PDHonline Course E360 (2 PDH)

Power Cycles

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COURSE CONTENT

Introduction

Vapor and gas power systems develop electrical or mechanical power from energy sources of chemical, solar, or nuclear origin. In vapor power systems the working fluid, normally water, undergoes a phase change from liquid to vapor, and conversely. In gas power systems, the working fluid remains a gas.

The present section introduces vapor and gas power systems. The processes taking place in power systems are very complicated hence to understand the same they are idealized with basic thermodynamic processes.

1 Rankine cycle and Brayton cycle

In their simplest form vapor power Rankine cycle and gas power Brayton cycle are shown in figure 1. They are made of four internally reversible processes which are two isentropic and two constant pressures. Both actual cycles is denoted by *1-2-3-4-1*while the ideal cycle is *1-2s-3-4s-1*. It is assumed that there is no pressure drop during boiler, condenser and heat exchangers.

The heat added is represented by the area under the isobar *2s – 3* and the heat rejected is represented by the area under the isobar 4s to 1.Enclosed area *1-2s-3-4s-1* represents the net heat added per unit of mass flowing. As we know for any power cycle, the net heat added equals the net work done.

Basic expressions for principle energy transfer are listed below:

$\dot{W}_p = \dot{m}(h_2 - h_1)$ In case of Rankine cycle (1)

$\dot{W}_c = \dot{m}(h_2 - h_1)$ In case of Brayton cycle (2)

$$\dot{Q}_{in} = \dot{m}\,(h_3 - h_2) \tag{3}$$

$$\dot{W}_t = \dot{m}\,(h_3 - h_4) \tag{4}$$

$$\dot{Q}_{out} = \dot{m}\,(h_1 - h_4) \tag{5}$$

Using these expressions, the thermal efficiency of Rankine cycle is

$$\eta = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2} \tag{6}$$

In equation 6 when h_2 is replaced with h_{2s} and h_4 is replaced with h_{4s}, it gives efficiency of ideal cycle. Equation 6 reveals that as average temperature of heat addition increases thermal efficiency increases. Also decrease in temperature of heat rejection increases thermal efficiency of Rankine and Brayton cycle.

In the Rankine cycle, a high average temperature of heat addition can be achieved by superheating the vapor prior to entering the turbine, and/or by operating at an elevated steam-generator pressure. In the Brayton cycle an increase in the compressor pressure ratio p2/p1 tends to increase the average temperature of heat addition. Owing to materials limitations at elevated temperatures and pressures, the state of the working fluid at the turbine inlet must observe practical limits, however. The turbine inlet temperature of the Brayton cycle, for example, is controlled by providing air far in excess of what is required for combustion. In a Rankine cycle using water as the working fluid, a low temperature of heat rejection is typically achieved by operating the condenser at a pressure below atmosphere. To reduce erosion and wear by liquid droplets on the blades of the Rankine cycle steam turbine, at least 90% quality should be maintained at the turbine exit i.e. $x4 > 0.9$. Brayton cycle is used in Gas Turbine power plant and Air craft engine while based on Rankine cycle Thermal Power plant works.

2 Modifications in Brayton cycle

Figure 2 shows schematic of open gas turbine cycle. The gas enters a compressor where it is compressed and delivered to combustor. Heat is added at constant pressure in combustor (theoretically) and hot gas expands through the turbine and then after mixes with atmosphere and fresh air is supplied to the compressor. The compressor is driven by turbine and difference is available on shaft as net power output. The compression of air in compressor and expansion of gas in turbine are ideally isentropic in nature.

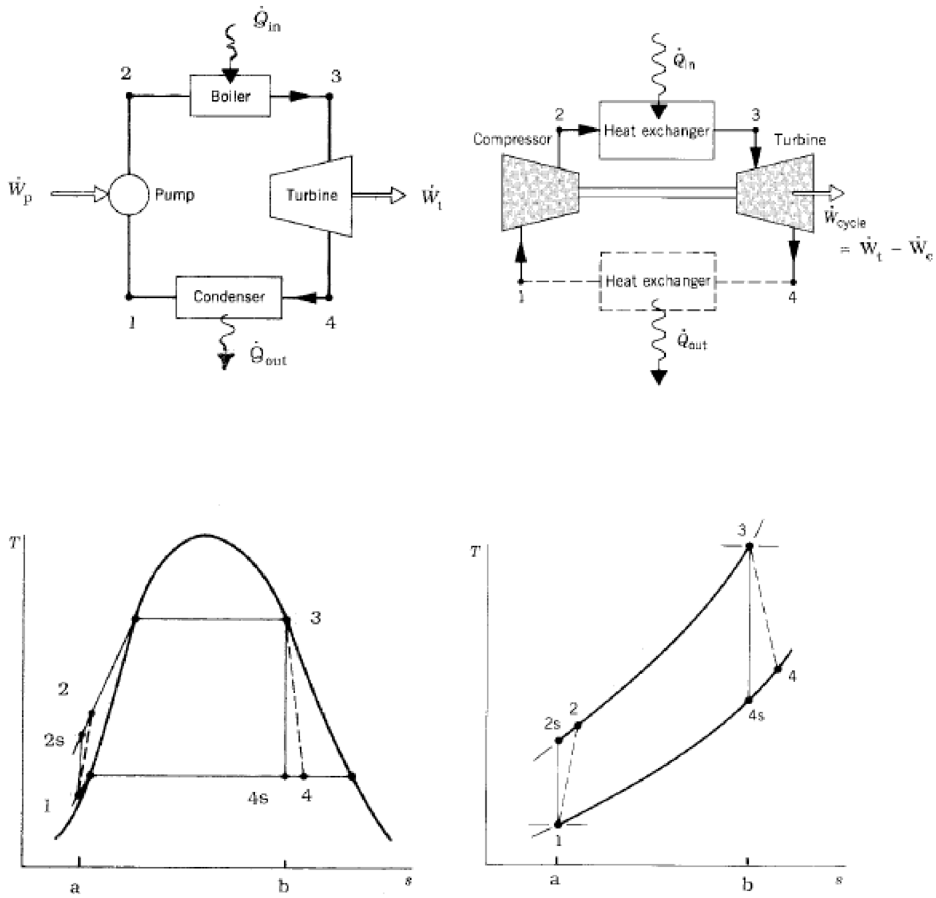

Figure 1 Rankine and Brayton cycles

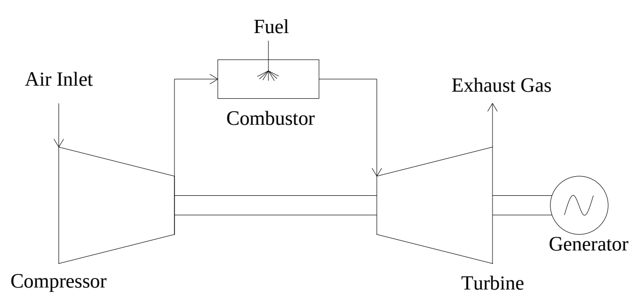

Figure 2 Open cycle gas turbine plant

Figure 3 shows intercooling and reheating on open cycle gas turbine plant and figure 4 shows regeneration on open cycle gas turbine plant both are the modifications of Brayton cycle. Use of intercooling between two stages of compression increases efficiency of cycle and similarly using staged heat supply increase power out put of turbine. In regeneration the waste heat of exhaust gas of turbine is utilized to increase the temperature of compressed air and hence the efficiency of the plant is shown in figure 4.

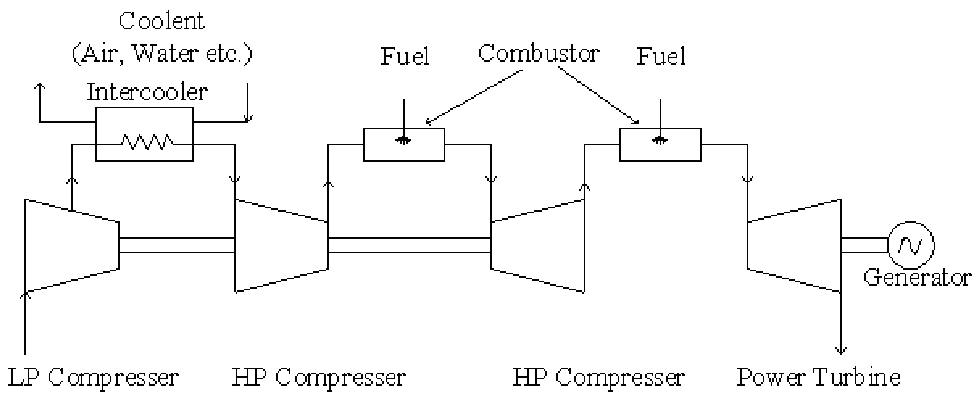

Figure 3 Intercooling and Reheating on Open Cycle Gas Turbine Plant

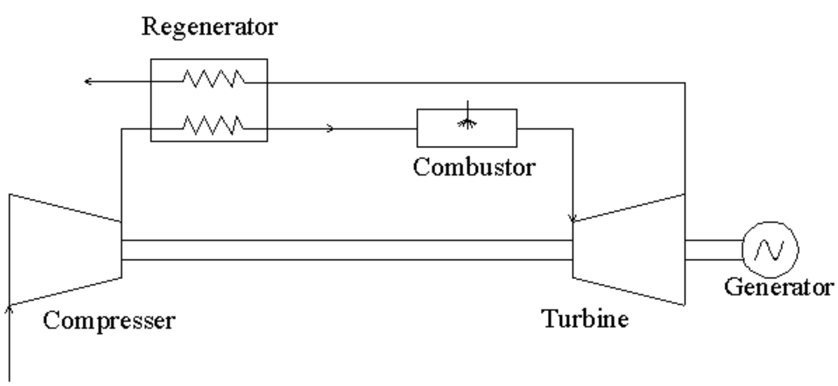

Figure 4 Regeneration on Open Cycle Gas Turbine Plant

Figure 5 shows schematic flow diagram of combined cycle consist of air compressor, combustor and gas turbine in topping cycle and heat recovery steam generator, steam turbine, condenser and pump in bottoming cycle. Path of open cycle gas turbine is indicated as *abcdef* Gas leaves the turbine at point *d* is further heated in combustion chamber where fuel is supplied and passes through heat recovery steam generator, which is a conventional steam generator having heat exchangers like evaporator, economizer, superheater, reheater etc. Gas turbine is usually operated with a high air-fuel ratio to make sufficient air available for further combustion. Gas leaves the Heat Recovery Steam Generator at *f*. Path followed by steam cycle is shown as *1234*. Efficiency of combined cycle power plant is in normally 55 to 60%.

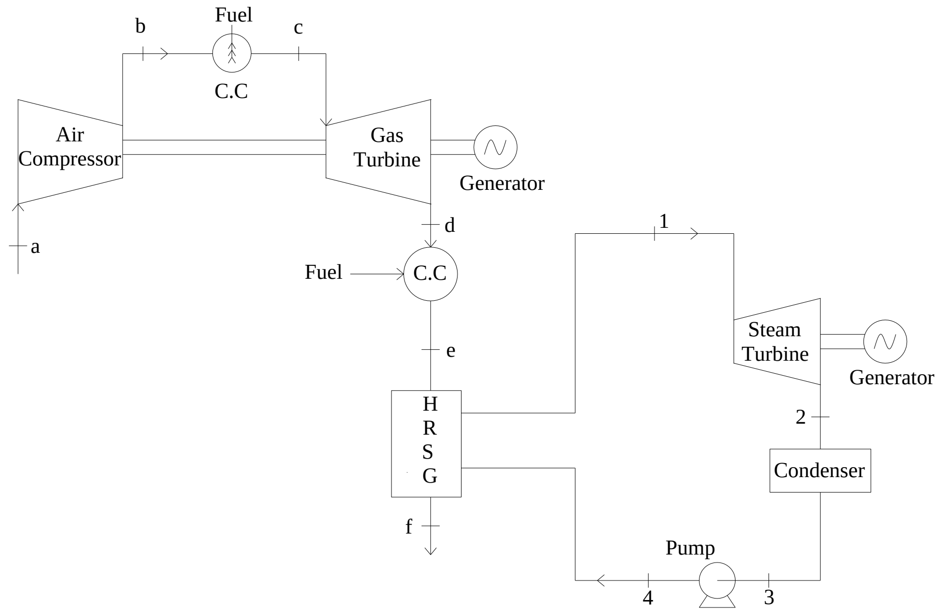

Figure 5 Schematic Flow Diagram of Combined Cycle Power Plant

3 Modifications in Rankine Cycle

The combustion gases leaving the boiler are at much higher temperature than saturation temperature at which steam is produced in a steam drum in ideal Rankine cycle resulting in irreversibility. Use of superheat and reheat reduces overall temperature difference between steam and gases and would improve the cycle thermal efficiency. Figure 6 and 7 shows Rankine cycle with superheat and reheat in which *ab* shows temperature drop in combustion gas and *1234* represents superheat cycle and *123456* is reheat cycle. Reheating is carried out at 20 to 25% of initial steam pressure to optimize the performance.

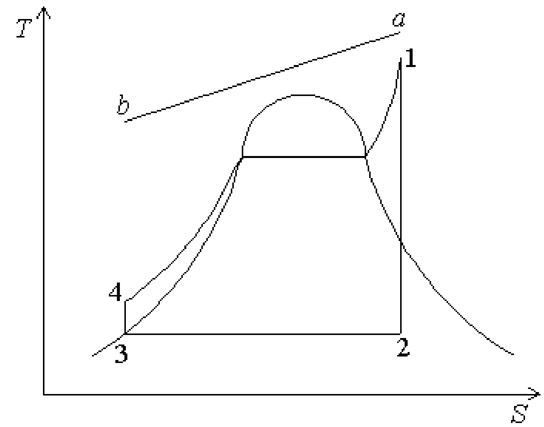

Figure 6 Rankine cycle with superheat

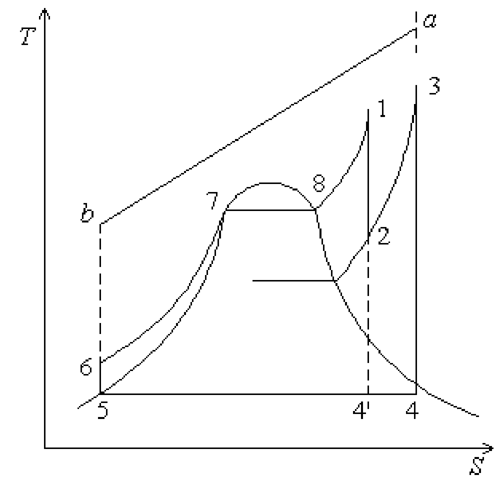

Figure 7 Rankine cycle with reheat

Another method to improve efficiency of ideal Rankine cycle is use of Regeneration through feed water heaters. Feed water heaters are basically of two types – open or closed, they extract live steam and use its energy to heat the condensate. In most thermal power plants closed feed water heaters are used with at least one open feed water heater to serve the purpose of deaeration. Though regeneration substantially increases thermal efficiency of Rankine cycle, the gain in efficiency successively diminishes with the increase in the number of feed water heaters. The schematic and T-s diagram of regeneration is shown in figure 8 and 9 respectively.

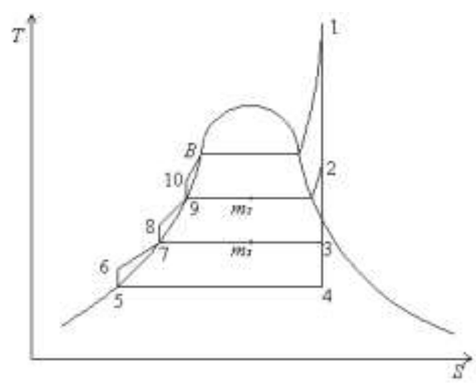

Figure 8 Rankine cycle with Regeneration

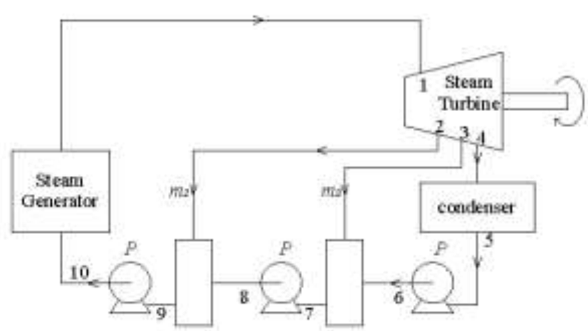

Figure 9 Schematic diagram of Regeneration

The overall efficiency of thermal power plant is given as:

$$\eta_{overall} = \frac{\text{power availlable at the generator}}{\text{rate of energy release by the combustion of fuel}} = \eta_{generator} \times \eta_{turbine} \times \eta_{thermal} \times \eta_{boiler} \quad (7)$$

The value of $\eta_{overall}$ is around 35% hence remaining 65% is lost to environment contributed by condenser loss, exhaust gas loss, generator and turbine inefficiency etc. Heat rate and Steam rate are two terms commonly used in thermal power plant. They are defined as following:

$$Heat\,rate = \frac{Q_1}{W_{net}} \tag{8}$$

$$Steam\,rate = \frac{1}{W_{net}} \frac{kg}{kWs} \tag{9}$$

This expresses the cycle efficiency and capacity of plant respectively.

4 Otto, Diesel and Dual Cycles

Two principal types of reciprocating internal combustion engines are the spark-ignition engine and the compression-ignition engine. In a spark-ignition engine a mixture of fuel and air is ignited by a spark plug. In a compression ignition engine air is compressed to a high-enough pressure and temperature that combustion occurs spontaneously when fuel is injected.

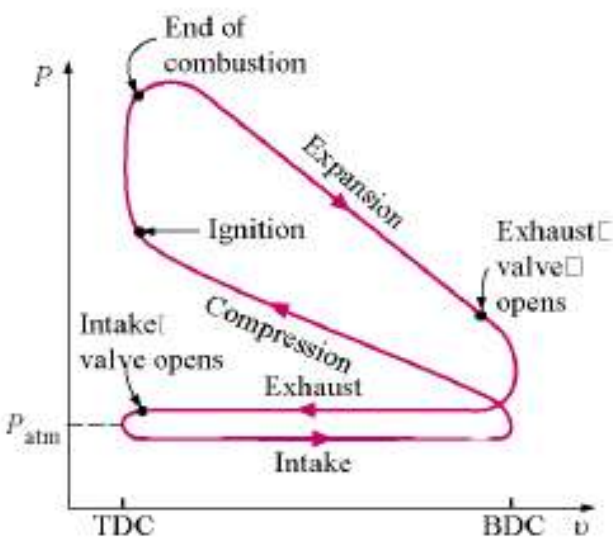

Figure 10 Pressure Displacement Diagram

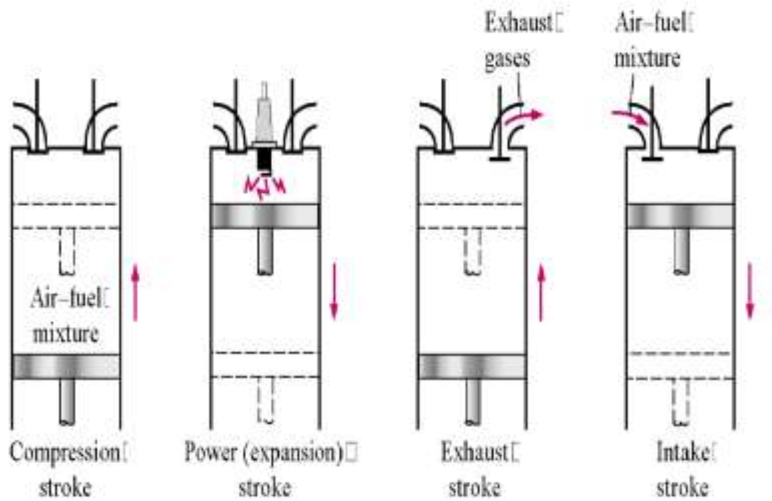

Figure 11 Actual four stroke spark ignition engine

In a four-stroke internal combustion engine, a piston executes four distinct strokes within a cylinder for every two revolutions of the crankshaft. Figure 10 shows pressure displacement diagram while the actual four stroke spark ignition engine with different piston positions is shown in figure11.

With the intake valve open, the piston executes an intake stroke to draw a fresh charge into the cylinder. Next, with both valves closed, the piston undergoes a compression stroke raising the temperature and pressure of the charge. A combustion process is then started, resulting in a high-pressure, high-temperature gas mixture. A power stroke follows the compression stroke, during which the gas mixture expands and work is done on the piston. The piston then executes an exhaust stroke in which the burned gases are expelled from the cylinder through the exhaust valve which is open. The process is completed in two strokes in smaller engines. In two-stroke engines, the intake, compression, expansion, and exhaust operations are accomplished in one revolution of the crankshaft.

The parameter measuring the performance of reciprocating engine is given as:

$$mean\ effective\ pressure = \frac{work\ done\ per\ cycle}{swept\ volume} \qquad (10)$$

Where the swept volume is the displacement volume, which is swept out by the piston as it moves from top dead center to the bottom dead center. For two engines of equal displacement volume, the one with a higher mean effective pressure would produce the greater net work and, if the engines run at the same speed, greater power.

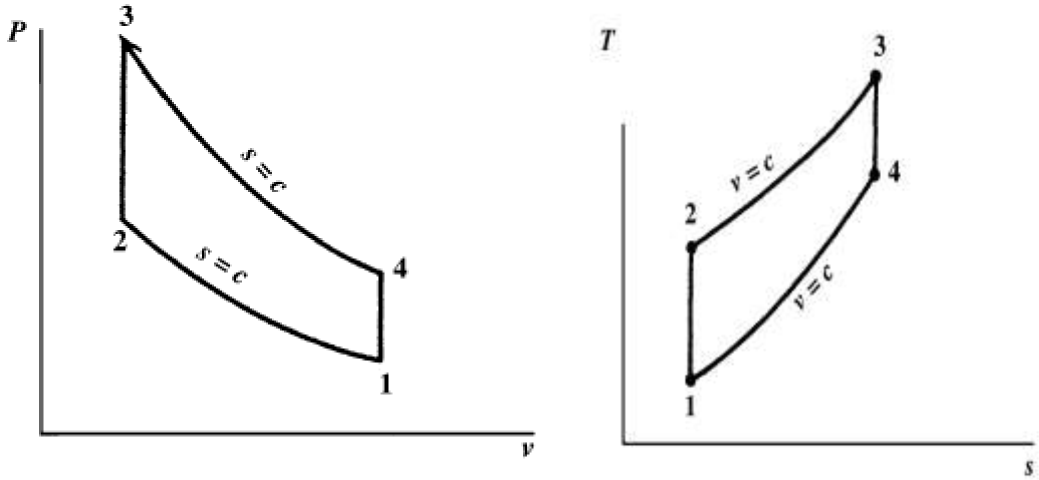

Figure 12 p-v and T-s diagram of Otto cycle.

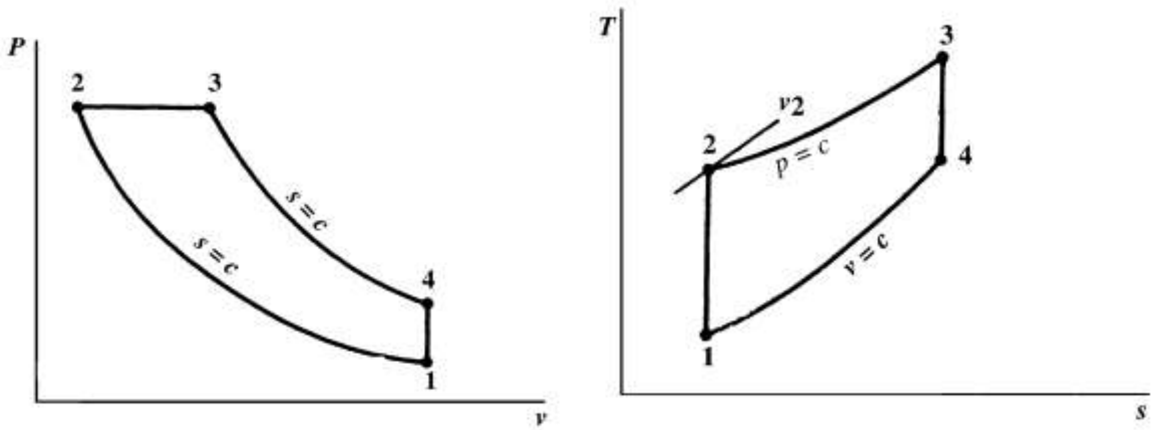

Figure 13 p-v and T-s diagram of Diesel cycle.

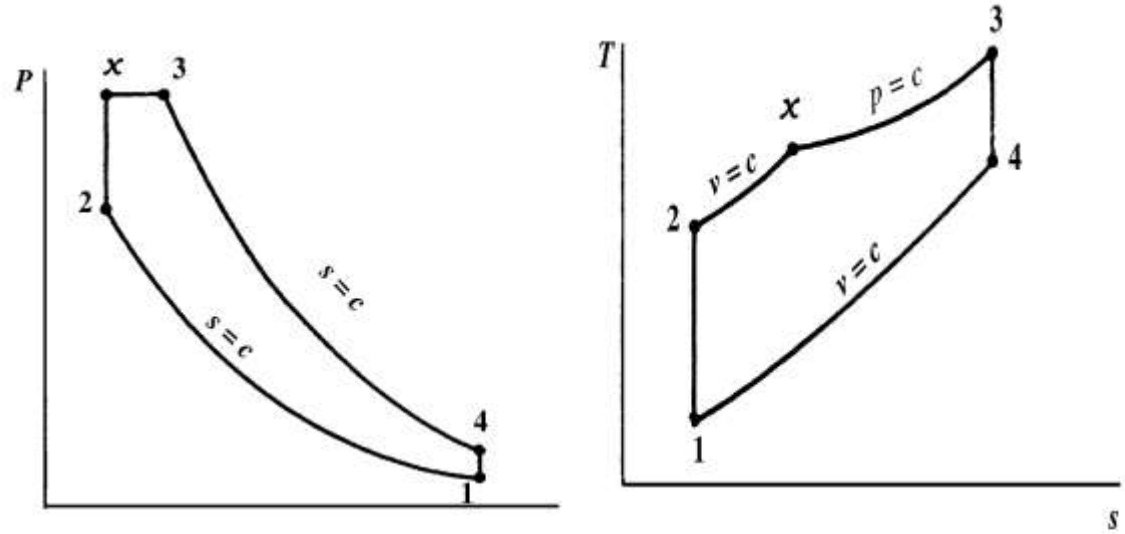

Figure 14 p-v and T-s diagram of Dual cycle.

Representation of Otto, Diesel and Dual cycle on p-v and T-s coordinates are shown in figure 12, 13 and 14 respectively. In all the cycle process *12* is isentropic compression. Heat addition is represented by process *23*, which is constant volume in Otto cycle, constant pressure in Diesel cycle and combined mode in Dual cycle. Heat addition is followed by isentropic expansion process *34* and finally heat is rejected at constant volume which is shown by process *41*.