΔE_{int}. However, something else must change for the gas to satisfy the condition set by the ideal gas law, $PV = nRT$. As we discussed in Chapter 14, in a cylinder in which the piston is free to move, the pressure is determined by the forces on the piston's free-body diagram (see Figure 15.3).

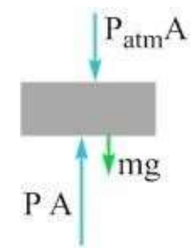
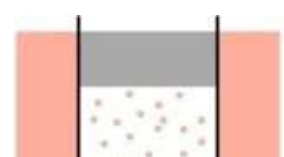


Figure 15.3: Applying Newton's second law to the free-body diagram tells us that, with the piston at equilibrium, the pressure of the gas is given by $P = P_{atm} + mg / A$, where *A* is the area of the top or bottom of the piston.

When the gas temperature reaches 90°C, the piston is at a new equilibrium position, but the pressure in the cylinder is the same as it was before – nothing has changed on the free-body diagram. Thus, to satisfy the ideal gas law, the volume occupied by the gas increases when the pressure increases. This is shown in Figure 15.4. The expanding gas does a positive amount of work *W*, exerting an upward force and causing an upward displacement of the piston. Like the change in internal energy, the work *W* comes from the heat *Q* transferred from the water bath into the gas. Thus, some of the transferred heat goes into raising the internal energy of the system, and some goes into doing work.



is defined more formally below. **Related End-of-Chapter Exercises: 1 and 13.**

The first law of thermodynamics is a statement of energy conservation as it relates to a thermodynamic system. Heat, which is energy transferred into or out of a system, can be transformed into (or come from) some combination of a change in internal energy of the system and the work done by (or on) the system.

$$Q = \Delta E_{int} + W \quad .$$ (Equation 15.1: **The First Law of Thermodynamics**)

Q is positive when heat is added to a system, and negative when heat is removed.
ΔE_{int} is positive when the temperature of a system increases, and negative when it decreases.

W is positive when a system expands and does work, and negative when the system is compressed.

EXAMPLE 15.1 – Some numerical calculations

Let's do two numerical calculations related to Exploration 15.1. Let's say that 3500 J is transferred to the cylinder as heat. The work done by the gas while the heat is being transferred is 1400 J. (a) Calculate the change in internal energy experienced by the gas in the cylinder. (b) If the change in internal energy can be calculated, in this case, using the equation $\Delta E_{int} = (3/2)nR\Delta T$, calculate the number of moles of gas in the cylinder.

SOLUTION

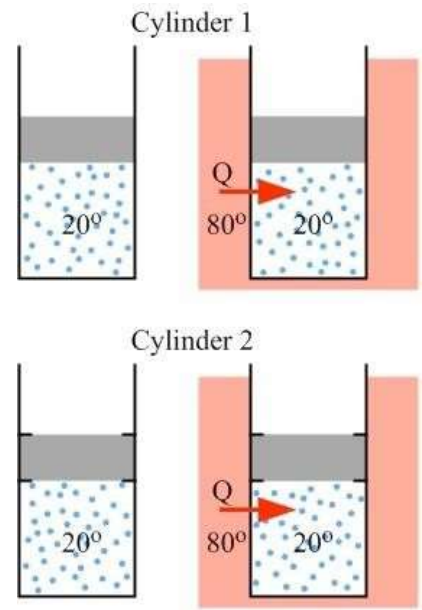
(a) We can calculate the change in internal energy by re-arranging the equation for the first law.

$$\Delta E_{int} = Q - W = 3500 \text{ J} - 1400 \text{ J} = 2100 \text{ J} .$$

(b) Now, we can solve for the number of moles by re-arranging the equation that was given for the change in internal energy.

$$n = \frac{(2/3)\Delta E_{int}}{R\Delta T} = \frac{(2/3)\,2100 \text{ J}}{(8.31 \text{ J/mol K})(+70\text{K})} = \frac{1400 \text{ J}}{(8.31 \text{ J/mol K})(+70\text{K})}$$

$$n = \frac{20 \text{ J/K}}{8.31 \text{ J/mol K}} = 2.4 \text{ moles}$$



***Essential Question 15.1*:** Figure 15.5 shows two cylinders containing equal amounts of the same ideal gas in the same initial state – the gas in the two cylinders has the same pressure, volume, and temperature. The difference between them is that, in cylinder 1, the piston sealing the cylinder is free to move up or down without friction, while the piston in cylinder 2 is fixed so the volume occupied by the gas is constant. Both cylinders are initially at 20°C, but are then placed in a water bath that is maintained at a constant temperature of 80°C and allowed to both cases. The difference between the cylinders is that the gas in cylinder 1 will expand when the temperature increases, so the gas does work moving the piston. No work is done by the gas in cylinder 2. Thus $Q_1 = \Delta E_{int} + W$ is larger than $Q_2 = \Delta E_{int}$. More heat needs to be added to cylinder 1 than cylinder 2, the difference corresponding to the work done by the gas in cylinder 1.

15-2 Work, and Internal Energy

The first law involves three parameters. Heat (*Q*) involves a transfer of energy into or out of a system. Let's now explore the ideas of work (*W*) and change in internal energy (ΔE_{int}).

For the case of the cylinder in section 15-1, the work done by the gas on the piston is the magnitude of the force the gas exerts on the piston multiplied by the magnitude of the piston's displacement, Δh. Using the fact that *F* = *PA*, and that the volume and height are related by area:

$$W = F\Delta h = (PA)\Delta h = P(A\Delta h) = P\Delta V .$$

Thus, for a constant pressure process we have:

$W = P\Delta V$. (Eq. 15.2: **Work done at constant pressure**)

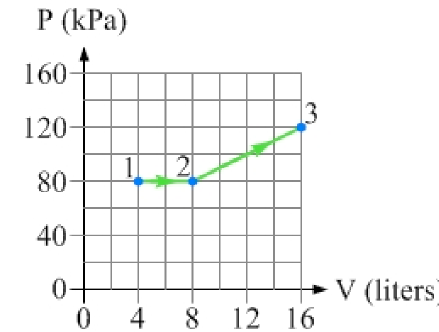
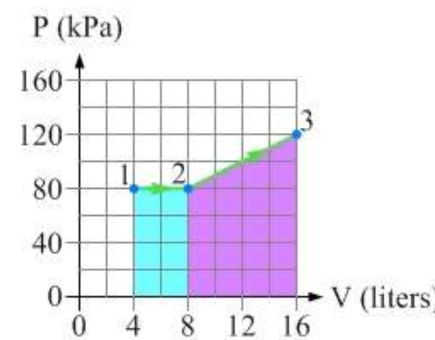


Figure 15.6: The P-V diagram shows an expansion from state 1 to state 2 at constant pressure, followed by another expansion that takes the system to state 3 along the path indicated.

If the pressure changes, Equation 15.2 does not apply. Is there a general method of finding work that is valid in all cases? Consider now the two processes shown in the P-V diagram in Figure 15.6.

For the constant pressure process, in which the system expands from state 1 to state 2, Equation 15.2 tells us that the work done by the gas in that process is $P\Delta V$. This is the area under the curve defining the process. For the expansion from state 2 to state 3, which is not at constant pressure, the work is still equal to the area under the curve defining the process. This gives us our general method of finding work. The two shaded areas shown in Figure 15.7 represent the work done by the gas in the two processes.



Work: A practical way to calculate the work done by a gas in a particular thermodynamic process is to find the area under the curve for that process on the P-V diagram.

Figure 15.7: The area of the rectangular region under the 1 to 2

$$W_{1\to 2} = P\Delta V = (80 \text{ kPa})(8.0 \text{ L} - 4.0 \text{ L}) = (80\times 10^3 \text{ Pa})(4.0\times 10^{-3} \text{ m}^3) = +320 \text{ J}.$$

For the expansion from state 2 to 3, the work is the area under the 2 to 3 line in Figure 15.7. This is equal to the area of a rectangle, with the top of the rectangle at the average pressure.

$$W_{2\to 3} = P_{av}\Delta V = (100 \text{ kPa})(16 \text{ L} - 8.0 \text{ L}) = (100\times 10^3 \text{ Pa})(8.0\times 10^{-3} \text{ m}^3) = +800 \text{ J}.$$

Let's turn now to the change in internal energy. The change in internal energy is independent of the process that moves a system from one state to another. Thus, if we know what the change in internal energy is for one process, we can apply that to all processes.

Change in internal energy: If the temperature of an ideal gas changes, the change in internal energy of the gas is proportional to the change in temperature. If there is no change in temperature, there is no change in internal energy (as long as the number of moles of gas remains constant).

$$\Delta E_{int} = nC_V\,\Delta T \,.$$ (Equation 15.4: **Change in internal energy**)

Monatomic: $C_V = \frac{3}{2}R$ Diatomic: $C_V = \frac{5}{2}R$ Polyatomic: $C_V = 3R$

C_V is the heat capacity at constant volume, which we will examine in Section 15-3.

If we just want the internal energy, we remove the deltas.

$$E_{int} = nC_V\,T \,.$$ (Equation 15.5: **Internal energy of an ideal gas**)

EXAMPLE 15.2B – Calculating the change in internal energy

Consider again the P-V diagram shown in Figure 15.6. If the gas is diatomic, find the change in internal energy associated with the two processes shown on the diagram.

SOLUTION

To do this, we will combine the ideal gas law with the information on the graph.

$$\Delta E_{int} = \frac{5}{2}nR\Delta T = \frac{5}{2}nR(T_2 - T_1) = \frac{5}{2}(nRT_2 - nRT_1) = \frac{5}{2}(P_2V_2 - P_1V_1)\,.$$

Plugging in the values for the pressures and volumes shown on the P-V diagram gives:

$$\Delta E_{int,1\to 2} = \frac{5}{2}\left[(80 \text{ kPa})(8.0 \text{ L}) - (80 \text{ kPa})(4.0 \text{ L})\right] = 1600 \text{ J} - 800 \text{ J} = +800 \text{ J}.$$

Using a similar process for the expansion from state 2 to state 3 gives:

$$\Delta E_{int,2\to 3} = \frac{5}{2}\left[(120 \text{ kPa})(16.0 \text{ L}) - (80 \text{ kPa})(8.0 \text{ L})\right] = 3800 \text{ J} - 1600 \text{ J} = +2200 \text{ J}.$$

Related End-of-Chapter Exercises: 14, 16, 46, 47.

processes have different amounts of work associated with them. On the other hand, we can find the change in internal energy, because we know the pressure and volume of the initial and final states. No matter what the process, for a diatomic ideal gas the change in internal energy in moving from state 2 to state 3 will be the +2200 J we calculated in Example 15.2B.

15-3 Constant Volume and Constant Pressure Processes

Let's consider once again two different thermodynamic processes, one in which heat is added to a system at constant volume, and the other when heat is added at constant pressure.

EXPLORATION 15.3A – A constant-volume process

A sample of monatomic ideal gas is initially at a temperature of 200 K. The gas occupies a constant volume. Heat is then added to the gas until the temperature reaches 400 K. This process is shown on the P-V diagram in Figure 15.8, where the system moves from state 1 to state 2 by the process indicated. The diagram also shows the cylinder in state 1 and again in state 2. The figure also shows the 200 K isotherm (lower) and the 400 K isotherm (higher).

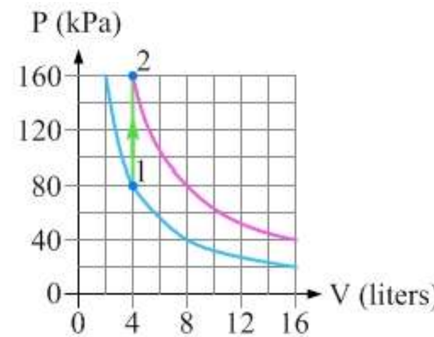


Figure 15.8: A P-V diagram showing a constant-volume process that moves a system of monatomic ideal gas from state 1 to state 2.

Step 1 – ***Find the number of moles of gas in the cylinder.***
Applying the ideal gas law to state 1 gives:

$$n = \frac{PV}{RT} = \frac{(80 \text{ kPa})(4.0 \text{ L})}{(8.31 \text{ J/mol K})(200 \text{ K})} = 0.19 \text{ moles}.$$

Step 2 – ***Find the work done in this process.***
The work done is the area under the curve for the process. Because there is no area under the curve in a constant-volume process the work done by the gas is zero: $W = 0$.

Step 3 – ***Find the change in internal energy for this process.***
In a constant-volume process all the heat added goes into changing the internal energy of the gas. Because the gas is monatomic we have $C_V = 3R/2$. This gives:

$$\Delta E_{\text{int}} = \frac{3}{2} n R \Delta T = \frac{3}{2}(0.19 \text{ moles})(8.31 \text{ J/mol K})(400 \text{ K} - 200 \text{ K}) = +480 \text{ J} .$$

Step 4 – ***Find the heat added to the gas in this process.*** The First Law of Thermodynamics tells us that $Q = \Delta E_{\text{int}} + W$, but if the work done by the gas is zero we have $Q = \Delta E_{\text{int}}$. In this case we have Q = +480 J.

Key ideas for a constant-volume process: There is no work done by the gas: $W = 0$.

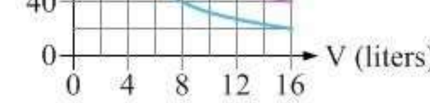


Figure 15.9: A P-V diagram showing a constant-pressure process that moves a system of monatomic ideal gas from state 1 to state 3.

Step 1 – ***Find the work done in this process.*** The work done by the gas in this process is the area under the curve on the P-V diagram. Because the pressure is constant we can use Equation 15.2:

$$W = P\Delta V = (80 \text{ kPa})(8.0 \text{ L} - 4.0 \text{ L}) = (80 \text{ kPa})(+4.0 \text{ L}) = +320 \text{ J} .$$

Step 2 – ***Find the change in internal energy for this process.*** Because the temperature change is the same, the change in internal energy is the same as it is in the constant-volume process:

$$\Delta E_{\text{int}} = \frac{3}{2} n R \Delta T = \frac{3}{2}(0.19 \text{ moles})(8.31 \text{ J/mol K})(400 \text{ K} - 200 \text{ K}) = +480 \text{ J} .$$

Step 3 – ***Find the heat added to the gas.*** Applying the First Law of Thermodynamics gives:

$$Q = \Delta E_{\text{int}} + W = +480 \text{ J} + 320 \text{ J} = +800 \text{ J}$$

Key ideas for a constant-pressure process: The work done by the gas is given by Equation 15.2: $W = P\Delta V$. **Related End-of-Chapter Exercises: 3, 19 – 21.**

Heat Capacity

In Chapter 13, we used $Q = mc\Delta T$ to find the heat needed to change the temperature of a substance of mass *m* and specific heat *c*. For gases, a more convenient equation is

$Q = nC\Delta T$, where *C* is known as the heat capacity. The value of the heat capacity depends on the process the gas follows when the heat is added. At constant volume, when the work done is zero:

$Q = \Delta E_{\text{int}} = nC_V \Delta T$, (Eq. 15.6: **Heat needed to change temperature at constant volume**)

where C_V is the heat capacity at constant volume. As mentioned in Section 15-2, we apply $\Delta E_{\text{int}} = nC_V \Delta T$ to all processes, because the change in internal energy is process independent.

Monatomic: $C_V = \frac{3}{2}R$ Diatomic: $C_V = \frac{5}{2}R$ Polyatomic: $C_V = 3R$

In contrast, the **heat needed to change temperature at constant pressure** is given by:

$Q = W + \Delta E_{\text{int}} = P\Delta V + nC_V \Delta T = nR\Delta T + nC_V \Delta T = n(R + C_V)\Delta T = nC_P \Delta T$, (Eq. 15.7)

where $C_P = R + C_V$ is the heat capacity at constant pressure.

Monatomic: $C_P = \frac{5}{2}R$ Diatomic: $C_P = \frac{7}{2}R$ Polyatomic: $C_P = 4R$

$$\Delta T = \frac{2Q}{3nR} = \frac{2 \times 800 \text{ J}}{3(0.19 \text{ moles})(8.31 \text{ J/mol K})} = +333 \text{ K}.$$

Because the initial temperature is 200 K, the final temperature is 200 K + 333 K = 533 K. Applying the ideal gas law, gives the corresponding pressure:

$$P = \frac{nRT}{V} = \frac{(0.19 \text{ moles})(8.31 \text{ J/mol K})(533 \text{ K})}{4.0 \text{ L}} = 213 \text{ kPa}.$$

15-4 Constant Temperature and Adiabatic Processes

Let's now consider two more thermodynamic processes, the constant temperature (also known as isothermal) process and the adiabatic process.

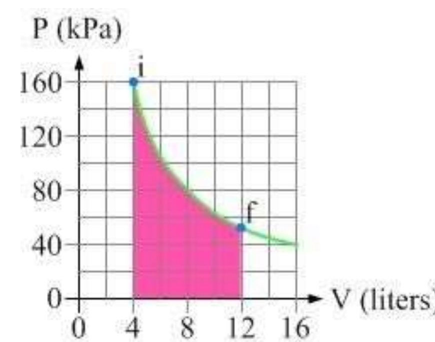
A constant-temperature (isothermal process: Because the temperature is constant there is no change in internal energy. The First Law of Thermodynamics tells us that, in this case, $Q = W$, and it can be shown (using calculus is the most straightforward way to prove this) that:

$$Q = W = nRT \ln\left(\frac{V_f}{V_i}\right).$$ (Eq. 15.8: **Heat and work for an isothermal process**)

EXAMPLE 15.4A – Add heat at constant temperature

700 J of heat is added to a system of ideal gas, while the temperature is kept constant at 400 K. The system initially has a pressure of 160 kPa and occupies a volume of 4.0 liters.

(a) Is this possible? Can temperature remain constant while heat is added? Explain.
(b) Sketch this process on a P-V diagram, keeping in mind the following question: When heat is added at constant temperature does the gas pressure increase, as in a constant-volume process, or does the volume increase, as in a constant-pressure process?
(c) What are the final values of the gas pressure and the volume of the gas?



SOLUTION

(a) This is possible. The first law of thermodynamics tells us that heat Q is converted into some combination of internal energy and/or work. When the temperature is constant we have the special case of no change in internal energy, so all the heat is converted into work.

(b) The temperature is constant so the process proceeds along an isotherm, shown in Figure 15.10. Because Q is positive,

Figure 15.10: A P-V diagram

Isolating the logarithm on the right side gives: $\frac{Q}{P_i V_i} = \ln\left(\frac{V_f}{V_i}\right)$.

Taking the exponential of both sides: $e^{Q/(P_i V_i)} = e^{\ln(V_f/V_i)} = \frac{V_f}{V_i}$.

The final volume is thus: $V_f = V_i\, e^{Q/(P_i V_i)} = (4.0\text{ L})\, e^{700\text{ J}/(160\text{ kPa}\times 4.0\text{ L})} = 11.9\text{ L}$.

Solving for the final pressure gives: $P_f = \frac{nRT}{V_f} = \frac{P_i V_i}{V_f} = \frac{(160\text{ kPa})(4.0\text{ L})}{11.94\text{ L}} = 54\text{ kPa}$.

An adiabatic process: In an adiabatic process no heat is added to or removed from the gas (i.e., Q = 0). Examples include systems insulated so no heat is exchanged with the surroundings, and systems in which processes happen so fast that there is no time to add or remove heat. Because $Q = 0$ for an adiabatic process the First Law of Thermodynamics tells us that $\Delta E_{int} = -W$. The energy for any work done comes from the change in the system's internal energy.

$P V^{\gamma} = \text{constant}$, (Equation 15.9: **Equation for an adiabatic process on the P-V diagram**)

where γ is the ratio of the heat capacity at constant pressure to the heat capacity at constant volume:

$\gamma = \frac{C_P}{C_V}$ (Equation 15.10: The constant γ for an adiabatic process.

EXAMPLE 15.4B – Analyzing an adiabatic process

A system of monatomic ideal gas experiences an adiabatic expansion that moves it from an initial state, at 400 K, to a final state at a temperature of 200 K. The process is shown on the P-V diagram in Figure 15.11. Calculate the values of the final pressure and volume.

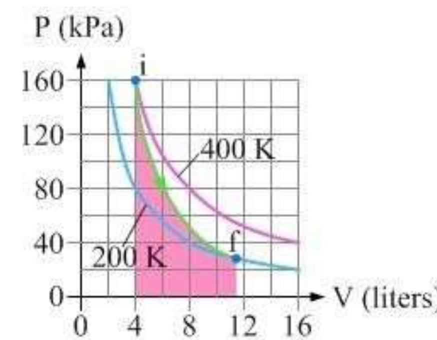


Figure 15.11: The P-V diagram for the adiabatic expansion.

SOLUTION

Because the gas is monatomic, we have: $\gamma = \frac{C_P}{C_V} = \frac{5R/2}{3R/2} = \frac{5}{3}$.

From Equation 15.9, we know that: $P_f V_f^{\gamma} = P_i V_i^{\gamma}$

From the ideal gas law, we have $P_f = nRT_f / V_f$, as well as $n = P_i V_i / (RT_i)$.

Combining these results leads to $T_f V_f^{\gamma-1} = T_i V_i^{\gamma-1}$. (Equation 15.11)

Solving for the final volume gives: $V_f = V_i \left(T_i / T_f\right)^{1/(\gamma-1)} = (4.0\text{ L})(2)^{3/2} = 11.3\text{ L}$.

The final pressure is thus: $P_f = P_i (V_i / V_f)^{\gamma} = (160\text{ kPa}) \left(\frac{4.0\text{ L}}{11.31\text{ L}}\right)^{5/3} = 28\text{ kPa}$.

Related End-of-Chapter Exercises for this section: 4, 22 – 27.

$$W = -\Delta E_{int} = -nC_V \Delta T = -\frac{3}{2}nR\left(T_f - T_i\right) = -\frac{3}{2}nRT_f + \frac{3}{2}nRT_i .$$

We could solve for the number of moles of gas, but let's instead apply the ideal gas law:

$$W = -\frac{3}{2}P_f V_f + \frac{3}{2}P_i V_i = \frac{3}{2}\left(P_i V_i - P_f V_f\right) = \frac{3}{2}\left(160\text{ kPa} \times 4.0\text{ L} - 28.3\text{ kPa} \times 11.31\text{ L}\right) = 480\text{ J}$$

15-5 A Summary of Thermodynamic Processes

There is no single step-by-step strategy that can be applied to solve every problem involving a thermodynamic process. Instead let's summarize the tools we have to work with. These tools can be applied in whatever order is appropriate to solve a particular problem.

Tools for Solving Thermodynamics Problems

- The P-V diagram can help us to visualize what is going on. In addition, the work done by a gas in a process is the area under the curve defining that process on the P-V diagram.
- The ideal gas law, $PV = nRT$.
- The first law of thermodynamics, $Q = \Delta E_{int} + W$.
- The general expression for the change in internal energy, $\Delta E_{int} = nC_V \Delta T$.
- In specific special cases (see the summary in Figure 15.14), there are additional relationships that can be used to relate the different parameters.

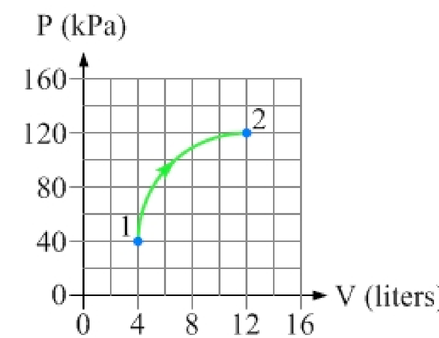


Figure 15.12: The process that moves the system from state 1 to state 2 follows a circular arc on the P-V diagram that covers ¼ of a circle.

EXAMPLE 15.5 – Applying the tools

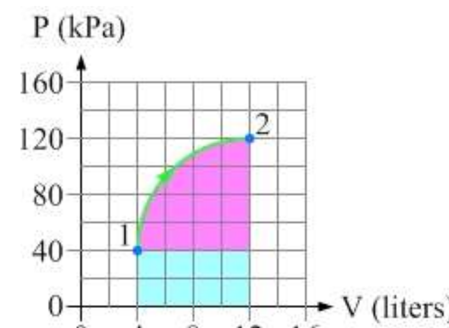
A system of monatomic ideal gas is taken through the process shown in Figure 15.12. For this process find (a) the work done by the gas, (b) the change in internal energy, and (c) the heat added to the gas.

SOLUTION

(a) The area under the curve has been split into two parts in Figure 15.13, a ¼-circle and a rectangle. Each box on the P-V diagram measures 20 kPa × 2.0 L, representing an area of 40 J. The rectangular area covers 8 boxes, for a total of 320 J of work. The radius of the quarter-circle is four boxes, so the area of that quarter circle is given by:

$$W_{1/4} = \frac{1}{4}\pi r^2 = \frac{1}{4}\pi\left(4\text{ units}\right)^2 = 4\pi\text{ boxes} = 4\pi\text{ boxes} \times 40\text{ J/box} = 500\text{ J} .$$

Thus, the total work done by the gas is 320 J + 500 J = 820 J.



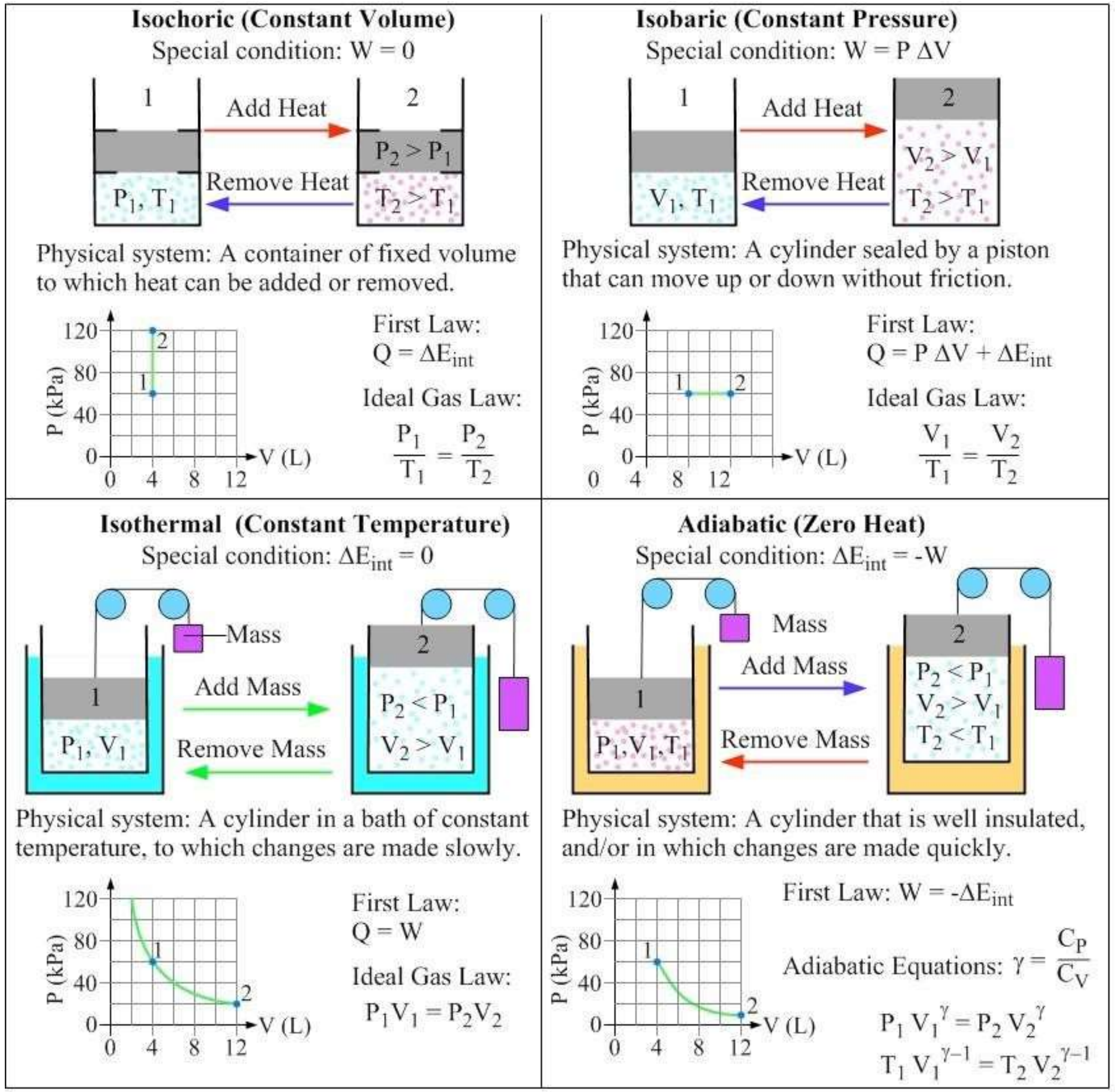


Figure 15.14: A summary of four special-case thermodynamic processes. For each, we see the special condition associated with that process; a pictorial representation and description in words of a corresponding physical system; a P-V diagram for the process; and equations we can apply to solve problems associated with the process.

Related End-of-Chapter Exercises for this section: 6, 7, 28 – 31.

Week -3

Lecture

on

Laws of Thermodynamics
(38-48)

Introduction

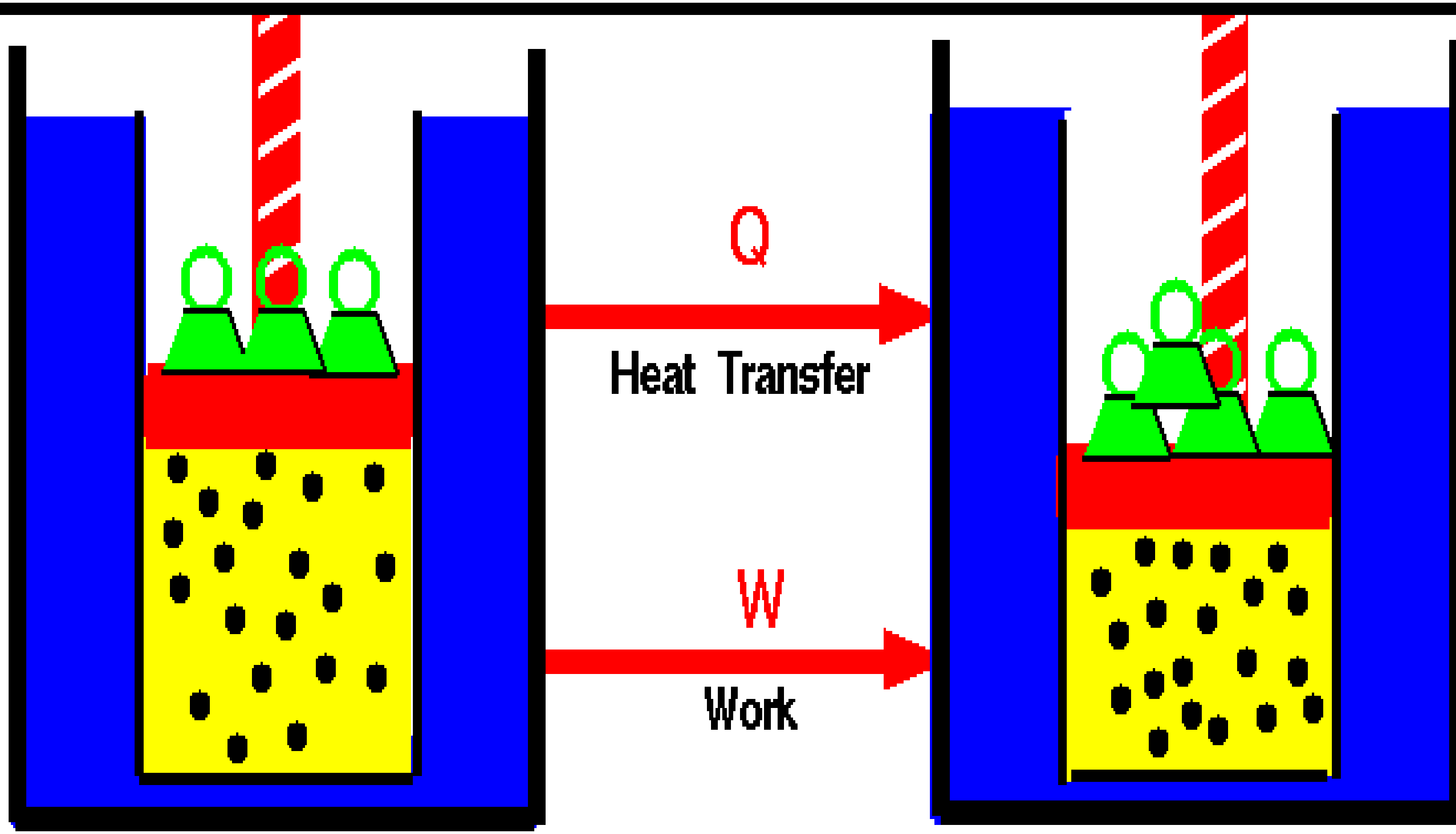
According to British scientist C. P. Snow, the three laws of thermodynamics can be (*humorously*) summarized as

1. You can't win
2. You can't even break even
3. You can't get out of the game

1.0 You can't win (1st law)

- The first law of thermodynamics is an extension of the law of conservation of energy
- The change in internal energy of a system is equal to the heat added to the system minus the work done by the system

$$\Delta U = Q - W$$



State 1 | E = Internal Energy | State 2

$$E_2 - E_1 = Q - W$$

Any thermodynamic system in an equilibrium state possesses a state variable called the internal energy (E). Between any two equilibrium states, the change in internal energy is equal to the difference of the heat transfer into the system and work done

1.1 Process Terminology

- Adiabatic - no heat transferred
- Isothermal - constant temperature
- Isobaric - constant pressure
- Isochoric - constant volume

1.1.1 Adiabatic Process

- An adiabatic process transfers no heat
  - therefore $Q = 0$
- $\Delta U = Q - W$
- When a system expands adiabatically, W is positive (the system does work) so ΔU is negative.
- When a system compresses adiabatically, W is negative (work is done on the system) so ΔU is positive.

1.1.2 Isothermal Process

- An isothermal process is a constant temperature process. Any heat flow into or out of the system must be slow enough to maintain thermal equilibrium
- For ideal gases, if ΔT is zero, $\Delta U = 0$
- Therefore, $Q = W$
  - Any energy entering the system (Q) must leave as work (W)

1.1.3 Isobaric Process

- An isobaric process is a constant pressure process. ΔU, W, and Q are generally non- zero, but calculating the work done by an ideal gas is straightforward

$$W = P \cdot \Delta V$$

- Water boiling in a saucepan is an example of an isobar process

1.1.4 Isochoric Process

- An isochoric process is a constant volume process. When the volume of a system doesn't change, it will do no work on its surroundings. $W = 0$

$$\Delta U = Q$$

- Heating gas in a closed container is an isochoric process

1.2 Heat Capacity

- The amount of heat required to raise a certain mass of a material by a certain temperature is called heat capacity

$$Q = mc_x \Delta T$$

- The constant c_x is called the specific heat of substance x, (SI units of J/kg·K)

1.2.1 Heat Capacity of Ideal Gas

- C_V = heat capacity at constant volume

$$C_V = 3/2\ R$$

- C_P = heat capacity at constant pressure

$$C_P = 5/2\ R$$

- For constant volume

$$Q = nC_V\Delta T = \Delta U$$

- The universal gas constant $R = 8.314$ J/mol·K

2.0 You can't break even (2nd Law)

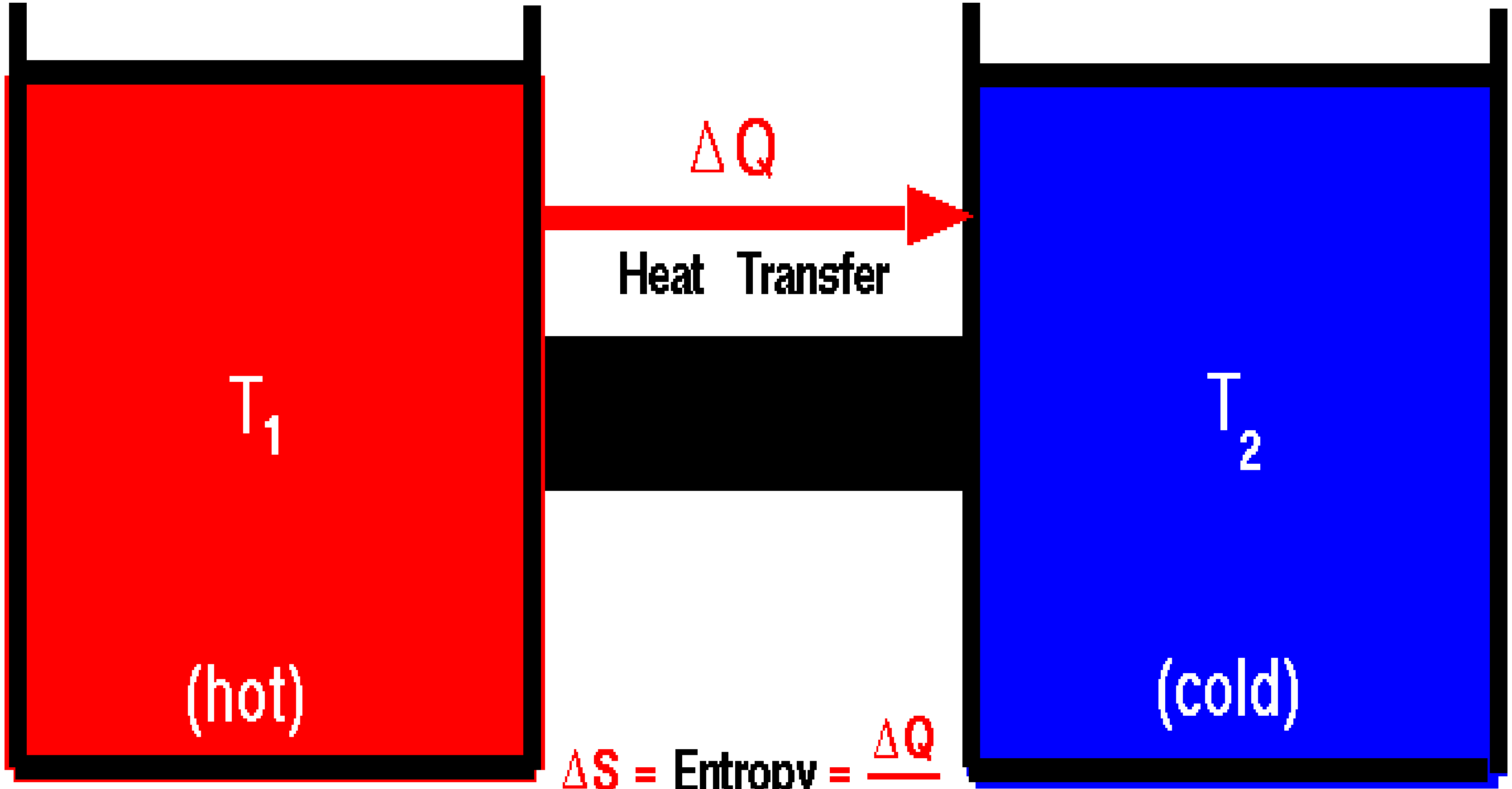
- Think about what it means to not "break even". Every effort you put forth, no matter how efficient you are, will have a tiny bit of waste.
- The 2nd Law can also be stated that heat flows spontaneously from a hot object to a cold object (spontaneously means without the assistance of external work)

Week-4

Lecture

on

Laws of Thermodynamics
(50-57)



$$\Delta S = \text{Entropy} = \frac{\Delta Q}{T}$$

There exists a useful thermodynamic variable called entropy (S). A natural process that starts in one equilibrium state and ends in another will go in the direction that causes the entropy of the system plus the environment to increase for an irreversible process and to remain constant for a reversible process.

2.1 Concerning the 2nd Law

- The second law of thermodynamics introduces the notion of entropy (S), a measure of system disorder (messiness)
- U is the quantity of a system's energy, S is the quality of a system's energy.
- Another C.P. Snow expression:
  - not knowing the 2nd law of thermodynamics is the cultural equivalent to never having read Shakespeare

2.2 Implications of the 2nd Law

- Time marches on
  - If you watch a movie, how do you know that you are seeing events in the order they occurred?
  - If I drop a raw egg on the floor, it becomes extremely "disordered" (greater Entropy) – playing the movie in reverse would show pieces coming together to form a whole egg (decreasing Entropy) – highly unlikely!

2.3 Direction of a Process

- The 2nd Law helps determine the preferred direction of a process
- A reversible process is one which can change state and then return to the original state
- This is an idealized condition – all real processes are irreversible

3.0 You can't get out (3rd Law)

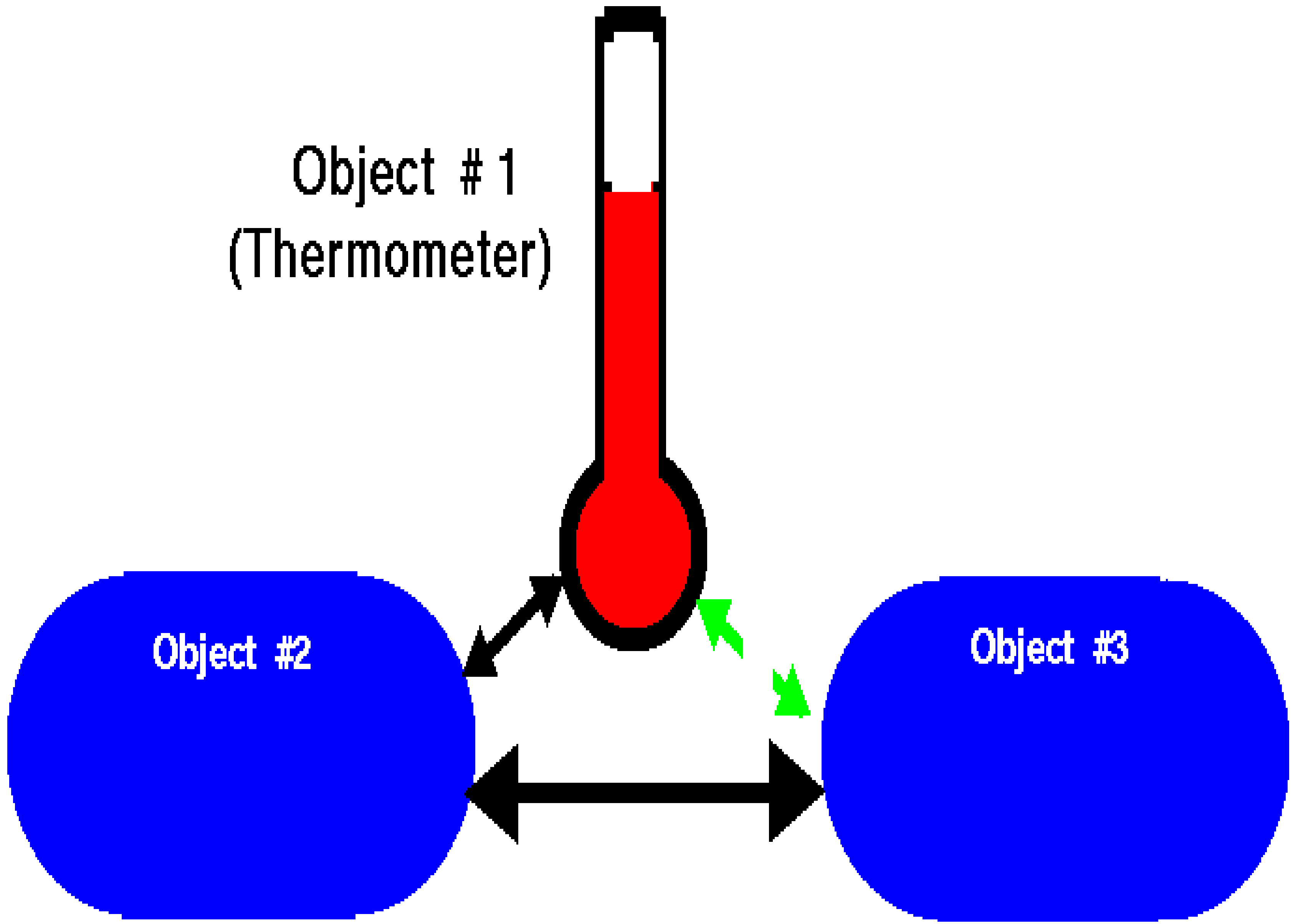
- No system can reach absolute zero
- This is one reason we use the Kelvin temperature scale. Not only is the internal energy proportional to temperature, but you never have to worry about dividing by zero in an equation!
- There is no formula associated with the 3rd Law of Thermodynamics

3.1 Implications of 3rd Law

- MIT researchers achieved 450 picokelvin in 2003 (less than ½ of one billionth!)
- Molecules near these temperatures have been called the fifth state of matter:
  Bose-Einstein Condensates
  - Awesome things like super-fluidity and super- conductivity happen at these temperatures
  - Exciting frontier of research

4.0 The Zeroth Law

- The First and Second Laws were well entrenched when an additional Law was recognized
- If objects A and B are each in thermal equilibrium with object C, then A and B are in thermal equilibrium with each other
- Allows us to define temperature relative to an established standard



When two objects are separately in thermodynamic equilibrium with a third object, they are in equilibrium with each other.

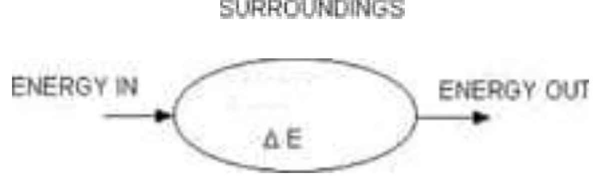
Week-5

Lecture

on

Thermodynamic Cycle

(59-68)



1st law of Thermodynamics

2nd law of Thermodynamics

•Convcrt'some headinput Inro a mechanicat york ourput

7.neat pvoip cycles

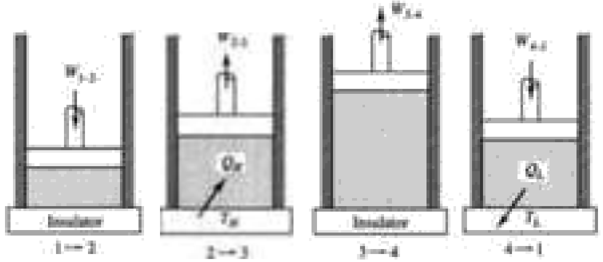
-transfer heat from how to high temperatures by using mechanicat work as the input

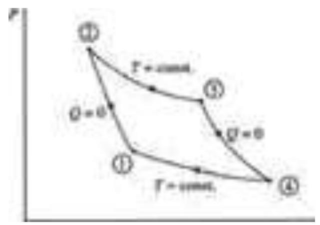
- sdrling cycle
- Erlcson cycle
- Regeneratlve gas turbGe cycle
- Intercoofln$, reheat regenerative s cycles
- Combined brat4nn-rankine.tycle

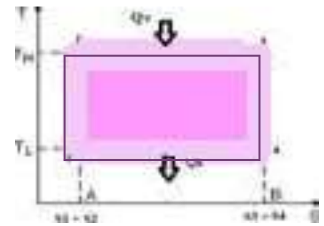
Pure Substance

- Itankine cycle
- fleheet cycle
- Supercr|ticaT rankine cycle
- Regenerative cycle

- Vapor ref/4geration wc!e
- Multistage vapor refrigeration cycle
- Absorption refrigeration cycle
- Heat pump



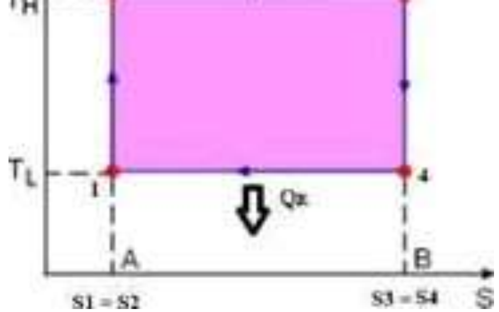




2-3 Isothermal Expansion. Heat is transferred reversibly from the high tempera'túre reśervoir ał the i:ónstanŁ tempera'ture T«. The plstoń In' the cylinder' is w\thdravm and the volurrie Increases.

3-4 Adiabaefc Reversible Gpøps[gn, The .f;yTinder is completely insulated so thaF ne heät tiansfer occun durir\g thls reuemible process. The piston Tn the ¢yTinder continues to be withdrawn ąnd the vulume Increasing

4-1 Isotherñ*aI Go‹npresclon. Heat is tmnsferred reversibly ta the Ion temperature reservoir at the constant temperature The plstan continues œ compress the working substance untİl the original volume, temperature, and pressure are reached, thereby compJerlng the cycle.



AREA 2-3-B-A-2 = QA

AREA 1-4-B-A-1 = QR

2-3-4-1-2 = WNET,OUT

$W = (T_2 - T_1)\,(S_4 - S_1)$

D. Change in entropy

$\Delta S = \frac{Q_A}{r\ .} = \frac{Q_R}{r,} = \frac{W}{ra\text{-}ci}$

E. Cycle'Efficlency

$e = \frac{W}{Q_A} = \frac{Q_A - Q_R}{Q_A} = \frac{W}{W + Q_R}$

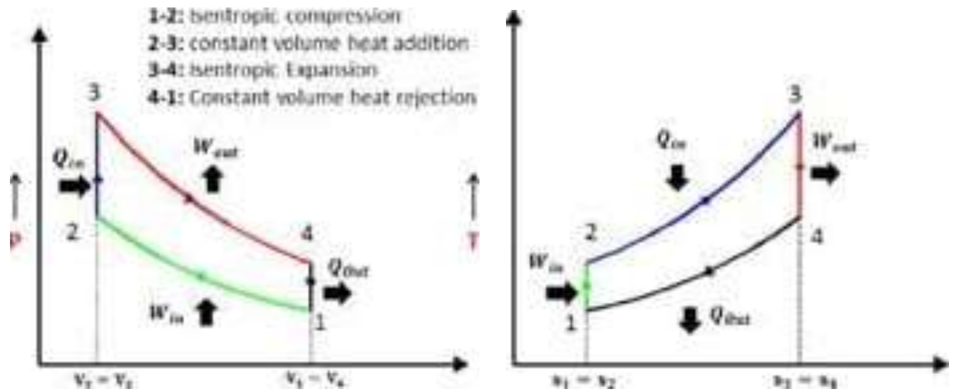
$e = \frac{T_2 - T_1}{T_2} = 1 - \frac{T_1}{T_2} = 1 - \frac{T_L}{T_H}$

F. Mean Effective Pressure, Pm

$P_m = \frac{W}{V_D}$ where: $V_D = V_1 - V_2$

e if compression ratio increases, it's cycle efficiency will increase

- cyEle Efficiency depends on compression ratio and it's specific heat ratio
- typical compression ratio is <u>8.0</u>



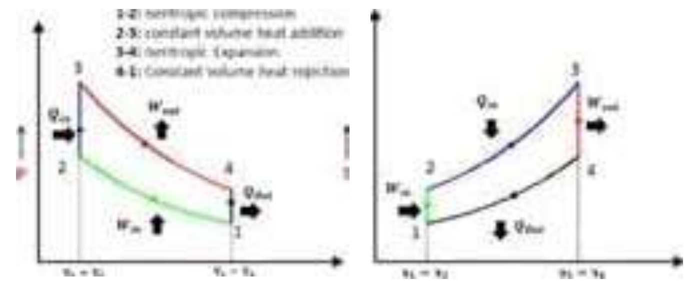
P-V and T-5 DIAGRAM

Process 3-4: Isentropic Expansion

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{K-1} = \left(\frac{P_3}{P_4}\right)^{\frac{K-1}{K}}$$

T_3

$$\frac{P_3}{P_4} = \left(\frac{V_4}{V_3}\right)^{K}$$



r_K = compression ratio = $\frac{V_1}{V_2} = \frac{V_4}{V_3}$

r_P = pressure ratio = $\frac{P_2}{P_1} = \frac{P_3}{P_4}$

Week-6

Lecture

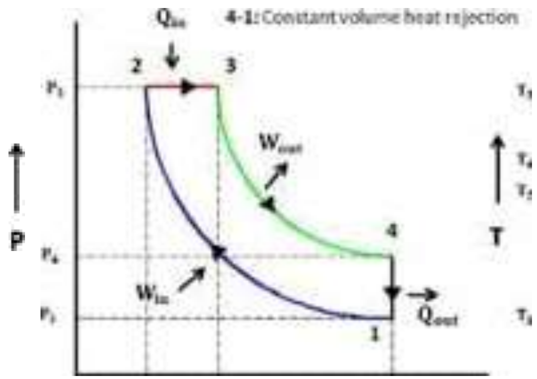
on

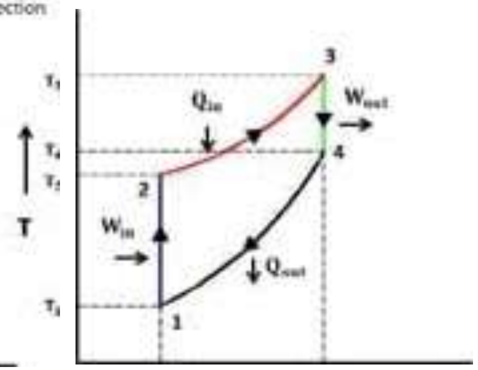
Thermodynamic Cycle

and

Problem Solving

(70-73)



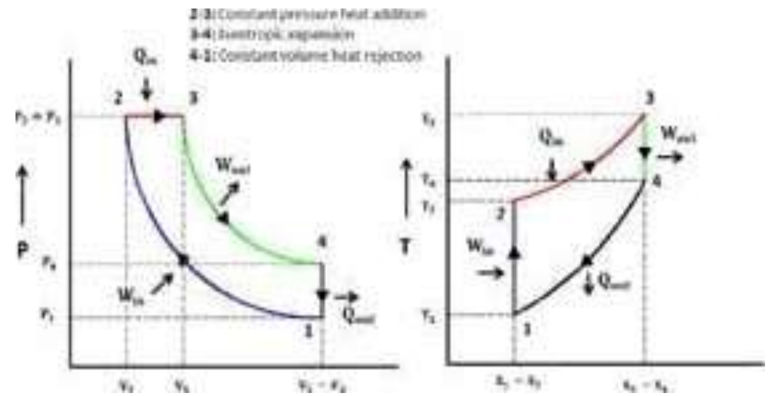


P-V and T-S DIAGRAM

Process 3-4: Isentropic Expansion

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3}\right)^{K-1} = \left(\frac{P_3}{P_4}\right)^{\frac{K-1}{K}}$$

$$\frac{T_3}{T_4} = (r_K)^{K-1} = (r_P)^{\frac{K-1}{K}}$$



$e = \frac{W}{Q_A} = \frac{Q_A - Q_R}{Q_A} = \frac{W}{W+Q_R} = \frac{(T_3-T_2)-(T_4-T_1)}{T_3-T_2}$

ft = Expartsion ratio = $\frac{V_4}{V_3}$

$e = 1 - \frac{1}{K-1}\left[\frac{r_c^{K}-1}{K\cdot(r_c-1)}\right]$

$r_K = r_c \cdot r_e$

K/ - V; = Volume of fuel injec ed

E. r_y ' ' l, r - coFDpressionratio where c- dearance volume

F. $P_m = \frac{W}{V_D} = \frac{W}{V_1 - V_2}$ where: '\ =

$P_2 = P_3$ = maximum pressure

ratio is 12 and the maximum cycle temperature is 2000 °K. determine the cycle efficiency. *Ans. S4.22%*

- A diesel cycle has a compression ratio of 8 and initial temperature of 34 ”C. If the maximum temperature of the cycle is 2000 ”K, find the Heat rejected. 726.RFP/kg
- A diesel cycle has a cycle efficiency of S8%. If heat added is 1600KJ/Kg, Find the work. *Ans. 928 KJ/Kg*
- A diesel has a compression ratio of 8 and cut off ratio of 2.5. Find the cycle efficiency. *Ans. 45.97 fi›*

Week-7

Lecture

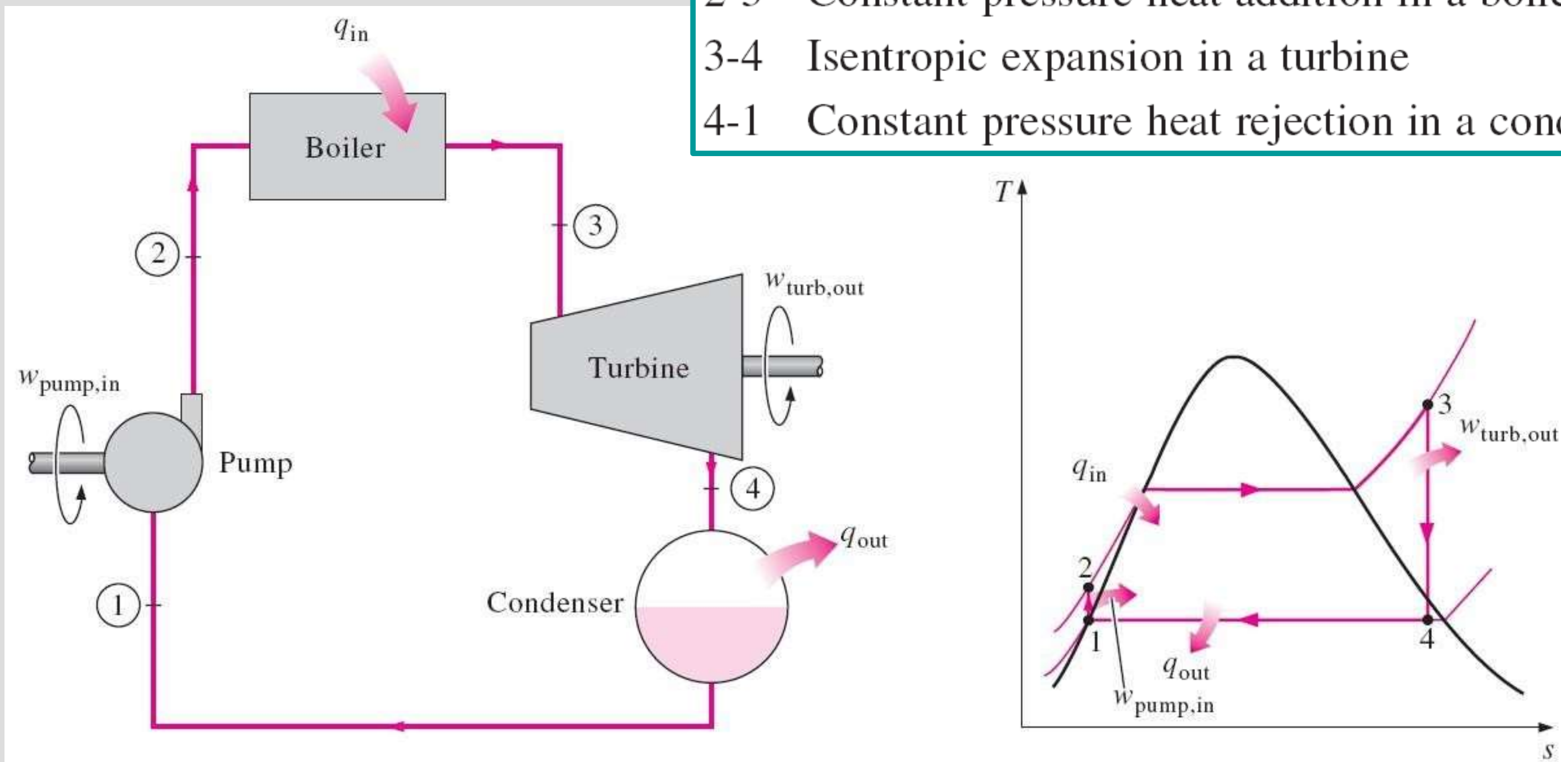
on

Rankine Cycle

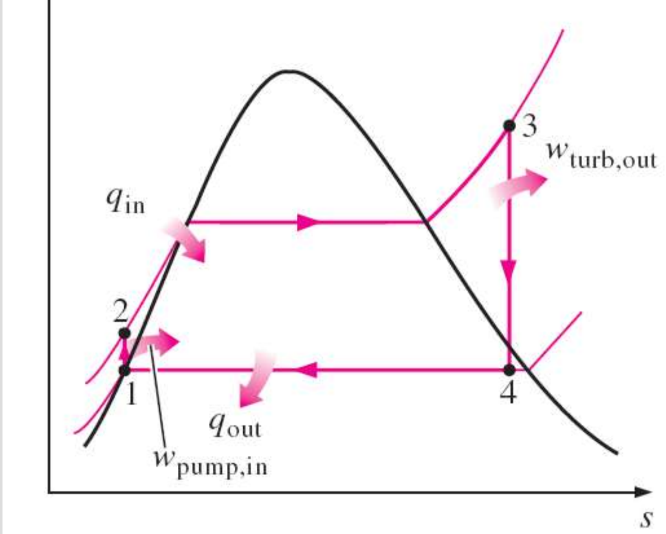
(75-86)

condenser. The cycle that results is the **Rankine cycle**, which is the ideal cycle for vapor power plants. The ideal Rankine cycle does not involve any internal irreversibilities.

1-2	Isentropic compression in a pump
2-3	Constant pressure heat addition in a boiler
3-4	Isentropic expansion in a turbine
4-1	Constant pressure heat rejection in a condenser



The simple ideal Rankine cycle.



Pump ($q = 0$): $w_{pump,in} = h_2 - h_1$

$$w_{pump,in} = v(P_2 - P_1)$$

$$h_1 = h_{f\,@\,P_1} \quad \text{and} \quad v \cong v_1 = v_{f\,@\,P_1}$$

Boiler ($w = 0$): $q_{in} = h_3 - h_2$

Turbine ($q = 0$): $w_{turb,out} = h_3 - h_4$

Condenser ($w = 0$): $q_{out} = h_4 - h_1$

$$w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{pump,in}$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

The efficiency of power plants in the U.S. is often expressed in terms of **heat rate**, which is the amount of heat supplied, in Btu's, to generate 1 kWh of electricity.

$$\eta_{th} = \frac{3412\ (\text{Btu/kWh})}{\text{Heat rate}\ (\text{Btu/kWh})}$$

The thermal efficiency can be interpreted as the ratio of the area enclosed by the cycle on a *T-s* diagram to the area under the heat-addition process.

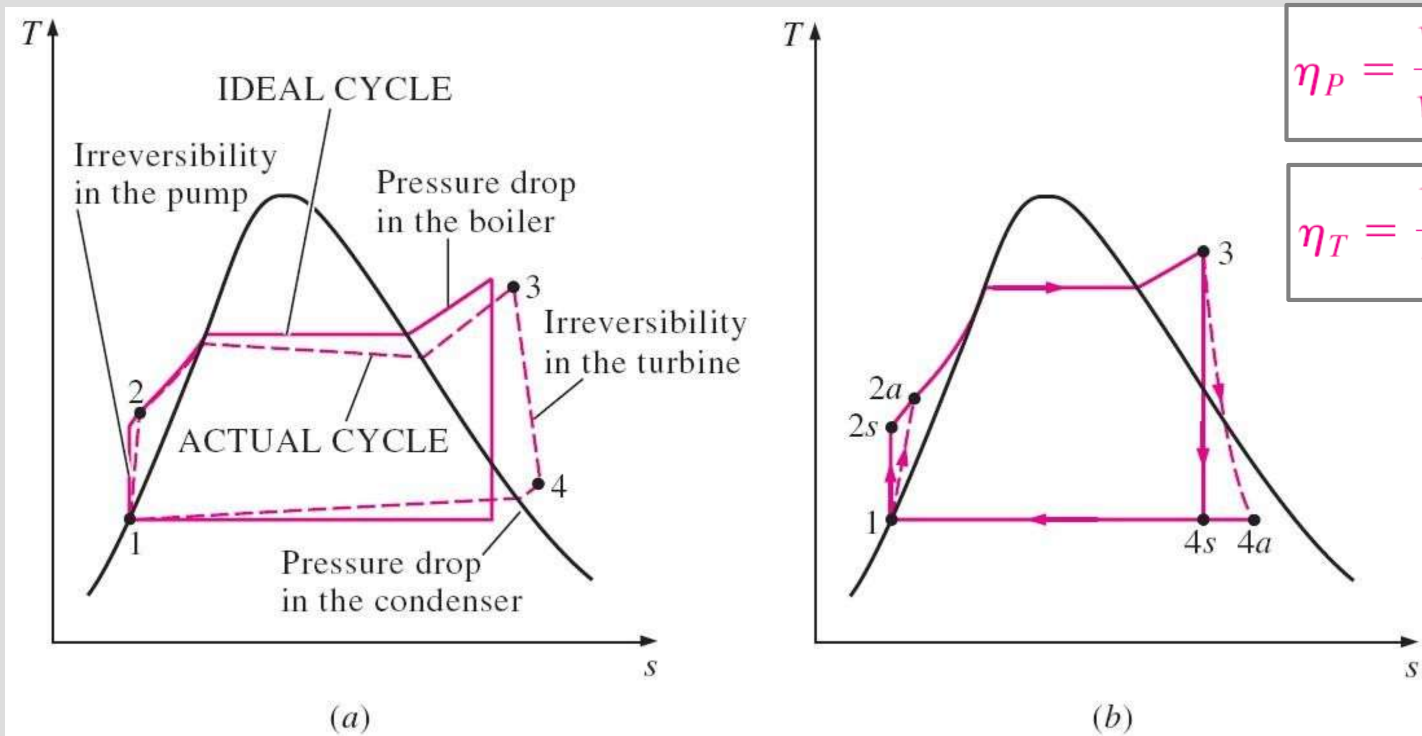
result of irreversibilities in various components.

Fluid friction and heat loss to the surroundings are the two common sources of irreversibilities.

Isentropic efficiencies

$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

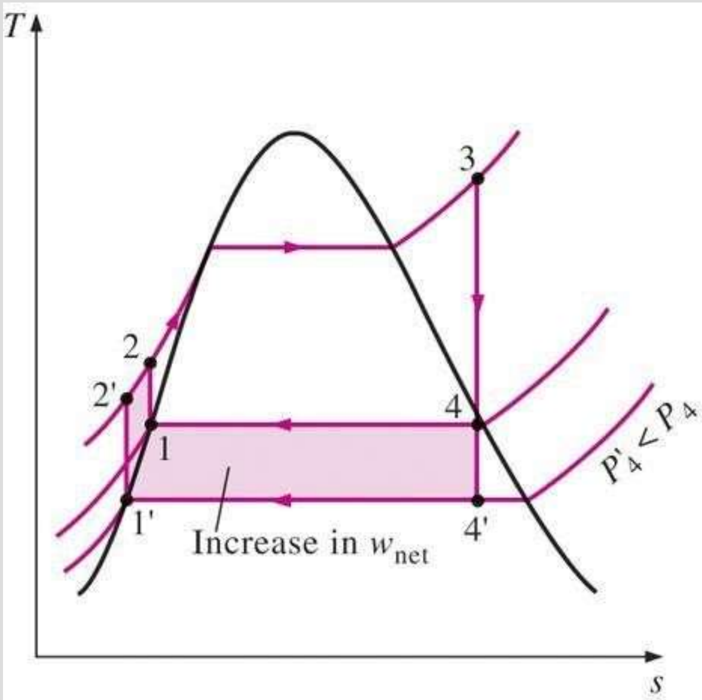
$$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$



(a) Deviation of actual vapor power cycle from the ideal Rankine cycle.
(b) The effect of pump and turbine irreversibilities on the ideal Rankine cycle.

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

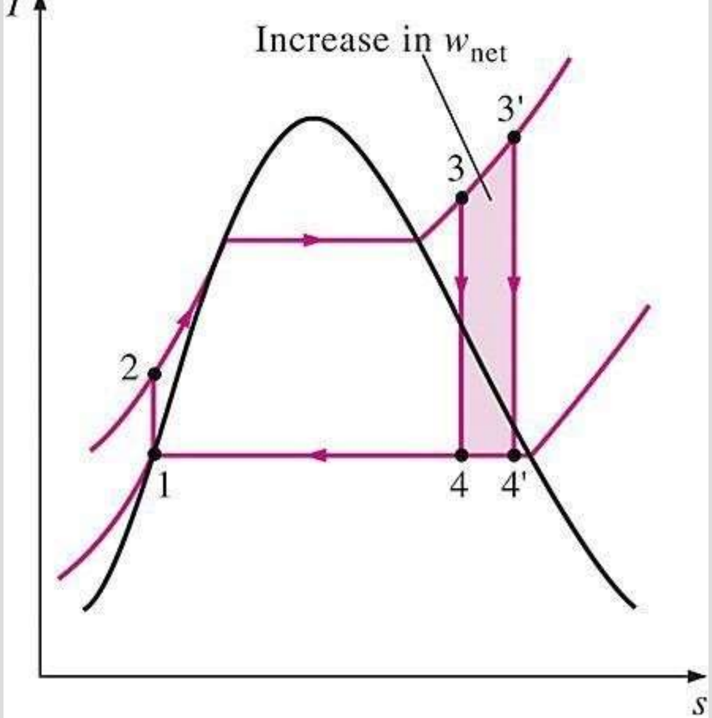
Lowering the Condenser Pressure (*Lowers* $T_{low,avg}$)



To take advantage of the increased efficiencies at low pressures, the condensers of steam power plants usually operate well below the atmospheric pressure. There is a lower limit to this pressure depending on the temperature of the cooling medium

Side effect: Lowering the condenser pressure increases the moisture content of the steam at the final stages of the turbine.

The effect of lowering the condenser pressure on the ideal Rankine cycle.



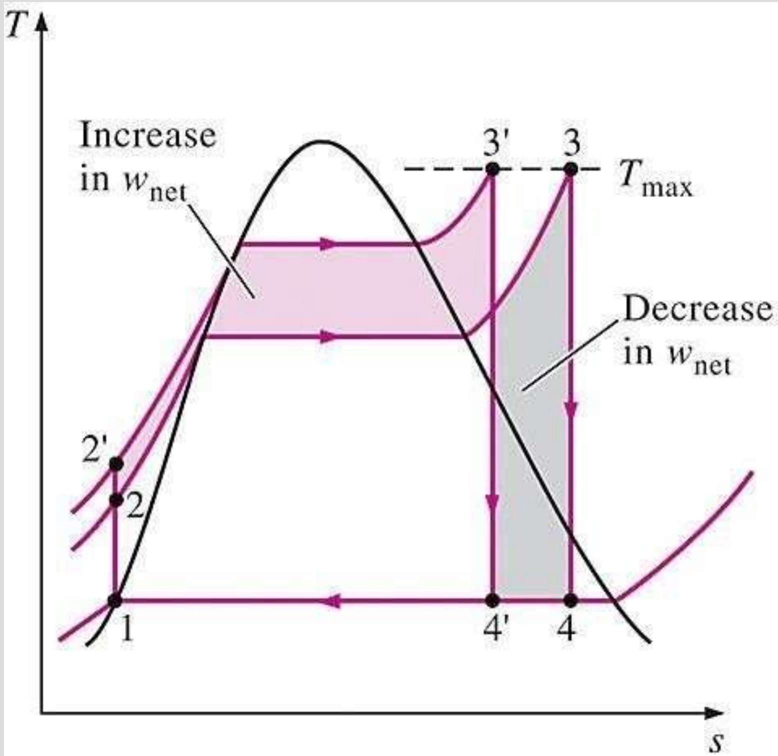
The effect of superheating the steam to higher temperatures on the ideal Rankine cycle.

increase as a result of superheating the steam to a higher temperature. The overall effect is an increase in thermal efficiency since the average temperature at which heat is added increases.

Superheating to higher temperatures decreases the moisture content of the steam at the turbine exit, which is desirable.

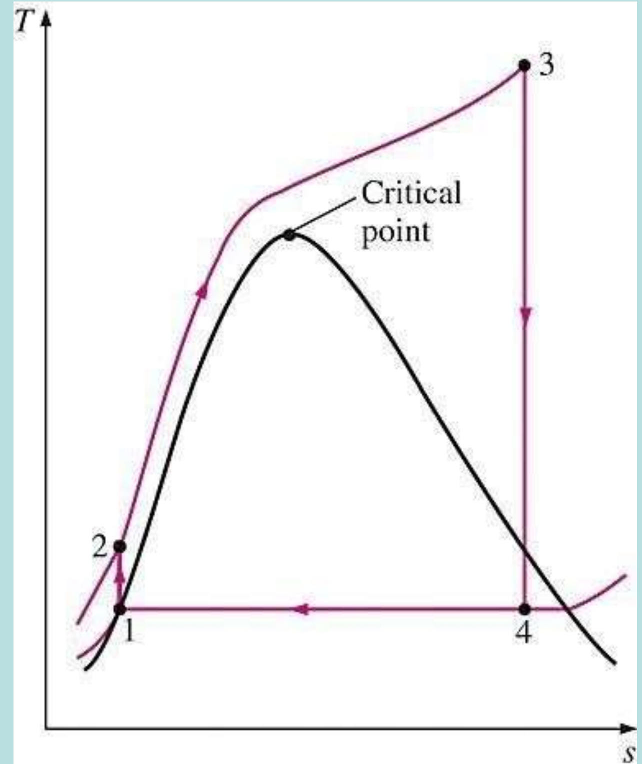
The temperature is limited by metallurgical considerations. Presently the highest steam temperature allowed at the turbine inlet is about 620°C.

turbine exit increases. This side effect can be corrected by reheating the steam.



The effect of increasing the boiler pressure on the ideal Rankine cycle.

have thermal efficiencies of about 40% for fossil-fuel plants and 34% for nuclear plants.



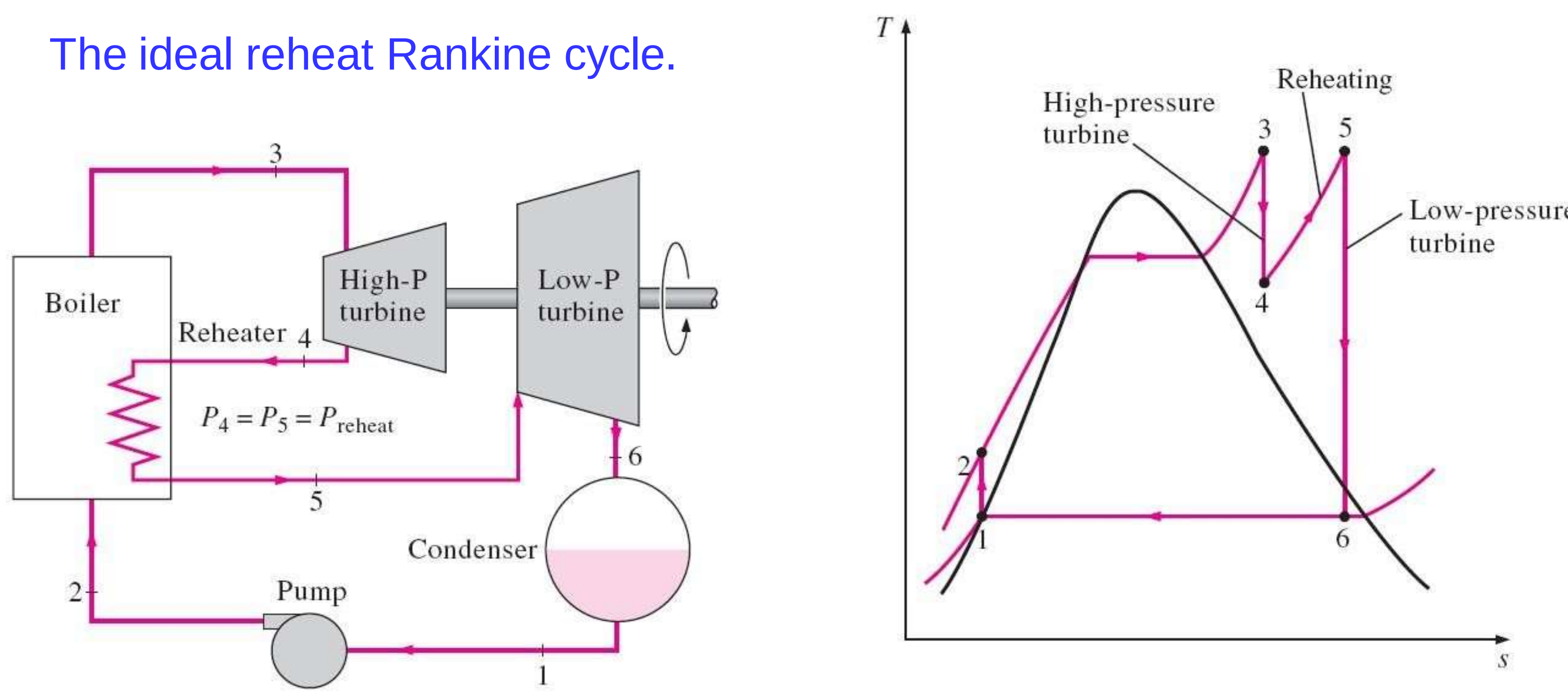
A supercritical Rankine cycle.

1. Superheat the steam to very high temperatures. It is limited metallurgically.

2. Expand the steam in the turbine in two stages, and reheat it in between (**reheat**)

$$q_{in} = q_{primary} + q_{reheat} = (h_3 - h_2) + (h_5 - h_4)$$

$$w_{turb,out} = w_{turb,I} + w_{turb,II} = (h_3 - h_4) + (h_5 - h_6)$$

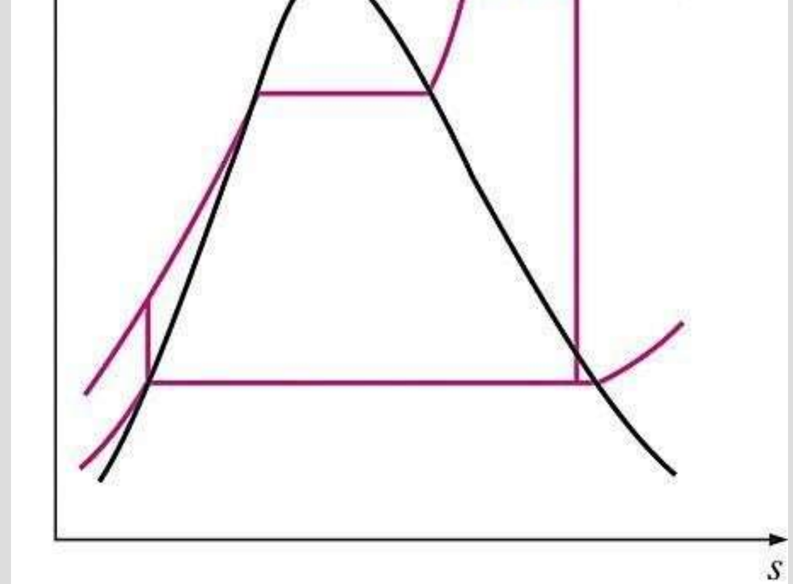


The ideal reheat Rankine cycle.

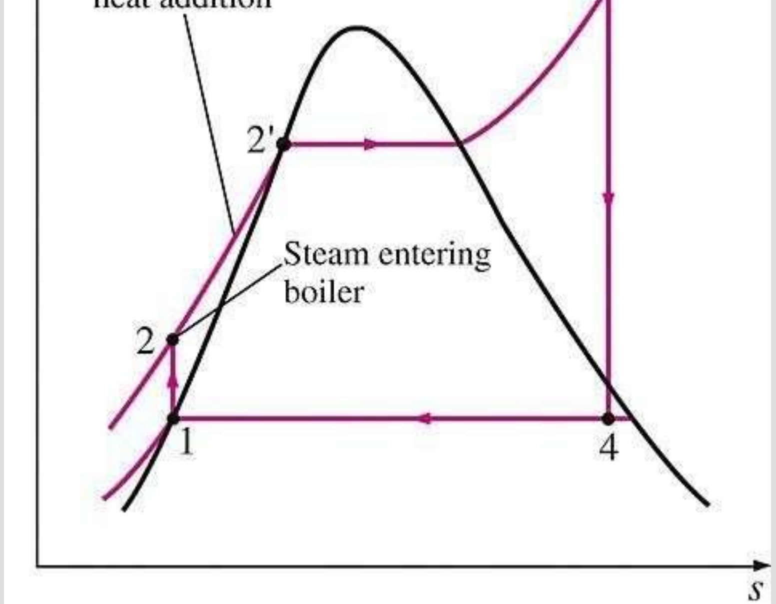
The average temperature during the reheat process can be increased by increasing the number of expansion and reheat stages. As the number of stages is increased, the expansion and reheat processes approach an isothermal process at the maximum temperature. The use of more than two reheat stages is not practical. The theoretical improvement in efficiency from the second reheat is about half of that which results from a single reheat.

The reheat temperatures are very close or equal to the turbine inlet temperature.

The optimum reheat pressure is about one-fourth of the maximum cycle pressure.



The average temperature at which heat is transferred during reheating increases as the number of reheat stages is increased.



The first part of the heat-addition process in the boiler takes place at relatively low temperatures.

temperature. This lowers the average heat-addition temperature and thus the cycle efficiency.

In steam power plants, steam is extracted from the turbine at various points. This steam, which could have produced more work by expanding further in the turbine, is used to heat the feedwater instead. The device where the feedwater is heated by regeneration is called a **regenerator**, or a **feedwater heater (FWH)**.

A feedwater heater is basically a heat exchanger where heat is transferred from the steam to the feedwater either by mixing the two fluid streams (open feedwater heaters) or without mixing them (closed feedwater heaters).

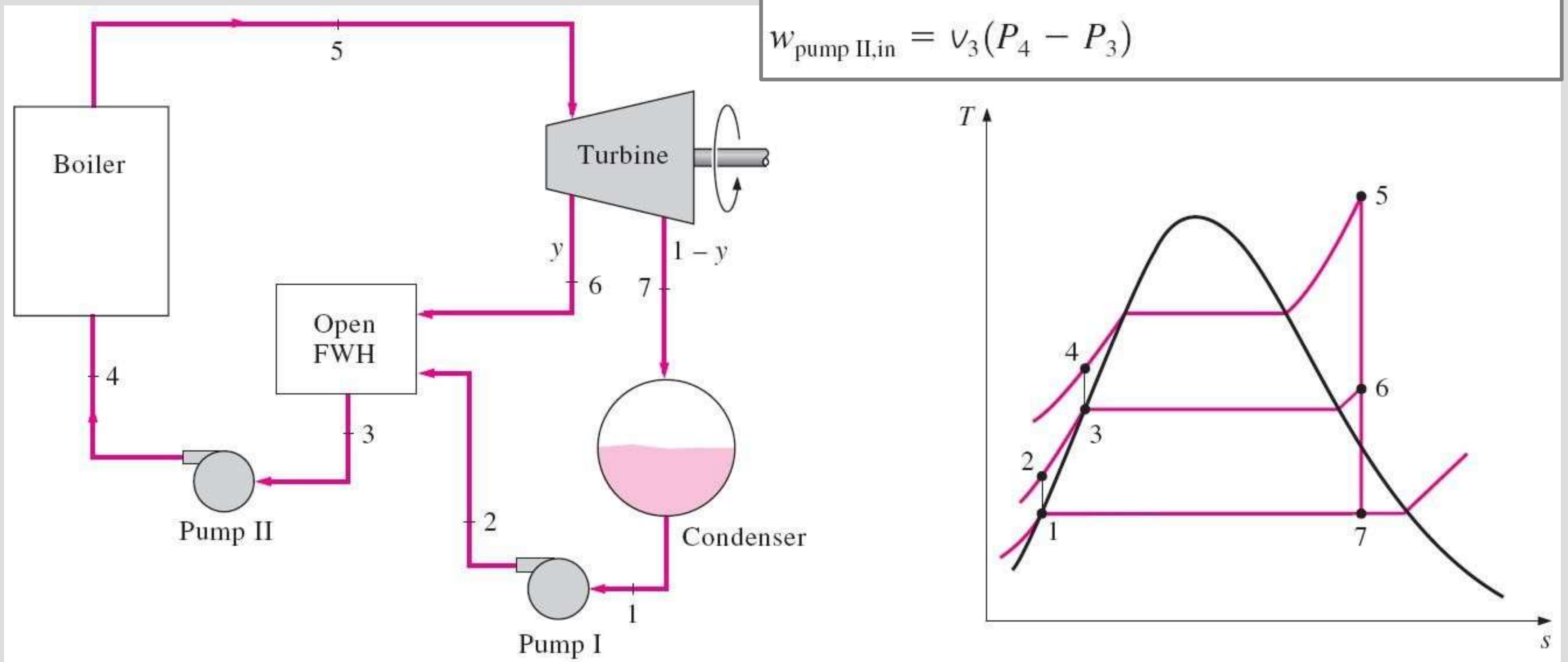
turbine mixes with the feedwater exiting the pump. Ideally, the mixture leaves the heater as a saturated liquid at the heater pressure.

$$w_{\text{pump,in}} = (1 - y)w_{\text{pump I,in}} + w_{\text{pump II,in}}$$

$$y = \dot{m}_6/\dot{m}_5 \qquad \text{(fraction of steam extracted)}$$

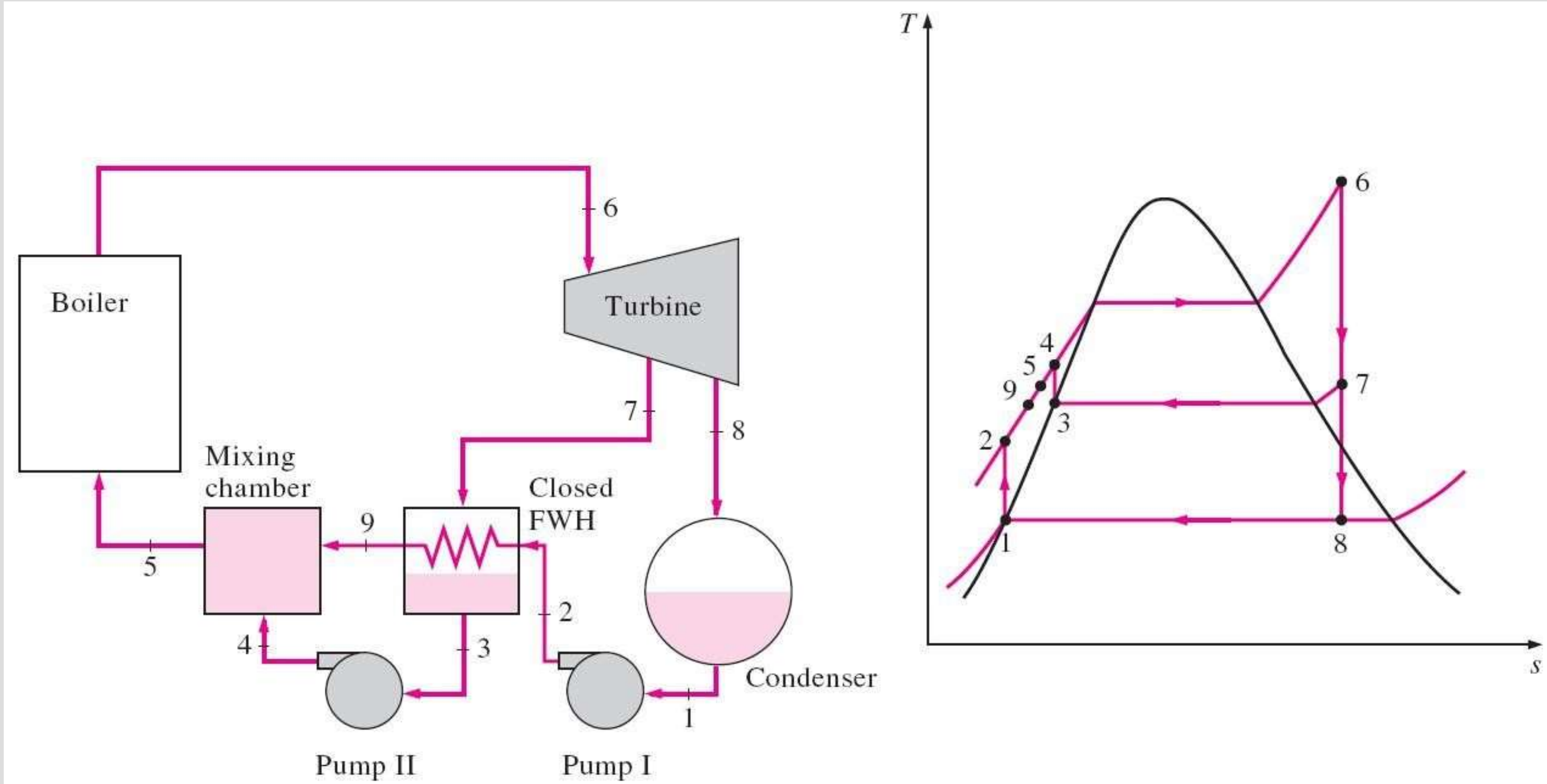
$$w_{\text{pump I,in}} = v_1(P_2 - P_1)$$

$$w_{\text{pump II,in}} = v_3(P_4 - P_3)$$

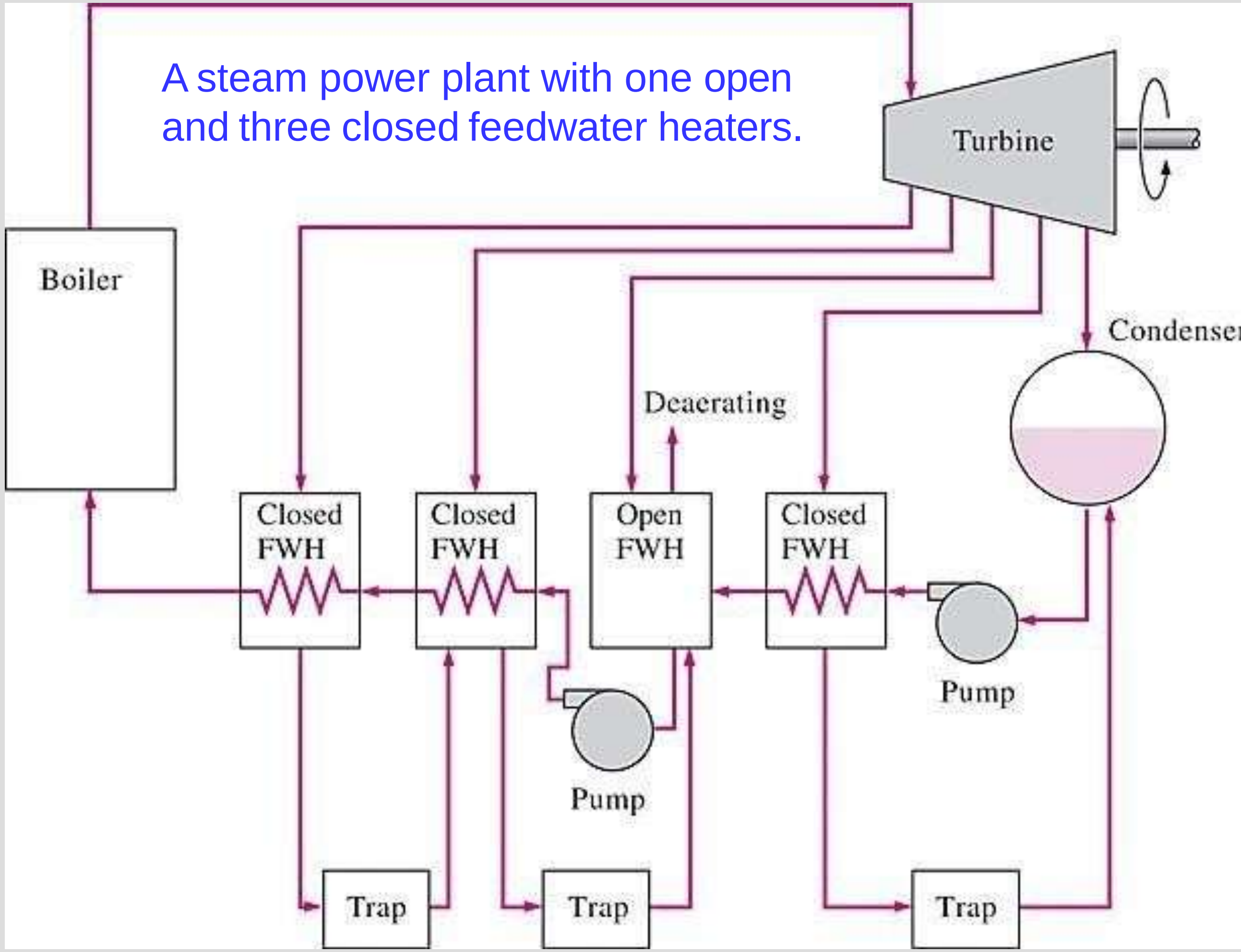


The ideal regenerative Rankine cycle with an open feedwater heater.

extracted steam to the feedwater without any mixing taking place. The two streams now can be at different pressures, since they do not mix.



The ideal regenerative Rankine cycle with a closed feedwater heater.



Open feedwater heaters are simple and inexpensive and have good heat transfer characteristics. For each heater, however, a pump is required to handle the feedwater.

Most steam power plants use a combination of open and closed feedwater heaters.

Week-8

Lecture

on

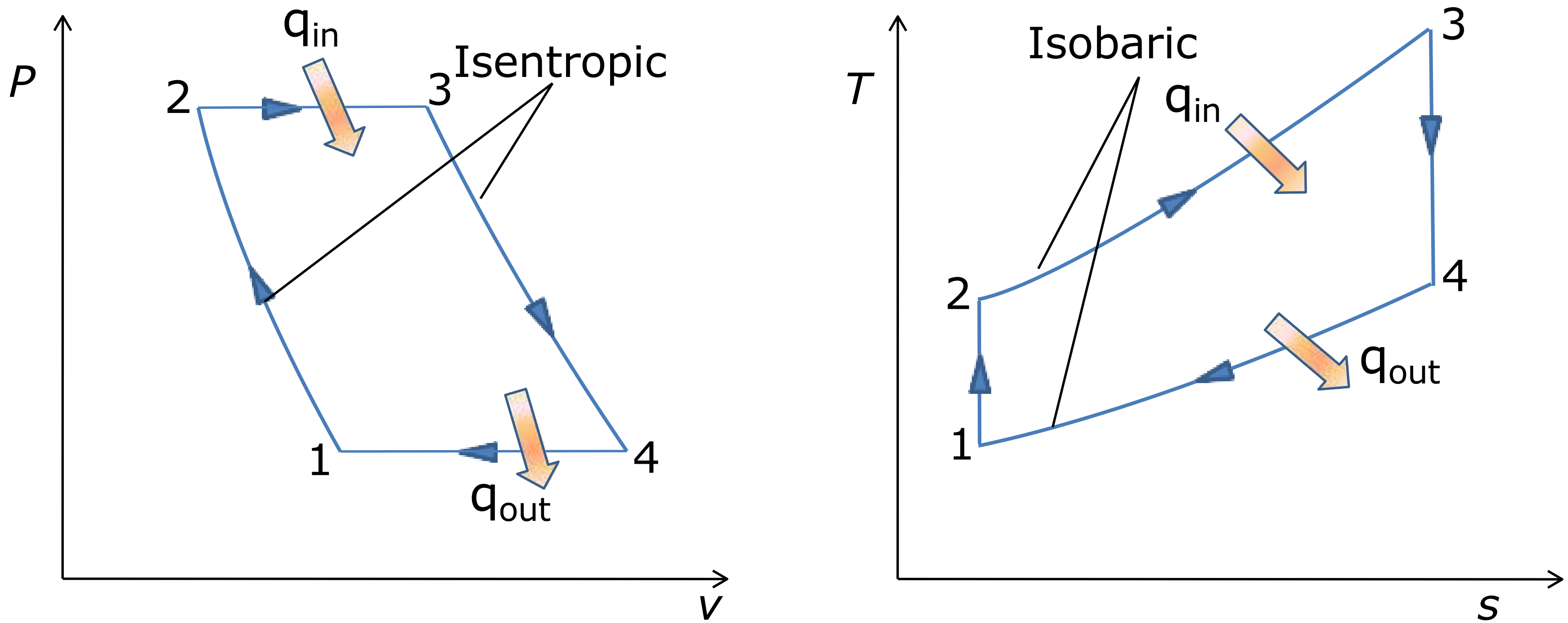
Bryton Cycle

(88-98)

- The Brayton cycle was proposed by George Brayton in 1870 for use in reciprocating engines.
- Modern day gas turbines operate on Brayton cycle and work with rotating machinery.
- Gas turbines operate in open-cycle mode, but can be modelled as closed cycle using air-standard assumptions.
- Combustion and exhaust replaced by constant pressure heat addition and rejection.

Ideal Brayton cycle

- The Brayton cycle consists of four internally reversible processes:
  - 1-2 Isentropic compression (in a compressor)
  - 2-3 Constant-pressure heat addition
  - 3-4 Isentropic expansion (in a turbine)
  - 4-1 Constant-pressure heat rejection



Brayton cycle on *P-v* and *T-s* diagrams

- The energy balance for a steady-flow process can be expressed as:

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = \Delta h$$

The heat transfer to and from the working fluid can be written as:

$$q_{in} = h_3 - h_2 = c_p (T_3 - T_2)$$
$$q_{out} = h_4 - h_1 = c_p (T_4 - T_1)$$

cycle under the cold air standard assumptions becomes:

$$\eta_{th,Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1(T_4 / T_1 - 1)}{T_2(T_3 / T_2 - 1)}$$

Processes 1-2 and 3-4 are isentropic and $P_2 = P_3$ and $P_4 = P_1$.

Therefore, $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(\gamma - 1)/\gamma} = \left(\frac{P_3}{P_4}\right)^{(\gamma - 1)/\gamma} = \frac{T_3}{T_4}$

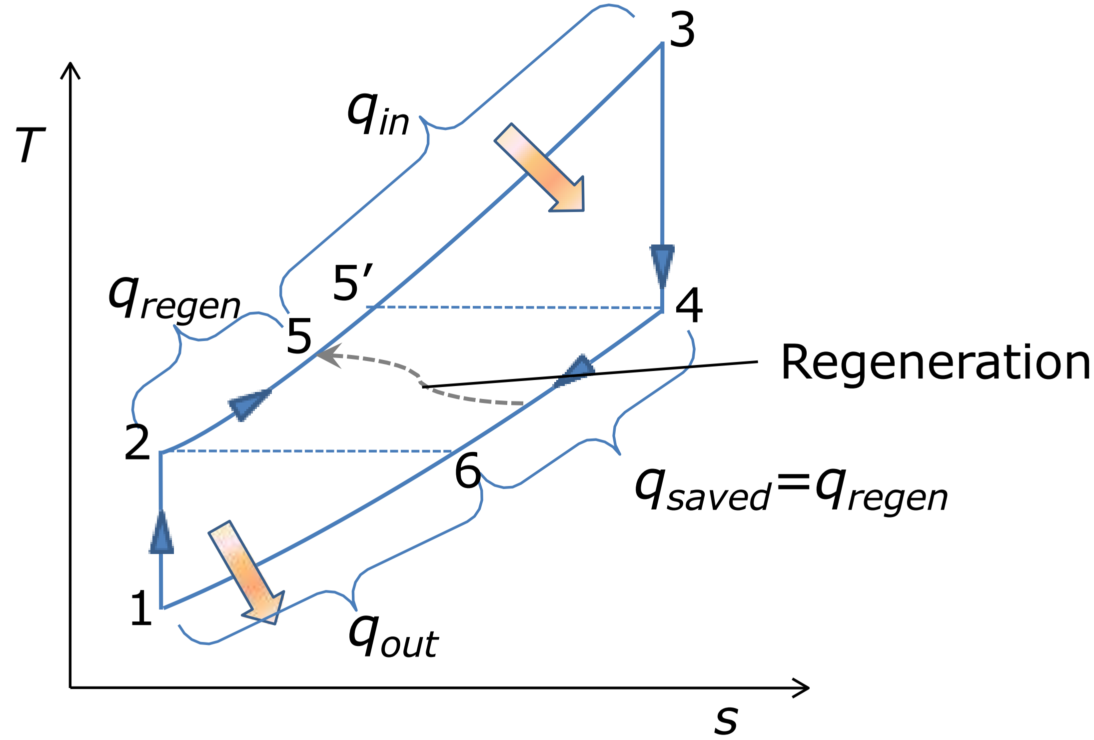
- Substituting these equations into the thermal efficiency relation and simplifying:

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{(\gamma - 1)/\gamma}}$$

$$\text{where, } r_p = \frac{P_2}{P_1} \text{ is the pressure ratio.}$$

- The thermal efficiency of a Brayton cycle is therefore a function of the cycle pressure ratio and the ratio of specific heats.

- Regeneration can be carried out by using the hot air exhausting from the turbine to heat up the compressor exit flow.
- The thermal efficiency of the Brayton cycle increases as a part of the heat rejected is re-used.
- Regeneration decreases the heat input (thus fuel) requirements for the same net work output.



T-s diagram of a Brayton cycle with regeneration

- The extent to which a regenerator approaches an ideal regenerator is called the effectiveness, ε and is defined as

  $\varepsilon = q_{regen,act} \,/\, q_{regen,max} = (h_5 - h_2)/(h_4 - h_2)$

- Under the cold-air-standard assumptions, the thermal efficiency of an ideal Brayton cycle with regeneration is:

$$\eta_{th,regen} = 1 - \left(\frac{T_1}{T_3}\right)(r_p)^{(\gamma - 1)/\gamma}$$

- The thermal efficiency depends upon the temperature as well as the pressure ratio.

- The net work of a gas-turbine cycle is the difference between the turbine work output and the compressor work input.
- It can be increased by either decreasing the compressor work or increasing the turbine work, or both.
- The work required to compress a gas between two specified pressures can be decreased by carrying out the compression process in stages and cooling the gas in between: multi-stage compression with intercooling.

- Similarly the work output of a turbine can be increased by: multi-stage expansion with reheating.
- As the number of stages of compression and expansion are increased, the process approaches an isothermal process.
- A combination of intercooling and reheating can increase the net work output of a Brayton cycle significantly.

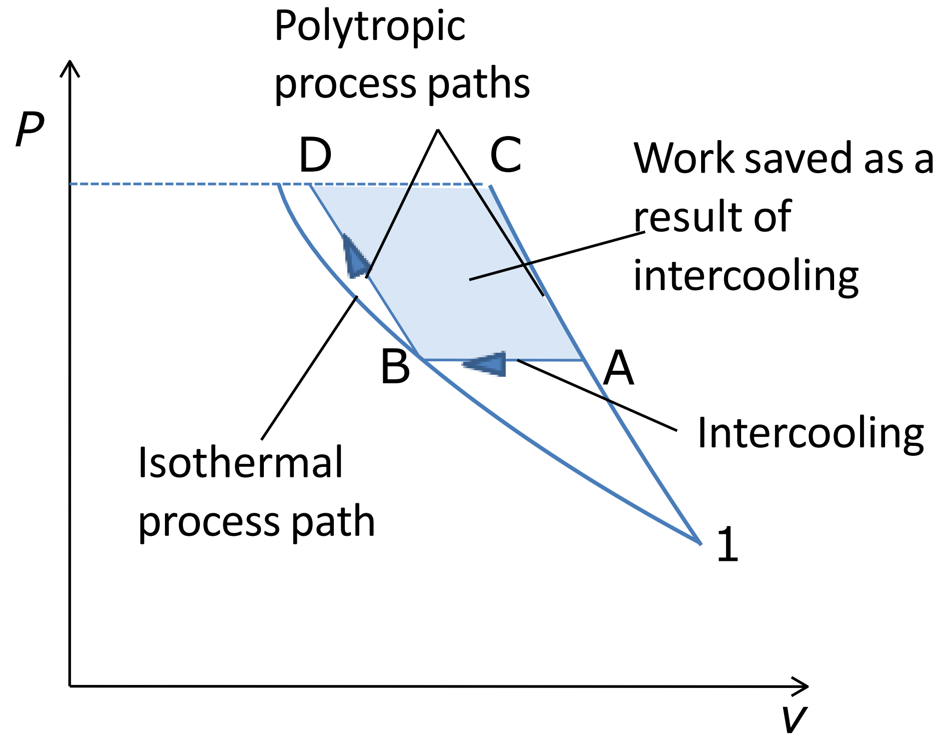
Week-9

Lecture

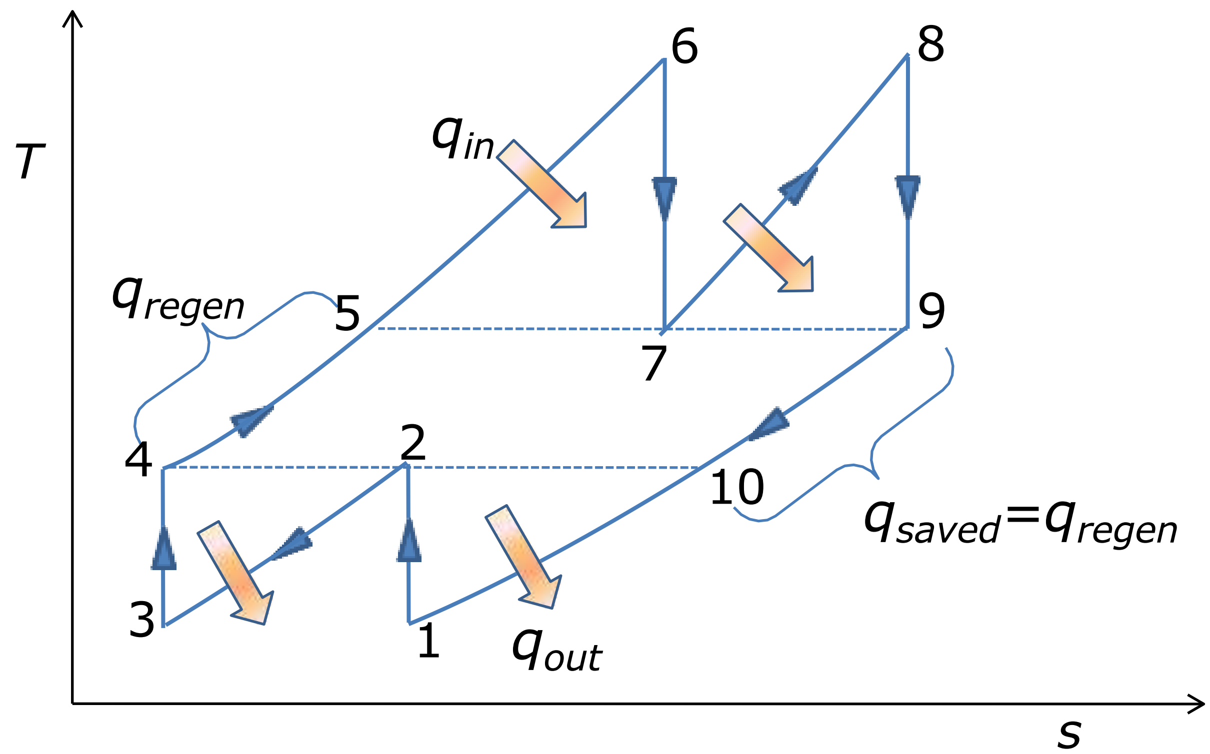
on

Bryton Cycle

(100-109)

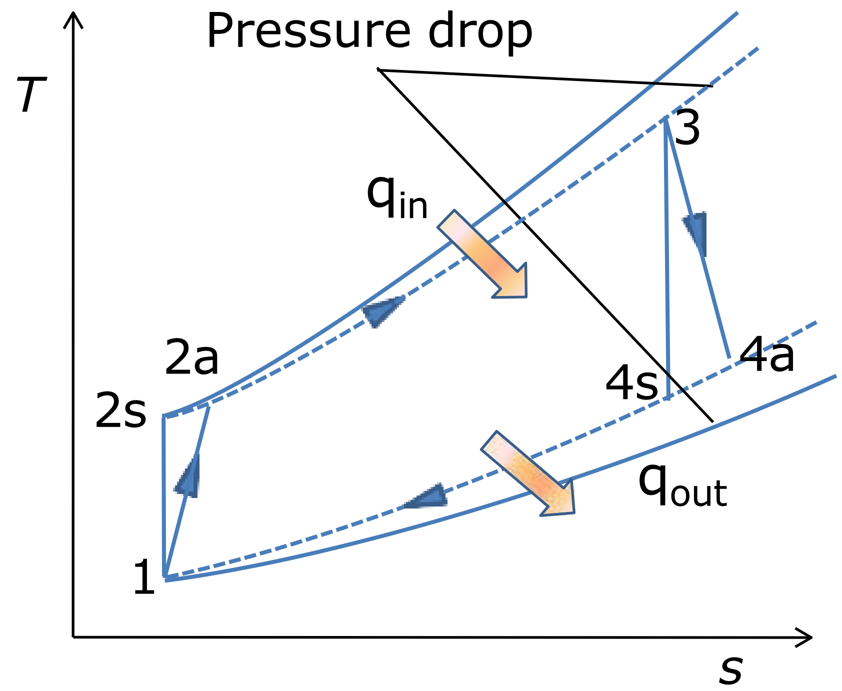


Work inputs to a single-stage compressor (process: 1*AC) and a* two-stage compressor with intercooling (process: 1*ABD).*



T-s diagram of an ideal gas-turbine cycle with intercooling, reheating, and regeneration

- Actual Brayton cycles differ from the ideal cycles in all the four processes.
- The compression process and expansion processes are non-isentropic.
- Pressure drop during heat addition and heat rejection.
- The presence of irreversibilities causes the above deviations.



Actual Brayton cycle *T*-*s* diagram

- The deviation of actual compressors and turbines from the isentropic versions can be accounted for by using the isentropic efficiencies.

$$\eta_C = \frac{\text{Isentropic work}}{\text{Actual work}} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{\text{Actual work}}{\text{Isentropic work}} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

- Where, *2a* and *4a* are the actual states at the compressor and turbine exit and *2s* and *4s* are the corresponding isentropic states.

- As a result of non-isentropic compression and expansion, the compressor needs more work than the ideal cycle and turbine generates less work.
- Isentropic efficiencies reflect the amount of deviation of the actual compression/expansion processes from the ideal.
- Total pressure losses in the heat addition/rejection processes also need to be considered.

- Other differences between ideal and actual Brayton cycles
  - Change of specific heats with temperature
  - Heat exchanger effectiveness (in case of regenerative cycles)
  - Mass flow rate of fuel
  - Combustion efficiency
- These parameters are often used in actual cycle analysis.

- Variants of the simple Brayton cycle
  - Reheating
  - Intercooling
  - Regeneration
- Actual cycles with the above will be different from the ideal cycles in terms of the irreversibilities present.
- Isentropic efficiencies, total pressure losses, heat exchanger effectiveness for each additional components of the cycle.

- Actual Brayton cycle with intercooling
  - Isentropic efficiencies of each stage of intercooling
  - Heat exchanger effectiveness of the intercooling duct
- Actual Brayton cycle with reheating
  - Isentropic efficiencies of each stage of reheating
  - Total pressure loss and combustion efficiency during reheating

- Actual Brayton cycle with regeneration
  - Heat exchanger effectiveness
- Actual Brayton cycle with all three of these modifications need to be analysed considering the above discussed irreversibilities.

Week-10

Lecture

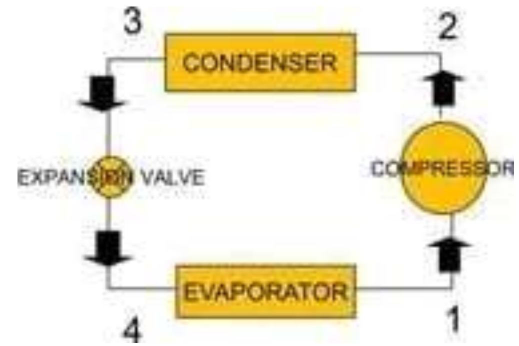
on

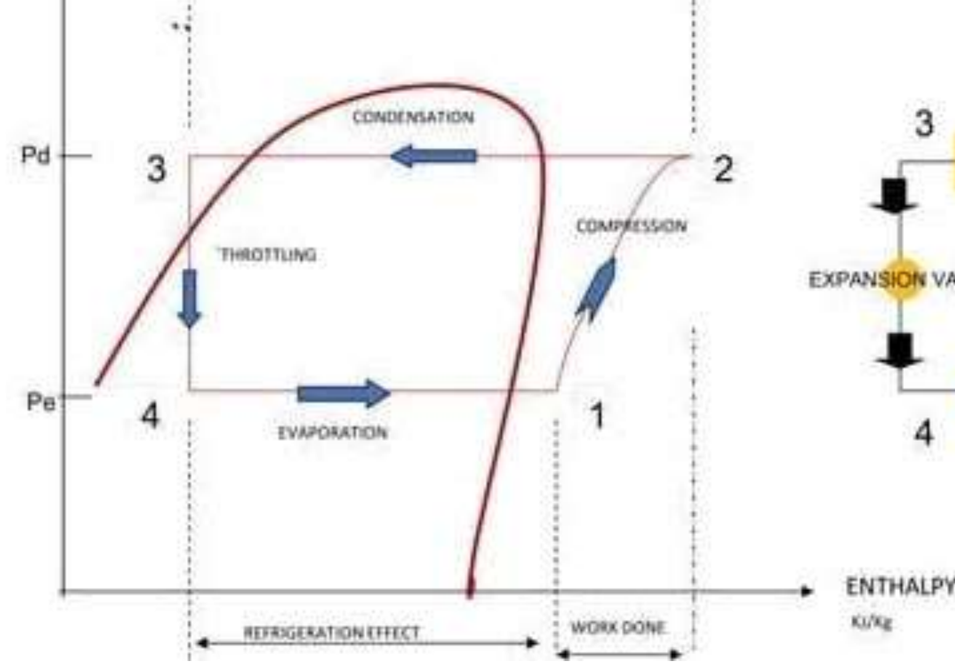
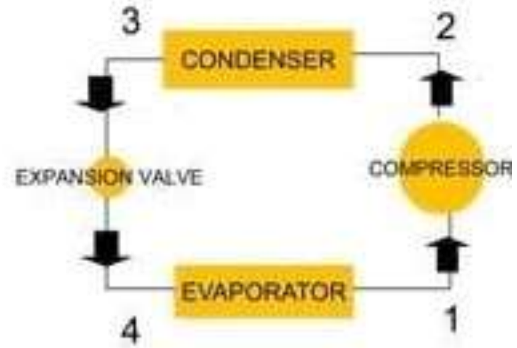
Vapor Compression Cycle

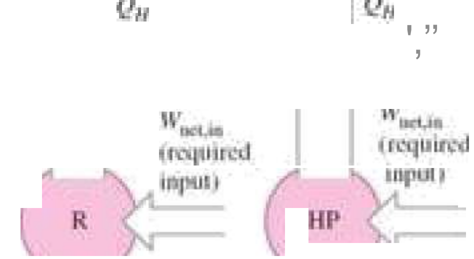
(111-128)

compression refrigeration system

- Compressor
- Condenser
- Thtottling Device
- Evaporador




Pd
Pe
3
2
4
1
CONDENSATION
COMPRESSION
THROTTLING
EVAPORATION
ENTHALPY
KJ/Kg
REFRIGERATION EFFECT
WORK DONE

3
2
CONDENSER
EXPANSION VALVE
COMPRESSOR
EVAPORATOR
4
1



regio 1 to a high-lenJperalure one requires special devices. called! refrigerators.

Rafrigeralors and heal pumps are essentially the came devices; lhey differ in lheir objectives only.

$$\frac{\text{Desired output}}{} \quad \frac{\text{Heating effect}}{} = \frac{Q_H}{}$$

$$\text{COP}_{HP} = \text{COP}_R + 1 \quad \text{for fixed values of } Q_L \text{ and } Q_H$$

The objective of a refrigerator is to remove hea\ fO,) from lie cold rne‹liurfi; lhe objective uf 9 heat pump is to supply heat (Q„) lo a warm medium.

Unit of Refrigeration

The unit of refrigeration is KW or TR

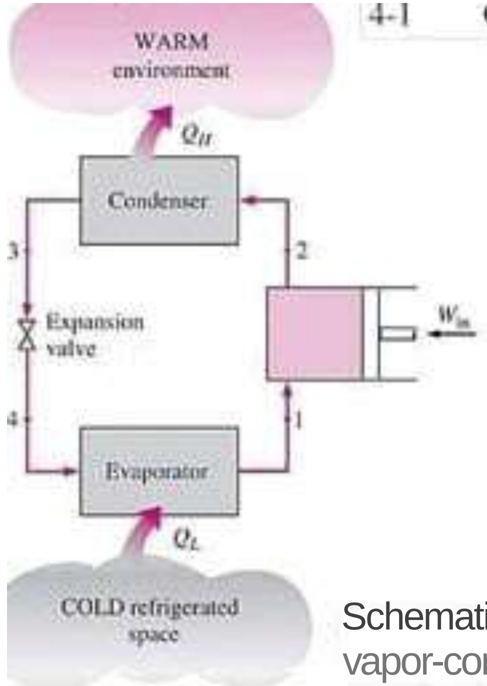
TON OF REFRIGERATION (TR)

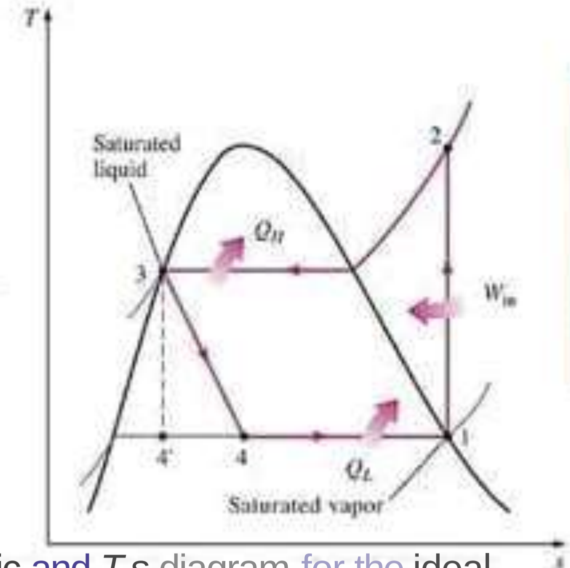
1 TR = 12'000 Btu/hr BRITISH UNITS

1 TR = 3.517 KW SI UNITS

2-3 Constant-pressure heat rejection in a condenser

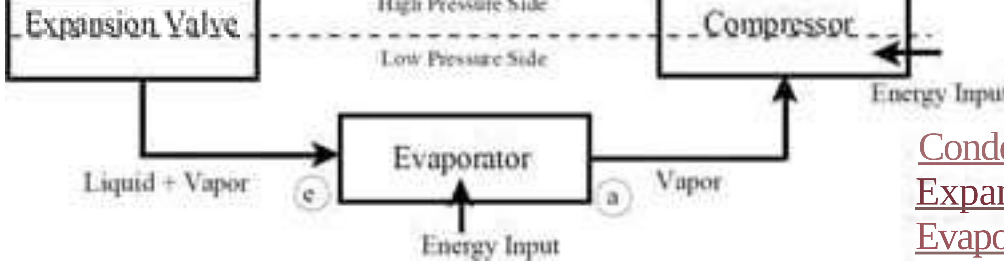
4-1 Constant-pressure heat absorption in an evaporator



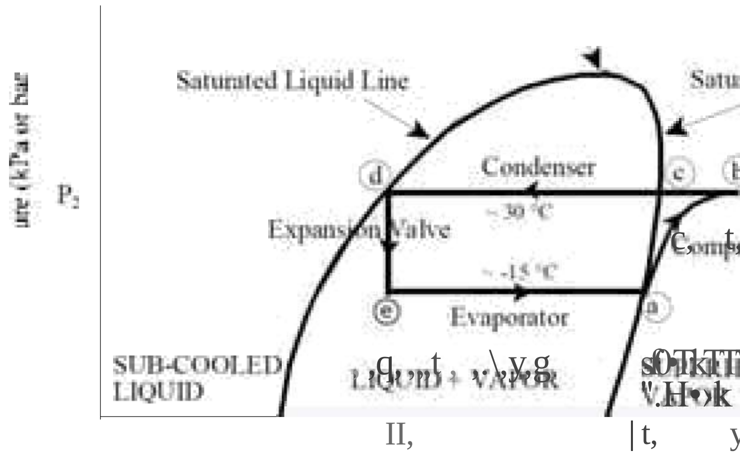


Schematic and *T-s* diagram for the ideal vapor-compression refrigeration cycle.

This is the most widely used cycle for refrigerators, A-C systems, and heat pumps.



Condensing: Constant Pr. (P)
Expansion: Constant Enthalpy (H$_1$)
Evaporation: Constant Pr. {P,)
Compression: Constant Entropy (S)



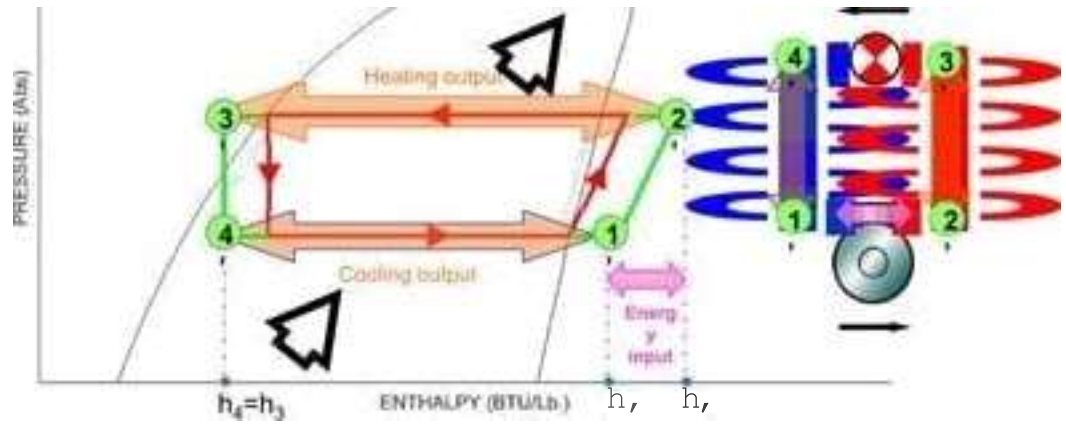
$n per I.in

€onslant Temperature fine
tett of dome: Vertical
Within dome: Horizontal
Rlght of dome: Curved down

IDEAL CONOfYIOK

RelYigerant is IeoK vapor at end of evap. AN0
Refrigerant Ts 10a liquid at and of coWansar

Coolingg output $(h_1 - h_4)$



$h_4 = h_3$ $h_,$ $h_,$

- Extract heat llam ine producPair and use it as the latent heat of vaporisation ofthe mfĩigeræit

COITÏpI9SSO£

- Raise temperature of refrigerant to well abDve that DCsurroundings to facilitate transfer of energy to surroundings in condenser

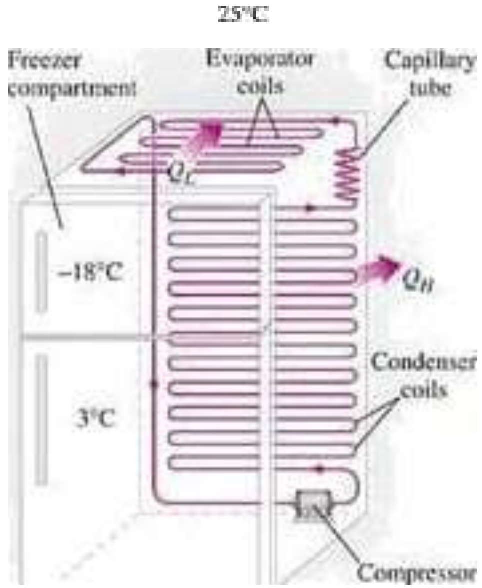
Condenser

- Transfer energy from the refrigerant to the surroundings (air/water)
- Sligbt\y sub-cool tbe refrigerant to minimire amount of vapor genereted as it passes through the expansion valve

Expansion valve

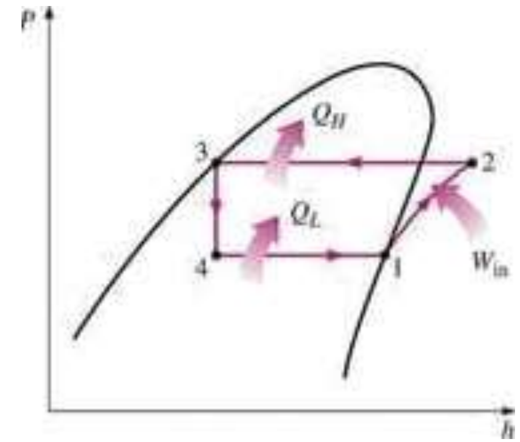
- SerVe BS meteri Rg deYiCe fOr fiOW Of Fefrigerant
- Expand the liquid refrigerant from the compressor pressiire io the evaporator pressure (with minimal conversion to vapor)

energy balance $h_2 - h_1$



An ordinary household refrigerator.

$h_1 = h_{g\,@\,P_1}$ and $h_3 = h_{f\,@\,P_3}$ for the ideal case



The *P-h* diagram of an ideal vapor-compression refrigeration cycle1,

Refrigeration Cycle Efficiency

The refrigeration cycle efficiency is known as

COEFFICIENT OF PERFORMANCE (COPREfit

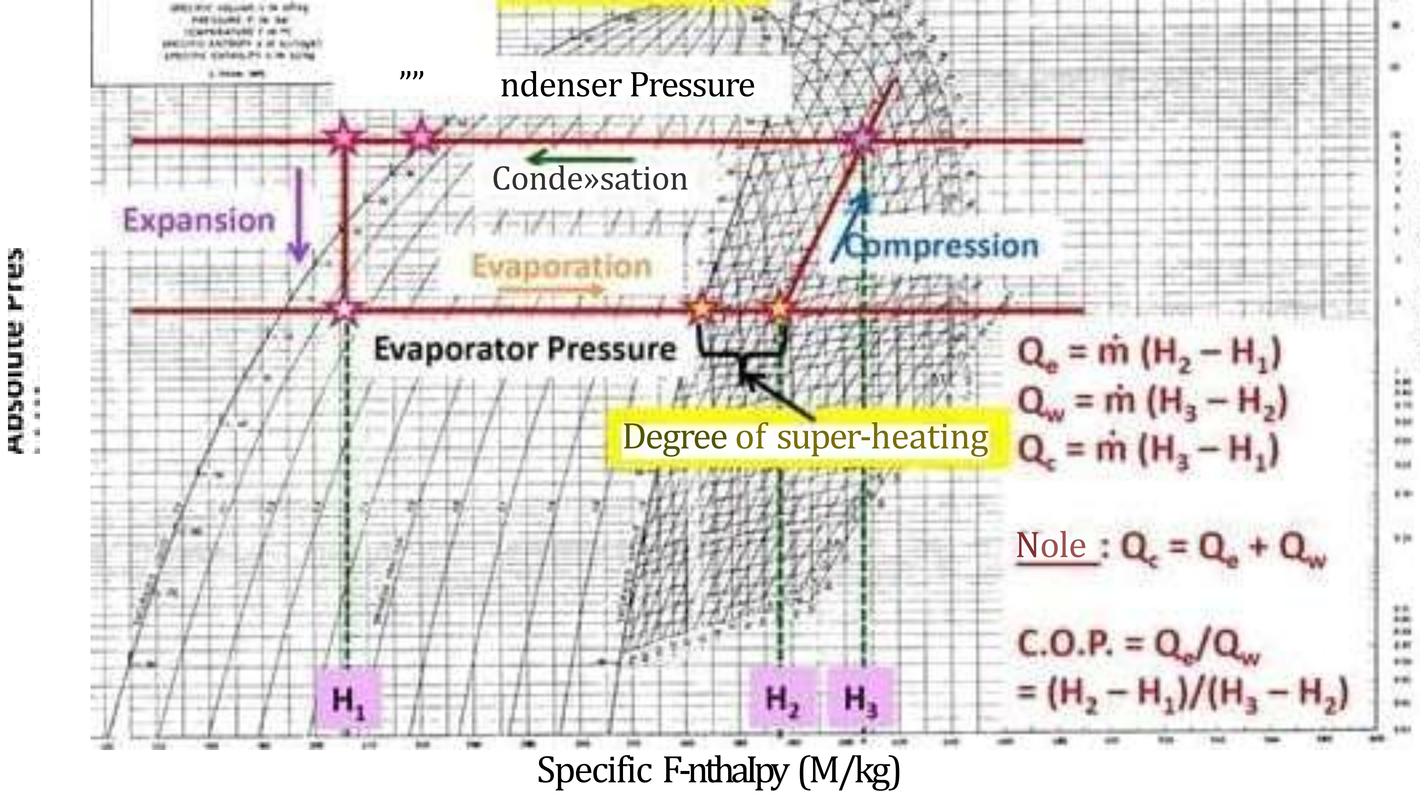
(COPES) = Refrigeration Effect »‹,

Work Done u »

(COPY›) = Condenser Heat Rejection «,

Work Done »

Specific EnthaTpy {M/kg}



”” ndenser Pressure
Condensation
Expansion
Evaporation
Compression
Evaporator Pressure
Degree of super-heating
$Q_e = \dot{m}\,(H_2 - H_1)$
$Q_w = \dot{m}\,(H_3 - H_2)$
$Q_c = \dot{m}\,(H_3 - H_1)$
Nole : $Q_c = Q_e + Q_w$
C.O.P. $= Q_e/Q_w$
$= (H_2 - H_1)/(H_3 - H_2)$
H_1
H_2
H_3
Absolute Pres
Specific F-nthalpy (M/kg)

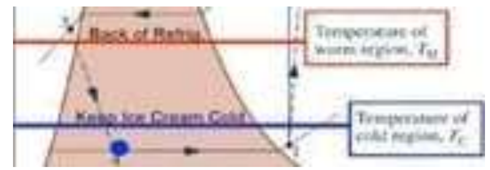
Features of
Actual Vapor-Com pression Cycle

- Heat transfers between refrigerant and cold and warm regions are not re versi ble.

n- Refrigerant temperature in evaporator is less than *T*,

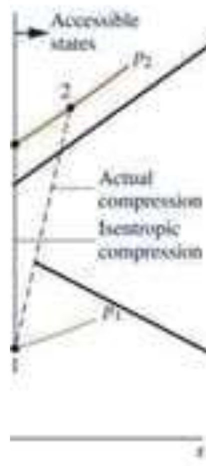
,•

>- Refrigerant temperature in condenser is greater



>- Irreversible heat lransfers have negative effect on performance.

y The isentropic compressor efficiency is the ratio of the minimum theoretical work input to the actual *work* input. each per unit of mass flowing



›xork requ red i an isentropic compress on from compressor inlet state la Ede exit pre ssure

$$\eta_c = \frac{(-\dot{W}_{cv}/\dot{m})_s}{(-\dot{W}_{cv}/\dot{m})} = \frac{h_{2s} - h_1}{h_2 - h_1} \quad \textbf{(Eq.}$$

\vork requlred in an actual compression from compressor inlet state \o exit pressure

Example: The table provides steady-state operating data for a vapor-compression refrigeration cycle using R-134x as the working fluid. For a refrigerant mass flow rate of 0.08 kg/s, determine the

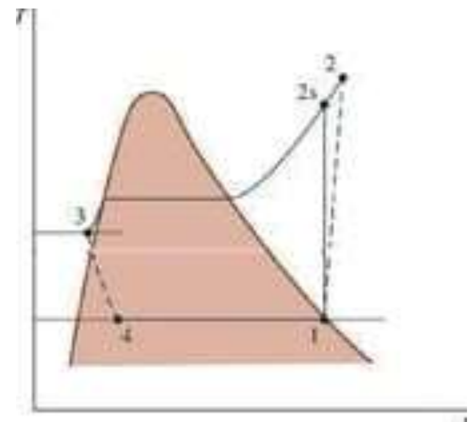
(a) compressor power, in LW,

(b) refrigeration capacity, in tons,

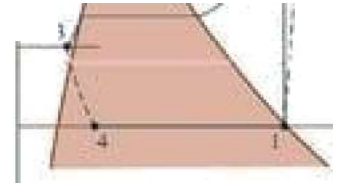
(c) coefficient of performance,

(d) isentropic compressor efficiency.

State	1	2s	2	3	4
h (kJ/kg)	241.35	272.39	280.15	91.49	91.49



(a) The **compressor power** is



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

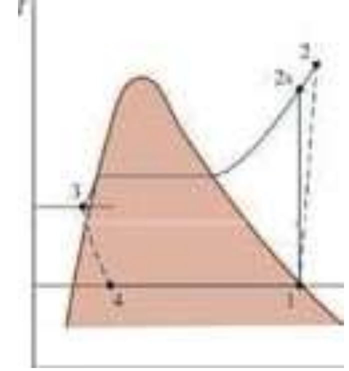
$$\dot{W}_c = 0.›\frac{g\,kg}{s}(280.15 - 241.35)\frac{kJ}{kg}\left(\frac{1\,kW}{\backslash kJ/s}\right) = 3.\,I\ kW$$

(b) The refrigeration capacity is

$$\dot{Q}_{in} = \dot{m}(h_1 - h_4)$$

$$\dot{Q}_{in} = \left(0.08\frac{'}{s}\right)(2J1.35 - 91.49) - \left|\frac{1\,ton}{211\,kJ/min}\right|\left|\frac{60\,s}{min}\right| = \mathbf{3.41\ tons}$$

h (kJ/kg)	241.35	272.39	280.15	91.49	91.49

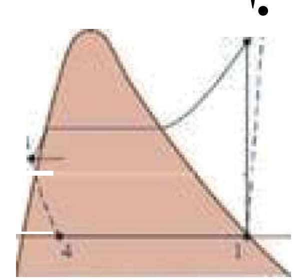


(c) The coefficient of performance is

$$\beta = \frac{(h_1 - h_4)}{(h_2 - h_1)}$$

$$\beta = \frac{(241.33 - 91.49)\,\text{kJ/kg}}{(280.15 - 241.35)\,\text{kJ/kg}} \quad 3.86$$

State	T	2	•	J	4
ikJ/kçj	:J I.31	:7z.3'›	*xi,i.i	ui.*'›	'›i.J'›



(d) The isentropic compressor efficiency is

$$\eta_c = \frac{(\dot{W}_c / \dot{m})_s}{\dot{W}_c / \dot{m}} = \frac{(h_{2s} - h_1)}{(h_2 - h_1)}$$

$$\eta_c = \frac{(272.39 - 241.35)\,\text{kJ/kg}}{(280.15 - 241.35)\,\text{kJ/kg}}$$

Week-11

Lecture

on

Boiler

(130-140)

reaction turbine and boiler.

Boiler, also called steam generator is the engineering device which generates steam at constant pressure. It is a closed vessel, generally made of steel in which vaporization of water takes place. Heat required for vaporization may be provided by the combustion of fuel in furnace, electricity, nuclear reactor, hot exhaust gases, solar radiations etc.

Earlier boilers were closed vessels made from sheets of wrought iron which were lapped, riveted and formed into shapes of simple sphere type or complex sections such as the one shown in Fig. 1.1. It is the 'Wagon boiler' o

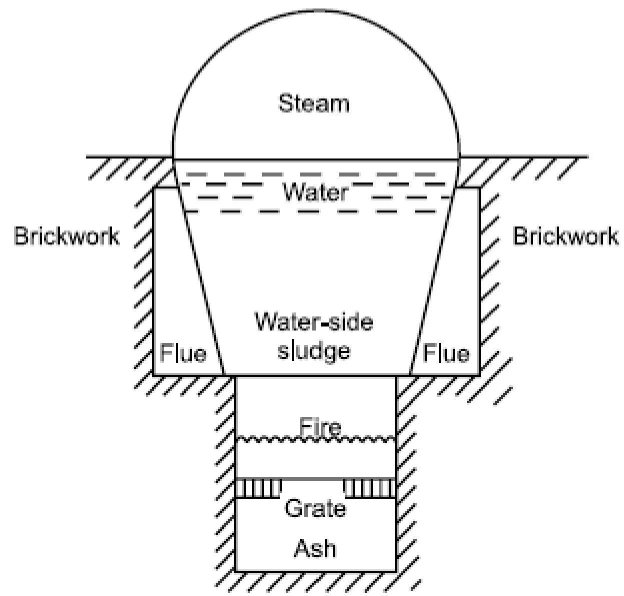


Fig. 1.1 *Wagon boiler of Watt,* (1788)

According to A.S.M.E. (American Society of Mechanical Engineers, U.S.A.) code a boiler is defined as a combination of apparatus for producing, furnishing or recovering heat together with the apparatus for transferring the heat so made available to water which could be heated and vaporized to steam form.

Types of Boilers

Boilers are of many types. Depending upon their features they can be classified as given under:

(a) Based upon the orientation/axis of the shell: According to the axis of shell boiler can be classified as vertical boiler and horizontal boiler.

(i) *Vertical boiler* has its shell vertical.

(ii) *Horizontal boiler* has its shell horizontal.

(iii) *Inclined boiler* has its shell inclined.

(b) Based upon utility of boiler: Boilers can be classified as

(i) *Stationery boiler*, such boilers are stationery and are extensively used in power plants, industrial processes, heating etc.

(ii) *Portable boiler*, such boilers are portable and are of small size. These can be of the following types,

Locomotive boiler, which are exclusively used in locomotives.

Marine boiler, which are used for marine applications.

(c) Based on type of firing employed: According to the nature of heat addition process boilers can be classified as,

(i) Externally fired boilers, in which heat addition is done externally i.e. furnace is outside the boiler unit. Such as Lancashire boiler, Locomotive boiler etc.

(ii) Internally fired boilers, in which heat addition is done internally i.e. furnace is within the boiler unit. Such as Cochran boiler, Bobcock Wilcox boiler etc.

(d) Based upon the tube content: Based on the fluid inside the tubes, boilers can be,

(i) *Fire tube boilers*, such boilers have the hot gases inside the tube and water is outside surrounding them. Examples for these boilers are, Cornish boiler, Cochran boiler, Lancashire boiler, Locomotive boiler etc.

(ii) *Water tube boilers*, such boilers have water flowing inside the tubes and hot gases surround them. Examples for such boilers are Babcock Wilcox

(iii) *Gas fired boilers*, such as natural gas fired boilers etc.

(f) Based on circulation: According to the flow of water and steam within the boiler circuit the boilers may be of following types,

(i) *Natural circulation boilers*, in which the circulation of water/steam is caused by the density difference which is due to the temperature variation.

(ii) *Forced circulation boilers*, in which the circulation of water/steam is caused by a pump i.e. externally, assisted circulation.

(g) Based on extent of firing: According to the extent of firing the boilers may be,

(i) *Fired boilers*, in which heat is provided by fuel firing.

(iii) *Unfired boilers*, in which heat is provided by some other source except fuel firing such as hot flue gases etc.

(iv) *Supplementary fired boilers*, in which a portion of heat is provided by fuel firing and remaining by some other source.

Fire and Water tube Boilers

Fire tube boilers are those boilers in which hot gases (combustion products) flow inside the tubes and water surrounds them. Water extracts heat for its phase transformation from the hot gases flowing inside the tubes, thus heat is indirectly transferred from hot gas to water through a metal interface.

Such boilers came up in eighteenth century and were extensively used for steam

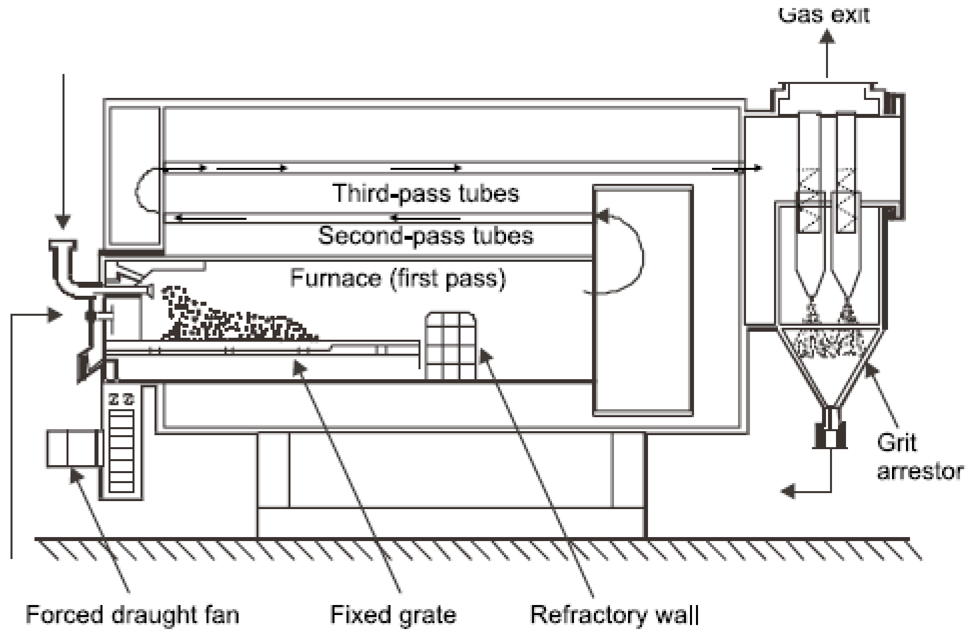


Fig. 1.2 *Fire tube boiler*

Water tube boilers are those boilers in which water flows inside the tubes and hot gases surround them. This type of boilers came up as a solution to the problem of explosion faced in fire tube boilers when the pressure and steam generation capacity were increased. In such boilers the shell behaved as heated pressure vessel subjected to internal pressure which set up tensile stresses (hoop stress) in walls.

Mathematically, this stress can be given as,

Hoop stress = P**D/ (2t)*

Where *P* is internal working pressure, *D* is diameter of shell and *t* is thickness of shell wall.

Above expression shows that if ‘*P*’ (pressure) increases then either ‘*D*’ (diameter) should be decreased or‘t’ (thickness) be increased to keep stress within acceptable limits. While increasing thickness the mass of boiler and cost of manufacturing both increase therefore the reduction of ‘*D*’ (diameter) is an attractive option. This became the basis for water tube

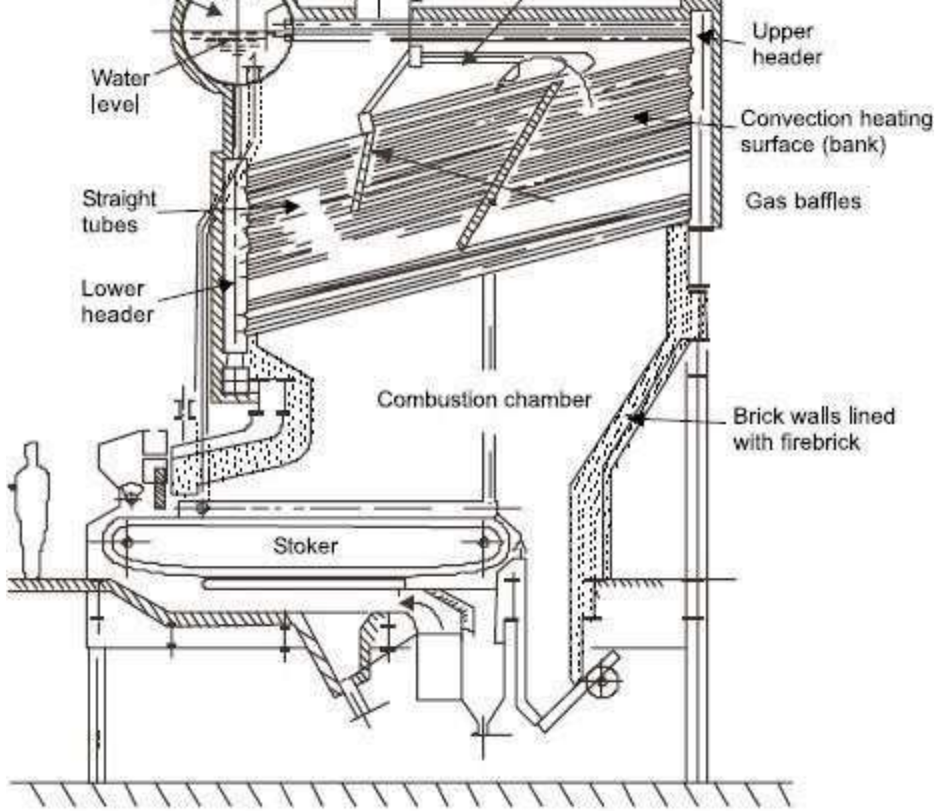


Fig. 1.3 *Water tube boiler*

Water tube boilers may be further classified based on type of tubes employed. These can be *Straight water tube boilers* and *Bent water tube* boilers. Straight water tube boilers are those in which tubes carrying water are straight from one end to the other end. At the two ends headers are provided.

In general water comes down from drum into down header and after passing through tubes get heated and evaporated to steam which is carried back to drum through up-comer header or riser. Circulation of water is caused by the density difference as density of feed water is more than density of hot water/wet/dry steam due to lower temperature of feed water.

Bent water tube boilers are those in which bent tubes are employed for carrying water. Bent water tubes are advantageous over straight water tubes in many respects. Bent tubes offer later it is horizontal. Stirling boiler is one such boiler. In water tube boilers the heat distribution generally occurs amongst economizer tubes, evaporator tubes, super heater tubes. Hottest gases are designed to come in contact with super heater tubes. The evaporator tubes are in between super heater and economizer tubes.

Simple Vertical Boiler

Simple vertical boiler shown in Fig. 1.4 has a vertical boiler shell of cylindrical shape. It has fire box of cylindrical type inside the shell. Vertical passage of tubular type called uptake is provided over fire box for exhaust of flue gases. Cross tubes are provided for improving water circulation and increasing heating surface. At the bottom of fire box a fire grate is provided for burning fuel. Total heating surface area is about 7–10 times grate area. Man hole and hand holes are provided in the shell for access to inside of shell. Hot gases raising from fire grate go upwardly and heat the water contained in shell and tubes.

Steam generated in shell can be tapped through a steam stop valve placed on the crown of shell. Such boilers have steam generation capacity up to 1000 kg per hour and maximum steam pressure up to 10 bar. Size of the boiler ranges from 0.6 m diameter to 2 m diameter and height from 1.2 m to 4 m high. Boiler efficiency is nearly 50%.

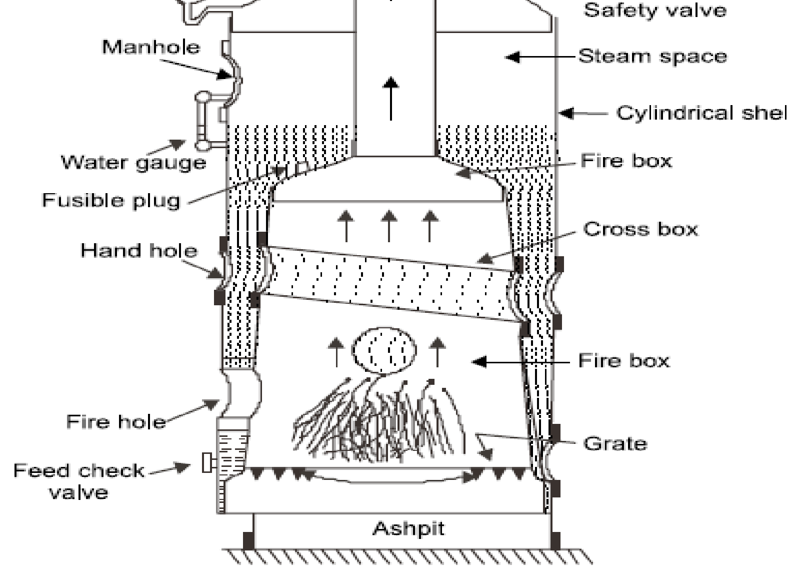


Fig. 1.4 *Simple vertical boiler*

times the grate area. It has cylindrical shell with hemispherical crown. Hemispherical geometry offers maximum volume space for given mass of material and is also very good for strength and maximization of radiant heat absorption. Figure. 1.5 shows the schematic of Cochran boiler with various mountings upon it. Fire box is also of hemispherical form. Flue gases flow from fire box to refractory material lined combustion chamber through a flue pipe. Incomplete combustion if any can get completed in combustion chamber and hot gases subsequently enter into tubes. After coming out of fire tubes hot gases enter into smoke box having chimney upon it. As the fire box is separately located so any type of fuel such as wood, paddy husk, oil fuel etc. can be easily burnt. These boilers are capable of generating steam up to pressure of 20 bar and steam generating capacity from 20 kg/hr to 3000 kg/hr. Boilers have dimensions ranging from 1m diameter and 2 m height to 3 m diameter and 6 m height. Efficiency of such boilers ranges between 70 and 75%.

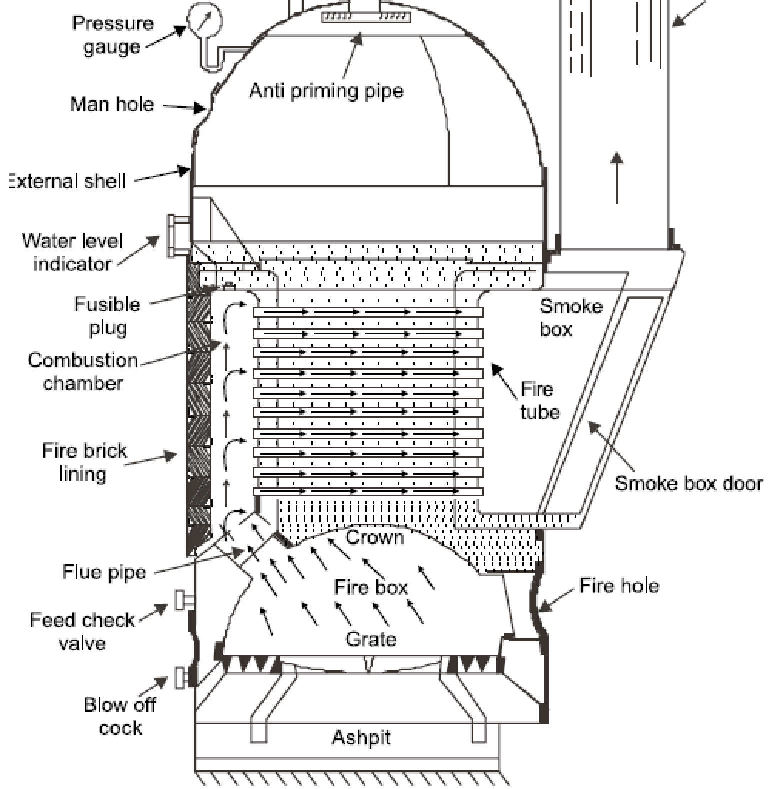
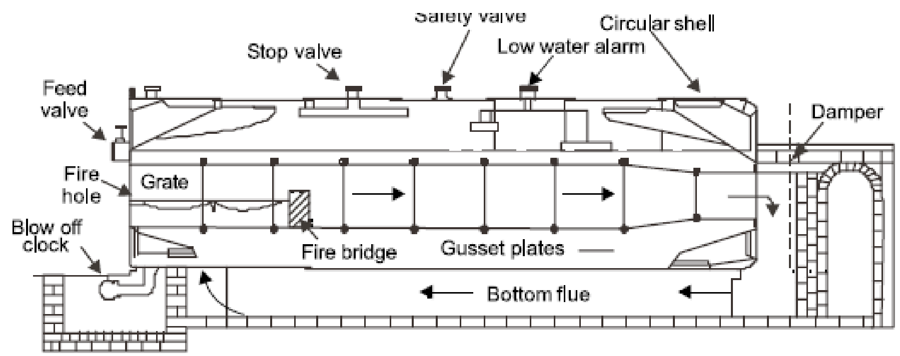


Fig. 1.5 *Cochran boiler*

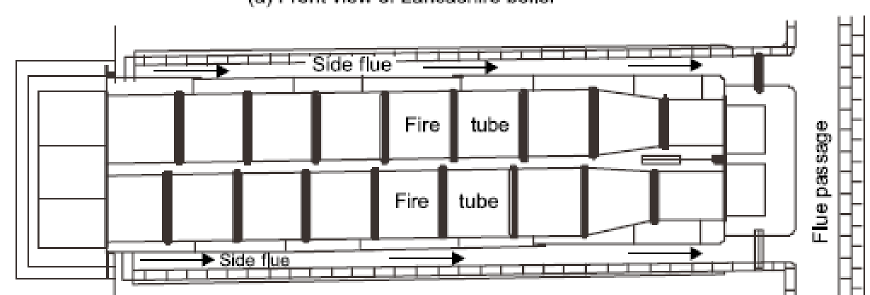
Boiler is mounted on brickwork *setting* with front end of shell sloping about 1: 250 for emptying the shell. It has a circular shell connected *to end plates* supported by gusset plates. Two *fire tubes* run throughout the length of the boiler. Fire tubes are of diameter less than half the diameter of shell and diameter of fire tubes is reduced as shown to have access to lower side of boiler.

Fire Bridge is provided to prevent fuel from falling over the end of furnace. Fire bridge also helps in producing a better mixture of air and gases for perfect combustion by partly enveloping the combustion space. Hot gases start from grate area, enter into fire tubes and come out at back of boiler from where these gases flow towards the front of boiler through *bottom flue*. Upon reaching the front these hot gases flow through the *side flues* and enter the *main outlet*. Outlet passage may also be used commonly by more than one boilers. About 85% of actual heat transferred is transferred through surface of fire tubes while 15% is transferred through bottom and side flues.

Plan, elevation and side views of Lancashire boiler shown in figure explain the furnace,



(a) Front view of Lancashire boiler



(b) Top view of Lancashire boiler

different firetubes, bottom flues, side flues etc. Dampers are provided at the end of side flues for regulating the pressure difference (draught) for exit of burnt gases. Other

gases after passing through the tube are divided into two portions at the end of boiler and pass through side flue passages to reach upto the front of boiler and then enter into bottom flue gas passage for escaping out through chimney after traversing the entire length of bottom passage. Hot gases thus traverse complete length of passage from end to end of boiler thrice i.e. through main flue gas tube, side flues and bottom flues. Heat transfer is more from side flues than bottom flue due to sedimentation in bottom. These boilers are generally capable of producing steam up to the rate of 1350 kg/hr and maximum steam pressure up to 12 bar. Shell is generally of length 4 to 7 m and diameter
1.2 to 1.8 m.

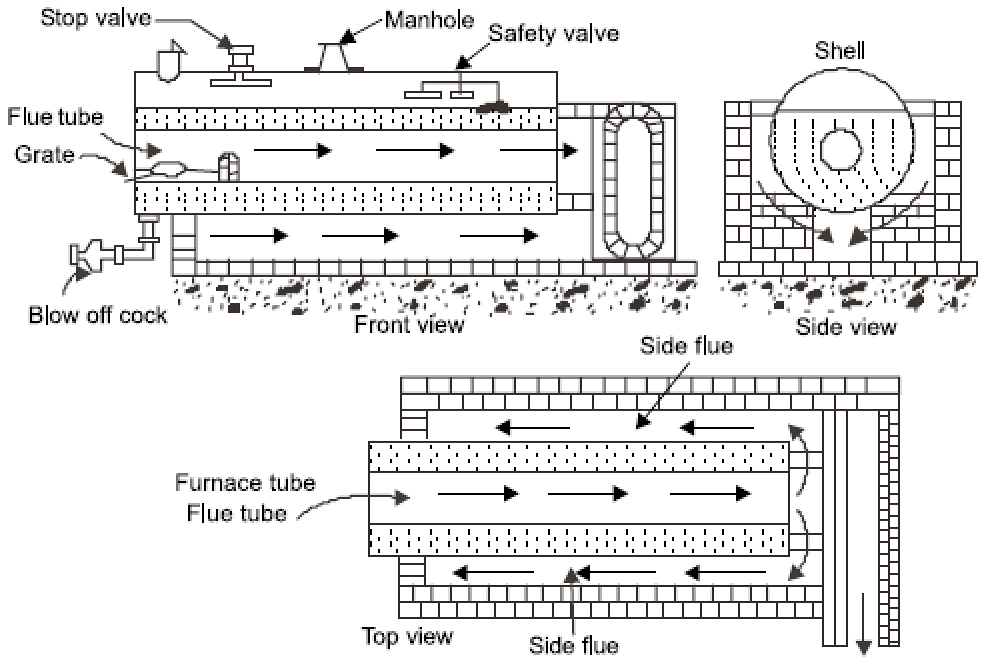


Fig. 1.7 *Cornish boiler*

Locomotive Boiler

These boilers were invented for getting steam to run a steam engine used in locomotives. These are fire tube type of boilers. It has basically three parts i.e. smoke box, shell and fire box. Figure 1.8 shows a general arrangement in locomotive boiler.

Inside *fire box* the fuel (coal) is burnt over the *grate*. For feeding fuel the *fire* hole is

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Lecture

on

Boiler

(142-154)

engine. A very large door is provided at the end of smoke box so as to facilitate cleaning and maintenance of complete boiler.

As it is a moving boiler, therefore, its chimney is completely eliminated. For expelling the burnt gases (draught) the exhaust steam coming out from steam engine is being used. Thus it is an artificial draught used in these boilers for expelling burnt gases.

Babcock and Wilcox Boiler

It is a water tube boiler suitable for meeting demand of increased pressure and large evaporation capacity or large sized boiler units. Figure 1.9 shows the Babcock and Wilcox boiler. It has three main parts:

(i) Steam and water drum
(ii) Water tubes
(iii) Furnace.

Steam and water drum is a long drum fabricated using small shells riveted together. End *cover plates* can be opened as and when required. Mountings are mounted on drum as shown. Drum is followed by water tubes which are arranged below drum and connected to one another and drum through headers. Header in which water flows from drum to tubes is called *down take header* while headers in which flow is from tubes to drum is called *uptake header*.

Soot deposition takes place in mud box which is connected to down take header. “Blow off cock” for blowing out the sediments settled in *mud box* is shown in figure. Super heater tubes are also shown in the arrangement, which are U-shape tubes placed horizontally between drum and water tubes. Superheating of steam is realized in super heater tubes.

Below the super heater and water tubes is the *furnace*, at the front of which *fuel feed hopper* is attached. *Mechanical stoker* is arranged below the hopper for feeding fuel. Bridge wall and baffles made of fire resistant bricks are constructed so as to facilitate hot gases moving upward from the *grate* area, then downwards and again upwards before escaping to the chimney. A *smoke box* is put at the back of furnace through which smoke

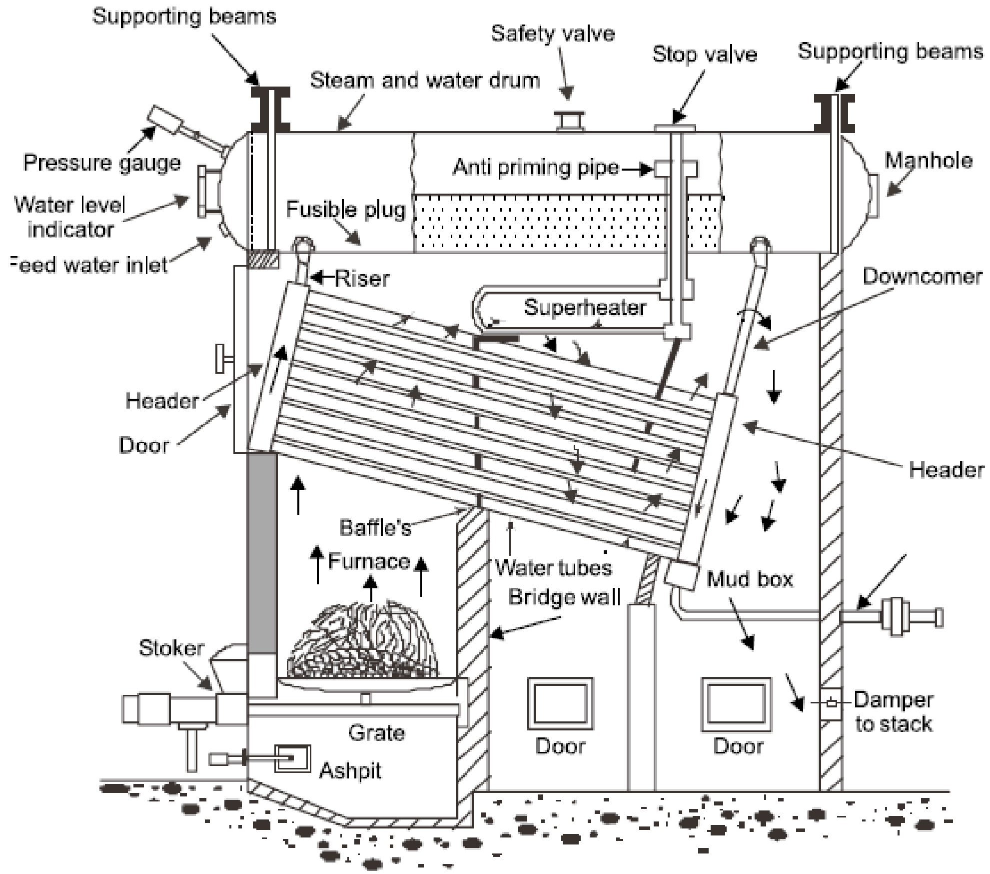


Fig. 1.9 *Babcock and Wilcox boiler*

High Pressure Boiler

High pressure boilers generally operate in supercritical range. Need of such boilers is felt because high pressure and temperature of steam generated in boiler improves plant efficiency. These boilers have forced circulation of water/steam in the boiler. This forced circulation is maintained by employing suitable pump. The steam drum is of very small size and in some cases it may be even absent too. This is because of using forced circulation. In case of natural circulation drum size has to be large. Schematic of high pressure boiler is shown in figure 1.10. In fact the high pressure boilers have been possible because of availability of high temperature resistant materials. Here direct heating of water

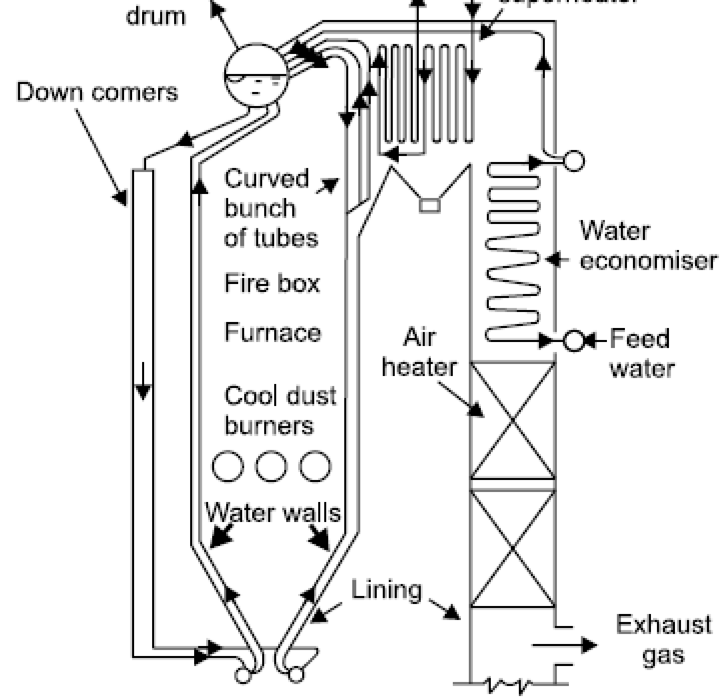


Fig. **1.10** *High pressure boiler with natural circulation*

High pressure boilers may have natural circulation in case the steam pressure desired lies between 100 and 170 bar and size is not constraint. High pressure boilers have capability of generating larger quantity of steam per unit of furnace volume.

High pressure boilers are disadvantageous from safety point of view and therefore, stringent reliability requirements of mountings is there.

Benson Boiler

It is a water tube boiler capable of generating steam at supercritical pressure. Figure 1.11 Shows the schematic of Benson boiler. Mark benson, 1992 conceived the idea of generating steam at supercritical pressure in which water flashes into vapour without any latent heat requirement. Above critical point the water transforms into steam in the absence of boiling and without any change in volume i.e. same density. Contrary to the critical pressure and steaming rate of about 130–135 tons/hr. Thermal efficiency of these boilers is of the order of 90%.

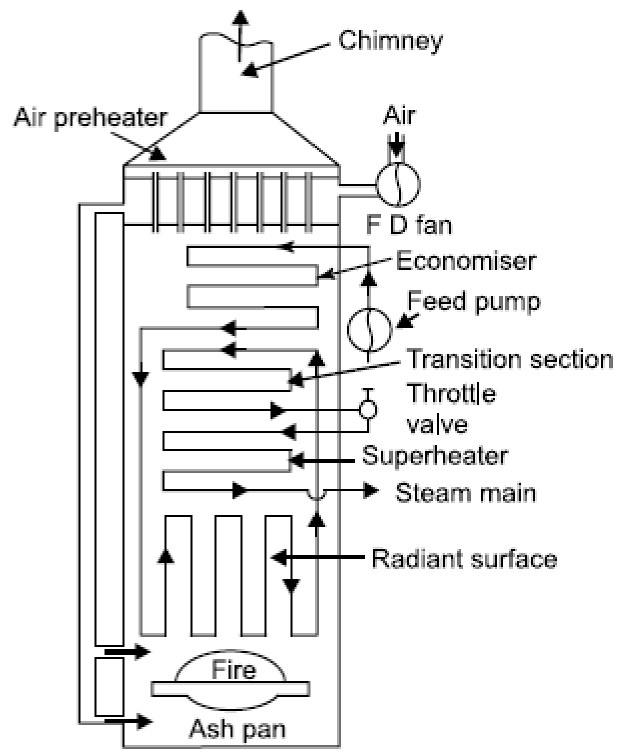


Fig. 1.11 *Benson boiler*

La Mont Boiler

This is a water tube boiler having forced circulation. Schematic showing the arrangement inside boiler is given in Fig. 1.12. Boiler has vertical shell having three distinct zones having water tubes in them, namely evaporator section, superheater section and economizer section.

Feed water is fed from feed pump to pass through economizer tubes. Hot water from economizer goes into drum from where hot feed water is picked up by a circulating pump. Centrifugal pump may be steam driven or of electric driven type. Pump increases pressure and water circulates through evaporation section so as to get converted into steam and enters back to drum. Steam available in drum enters into superheater tubes and after getting

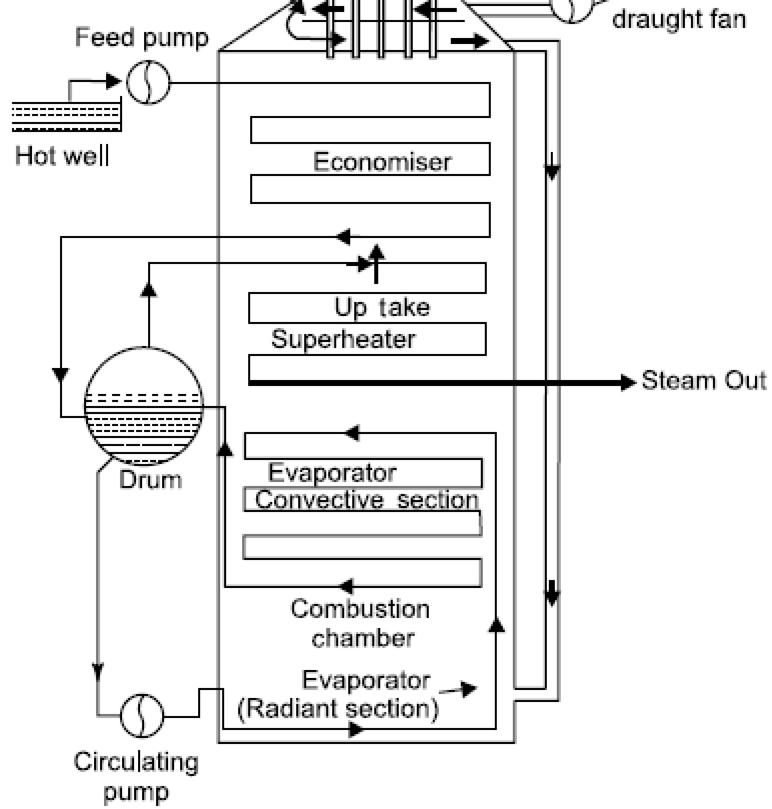


Fig. 1.12 *La Mont boiler*

Boiler Mountings and Accessories

Boiler mountings and accessories have been defined earlier and shown on the different boilers. Different mountings are

(i) Water level indicator
(ii) Safety valves
(iii) High steam and low water safety valves
(iv) Fusible plug
(v) Pressure gauge
(vi) Stop valve

(iii) Air preheater

(iv) Feed pump

Water level indicator: It is used for knowing the level of water in boiler as water level inside boiler should not go below a certain limit. General arrangement is shown in Fig. 1.13 with the different parts in it. It has two tubes one is front glass tube while other is metal tube. Water level is seen through glass tube which is made strong enough to withstand high steam pressure and temperature. Two control cocks are provided for regulating steam and water passage from boiler to glass tube.

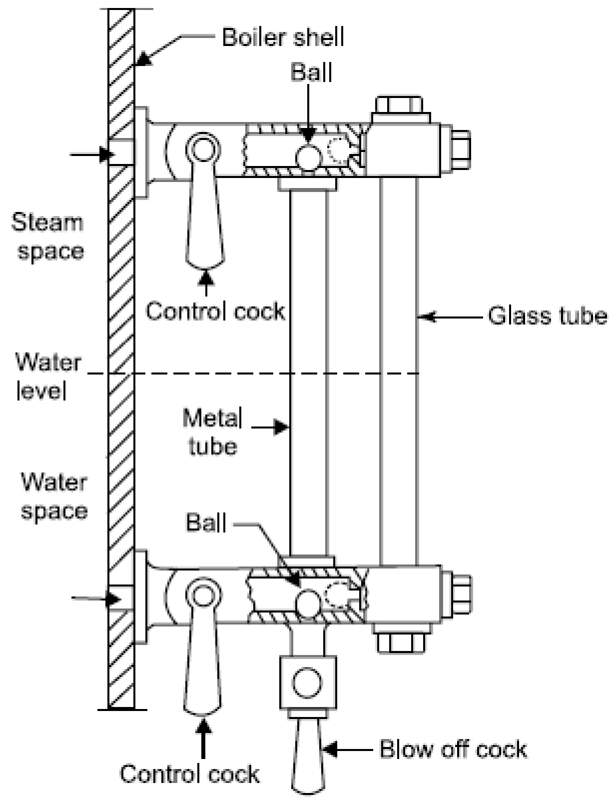


Fig. 1.13 *Water level indicator*

For blow off purpose a blowing cock is also provided as shown. In case of breakage of glass tube the possibility of accident is prevented by providing two balls. As glass tube

1.14 gives the general description of ‘dead weight safety valve’.

It has a large vertical pipe on the top of which a valve seat is fixed. Valve rests upon this valve seat. A weight carrier is hung on the top of valve upon which cast iron rings enclosed in cast iron cover are placed in weight carrier as dead weight.

When the pressure of steam exceeds the total weight of valve, it is lifted and falls back as steam pressure gets reduced.

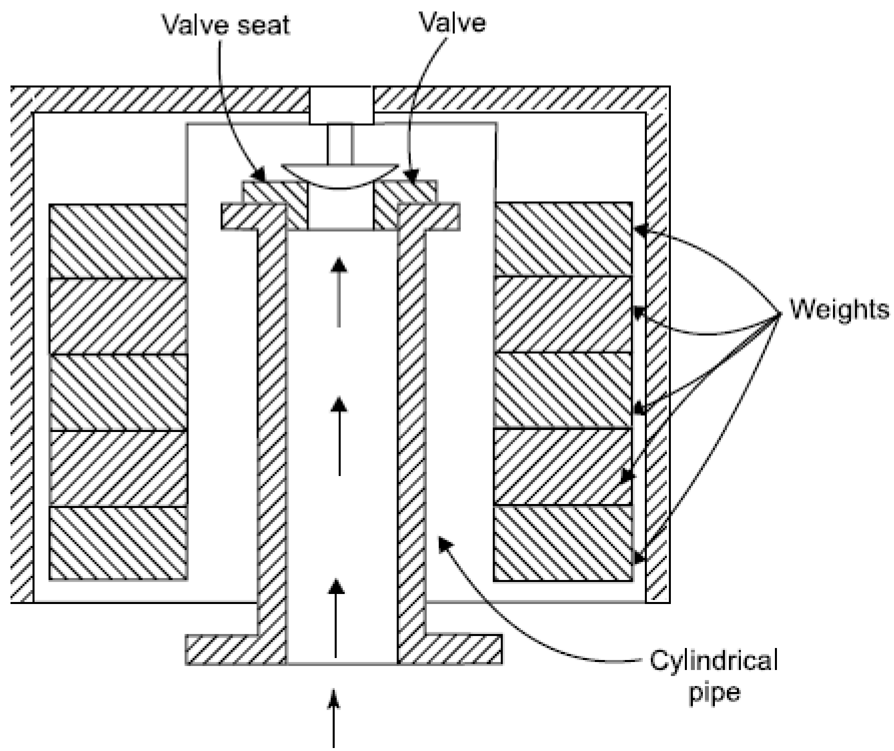


Fig. 1.14 *Dead weight safety valve*

It has a large vertical pipe on the top of which a valve seat is fixed. Valve rests upon this valve seat. A weight carrier is hung on the top of valve upon which cast iron rings enclosed in cast iron cover are placed in weight carrier as dead weight.

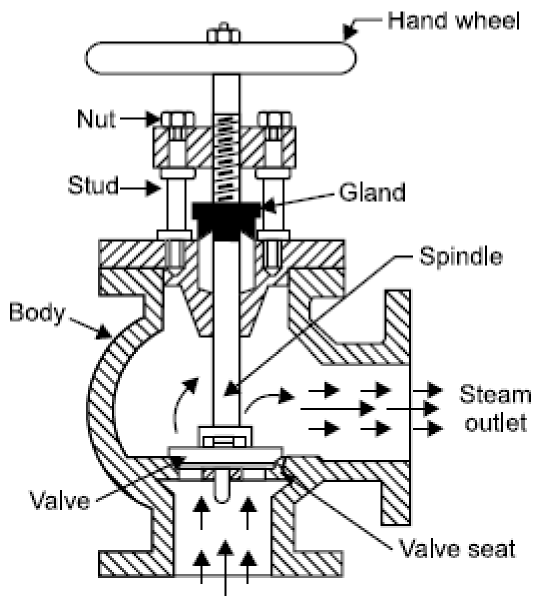
When the pressure of steam exceeds the total weight of valve, it is lifted and falls back as

copper plug and gun metal body. As water level goes down the heat available from furnace could not be completely utilized for steam formation and so the overheating may cause melting of fusible metal.

Fusible metal is a low melting point metal. Thus upon melting of lining the copper plug falls down and water falls from this opening onto furnace and thus quenches fire.

Pressure gauge: It is mounted at front top. Generally Bourdon type pressure gauge are being used for pressure measurement. Pressure is continuously monitored so as to avoid occurrence of over shooting of boiler pressure. Although safety devices to protect boiler against pressure rising beyond a limit are provided but pressure gauges are also used for monitoring pressure.

Stop valve: It regulates the flow of steam from the boiler as shown in Fig 1.15. This is generally mounted on highest part of boiler shell and performs function of regulating the flow of steam from boiler. Stop valve generally has main body of cast steel, valve, valve seat and nut etc. are of brass. Stop valve can be easily operated by rotating the hand wheel which causes lifting or lowering of spindle, thus causing opening or closing of valve.



arrangement in a feed check valve. It has a check valve whose opening and closing are regulated by the position of spindle. By hand wheel rotation the position of spindle can be altered suitably. Feed check valve permits unidirectional flow of water from feed pump to be boiler shell. Under normal running the pressure of feed water coming from pump is more than pressure inside the boiler and so the feed water continues to enter the shell. While during the non working of feed pump the pressure in boiler shell is more and so the check valve gets closed.

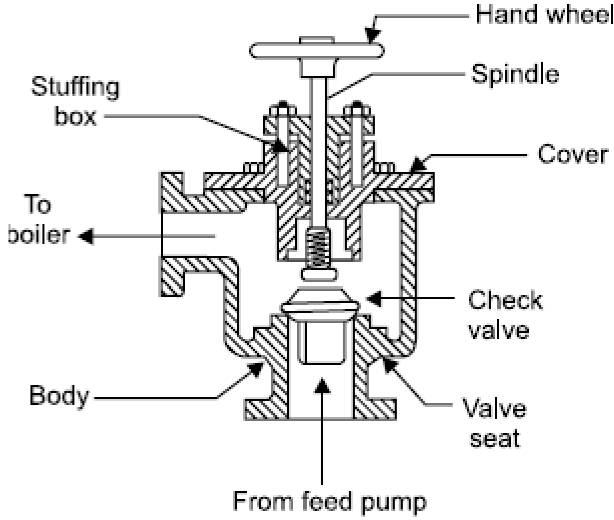


Fig. 1.16 *Feed check valve*

Blow off cock: It is used for periodical cleaning by discharging the water and sediments from bottom of boiler. Figure 1.17 shows the blow off cock. Blow off cock is fitted to the bottom of boiler shell. Blow off cock has a plug of conical type put into the mating casing. Plug position is altered for opening and closing the flow. Plug has rectangular opening which when comes in line with inlet and outlet passage then blow off cock is open and when opening is not in line then cock is closed. Plug is rotated by spindle.

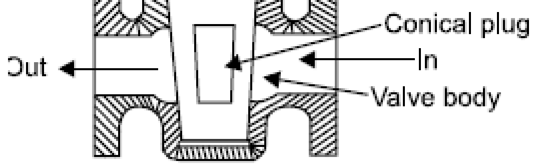
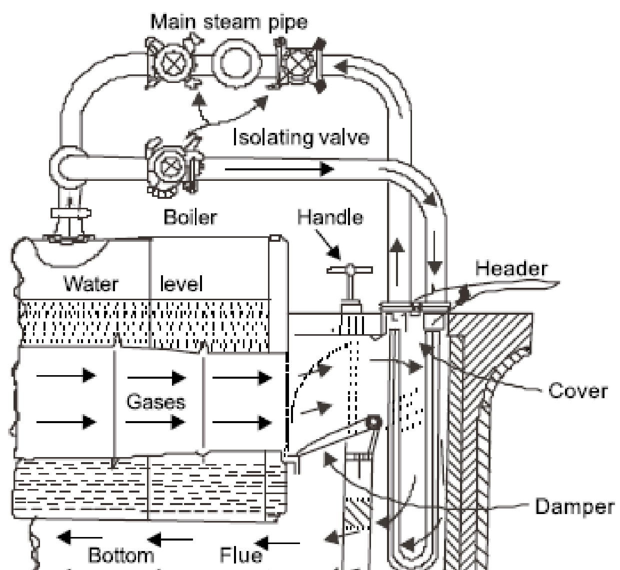


Fig. 1.17 *Blow off cock*

Blow off cock also helps in regulating the salt concentration as frequent draining helps in throwing out the salt deposited over period of time. Opening blow off cock removes deposited sediments in boiler.

Superheater: Its purpose is to super heat steam and is a type of heat exchanger in which steam flows inside tubes and hot gases surround it. Figure 1.18 shows the smooth tube hairpin type super heater (Sudgen's superheater) and convective and radiant superheater.

In hair pin superheater the steam generated is passed through isolating valve to U-shaped steel tubes. Superheated steam leaves superheater through tube connected to steam stop valve. Hot gases from fire tube are diverted over superheater tubes by damper as shown. These hot gases upon passing over steel tubes leave boiler through bottom flue. The convective and radiant superheater as shown has two set of tubes picking up heat through convection and radiation.



feed water as two fluids. General arrangement in economizer is shown in Fig. 1.19. Economizer also helps in removal of dissolved gases by preheating of water and thus minimizes tendency of corrosion and pitting. Hotter feed water also reduces thermal strain in boiler parts. Economizer is located in the boiler structure so as to expose the economizer surface to hot gases. Its location varies with the boiler designs. Typical economizer called Green's economizer as shown in Fig. 1.19 has vertical pipes of cast iron fitted with two headers at bottom and top respectively. Feed water passes through bottom header, economizer tubes and top header to boiler. Thus economizer is simply a heat exchanger where heat is transferred from hot flue gases to water inside the tubes through metal interface. Top header is also provided with a safety valve so as to avoid explosion due to excessive pressure of water developing inside economizer tubes. Bottom header is also provided with a blow off valve so as to throw out the sediments deposited in feed water. Economizer is also provided with scrapers fitted to clean pipes from the deposition of soot carried by the flue gases. Continuous scrapping is always desired so as to maximize heat transfer rate. Economizer also has a by pass provided so that flue gases can be diverted when economizer is out of full or part operation due to failure or cleaning purpose or feed water temperature control.

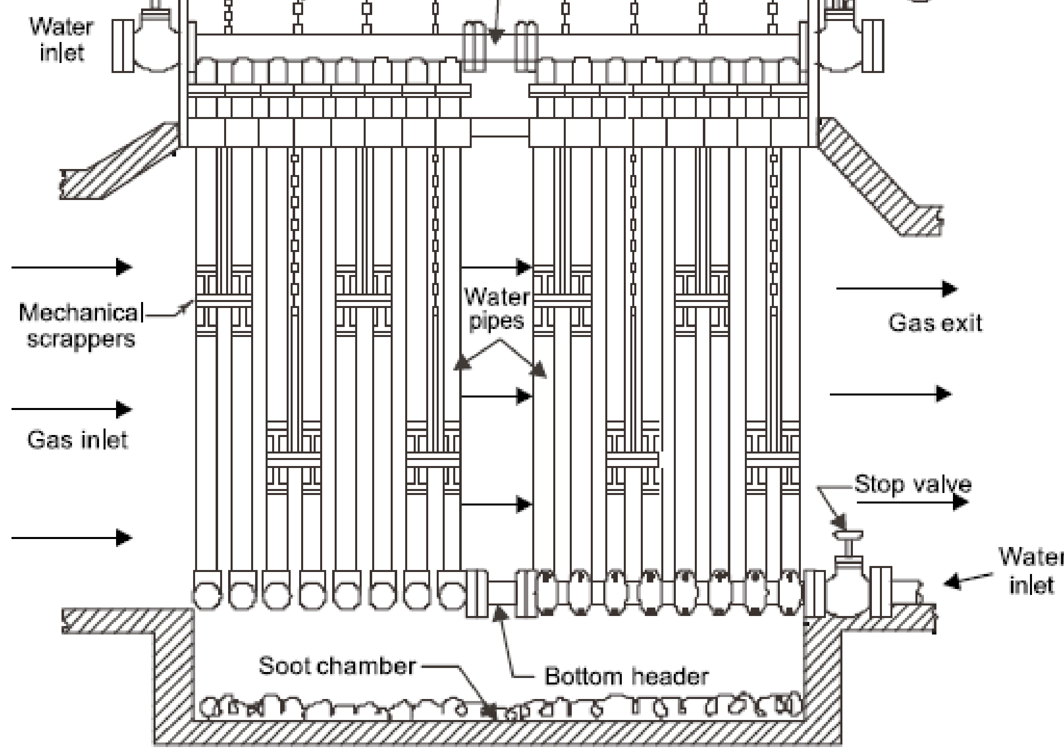


Fig. 1.19 *Economizer*

Air preheater: It is used for recovering the heat going along with exhaust gases by the air before being sent to furnace. Heat is recovered by passing exhaust gases through an air to air heat exchanger as shown in Fig. 1.20. Air preheaters are generally placed after economizer and before chimney. Air when preheated before supply to furnace/combustion chamber helps in achieving 'faster rate of combustion', 'possibility of burning inferior quality coal/fuel' and 'increased rate of evaporation from boiler' etc.

Air preheaters are of tubular type, plate type and regenerative type. This classification of air preheaters bases upon the kind of arrangement used for heat exchange between two fluids. Generally, tubular type air preheater are generally used in small boilers. Tubular air preheater has hot flue gases passing inside tubes and air blown over these tubes.

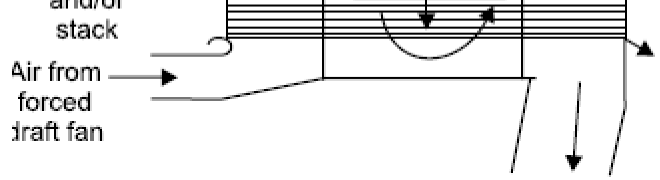


Fig. **1.20** *Tubular air preheater*

In case of plate type air preheater there are number of plates having air and flue gases flowing through alternative spacing. In regenerative type air preheater there is a wire mesh rotor which is alternatively heated and cooled by the hot flue gases and air to be used for combustion.

Feed pump: Feed pump is used for sending water into boiler at the pressure at which steam generation takes place. It is generally of three types i.e. centrifugal pump, reciprocating pump and injectors.

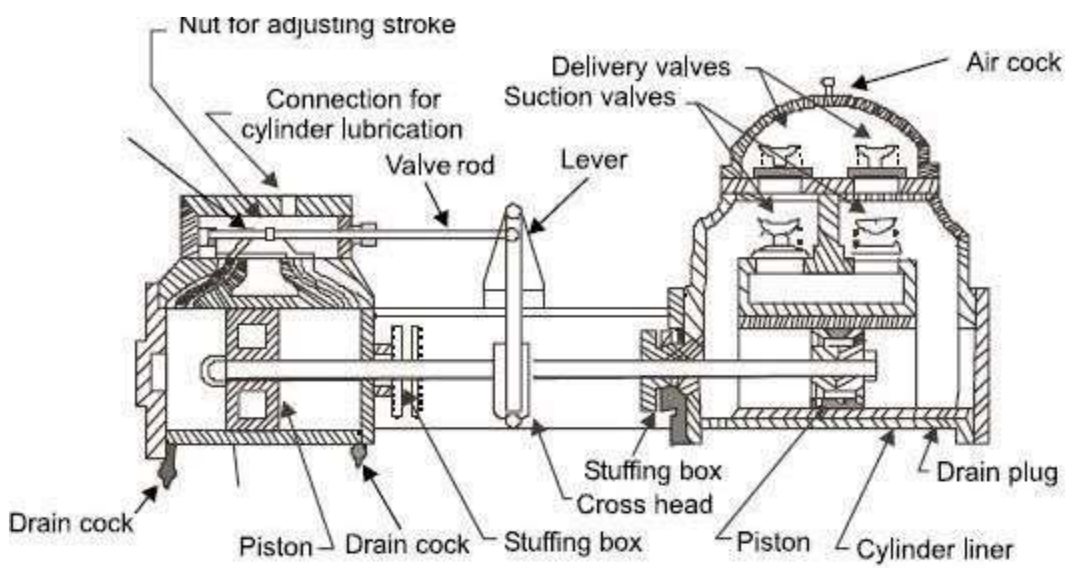


Fig. **1.21** *Reciprocating type pump, Duplex feed pump*

A reciprocating type feed pump is shown in Fig. 1.21. In boilers the pumps raise feed

Week-13

Lecture

on

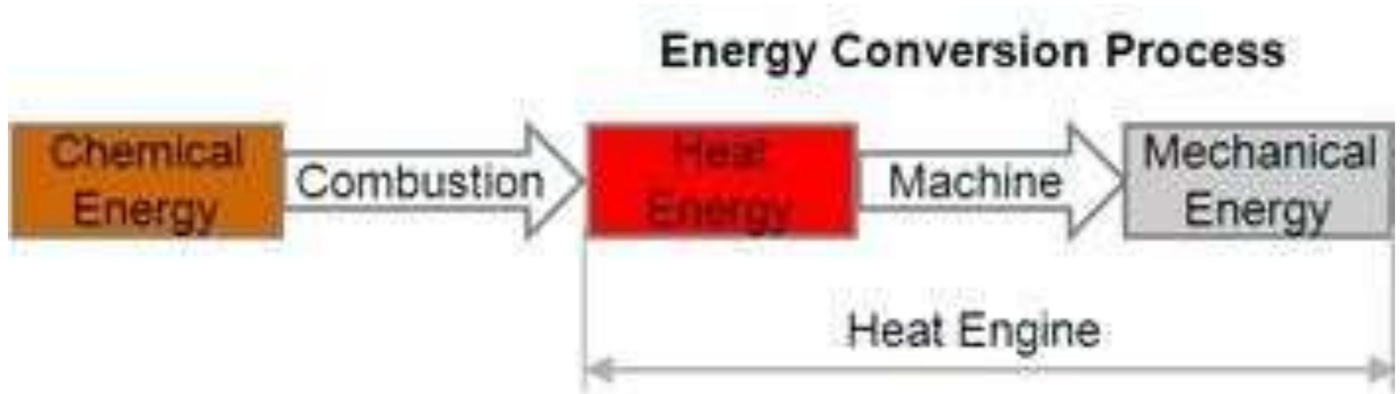
IC Engine Components

(156-170)

IC ENGINES

Engine

- Device transforms one form of energy to another form
- Heat engine- Engine which converts thermal energy in to mechanical energy. Ex: steam engine



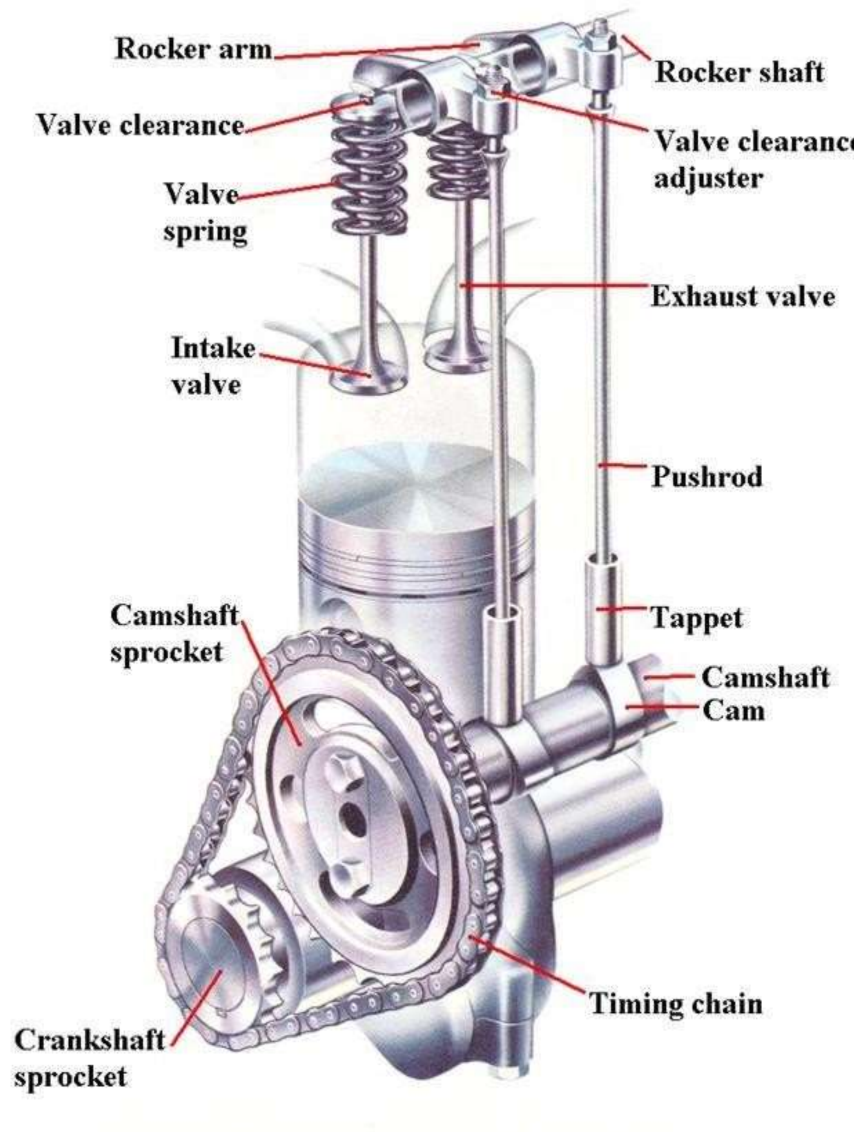
- Classified as
  - External Combustion engines (EC Engines)
  - Internal combustion engines(IC Engines)

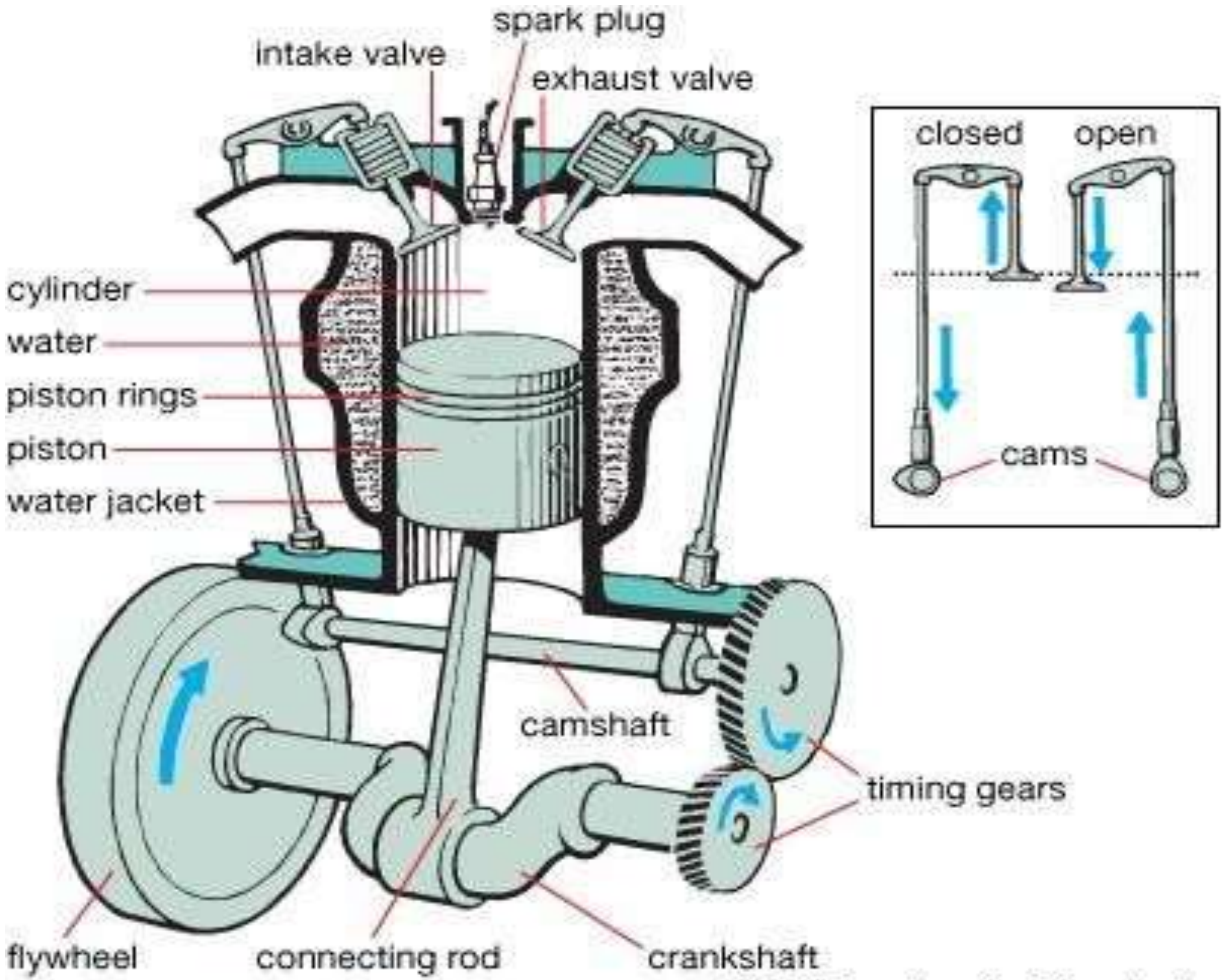
mechanical engine system, thus the working fluid does not come in contact with combustion products.

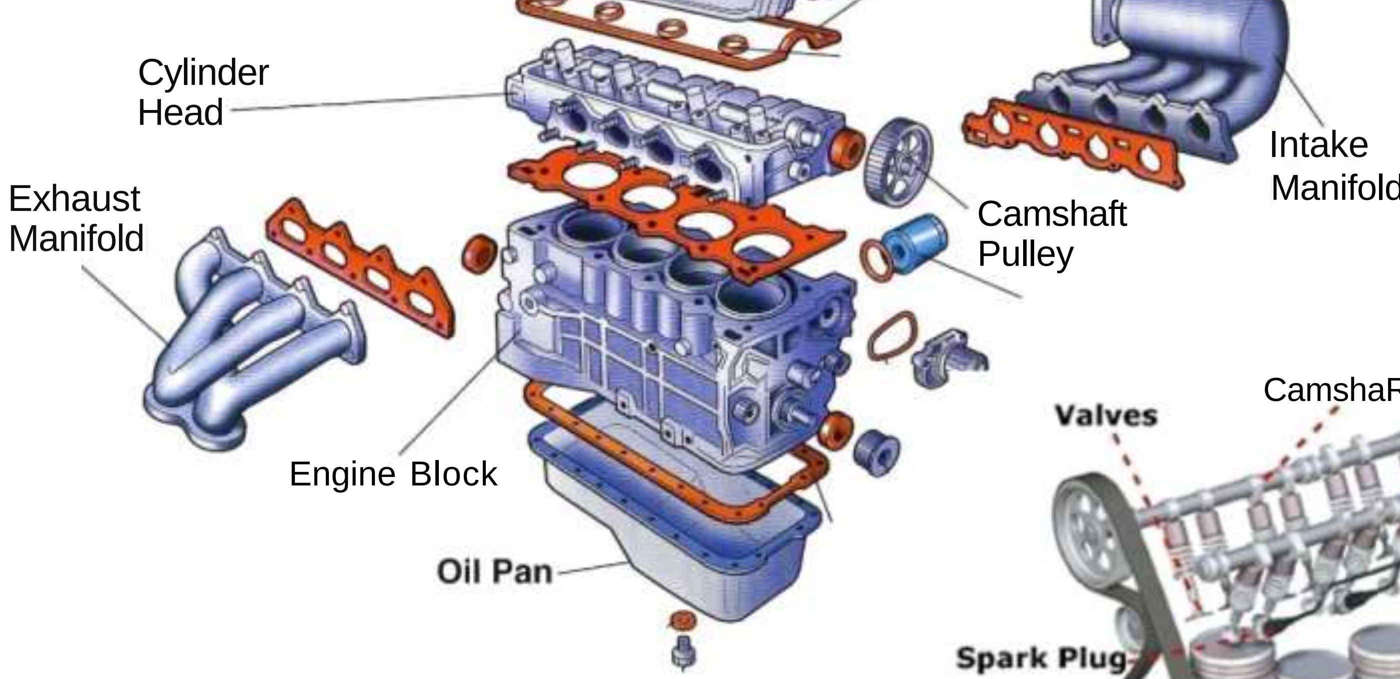
- Steam engine, where the working fluid is steam.
- Stirling engine, where the working fluid is air.

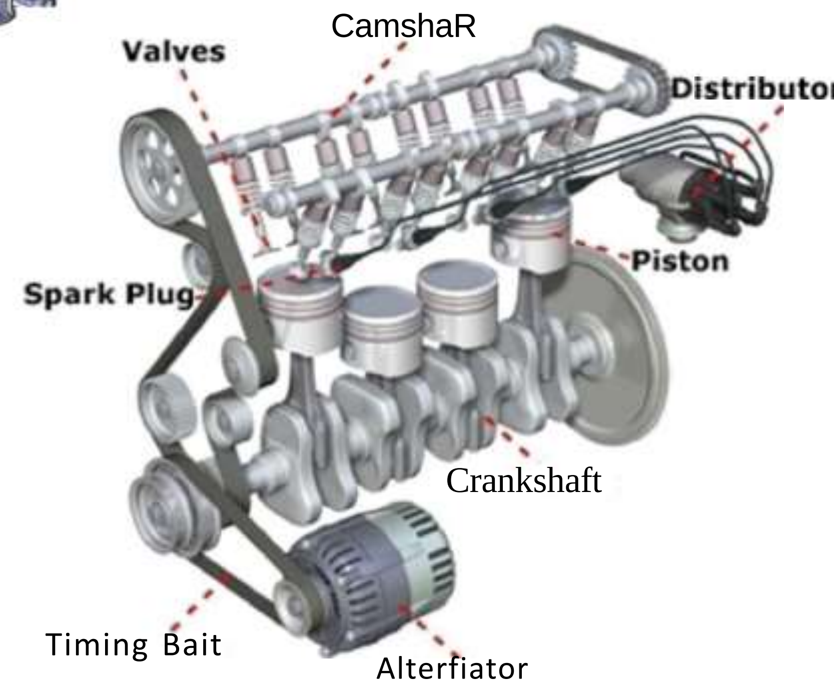
- In an **Internal combustion engine**, combustion takes place within working fluid of the engine, thus fluid gets contaminated with combustion products.
  - Petrol & Diesel engines are examples of internal combustion engine, where the working fluid is a mixture of air and fuel

1


Rocker arm
Rocker shaft
Valve clearance
Valve clearance adjuster
Valve spring
Exhaust valve
Intake valve
Pushrod
Tappet
Camshaft sprocket
Camshaft
Cam
Timing chain
Crankshaft sprocket


spark plug
intake valve
exhaust valve
closed
open
cylinder
water
piston rings
piston
water jacket
cams
camshaft
timing gears
flywheel
connecting rod
crankshaft


Cylinder Head
Exhaust Manifold
Engine Block
Oil Pan
Camshaft Pulley
Intake Manifold

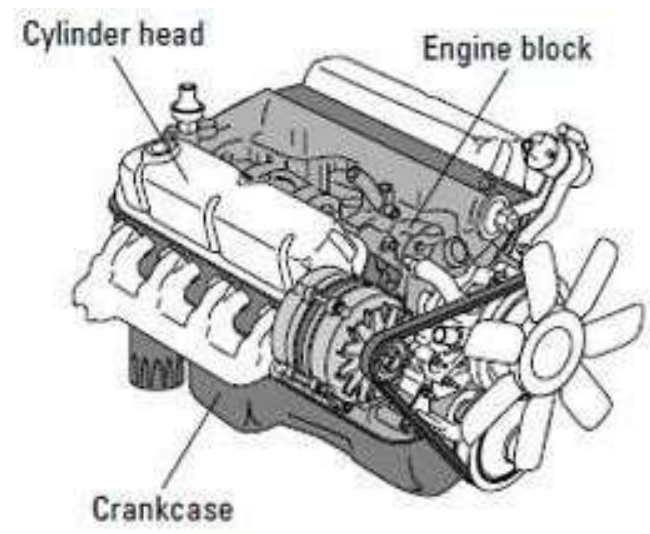

Valves
CamshaR
Distributor
Piston
Spark Plug
Crankshaft
Timing Bait
Alterfiator

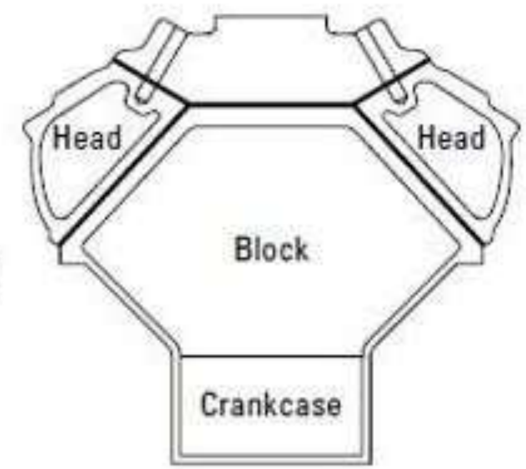
in which the pistons reciprocate back and forth

- Made of hard and high thermal conductivity materials
- Combustion of fuel takes place inside the cylinder

Cylinder head

- Covers one end of the cylinder and consists of valves/ports & spark plug/injector





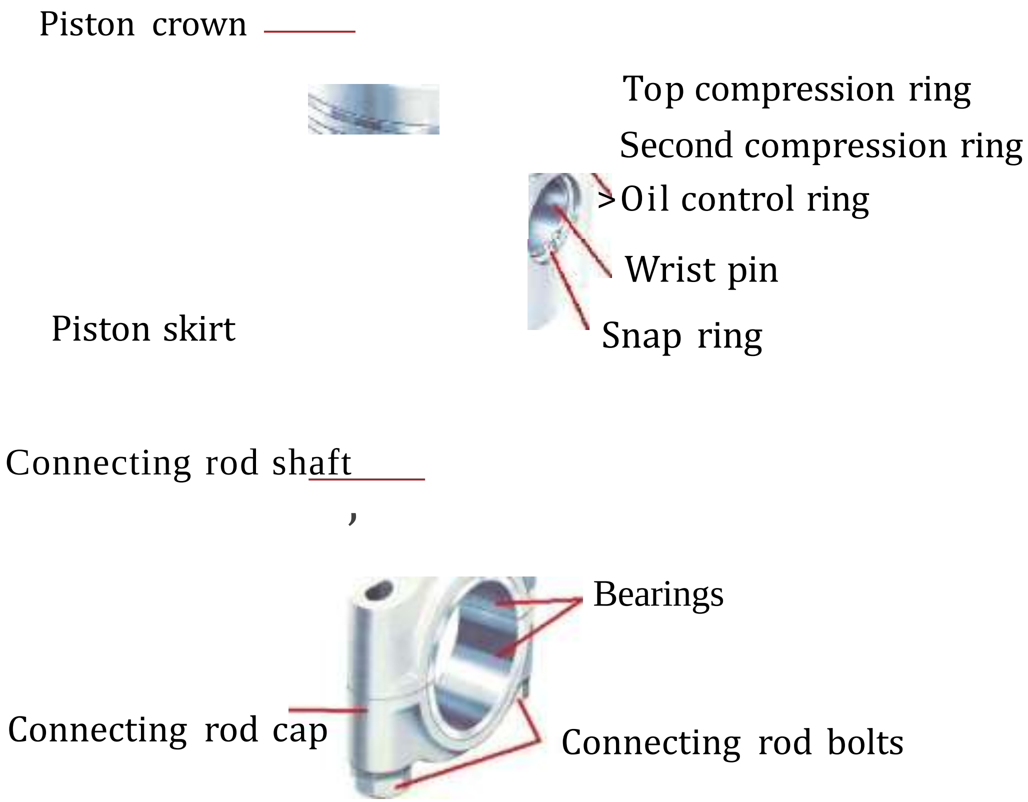
- The main function of piston is to transmit the force exerted by the burning of fuel to the connecting rod.

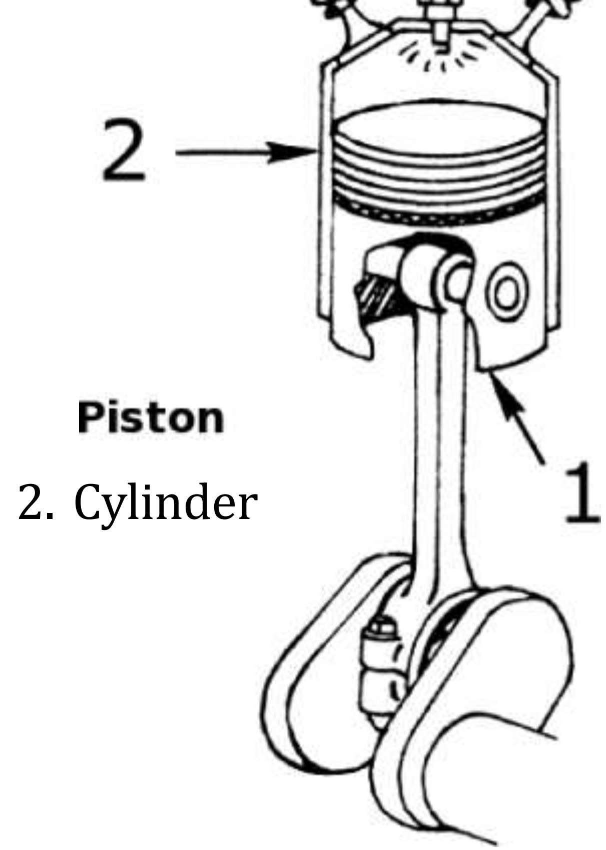
Piston Rings

- The outer periphery is provided with several grooves in to which the piston rings are fitted
- The upper ring is known as compression ring and the lower one is called oil rings

Water jackets

- Through which cooling water is circulated to prevent overheating of the engine


Piston crown
Top compression ring
Second compression ring
>Oil control ring
Wrist pin
Snap ring
Piston skirt
Connecting rod shaft
Bearings
Connecting rod cap
Connecting rod bolts


2
1
Piston
2. Cylinder

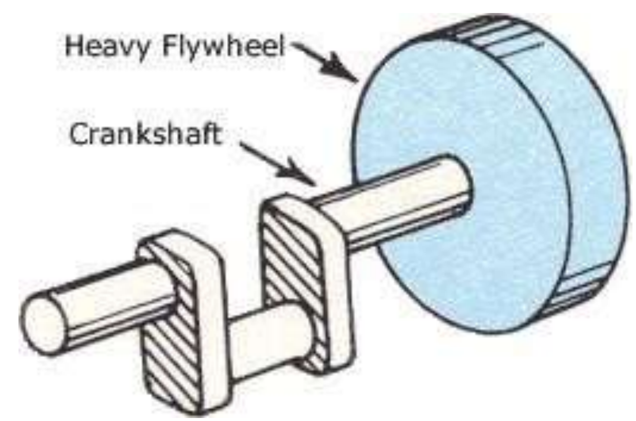
of the crankshaft

- Two ends: 1. **Small end**-connected to the piston by **Gudgeon pin**

  2. **Big end**-connected to the crankshaft by **Crank pin**

Crank and crank shaft

- Crank is the rotating member which receives power from the connecting rod and transmits to the crank shaft
- Crank shaft is the principal rotating part of the engine which controls the sequence of reciprocating motions of the piston



and release it during non power stroke

- Reduce the torque and speed fluctuations
- Absorbs vibration from the crankshaft
- Supports for clutch mechanism

Valves

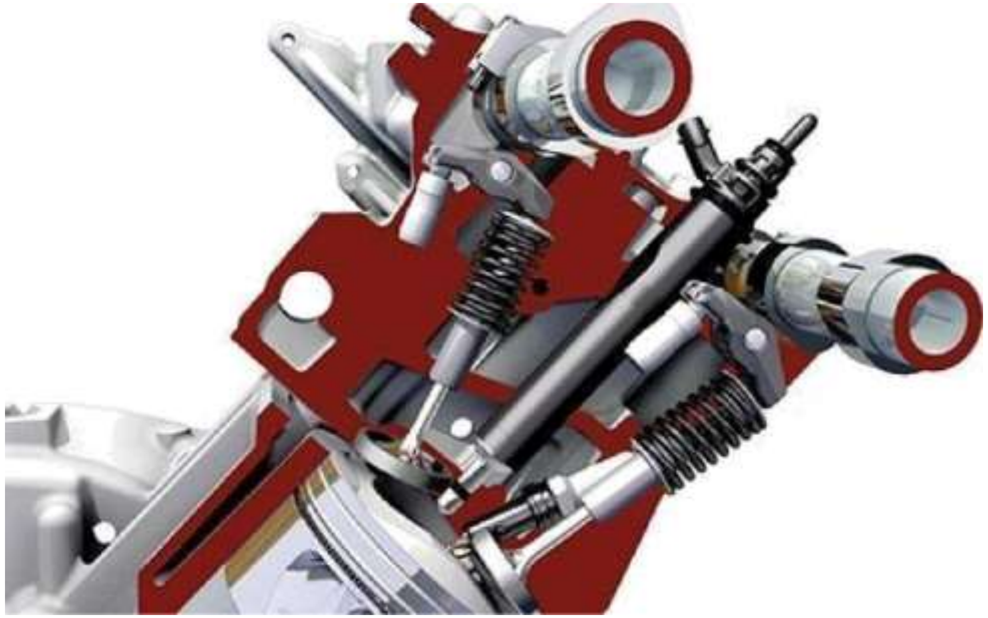
- Provided in the cylinder head for the admission of fresh air/air fuel mixture in to the engine cylinder and for rejection of burnt gases
- Operated by cams and camshaft

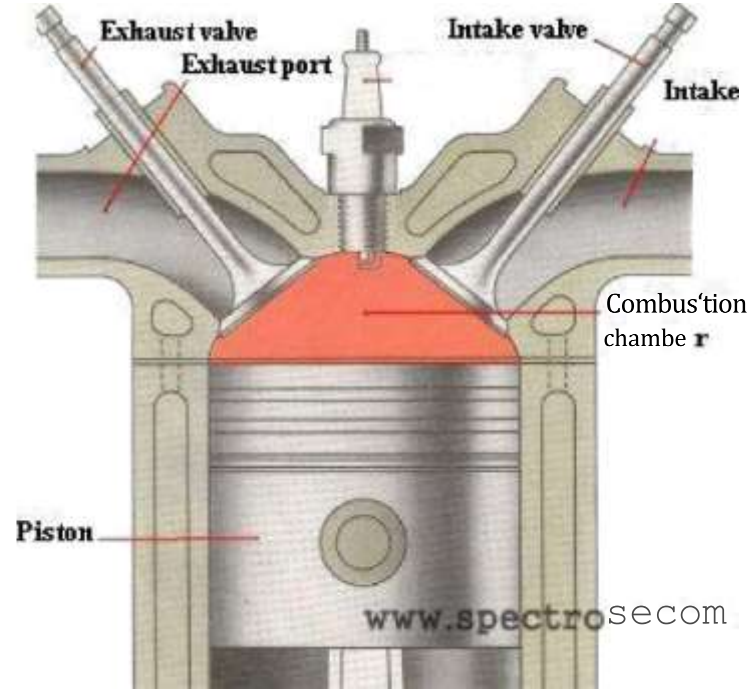
Inlet manifold

- The metal tube which connects the intake system to the inlet valve of the engine

Exhaust/ outlet manifold

- Connects exhaust system to the exhaust valve of the engine

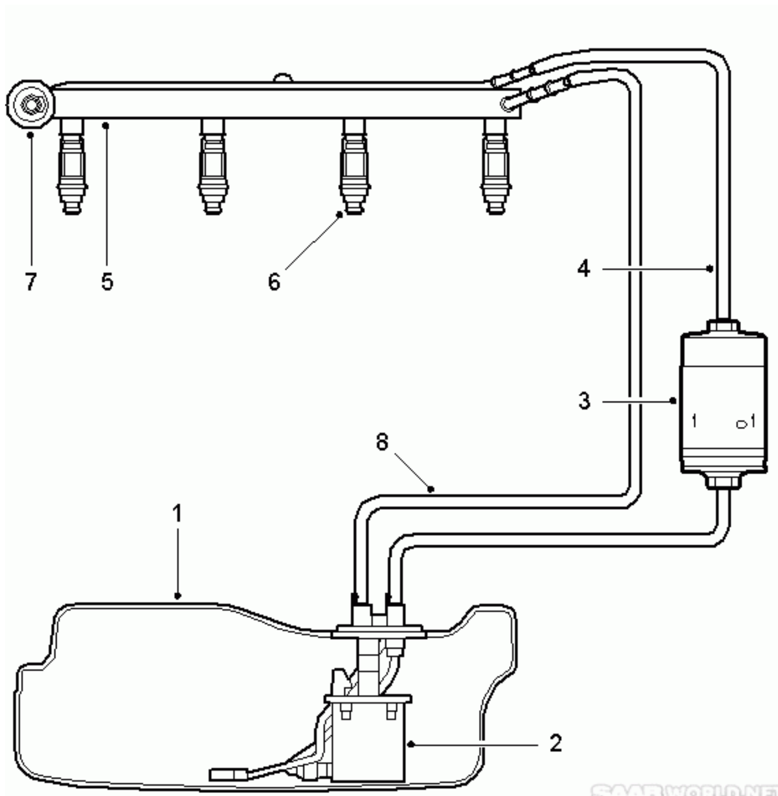



Exhaust valve
Exhaust port
Intake valve
Intake
Combus'tion chambe r
Piston
www.spectrosecom

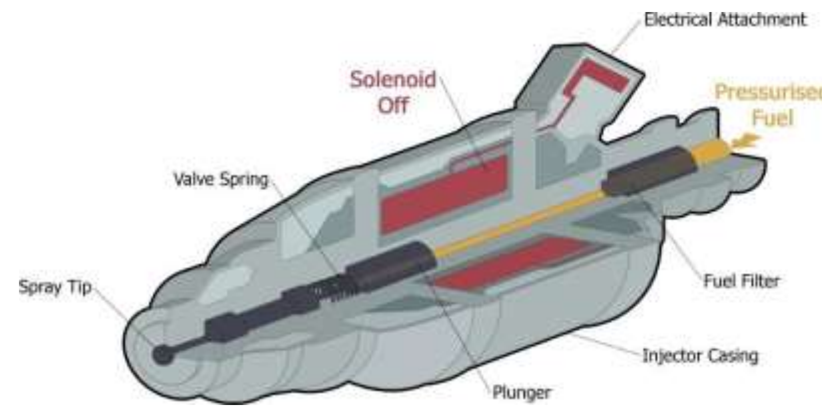

CHAMPION
Iridium

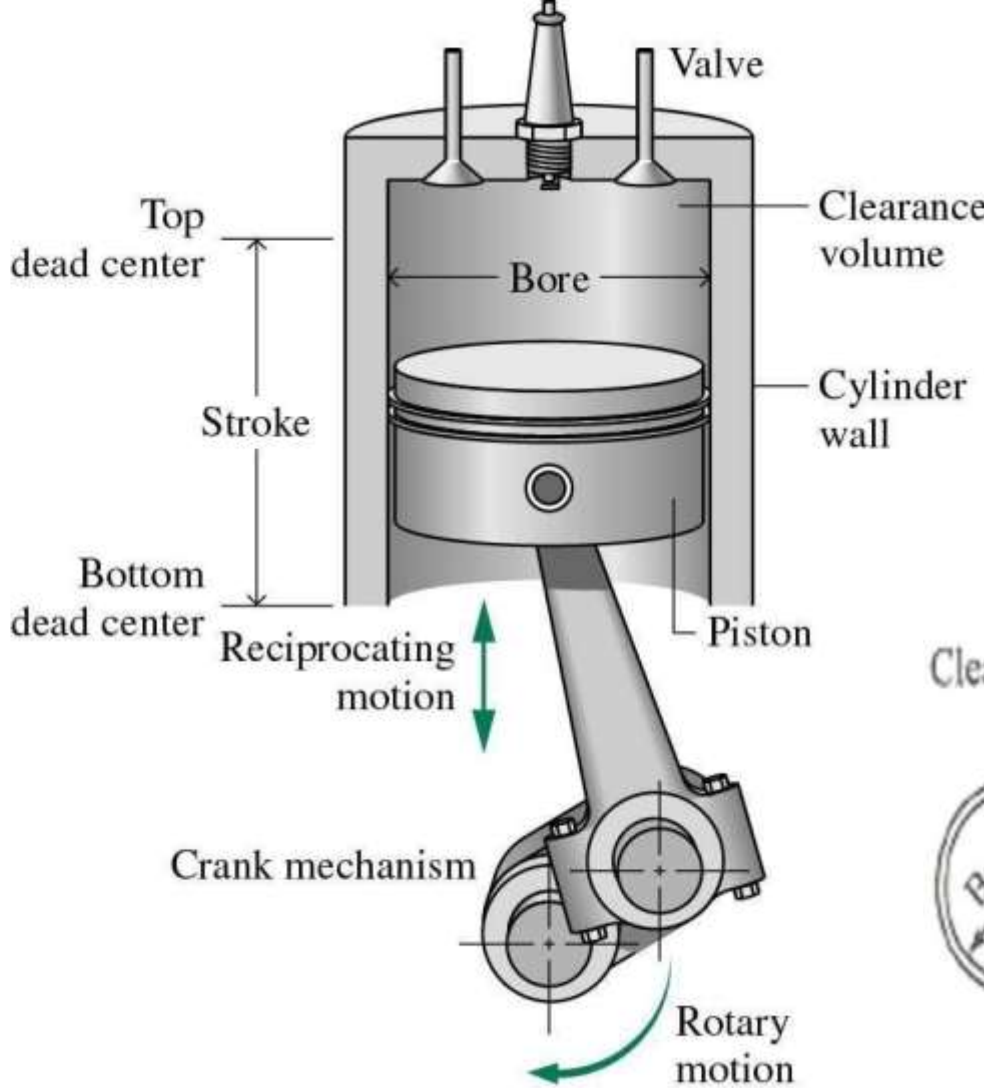
high pressure in to the cylinder of CI engine/ MPFI engine

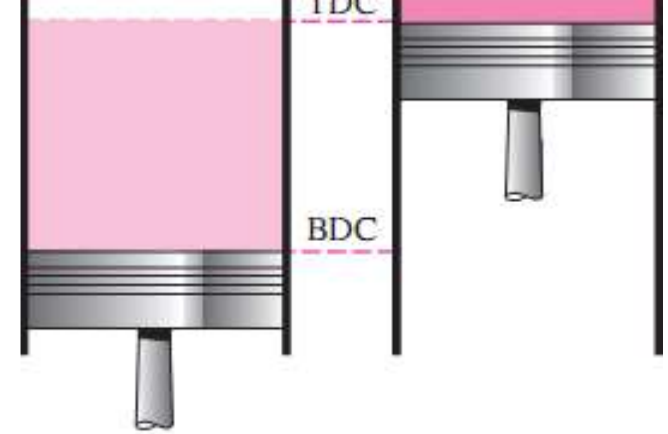
- Fuel pump : Electrically or mechanically driven pump to supply fuel from the fuel tank (reservoir) to the engine.



1. Fuel tank
2. Fuel pump
3. Fuel filter
4. Fuel line, delivery
5. Fuel rail
6. Injector
7. Pressure regulator
8. Fuel line, return

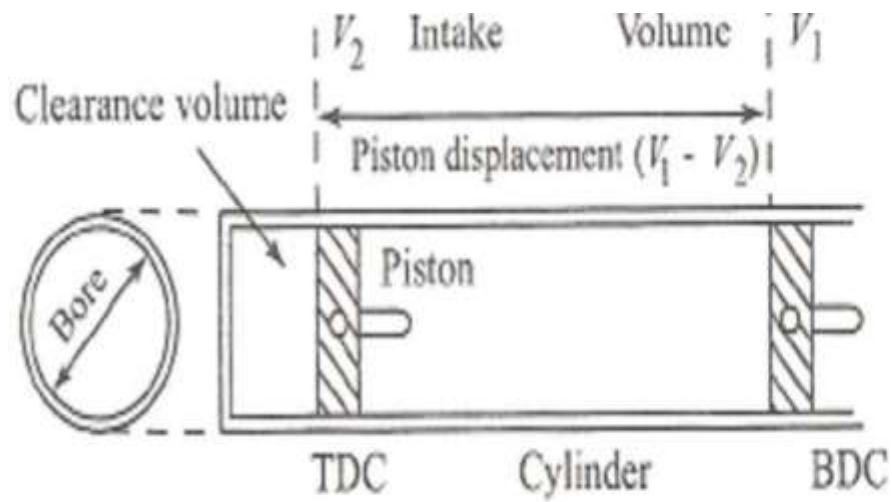






(*a*) Displacement volume

(*b*) Clearance volume



Week-14

Lecture

on

IC Engine Classification, Working Principle

(172-183)

Top because this position is at the top of the engines (not always), and dead because the piston stops as this point. In some engines **TDC** is not at the top of the engines(e.g: horizontally opposed engines, radial engines,etc,.)

When the piston is at TDC, the volume in the cylinder is a minimum called the clearance volume

Bottom Dead Center (BDC): Position of the piston when it stops at the point closest to the crankshaft.

- Some sources call this **Crank End Dead Center (CEDC)** because it is not always at the bottom of the engine.

Stroke (L) : Distance traveled by the piston from one extreme position to the other : TDC to BDC or BDC to TDC.

Swept volume/Displacement volume (V_s) : Volume displaced by the piston as it travels through one stroke.

- Swept volume is defined as stroke times bore.

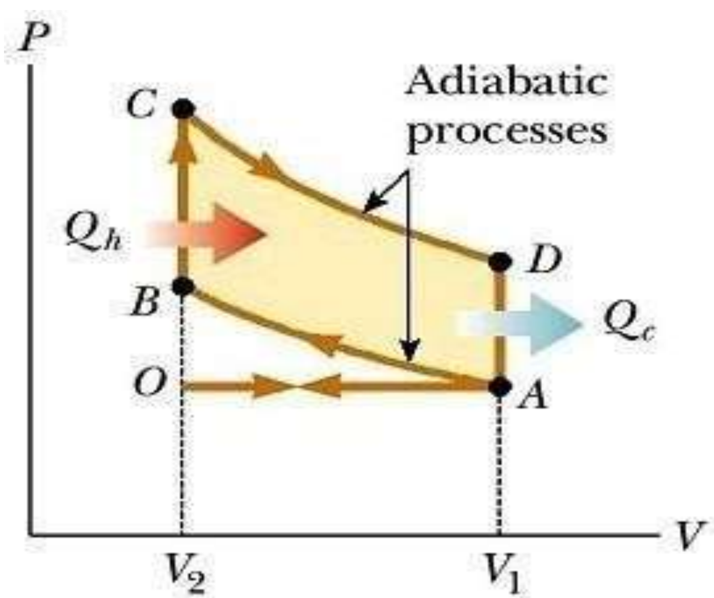
Clearance volume (V_c): It is the minimum volume of the cylinder available for the charge (air or air fuel mixture) when the piston reaches at its outermost point (top dead center or inner dead center) during compression stroke of the cycle.

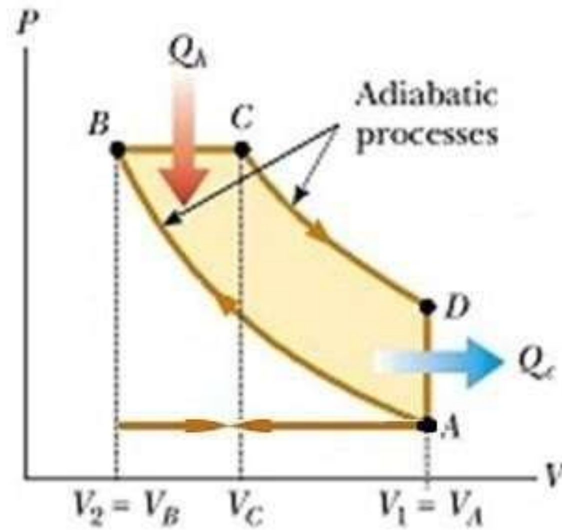
- Minimum volume of combustion chamber with piston at TDC.

Compression ratio (r) : The ratio of total volume to clearance volume of the cylinder is the compression ratio of the engine.

- Compression ratio for SI engines varies form 8 to 12 and for CI engines it varies from 12 to 24

- Based on working cycle
  - Otto cycle(eg. SI engine)
  - Diesel cycle(eg. CI engine)
  - Dual cycle





PV diagram for an ideal diesel engine.

- Based on no. of cylinders
  - Single cylinder
  - Multi cylinder

- Based on fuel used
  - Solid fuel(eg. coal)
  - Liquid fuel(eg. diesel)
  - Gaseous fuel (Natural gas)

- Based on cooling system
  - Air cooling
  - Liduid cooling

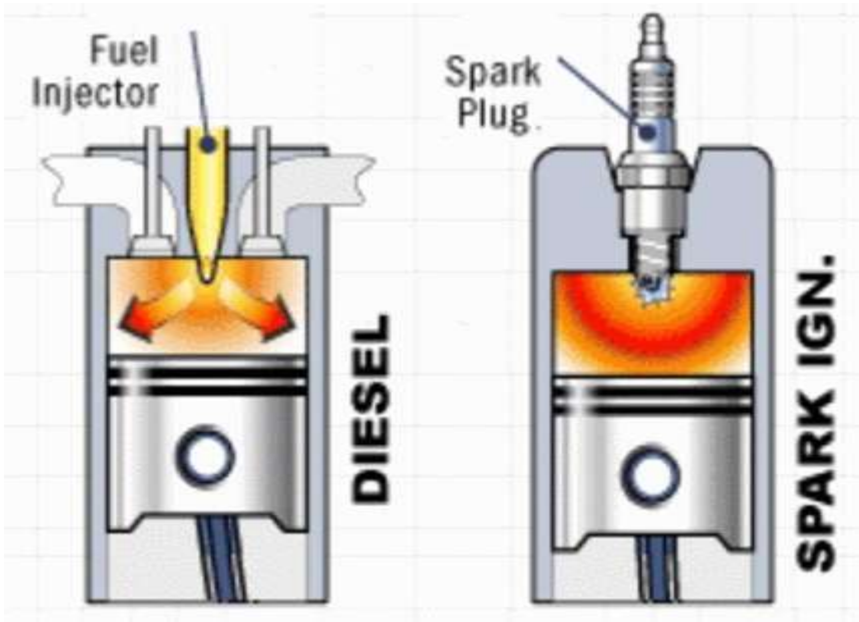
- Based on number of strokes per cycle
  - Two stroke
  - Four stroke

INTERNAL COMBUSTION ENGINES

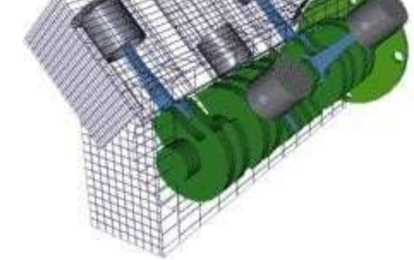
(ex. Gasoline/Petrol Engine)

Compression Ignition engines

(ex. Diesel Engine)

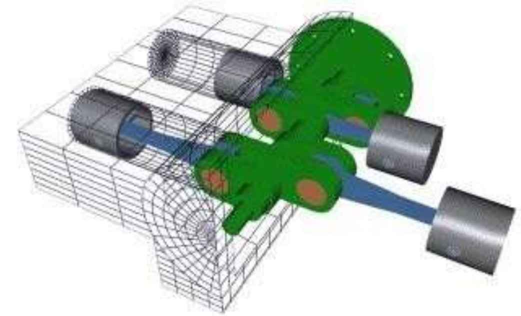


- Horizontal Engines



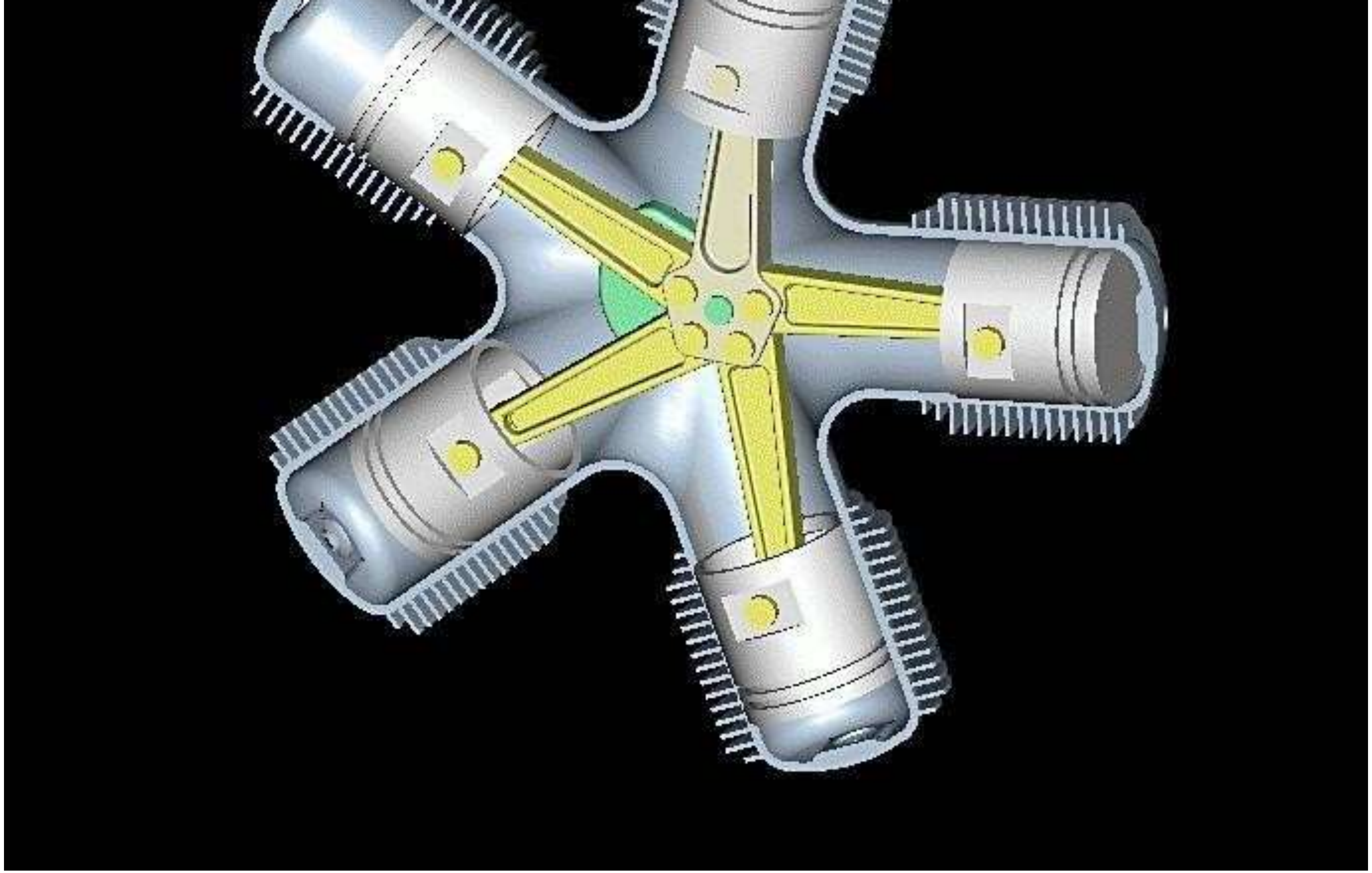
- Inline Engines: The cylinders are arranged in a line, in a single bank.

- V Engines: The cylinders are arranged in two banks, set at an angle to one another.



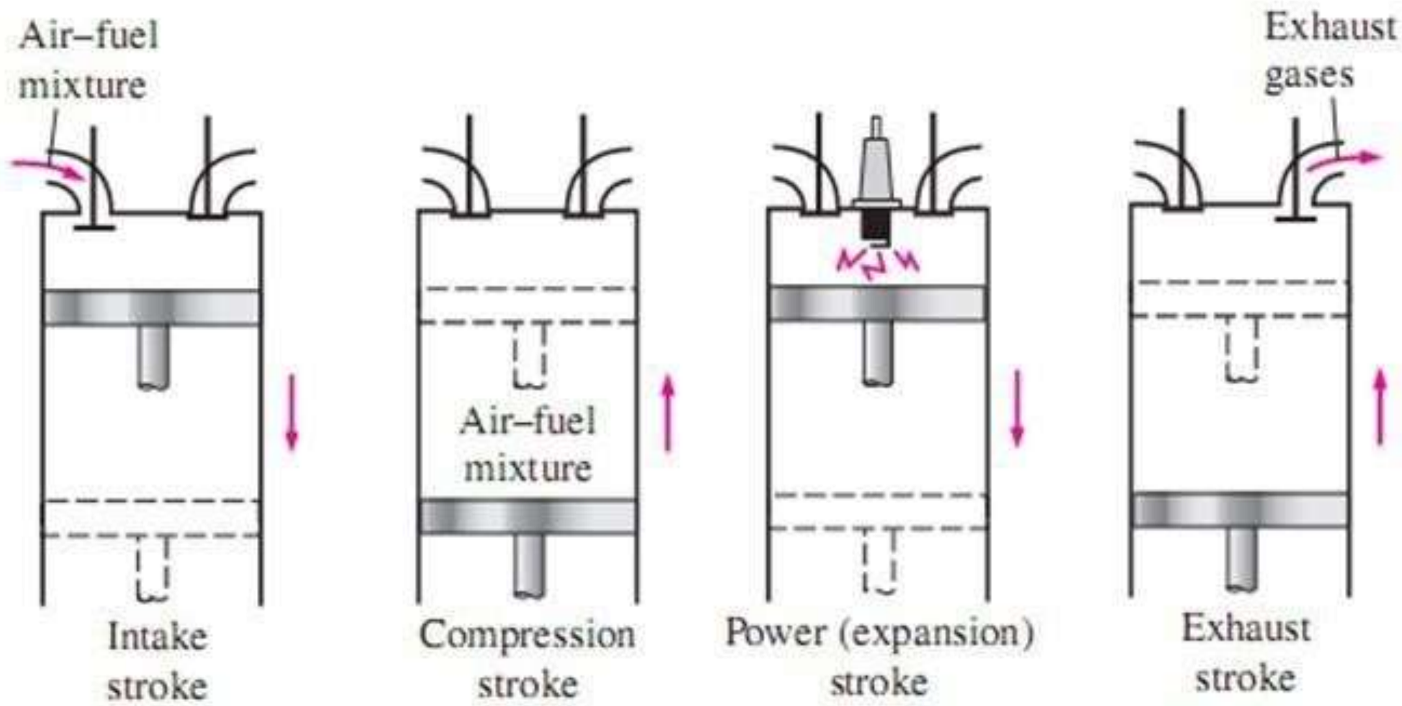
- Opposed cylinder Engines: The cylinders are arranged in two banks on opposite sides of the engine

- Radial Engines: The cylinders are arranged radially and equally spaced



Two stroke engine : It has two piston strokes over one revolution for each cycle.

- 4 Stroke engine

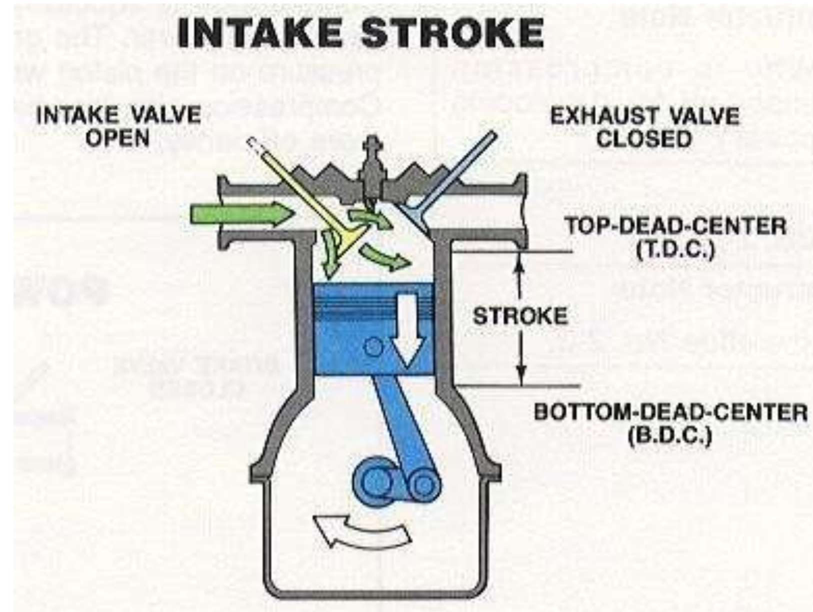


four-stroke spark-ignition engine

1. Suction/intake stroke

Intake of air-fuel mixture in cylinder through intake manifold when piston moves from TDC to BDC.

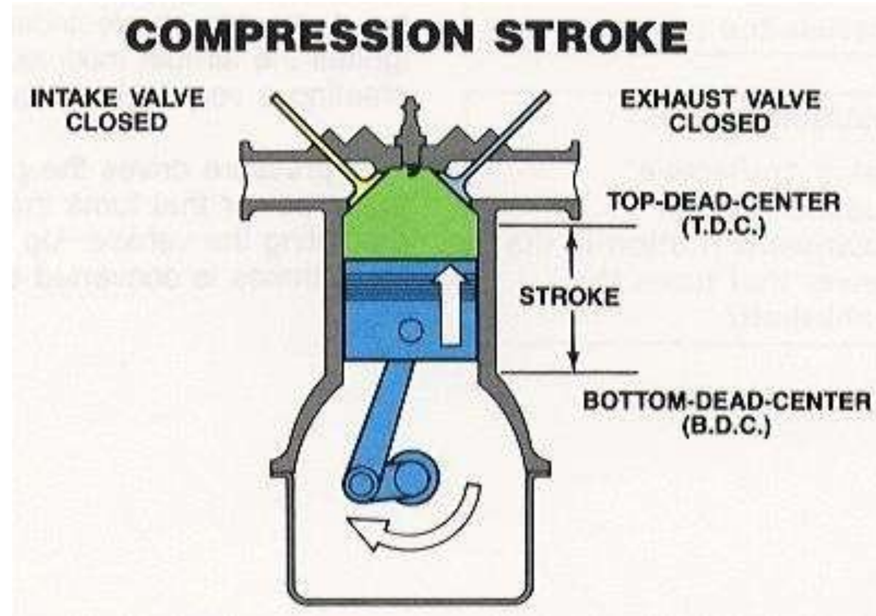
- The piston travel from TDC to BDC with the intake valve open and exhaust valve closed.



When the piston reaches BDC, the intake valve closes and the piston travels back to TDC with all valves closed.

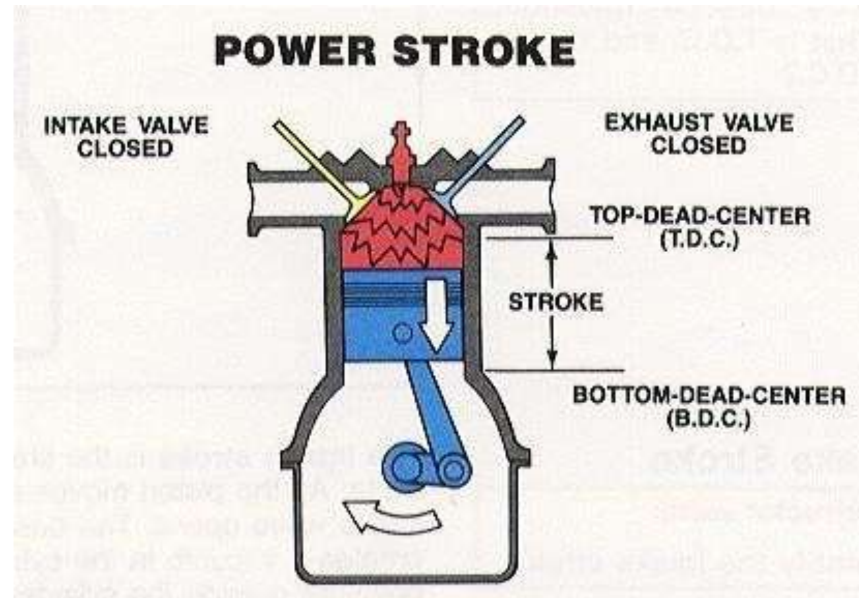
- This compresses air-fuel mixture, raising both the pressure and temperature in the cylinder.

- Near the end of the compression stroke the spark is given, and the combustion is initiated.



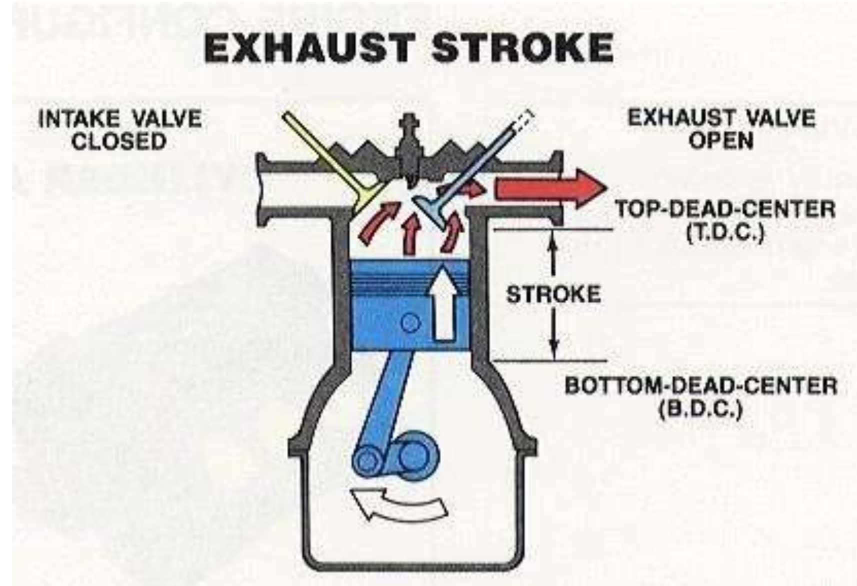
With all valves closed the high pressure created by the combustion process pushes the piston away from the TDC.

- This is the stroke which produces work output of the engine cycle.
- As the piston travels from TDC to BDC, cylinder volume is increased, causing pressure and temperature to drop.



4. Exhaust stroke

- With the exhaust valve remaining open, the piston travels from BDC to TDC in the exhaust stroke.
- This pushes most of the remaining exhaust gases out of the cylinder into the exhaust system at about atmospheric pressure, leaving only that trapped in the clearance volume when the piston reaches TDC.



Week-15

Lecture

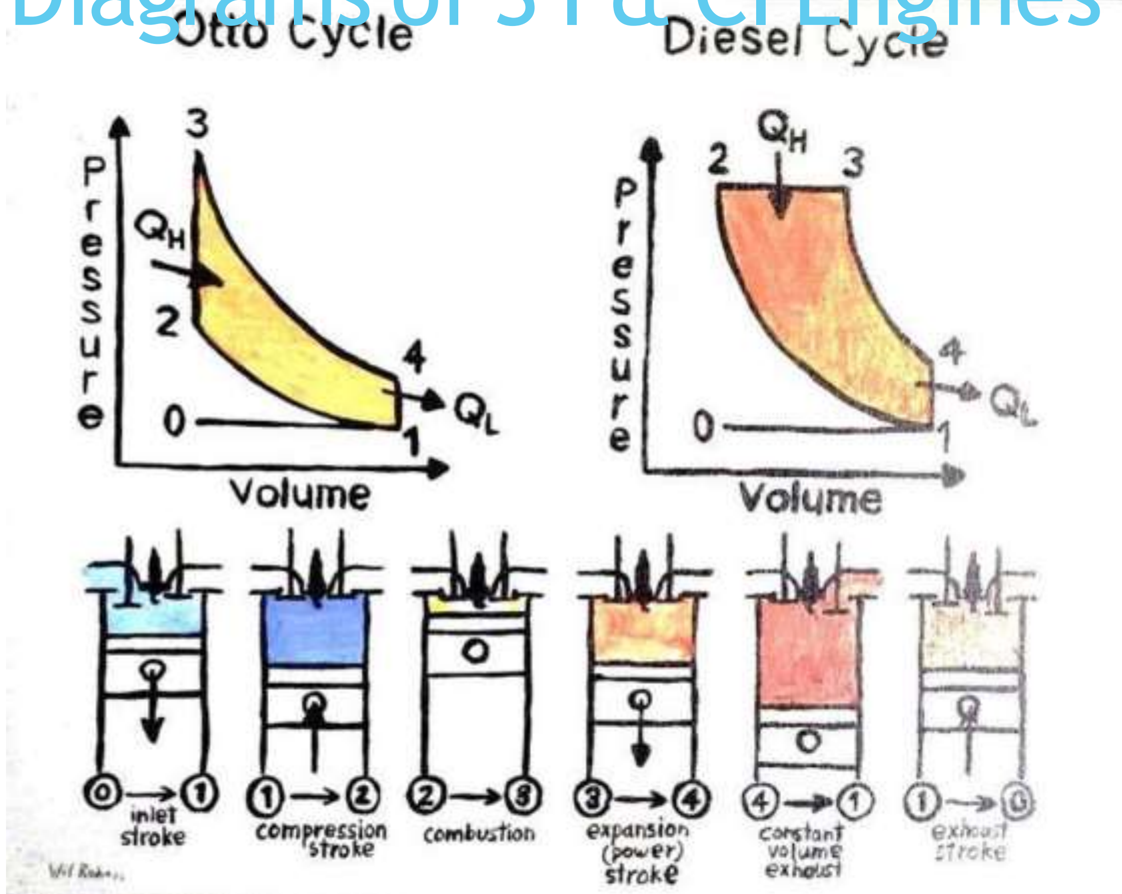
on

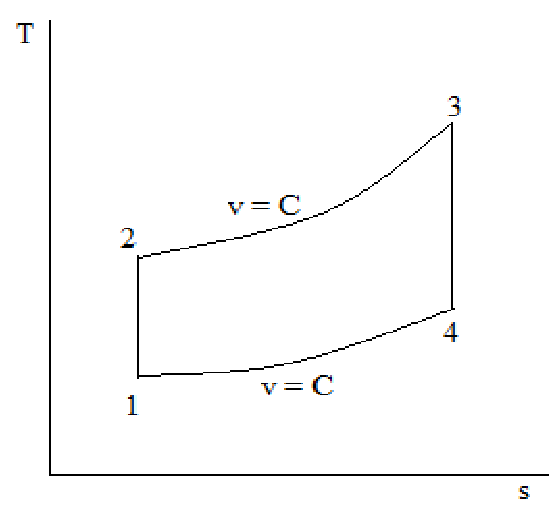
IC Engine

(SI and CI Engine)

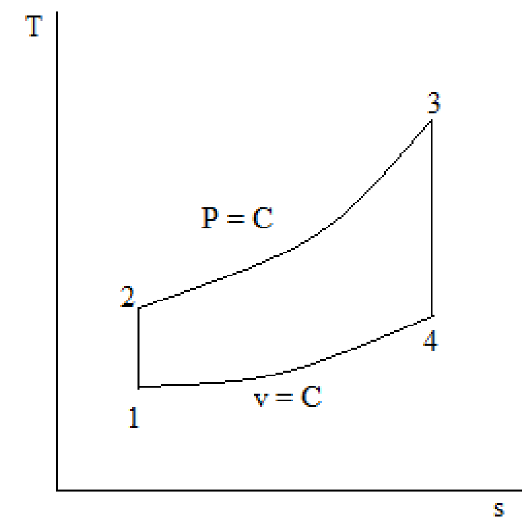
(185-195)

P-V Diagrams of SI & CI Engines





Otto Cycle

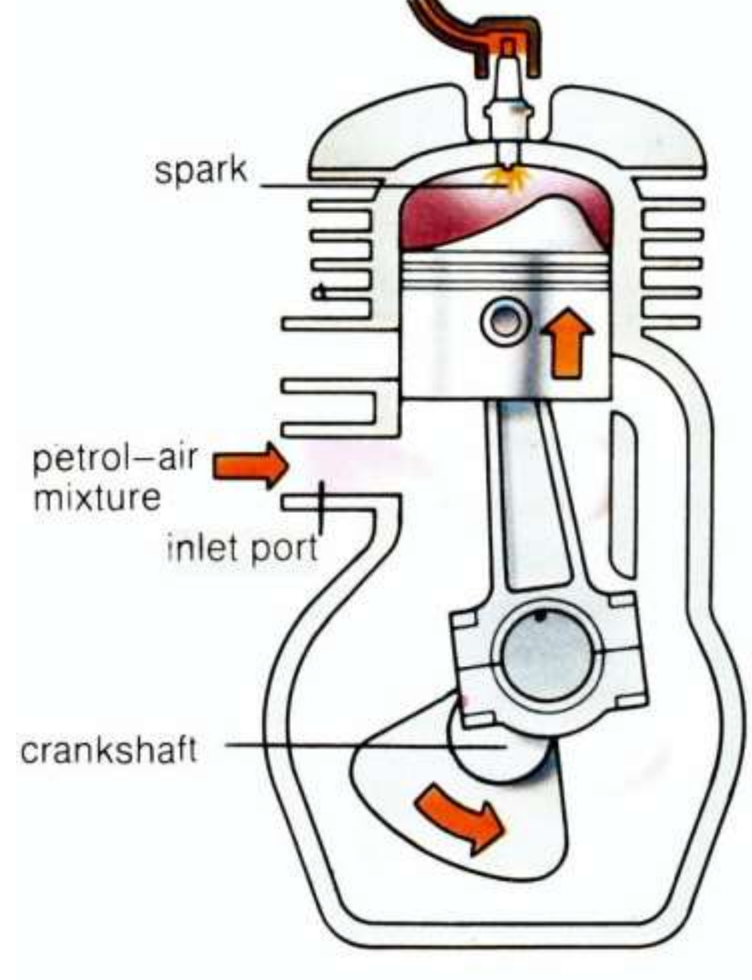


Diesel Cycle

Basic cycle	Otto	Diesel
Fuel	Volatile	Non-volatile
Introduction of Fuel	Carbureted/ Injected	Injected
Load control	Throttle Valve	Fuel Regulation
Ignition	Spark	Auto
r_k	6-10	16-20
Speed	High	Low
Thermal efficiency	Low (Low r_k)	High (High r_k)
Weight / Initial Cost	Low	High

Stroke 1

- The air fuel mixture in the cylinder compressed
- Air fuel mixture enters the crank case through inlet port
- Towards the end of the stroke, the fuel air mixture is ignited using the spark from the spark plug

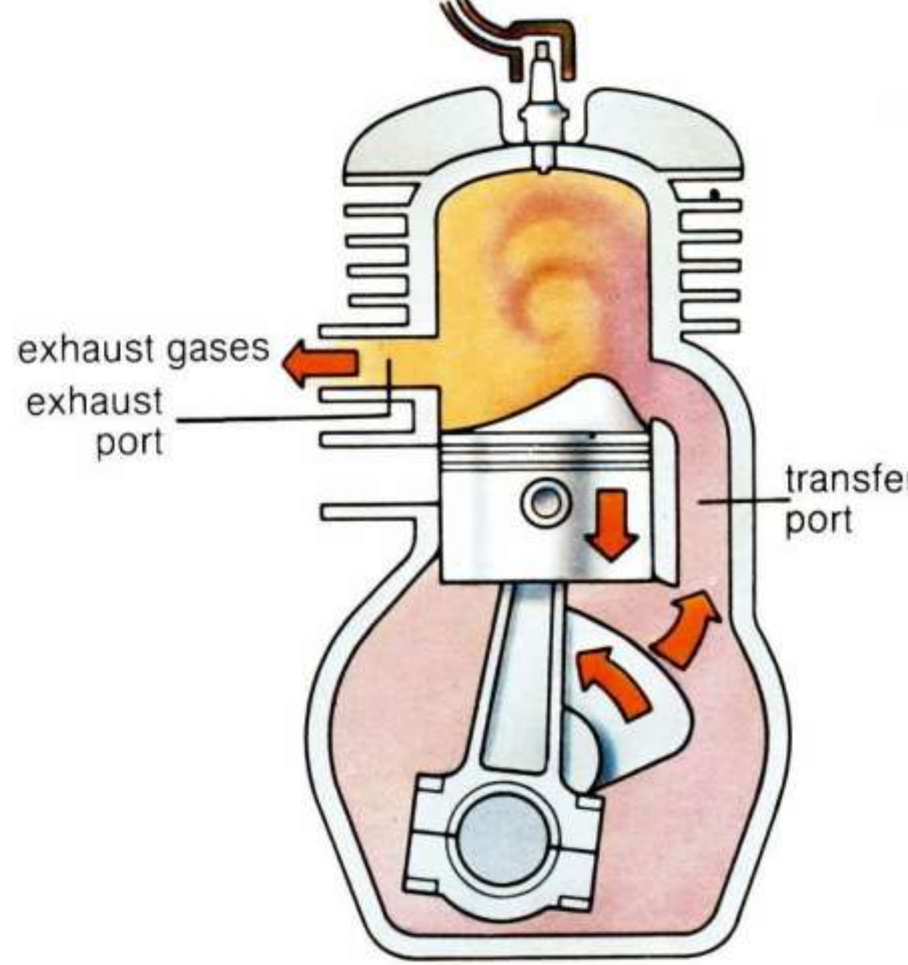


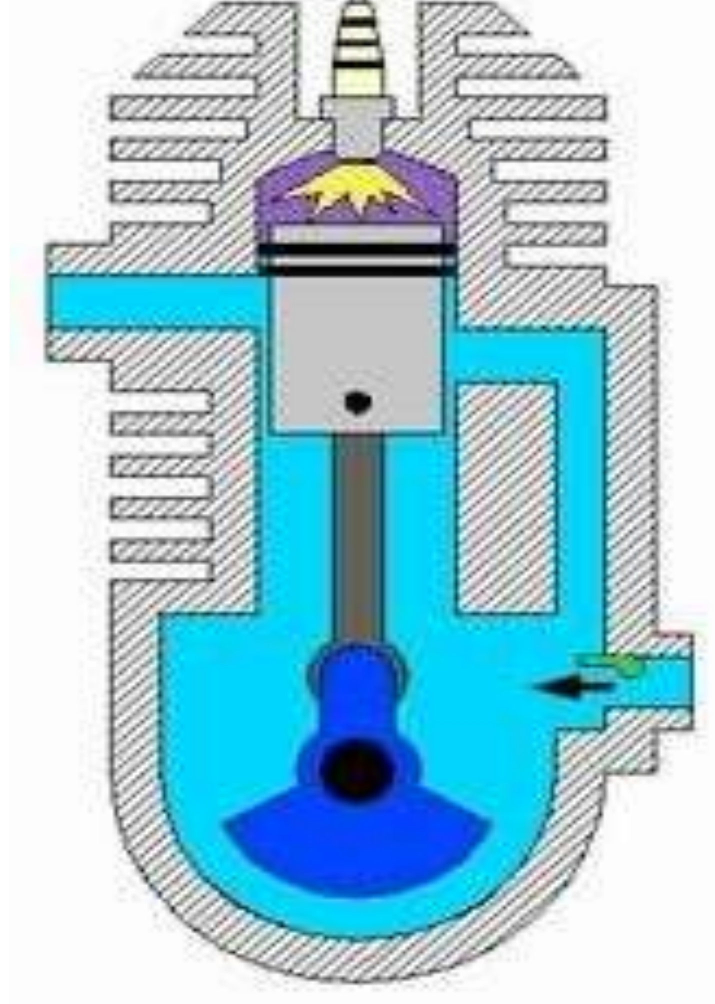
Stroke 2

- Piston moves downward due to the expansion of the gases

- Near the end of stroke, piston uncovers exhaust port and burnt gases escape through the port.

- Transfer port is uncovered and compressed air fuel mixture from the crankcase flows in to the cylinder





Advantages

- Two-stroke engines do not have valves, which simplifies their construction and lowers their weight.

- Two-stroke engines fire once every revolution, while four-stroke engines fire once every two revolutions. This gives two-stroke engines a significant power boost.

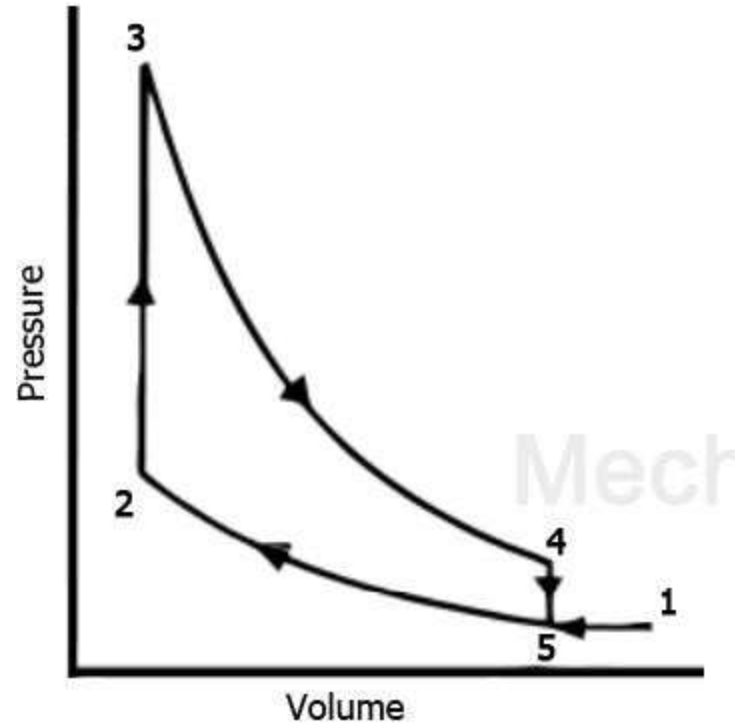
- Theoretically Two-stroke engines develops twice the power into the same space because there are twice as many power strokes per revolution.

- More uniform torque on crank shaft hence it requires a lighter flywheel than that for a four-stroke engine

Disadvantages

- The engines do not last as long due to poor lubrication.
- You have to mix engine oil with gasoline.
- The engines do not use fuel efficiently.
- These engines produce a lot of pollution.

Power stroke	1 for every two revolutions	1 for every revolutions
Turning moment	Less uniform	More uniform
Power/weight	less	more
Cooling/lubrication	lesser	greater
Mixing of fresh fuel and exhaust gases	Less (exhaust stroke)	More
Inlet and exhaust	Valves required	No valves, only ports
Initial cost	more	less
Volumetric/thermal efficiency	More	lower



Theoretical P-V Diagram for two-stroke petrol engine.

- Valve timing is the regulation of the points in the cycle at which the valves are set to open and close.

Reasons for actual valve timing:-

1. <u>Mechanical Factor</u>: - valves cannot be closed and opened abruptly because they are operated by cams. So that the opening of the valve must commence ahead of the time. (designed dead center)

2. <u>Dynamic Factor:</u> - actual valve timing is set taking into considering the dynamic effects of gas flow.

Week-16

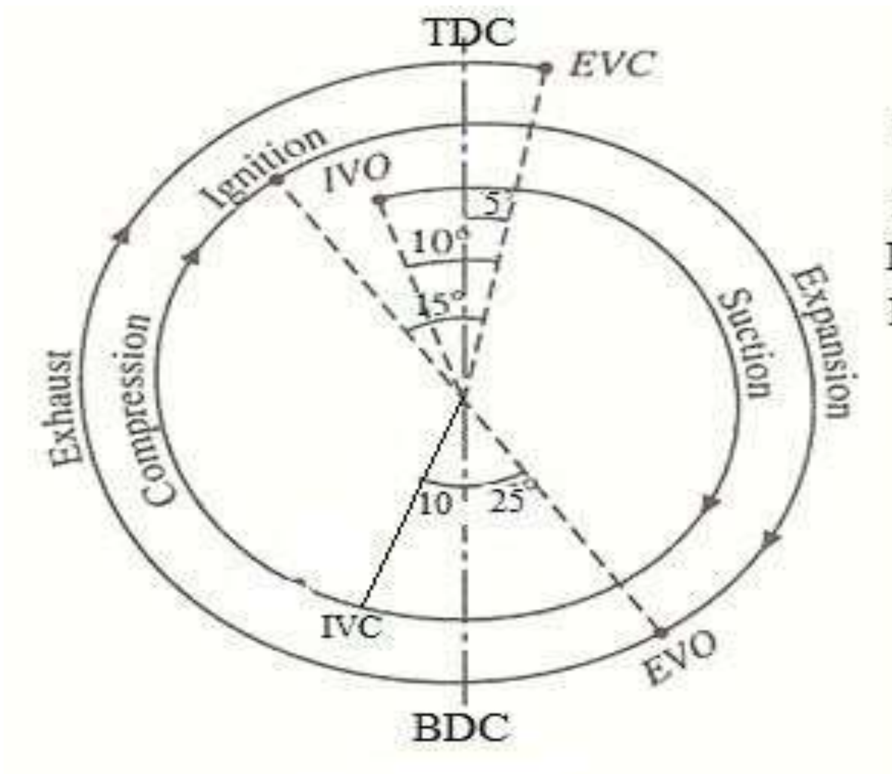
Lecture

on

IC Engine

Valve Timing Diagram

(197-202)



IVO - 10^0 bTDC

IVC - 10^0 - 60^0 aBDC

EVO - 25^0 - 55^0 bBDC

EVC - 5^0 - 20^0 aTDC

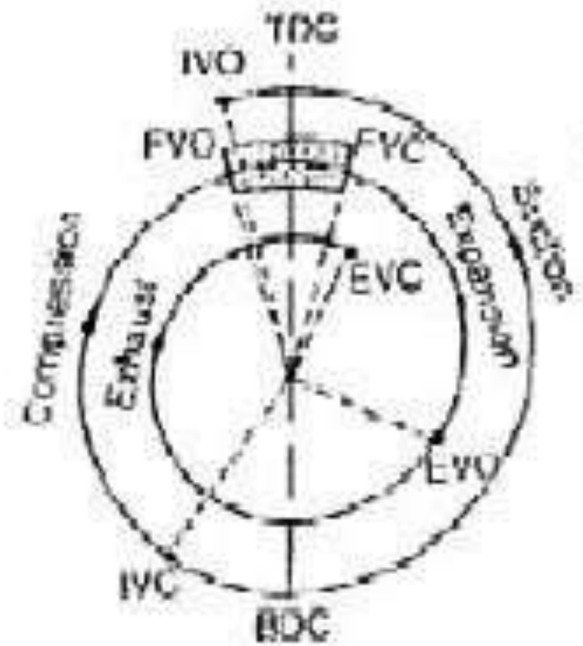
- The intake valve starts to open 10^0-20^0 before TDC.
- This is to ensure that the valve will be fully open and a fresh charge starts to flow into the cylinder as soon as the piston reaches TDC.
- As the piston moves out in the suction stroke, the fresh charge is drawn in through the intake valve, when the piston reaches the BDC and starts to move in the compression stroke, the inertia of the entering fresh tends to cause it to continue to move into cylinder.
- To take this advantage, inlet valve is closed 10^0-60^0 after TDC so that maximum air is taken in.
- This is called ram effect.

- Opening of exhaust valve earlier reduces the pressure near the end of the power stroke and thus causes some loss of useful work on this stroke.
- But it decreases the work necessary to expel the burned gases, results in overall gain in output.
- Closing of exhaust valve is delayed few degrees after TDC helps to scavenge the cylinder by carrying out a greater mass of exhaust gas due to its inertia force.
- This results in increased volumetric efficiency.

- It is a period when both the intake and exhaust valves are open at the same time.

- 15^o for low speed engines and 30^o for high speed engines.

- This overlap should not be excessive otherwise it will allow the burned gases to be sucked into the intake manifold, or the fresh charge to escape through exhaust valve.



TDC : Top dead centre

BDC : Bottom dead centre

IVO : Inlet valve opens (10^0 - 20^0 before *TDC*)

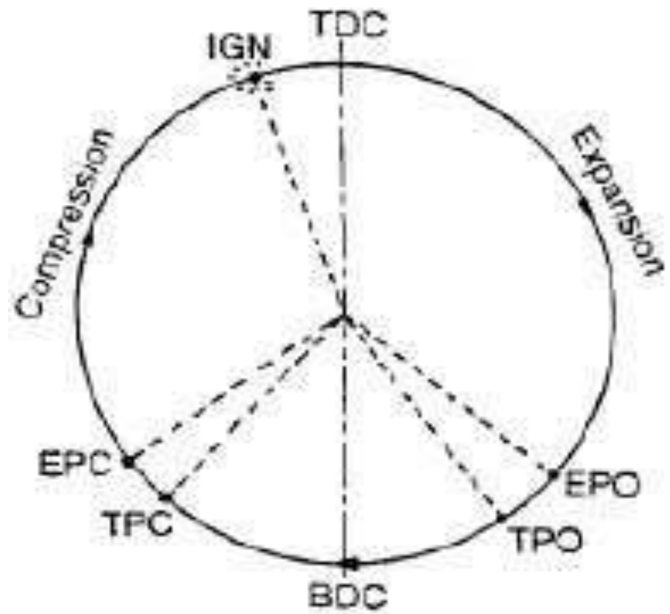
IVC : Inlet valve closes (25^0 - 40^0 after *BDC*)

FVO : Fuel valve opens (10^0 - 15^0 before *TDC*)

FVC : Fuel valve closes (15^0 - 20^0 after *TDC*)

EVO : Exhaust valve opens (39^0 - 50^0 before *BDC*)

EVC : Exhaust valve closes (10^0 - 15^0 after *TDC*)



TDC : Top dead centre

BDC : Bottom dead centre

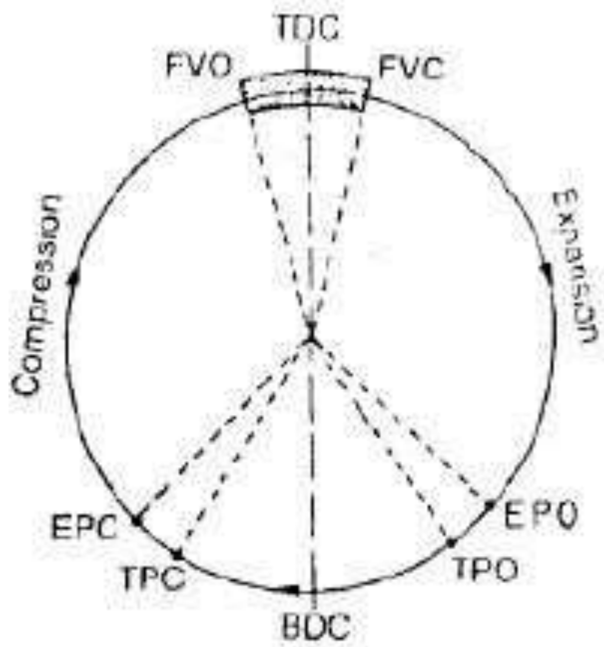
EPO : Exhaust port opens (35° - 50° before *BDC*)

TPO : Transfer port opens (30° - 40° before *BDC*)

TPC : Transfer port closes (30° - 40° after *BDC*)

EPC : Exhaust port opens (35° - 50° after *BDC*)

IGN : Ignition (15° - 20° before *TDC*)



TDC : Top dead centre

BDC Bottom dead centre

FVO : Fuel valve opens (10^0 - 15^0 before *TDC*)

FVC : Fuel valve closes (15^0 - 20^0 after *TDC*)

EPO : Exhaust port opens (35^0 - 50^0 before *BDC*)

TPO : Transfer port opens (30^0 - 40^0 before *BDC*)

TPC : Transfer port closes (30^0 - 40^0 after *BDC*)

EPC : Exhaust port closes (35^0 - 50^0 after *BDC*)

Thanks

For

Your Attention