SNS COLLEGE OF ENGINEERING

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Department of Mechanical Engineering

Academic Year 2024-2025

IAE 1 Answer key

Applied Thermodynamics

PART A

1. **Classify thermodynamic Systems.**

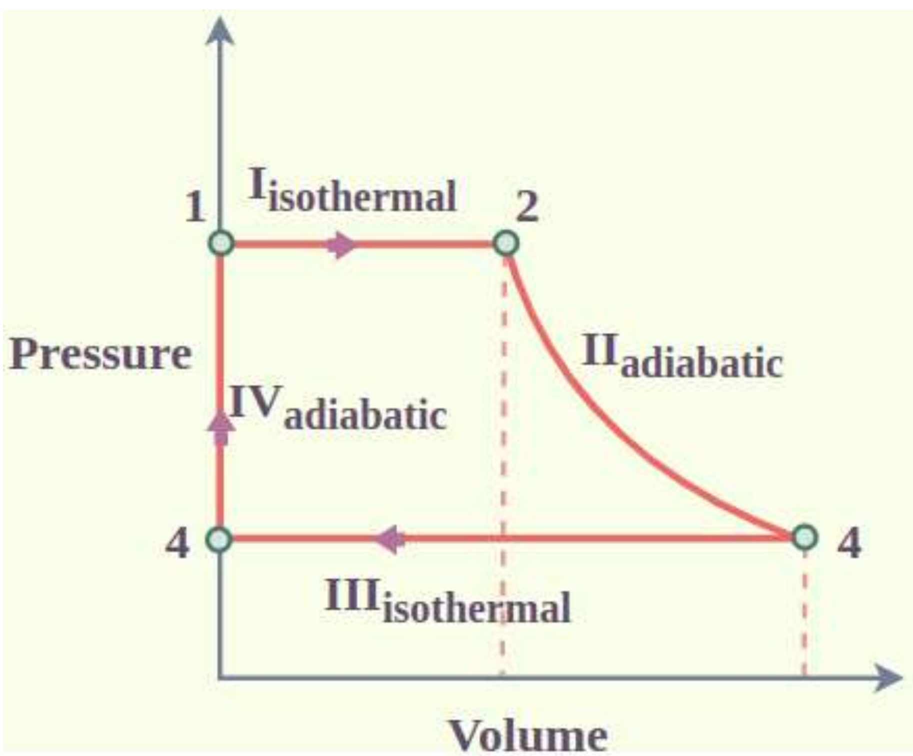
Type of System	Matter Exchange	Energy Exchange	Example
Open System	Yes	Yes	Boiling pot of water (steam escapes)
Closed System	No	Yes	Pressure cooker (heat transfer, no mass loss)
Isolated System	No	No	Thermos flask (no heat or matter exchange)

2. **What is meant by a thermodynamic System?**
A thermodynamic system is defined as a specific quantity of matter or a region in space that is separated from its surroundings by a boundary, allowing for the study of energy interactions and transformations according to the laws of thermodynamics. The system can be composed of matter and/or radiation, and its state is characterized by various thermodynamic properties such as temperature, pressure, and volume.
3. **State Kelvin Planck's statement of Second law of thermodynamics**
It is impossible to construct a device that operates on a cycle and produces no other effect than the transfer of heat from a single thermal reservoir to produce an equivalent amount of work.
4. **State Clausius statement of Second law of thermodynamics.**
It is impossible to design a device that operates on a cycle and produces no effect other than the transfer of heat from a colder body to a hotter body.

5. **Name the different components of a steam power plant working on a Simple Rankine cycle**

Component	Description
Boiler	Heats water to generate steam using fuel combustion or nuclear energy. It converts water into high-pressure steam.
Turbine	The high-pressure steam from the boiler drives the turbine blades, converting thermal energy into mechanical energy.
Generator	Connected to the turbine, it converts mechanical energy from the turbine into electrical energy through electromagnetic induction.
Condenser	Cools and condenses the exhaust steam from the turbine back into water, allowing for the reuse of water in the boiler.
Pump	Moves the condensed water back to the boiler for reheating, completing the cycle. The boiler feed pump is commonly used for this purpose.
Cooling System	Dissipates excess heat from the condenser, often utilizing cooling towers or nearby water sources to maintain efficiency.

6. Sketch p-v diagram of Simple Rankine Cycle.



7. What is thermodynamic definition of work?

Thermodynamic work is a process in which a thermodynamic system interacts with its surroundings to exchange energy, resulting in measurable macroscopic forces.

8. Enlist the similarities between heat and work

Both heat and work are fundamental concepts in thermodynamics, representing two distinct modes of energy transfer. Despite their differences, they share several similarities:

- Energy Transfer Mechanisms: Both heat and work are forms of energy transfer between a system and its surroundings. They are the only ways in which energy can be exchanged in thermodynamic processes, as stated in the first law of thermodynamics.
- Boundary Phenomena: Heat and work are recognized at the boundaries of a system. They occur when energy crosses the system's boundary, making them boundary phenomena rather than properties of the system itself.
- Path Functions: Both heat and work are path-dependent; their magnitudes depend on the specific process or path taken during the energy transfer. This contrasts with state functions, which depend only on the state of the system and not on how that state was reached.
- Not Exact Differentials: Neither heat nor work is described by exact differentials. Instead, they are considered inexact differentials, which means that their values cannot be determined solely from the initial and final states of a system

9. List the methods to increase efficiency of Rankine cycle.

- Increase Boiler Pressure: Raising the boiler pressure increases the temperature at which heat is added to the working fluid, thereby improving the thermal efficiency of the cycle. Higher pressure results in a greater temperature difference between the heat source and the working fluid, enhancing efficiency .

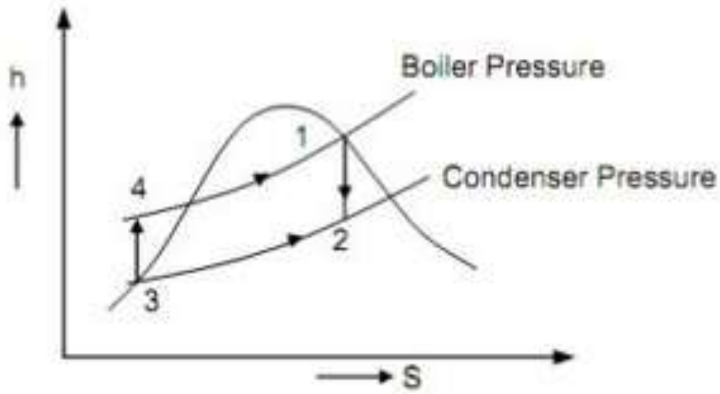
- Superheat the Steam: By superheating the steam before it enters the turbine, more energy can be extracted during expansion. This process increases the net work output and reduces moisture content at the turbine exit, which can also prevent turbine erosion .

- Decrease Condenser Pressure: Lowering the condenser pressure allows for greater expansion of steam in the turbine, leading to increased work output and improved cycle efficiency. However, care must be taken to avoid excessive moisture content in the steam

- Increase Mean Temperature of Heat Addition: Enhancing the average temperature at which heat is transferred to the working fluid in the boiler can significantly boost efficiency. This can be achieved through various design modifications or operational strategies .

- Use Regenerative Heating: Implementing a regenerative heating system can recover some of the waste heat from the exhaust steam to preheat the feedwater entering the boiler. This process improves overall thermal efficiency by reducing fuel consumption

10. Sketch h-s diagram of Simple Rankine cycle.



PART B &C

11.

2 kg of gas at a pressure of 1.5 bar occupies a volume of 2.5 m³. If this gas is isothermally compressed to 1/3 times the initial volume, find the (i) initial temperature (ii) final temperature (iii) work done and (iv) heat transfer. Assume R = 0.287 kJ/kgK.

Given data:

$m = 2\ kg$

$p_1 = 1.5\ bar = 150\ kN/m^2$

$V_1 = 2.5\ m^3$

$V_2 = \frac{1}{3} V_1 = \frac{1}{3} \times 2.5 = 0.83\ m^3$

$R = 0.287\ kJ/kgK$

Process : Isothermal or Constant temperature process

To find:

T_1, T_2, W and Q

Solution:

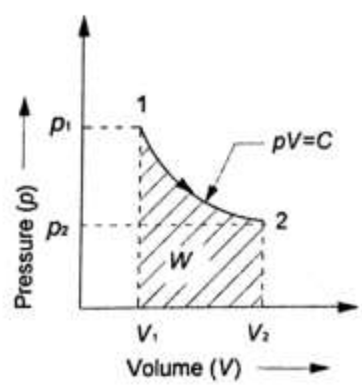


Figure 1.49

(i) Initial and final temperatures (T_1 and T_2):

$$p_1V_1 = mRT_1$$

$$\therefore \quad T_1 = \frac{p_1V_1}{mR} = \frac{150 \times 2.5}{2 \times 0.287} = \mathbf{653.31\ K} \qquad \textbf{Ans.}$$

For isothermal process, $T_1 = T_2 = \mathbf{653.31\ K}$ **Ans.**

(ii) Wok done (W):

$$W = mRT_1 \ln\left(\frac{V_2}{V_1}\right)$$

$$= 2 \times 0.287 \times 653.31 \times \ln\left(\frac{0.83}{2.5}\right)$$

$$= \mathbf{-413.48\ kJ} \qquad \textbf{Ans.}$$

Note: Here, negative sign indicates that the work is done on the system.

(iii) Heat transfer (Q):

From first law, $Q = W + \Delta U$

For isothermal process, $\Delta U = 0$

$$\therefore \quad Q = W = \mathbf{-413.48\ kJ} \qquad \textbf{Ans.}$$

Note: Here negative sign indicates that the heat is rejected by the system.

12.

One kg of gas expands at constant pressure from 0.085 m^3 to 0.13 m^3. If the initial temperature of the gas is 225°C, find the final temperature, net heat transfer, change in internal energy and the pressure of gas.

Given data:

$m = 1 kg$

$V_1 = 0.085 m^3$

$V_2 = 0.13\ m^3$

$T_1 = 225^oC = 225 + 273 = 498\ K$

Assume $C_p = 1.005\ kJ/kg\ K;\ C_v = 0.71 kJ/kg\ K$

To find:

T_2, Q, ΔU and p

☺ ***Solution:***

(i) Final Temperature (T_2):

By using p, V and T relation, $\frac{V_1}{V_2} = \frac{T_1}{T_2}$

$$T_2 = \frac{V_2}{V_1} \times T_1 = \frac{0.13}{0.085} \times 498 = \mathbf{761.6\ K}$$ **Ans.**

(ii) Heat Transfer (Q):

$$Q = mC_p (T_2 - T_1) = 1 \times 0.7\ (761.6 - 498) = \mathbf{264.9\ kJ}$$ **Ans.**

(iii) Change in internal energy (ΔU):

$$\Delta U = mC_v(T_2 - T_1) = 1 \times 0.7\ (761.6 - 498) = \mathbf{187.16\ kJ}$$ **Ans.**

(iv) Pressure (p):

$$p_1V_1 = mRT_1$$

$$p_1 = \frac{mRT_1}{V_1} = \frac{1 \times 0.295 \times 498}{0.085}$$

$$\left[\begin{array}{l} \because R = C_p - C_v \\ \quad = 1.005 - 0.71 \\ R = 0.295\ kJ/kg\ K \end{array}\right]$$

$$p_1 = \mathbf{1728.3\ kN/m^2} = p_2$$ **Ans.**

13.

10 kg of gas at 10 bar and 400°C expands reversibly and adiabatically to 1 bar. Find the work done and change in internal energy.

Given data:

$m = 10\ kg$

$p_1 = 10\ bar = 1000\ kN/m^2$

$T_1 = 400^oC = 400+273 = 673\ K$

$p_2 = 1\ bar = 100\ kN/m^2$

To find:

W and ΔU

☺ ***Solution:***

By adiabatic relation,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = \left(\frac{100}{1000}\right)^{\frac{1.4-1}{1.4}} \times 673 = 348.58\,K$$

Work done, $W = \dfrac{mR(T_1 - T_2)}{\gamma - 1}$

$$= \frac{10 \times 0.287 \times (673 - 348.58)}{1.4 - 1} = \mathbf{2327.74\,kJ} \quad \textbf{Ans.}$$

Change in internal energy,

$$\Delta U = m \times C_v \times (T_2 - T_1)$$

$$= 10 \times 0.718 \times (348.58 - 673) = \mathbf{-2327.74\,kJ} \quad \textbf{Ans.}$$

Alternately, from first law, $Q = W + \Delta U$

In adiabatic process, $Q = 0$

$$\therefore \quad W = -\Delta U = \mathbf{-2327.74\,kJ} \quad \textbf{Ans.}$$

14. A mass of 1.5 kg of air is compressed in an isothermal process from 0.1 MPa to 0.7 MPa. The initial density of air is 1.16 kg/m^3. Find the work done.

Given data:

$m = 1.5\,kg$

Process = quasi-static, $pV = C$ (Isothermal)

$p_1 = 0.1\,MPa = 100\,kN/m^2$

$p_2 = 0.7\,MPa = 700\,kN/m^2$

Initial density $(\rho_1) = 1.16\,kg/m^3$

To find:

Work done, W

☺ ***Solution:***

$$\text{Density} = \frac{\text{Mass }(m)}{\text{Volume}(V_1)}$$

$$\therefore \quad \text{Volume}, (V_1) = \frac{\text{Mass}(m)}{\text{Density}(\rho_1)} = \frac{1.5}{1.16} = 1.293\, m^3$$

For isothermal process, $p_1 V_1 = p_2 V_2$

$$V_2 = \frac{p_1 V_1}{p_2} = \frac{100 \times 1.293}{700} = 0.1847\ m^3$$

Work done for isothermal process, $W = p_1 V_1 \ln \frac{V_2}{V_1} = 100 \times 1.293 \times \ln\left(\frac{0.1847}{1.293}\right)$

$$= -251.6\ kJ$$

Ans.

(– ve sign indicates that the work is done on the system)

15. Three grams of Nitrogen gas at 6 atm and 160^{0}C in a frictionless piston is expanded adiabatically to double its initial volume, then compressed at constant pressure to its initial volume and again compressed at constant volume to its initial state. Calculate the net work done on the gas. Sketch the process in p-V plane.

Given data:

$m = 3\,g = 0.003\,kg$

$p_1 = 6\,atm = 6\times1.0132 = 6.0792\,bar$ [since, 1 atm = 1.0132 bar & 1 bar = 100 kPa]

$= 6.0792\times100 = 607.92\,kPa$

$T_1 = 160°C = 273+160 = 433\,K$

Process 1-2 is adiabatic expansion ($V_2 = 2V_1$)

Process 2 - 3 is constant pressure compression ($p_2 = p_3$ and $V_3 = V_1$)

Process 3 - 1 is constant volume compression ($V_3 = V_1$)

To find:

Net work done

Solution:

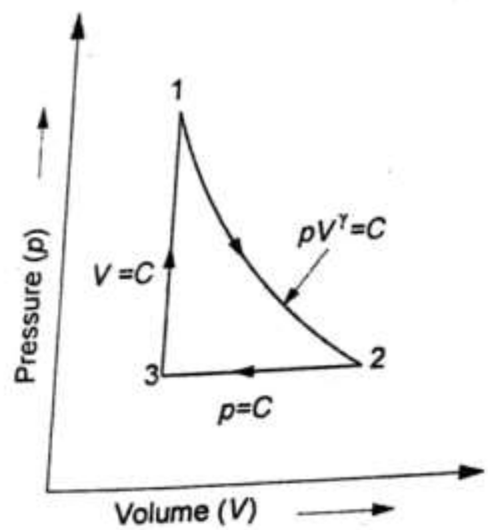


Figure 1.59 p-V diagram

$\gamma = 1.4$

$R = 0.287$

Molecular weight of nitrogen, $N_2 = 2\times14 = 28\,kg/kmol$

Gas constant of nitrogen, $R = \frac{\bar{R}}{M} = \frac{8.314}{28} = 0.297\,kJ/kgK$ [$\because \bar{R} = 8.314\,kJ/kgK$]

$R = C_p - C_v = 0.297\,kJ/kgK$

$\therefore \quad C_p = R + C_v$

By assuming

$C_v = 0.731\,kJ/kgK$

$\therefore \quad C_p = 0.297 + 0.731 = 1.028\,kJ/kgK$

So, $$\gamma = \frac{C_p}{C_v} = \frac{1.028}{0.731} = 1.406$$

Process 1-2: Adiabatic expansion process

From the relations of adiabatic expansion process,

$$p_1V_1^{\gamma} = p_2V_2^{\gamma}$$

$$p_2 = p_1\left(\frac{V_1}{V_2}\right)^{\gamma}$$

$$p_2 = p_1\left(\frac{V_1}{2V_1}\right)^{\gamma} = p_1\left(\frac{1}{2}\right)^{\gamma} \qquad [\because V_2 = 2V_1]$$

$$p_2 = 607.92 \times \left(\frac{1}{2}\right)^{1.406} = 229.4\ kPa$$

From ideal gas equation,

$$p_1V_1 = mRT_1$$

$$V_1 = \frac{mRT_1}{p_1} = \frac{0.003 \times 0.297 \times 433}{607.92} = 0.000635\ m^3$$

$$V_2 = 2V_1 = 2 \times 0.000635 = 0.00127\ m^3$$

Work done, $$W_{1-2} = \frac{p_1V_1 - p_2V_2}{n-1}$$

$$= \frac{607.92 \times 0.000635 - 229.4 \times 0.00127}{1.4 - 1}$$

$$= 0.237\ kJ$$

Process 2-3: Constant pressure process

For constant pressure process,

Work done, $W_{2-3} = p_2(V_3 - V_2)$

$$= 229.4 \times (0.000635 - 0.00127) \qquad [\because V_3 = V_1]$$

$$\therefore \quad = -0.147\ kJ$$

Process 3-1: Constant volume process

For constant volume process,

Work done, $W_{3-1} = 0$

Net work, $W_{net} = W_{1-2} + W_{2-3} + W_{3-1}$

$= 0.237 - 0.147 + 0 = \mathbf{0.09\ kJ}$ **Ans.**

16. **90 kJ of heat is supplied to a system at constant volume. The system rejects 95 kJ of heat at constant pressure and 18 kJ of work is done on it. The system is brought to its original state by adiabatic process. Determine (i) Adiabatic work (ii) Values of Internal energy at all states if initial value is 105 kJ.**

Given data:

Process 1-2 is constant volume

$Q_{1-2} = 90\ kJ$

Process 2-3 is constant pressure

$Q_{2-3} = -95\ kJ$ (–ve sign indicates the heat rejection)

$W_{2-3} = -18\ kJ$ (–ve sign indicates the work done on the system)

Process 3-1 is adiabatic. So, $Q_{2-3} = 0$

$U_1 = 105\ kJ$

To find:

(i) Adiabatic work

(ii) Internal energy at all salient points.

Solution:

Process 1-2: Constant volume process

For constant volume process,

Work done, $W_{1-2} = 0$

Based on first law of thermodynamics,

Heat suuply, $Q_{1-2} = W_{1-2} + \Delta U_{1-2}$

$$90 = 0 + \Delta U_{1-2}$$

$\therefore \quad \Delta U_{1-2} = 90\ kJ$

But, $\Delta U_{1-2} = U_2 - U_1$

$$90 = U_2 - 105$$

$\therefore$ $$U_2 = 195\ kJ$$ **Ans.**

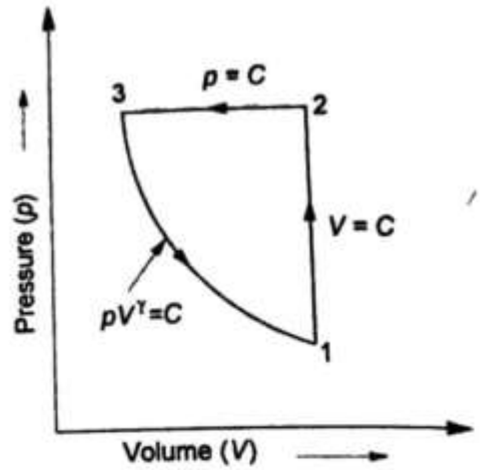


Figure 1.60 p-V diagram

Process 2-3: Constant pressure process

For constant pressure process,

$$Q_{2\text{-}3} = -95\ kJ$$

$$W_{2\text{-}3} = -18\ kJ$$

Based on first law of thermodynamics,

Heat done, $$Q_{2-3} = W_{2-3} + \Delta U_{2-3}$$

$$-95 = -18 + \Delta U_{2-3}$$

$\therefore$ $$\Delta U_{2-3} = -95 + 18 = -77\ kJ$$

But, $$\Delta U_{2-3} = U_3 - U_2$$

$$-77 = U_3 - 195$$

$\therefore$ $$U_3 = 195 - 77 = \mathbf{118\ kJ}$$ **Ans.**

Process 3-1: Adiabatic process

For adiabatic process,

$$Q_{2\text{-}3} = 0$$

From first law of thermodynamics for cyclic process,

$$\oint dQ = \oint dW$$

$$Q_{1\text{-}2} + Q_{2\text{-}3} + Q_{3\text{-}1} = W_{1\text{-}2} + W_{2\text{-}3} + W_{3\text{-}1}$$

$$90 - 95 + 0 = 0 - 18 + W_{3\text{-}1}$$

Adiabatic work, $W_{3\text{-}1} = 13\ kJ$ **Ans.**

17. 50 kg/min of air enters the control volume in a steady flow system at 2 bar and 100⁰C and at an elevation of 100 m above the datum. The same mass leaves the control volume at 150 m elevation with a pressure of 10 bar and the temperature of 300⁰C. The entrance velocity is 2400 m/min and exit velocity is 1200 m/min. During the process, 50000 kJ/hr of heat is transferred to the control volume and rise in enthalpy is 8 kJ/kg. Calculate power developed.

Given data:

$$m = 50\ kg/min = \frac{50}{60} = 0.83\ kg/s$$

$$p_1 = 2\ bar = 200\ kN/m^2$$

$$T_1 = 100°C = 100+273 = 373K$$

$$z_1 = 100\ m$$

$$z_2 = 150\ m$$

$$p_2 = 10\ bar = 1000\ kN/m^2$$

$$T_2 = 300°C = 300+273 = 573K$$

$$C_1 = 2400\ m/min = \frac{2400}{60} = 40\ m/s$$

$$C_2 = 1200\ m/min = \frac{1200}{60} = 20\ m/s$$

$$Q = 50000\ kJ/hr = \frac{50000}{3600} = 13.89\ kJ/s$$

$$h_2 - h_1 = 8\ kJ/kg$$

To find:

Power developed, P

Solution:

SFEE is given by

$$\frac{gz_1}{1000} + \frac{C_1^2}{2000} + h_1 + Q = \frac{gz_2}{1000} + \frac{C_2^2}{2000} + h_2 + W$$

$$W = \frac{g(z_1 - z_2)}{1000} + \frac{C_1^2 - C_2^2}{2} + (h_1 - h_2) + Q$$

$$W = \frac{9.81(100-150)}{1000} + \frac{(40^2 - 20^2)}{2000} - 8 + 13.89$$

$$W = 6\ kJ/kg$$

Power developed, $P = W \times m$

$$= 6 \times 0.83 = 4.98\ kJ/s = 4.98\ kW$$ **Ans.**

18.

In a steady flow process, 125 kJ of work is done by each kg of working fluid. The specific volume, velocity and pressure of the working fluid at inlet are 0.41 m³/kg, 15.5 m/s and 6 bar respectively. The inlet is 31 m above the ground and the exhaust pipe is at the ground level. The discharge conditions of the working fluid are 0.64 m³/kg, 1 bar and 263 m/s. The total heat loss between inlet and discharge is 8.7 kJ/kg of fluid. In flowing through this apparatus, does the specific internal energy increase or decrease and by how much?

Given data:

$W = 125\ kJ/kg$

$v_1 = 0.41\ m^3/kg$

$C_1 = 15.5\ m/s$

$p_1 = 6\ bar = 600\ kN/m^2$

$z_1 = 31\ m$

$z_2 = 0$

$v_2 = 0.64\ m^3/kg$

$C_2 = 263\ m/s$

$p_2 = 1\ bar = 100\ kN/m^2$

$Q = -8.7\ kJ/kg$ ($\because$ Heat loss)

To find:

Whether the internal energy increases or decreases and how much.

Solution:

The steady flow energy equation is given by

$$\frac{gz_1}{1000} + \frac{C_1^2}{2000} + u_1 + p_1v_1 + Q = \frac{gz_2}{1000} + \frac{C_2^2}{2000} + u_2 + p_2v_2 + W$$

$$u_1 - u_2 = \frac{g(z_2 - z_1)}{1000} + \frac{C_2^2 - C_1^2}{2000} + (p_2v_2 - p_1v_1) + W - Q$$

$$u_1 - u_2 = \frac{9.81(0-31)}{1000} + \frac{(263)^2 - (15.5)^2}{2000} + (100 \times 0.64 - 600 \times 0.4\ldots$$

$$+ 125 - (-8.7\ldots$$

$$u_1 - u_2 = -0.304 + 34.46 - 182 + 125 + 8.7$$

$$u_1 - u_2 = -14.14\ kJ/kg$$

$\therefore$ $\mathbf{u_2 - u_1 = 14.14\ kJ/kg}$ **Ans.**

19.

Dry saturated steam is supplied to a steam turbine at 12 bar and after the expansion its condenser pressure is 1 bar. Find the Rankine cycle efficiency, specific steam consumption. Neglect the feed pump work.

Given data:

$p_1 = 12\ bar$

$p_2 = 1\ bar$

To find:

1. $\eta_{Rankine}$
2. *SSC* and

Solution:

T-s diagram for Rankine cycle neglecting pump work is shown in Figure 3.27.

From saturated water table of pressure scale, corresponding to 12 *bar*,

$T_s = 187.99°C$ $h_1 = h_g = 2782.7\ kJ/kg,$

$s_1 = s_g = 6.519 kJ/kgK$

From saturated water table of pressure scale, corresponding to 1 *bar*,

$T_s = 99.63°C$

$h_{f_2} = 417.5\ kJ/kg,$ $h_{fg_2} = 2257.9\ kJ/kg,$

$s_{f_2} = 1.303\ kJ/kgK,$ $s_{fg_2} = 6.057\ kJ/kgK$

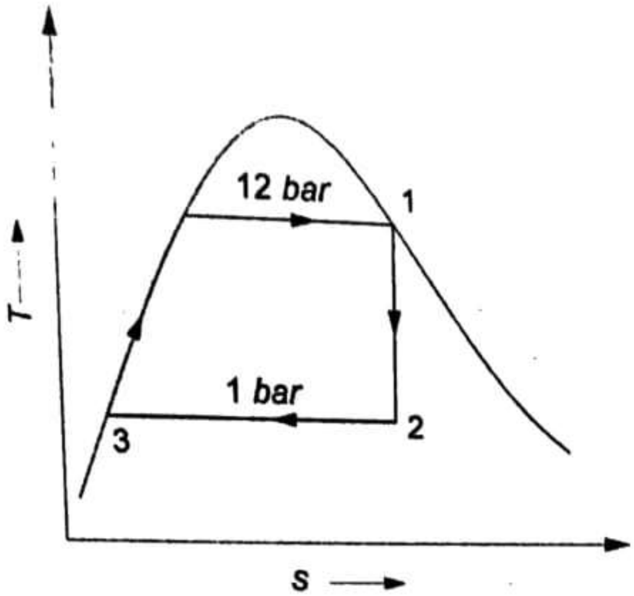


Figure 3.27 T-s diagram

Since the expansion process is isentropic.

$$s_1 = s_2 = 6.519 kJ/kgK$$

$$s_2 = s_{f_2} + x_2 s_{fg_2}$$

$$6.519 = 1.303 + x_2 \times 6.057$$

$$x_2 = 0.861$$

Dryness fraction of steam after expansion in the turbine = 0.861

$$h_2 = h_{f_2} + x_2 h_{fg_2}$$

$$= 417.5 + 0.861 \times 2257.9 = 2361.55 \ kJ/kg$$

Rankine cycle efficiency,

$$\eta_{Rankine} = \frac{h_1 - h_2}{h_1 - h_{f_2}} = \frac{2782.7 - 2361.55}{2782.7 - 417.5} = 0.1781 = \mathbf{17.81\%}$$ **Ans.**

Specific Steam Consumption (SSC),

$$SSC = \frac{3600}{W} = \frac{3600}{h_1 - h_2} = \frac{3600}{2782.7 - 2361.55} = \mathbf{8.55\ kg/kW\text{-}hr}$$ **Ans.**

20. A steam boiler generates steam at 30 bar, 300^{0}C and at the rate of 2 kg/s. The steam is expanded isentropically to a condenser pressure of 0.05 bar. Calculate (i) Heat Supplied to the boiler per hour (ii) Quality of steam after expansion (iii) Power generated by the turbine (iv) Rankine Cycle Efficiency.

Given data:

$p_1 = 30\ bar = 3000\ kPa$

$p_2 = 0.05\ bar = 5\ kPa$

$T_1 = 300°C$

$m = 2\ kg/s$

To find:

Q_s, x_2, W_T and η

☺ ***Solution:***

From saturated water table of pressure scale, corresponding to 30 *bar*, $T_{sat} = 233.8°C$

Since $T_1 > T_{sat}$, the state would be in the superheated region.

From superheated enthalpy and superheated entropy tables, at 30 *bar* and 300°C,

$$h_1 = 2995.1\ kJ/kg, \qquad s_1 = 6.542\ kJ/kgK$$

From saturated water table of pressure scale, corresponding to 0.05 *bar*,

$h_{f_2} = 137.8\ kJ/kg$, $h_{fg_2} = 2423.8\ kJ/kg$,

$s_{f_2} = 0.476\ kJ/kgK$, $s_{fg_2} = 7.920\ kJ/kgK$,

$v_{f_2} = 0.001005\ m^3/kg$

Since, the expansion process in turbine is isentropic,

$$s_1 = s_2 = 6.542\ kJ/kgK$$

But, $s_2 = s_{f_2} + x_2 \times s_{fg_2}$

$$\therefore\ x_2 = \frac{s_2 - s_{f_2}}{s_{fg_2}} = \frac{6.542 - 0.476}{7.920} = 0.766$$

$\therefore$ Quality of steam after expansion = **0.766 dry** **Ans.**

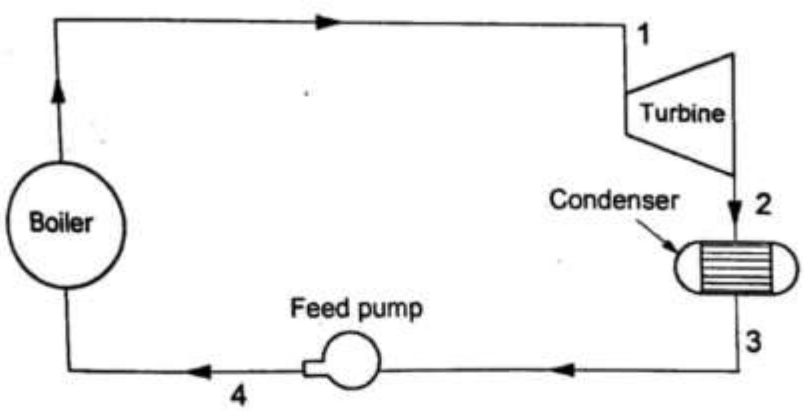


Figure 3.69 Schematic arrangement of the given plant

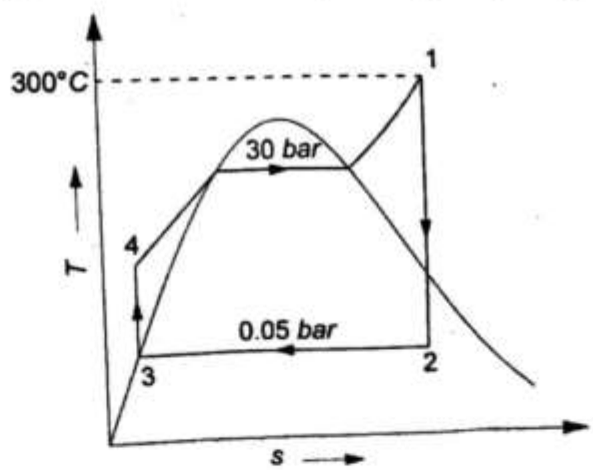


Figure 3.70 T-s diagram of Rankine cycle

$$h_2 = h_{f_2} + x_2 \times h_{fg_2} = 137.8 + 0.766 \times 2423.8 = 1994.43\ kJ/kg$$

$$h_3 = h_{f_2} = 137.8\ kJ/kg$$

Considering pump work,

$$h_4 - h_3 = v_{f_2}(p_1 - p_2)$$

$$h_4 = h_3 + v_{f_2}(p_1 - p_2)$$

$$= 137.8 + 0.001005 \times (3000 - 5) = 140.81\ kJ/kg$$

Heat supplied in the boiler,

$$Q_s = m \times (h_1 - h_4) = 2 \times (2995.1 - 140.81) = 5708.58\ kW$$ **Ans.**

Power generated by the turbine,

$$W_T = m \times (h_1 - h_2) = 2 \times (2995.1 - 1994.43) = \mathbf{2001.34\ kW}$$ **Ans.**

Rankine efficiency of the plant,

$$\eta = \frac{W_T - W_P}{Q_s} = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)}$$

$$= \frac{(2995.1 - 1994.43) - (140.81 - 137.8)}{(2995.1 - 140.81)}$$

$$= 0.3495 = \mathbf{34.95\%}$$

Ans.

21.

A steam plant working on a simple Rankine cycle operated between the temperature of 260°C and 95°C. The steam is dry and saturated when it enters the turbine and expanded isentropically. Find the Rankine efficiency.

Given data:

$T_1 = 260°C$

$x_1 = 1$

$T_2 = 95°C$

To find:

Rankine cycle efficiency

Solution:

From saturated water table of pressure scale, corresponding to $t_{sat} = 260°C$,

$$p_1 = p_{sat} = 46.943\ bar = 4694.3\ kN/m^2$$

$$h_1 = h_g = 2796.4\ kJ/kg,$$

$$s_1 = s_g = 6.001\ kJ/kgK$$

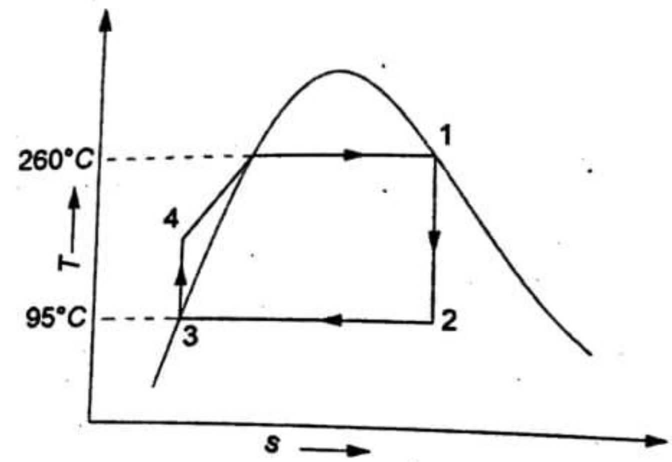


Figure 3.31 T-s diagram considering feed pump work

From saturated water table of temperature scale, corresponding to 95°C,

$$p_2 = p_{sat} = 0.84526\ bar = 84.526\ kN/m^2$$

$h_{f_2} = 398\ kJ/kg,$ $\quad h_{fg_2} = 2270.1\ kJ/kg,$

$s_{f_2} = 1.25\ kJ/kgK,$ $\quad s_{fg_2} = 6.167\ kJ/kgK,$ $\quad s_{g_2} = 7.417\ kJ/kgK,$

$v_{f_2} = 0.001040\ m^3/kg$

Since, the expansion process in turbine is isentropic,

$$s_1 = s_2 = 6.001\ kJ/kgK$$

Since $s_2 < s_{g_2}$, the steam is in wet state.

$$s_2 = s_{f_2} + x_2\, s_{fg_2}$$

$$6.001 = 1.25 + x_2 \times 6.167$$

$$x_2 = 0.77$$

Enthalpy of steam after expansion,

$$h_2 = h_{f_2} + x_2 \times h_{fg_2} = 398 + 0.77 \times 2270.1 = \mathbf{2145.98\ kJ/kg}$$

Pump work, $W_P = v_{f_2}(p_1 - p_2) = 0.001040 \times (4694.3 - 84.526) = \mathbf{4.79\ kJ/kg}$

Rankine cycle efficiency,

$$\eta_{Rankine} = \frac{(h_1 - h_2) - W_P}{h_1 - (h_{f_2} + W_P)}$$

$$= \frac{(2796.4 - 2145.98) - 4.79}{2796.4 - (398 + 4.79)} = 0.2697 = \mathbf{26.97\%} \qquad \textbf{Ans.}$$

Problem 3.33

22. Find the Efficiency of the Prime mover operating of Rankine cycle between 7 bar and 1 bar for Case (i) Inlet steam with x=0.8 Case (ii) Inlet Steam with x=1 Case (iii) Steam is super heated to 350^{0}C. Neglect pump work.

Given data:

$p_1 = 7\ bar$

$p_2 = 1\ bar$

(a) $x_1 = 0.8$

(b) $x_1 = 1$

(c) $T_{sup} = 350°C$

To find:

Rankine efficiency, $\eta_{Rankine}$

☺ ***Solution:***

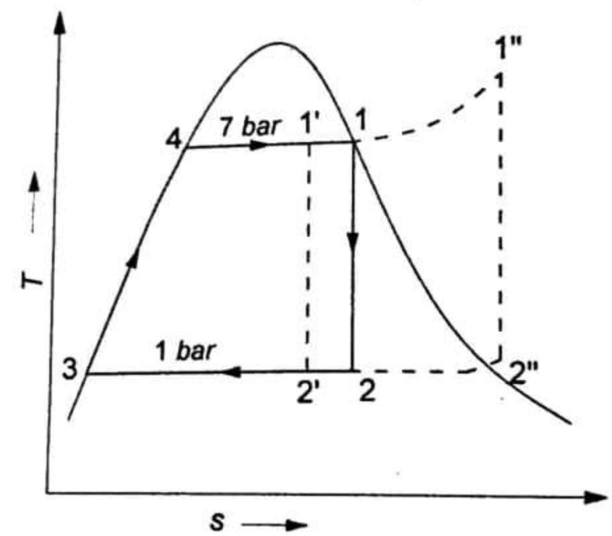


Figure 3.28 T-s diagram T-s diagram by neglecting feed pump work

From saturated water table of pressure scale, corresponding to 7 *bar*,

$T_{s_1} = 165°C$

$h_{f_1} = 697.1\ kJ/kg,$ $h_{fg_1} = 2064.9\ kJ/kg,$ $h_{g_1} = 2762.0\ kJ/kg$

$s_{f_1} = 1.992\ kJ/kgK,$ $s_{fg_1} = 4.173\ kJ/kgK,$ $s_{g_1} = 6.705\ kJ/kgK$

From saturated water table of pressure scale, corresponding to 1 *bar*,

$T_{s_2} = 99.63°C$

$h_{f_2} = 471.5$ *kJ/kg*, $h_{fg_2} = 2257.9$ *kJ/kg*, $h_{g_2} = 2675.4$ *kJ/kg*

$s_{f_2} = 1.307$ *kJ/kgK*, $s_{fg_2} = 6.057$ *kJ/kgK* $s_{g_2} = 7.36$ *kJ/kgK*

Case (a): When x = 0.8

The Rankine cycle when steam is wet is represented by 1′-2′-3-4.

Refer *T-s* diagram for process 1′-2′

Since the steam is at wet condition, for wet steam,

$$h_1 = h_{f_1} + x_1\, h_{fg_1} = 697.1 + 0.8 \times 2064.9 = 2349.02 \text{ kJ/kg}$$

$$s_1 = s_{f_1} + x_1\, s_{fg_1} = 1.992 + 0.8 \times 4.173 = 5.33 \text{ kJ/kg K}$$

To find the condition of steam and enthalpy of steam after expansion, the entropy of steam before and after expansion is compared.

Since, the expansion process in turbine is isentropic,

$$s_1 = s_2$$

$$s_2 = s_{f_2} + x_2\, s_{fg_2}$$

$$5.33 = 1.307 + x_2 \times 6.057$$

$$x_2 = 0.664$$

Enthalpy of steam after expansion,

$$h_2 = h_{f_2} + x_2\, h_{fg_2} = 417.5 + 0.664 \times 2257.9 = 1916.75 \text{ kJ/kg}$$

Rankine efficiency,

$$\eta_{Rankine} = \frac{h_1 - h_2}{h_1 - h_{f_2}} = \frac{2349.02 - 1916.75}{2349.02 - 417.5} = 0.2238 = \mathbf{22.38\%}$$

Ans.

Case (b): When steam is dry (Refer *T-s* diagram for *process 1-2-3-4)*

$$h_1' = h_{g_1} = 2762 \text{ kJ/kg}$$

$$s_1' = s_{g_1} = 6.705 \text{ kJ/kgK}$$

We know that for isentropic expansion process,

$$s_1' = s_2' = s_{f_2} + x_2'\, s_{fg_2}$$

$$6.705 = 1.307 + x_2' \times 6.057$$

$$x_2' = 0.891$$

$$h_2' = h_{f_2} + x_2' \, h_{fg_2}$$

$$= 417.5 + 0.891 \times 2257.9 = 2429.29 \text{ kJ/kg}$$

Rankine efficiency,

$$\eta_{Rankine} = \frac{h_1' - h_2'}{h_1' - h_{f_2}}$$

$$= \frac{2762 - 2429.29}{2762 - 417.5} = 0.1419 = \mathbf{14.19\%}$$

Ans.

Case (c): When steam is superheated to 350°C (Refer *T-s* diagram for process 1"-2"-3-4)

From superheated enthalpy and superheated entropy tables, corresponding pressure $p_1 = 7$ *bar* and 350°C,

$$h_1'' = 3164.3 \text{ kJ/kg}, \qquad s_1'' = 7.475 \text{ kJ/kgK}$$

Since $s_1'' > s_{g_1}$, the steam is again in superheated state after expansion.

Since, the expansion process in turbine is isentropic,

$$s_1'' = s_2'' = 7.475 \text{ kJ/kgK}$$

For finding h_2, the superheated temperature at the state 2 is calculated interpolating the above entropy value. So, from Mollier chart, corresponding $p_2 = 1$ *bar* and $s_2'' = 7.475$ *kJ/kgK*, read superheated temperature.

Superheated temperature of steam after expansion = 125°C

Enthalpy of steam at 1 *bar* and 125°C,

$$h_2'' = 2740 \text{ kJ/kg}$$

Rankine efficiency,

$$\eta_{Rankine} = \frac{h_1'' - h_2''}{h_1'' - h_{f_2}}$$

$$= \frac{3164.3 - 2740}{3164.3 - 417.5} = 0.1545 = \mathbf{15.45\%}$$

Ans.

Note: From the above problem, it is obvious that the Rankine efficiency depends on the inlet condition of the steam. The efficiency increases with increasing the temperature of the inlet steam at the same pressure.