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Civil Services Main Examination

(2001-2024)

Mechanical Engineering

Paper-II

Topicwise Presentation

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Preface

B. Singh (Ex. IES)

Civil Service is considered as the most prestigious job in India and it has become a preferred destination by all engineers. In order to reach this estimable position every aspirant has to take arduous journey of Civil Services Examination (CSE). Focused approach and strong determination are the pre-requisites for this journey. Besides this, a good book also comes in the list of essential commodity of this odyssey.

I feel extremely glad to launch the revised edition of such a book which will not only make CSE plain sailing, but also with 100% clarity in concepts.

MADE EASY team has prepared this book with utmost care and thorough study of all previous years papers of CSE. The book aims to provide complete solution to all previous years questions with accuracy.

On doing a detailed analysis of previous years CSE question papers, it came to light that a good percentage of questions have been asked in Engineering Services, Indian Forest Service and State Services exams. Hence, this book is a one stop shop for all CSE, ESE, IFS and other competitive exam aspirants.

I would like to acknowledge efforts of entire MADE EASY team who worked day and night to solve previous years papers in a limited time frame and I hope this book will prove to be an essential tool to succeed in competitive exams and my desire to serve student fraternity by providing best study material and quality guidance will get accomplished.

With Best Wishes

B. Singh (Ex. IES)

CMD, MADE EASY Group

Previous Years Solved Papers of

Civil Services Main Examination

Mechanical Engineering : Paper-II

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1 Thermodynamics

1. Basic Concepts, Heat and Work

Q.1 A rigid insulated tank of 3 m^3 volume is divided into 2 compartments. One compartment of volume 1 m^3 contains an ideal gas at 0.1 MPa and 300 K while the second compartment of volume 2 m^3 contains the same gas at 1 MPa and 1000 K. If the partition between the two compartments is ruptured, calculate the final temperature and pressure of the gas.

[CSE (Mains) 2002 : 20 Marks]

Solution:

Consider the gas contained in 2 compartments A and B of the rigid tank.

Assumption:

1. Ideal gas behaviour, 2. Rigid tank, 3. Insulated tank

Let the final temperature and pressure of gas after partition is removed be T and P, respectively.

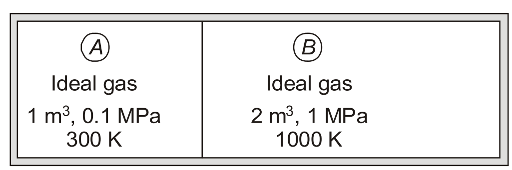
$$m_A = \frac{P_A V_A}{R T_A} = \frac{0.1 \times 1}{R \times 300} = \frac{1}{3000R}$$

and

$$m_B = \frac{P_B V_B}{R T_B} = \frac{1 \times 2}{R \times 1000} = \frac{1}{500R}$$

$$\Rightarrow \quad \frac{m_A}{m_B} = \frac{1}{6}$$

$$\Rightarrow \quad m_B = 6m_A$$



Comparing final and initial states,

$$R = \frac{P_A V_A}{m_A T_A} = \frac{P(V_A + V_B)}{(m_A + m_B)T}$$

$$\frac{0.1 \times 1}{m_A \times 300} = \frac{P \times 3}{7m_A \times T}$$

or

$$\frac{P}{T} = \frac{7}{9000}$$

Heat lost by one compartment = Heat gained by other compartment

$$\therefore \quad m_A c_v (T - 300) = m_B c_v (1000 - T)$$

$$m_A (T - 300) = 6\, m_A (1000 - T)$$

$$T - 300 = 6000 - 6T$$

or

$$T = 900 \text{ K}$$

$$\therefore \quad P = \frac{7 \times T}{9000} = \frac{7}{9000} \times 900 = 0.7 \text{ MPa}$$

Q.2 A mass of air initially at 760 kPa and 250°C occupies 0.026 m³. The air is expanded at constant pressure to 0.07 m³. A polytropic process with n = 1.52 is then carried out followed by an isothermal process and the cycle is thus completed. Assuming all the processes to be reversible,

(i) show all the processes on P–V and T–S planes

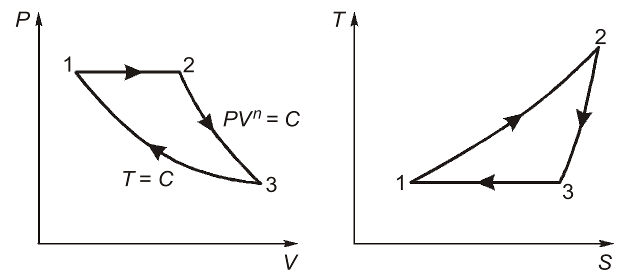
(ii) compute the heat received and rejected in the cycle

(iii) calculate the efficiency of the cycle.

[CSE (Mains) 2002 : 30 Marks]

Solution:

Processes can be represented on P-V and T-S diagram as shown in figure.



State 1: $P_1 = 760$ kPa , $T_1 = 250°C = 523$ K and $V_1 = 0.026$ m³

$$m = \frac{P_1V_1}{RT_1} = \frac{760 \times 0.026}{0.287 \times 523} = 0.1316 \text{ kg}$$

State 2: $P_2 = P_1 = 760$ kPa, $V_2 = 0.07$ m³

$$\frac{P_2V_2}{T_2} = \frac{P_1V_1}{T_1}$$

or
$$T_2 = \frac{V_2}{V_1}T_1 = 1408.08 \text{ K}$$

State 3: $T_3 = T_1 = 523$ K

Process 1-2:

Heat transfer,
$$Q_{1\text{-}2} = mc_p(T_2 - T_1) = 0.1316 \times 1.005 \times (1408.08 - 523) = 117.098 \text{ kJ}$$

Work done,
$$W_{1\text{-}2} = P_1(V_2 - V_1) = 760 \times (0.07 - 0.026) = 33.44 \text{ kJ}$$

Process 2-3: Work done in polytropic process,

$$W_{2\text{-}3} = \frac{P_2V_2 - P_3V_3}{n-1} = \frac{mR(T_2 - T_3)}{n-1} = \frac{0.1316 \times 0.287 \times (1408.08 - 523)}{1.52 - 1}$$
$$= 64.28 \text{ kJ}$$

Heat transfer in a polytropic process, $Q_{2-3} = \left(\frac{\gamma - n}{\gamma - 1}\right) \times W_{2-3} = \left(\frac{1.4 - 1.52}{1.4 - 1}\right) \times 64.31 = -19.29$ kJ

Process 3-1: Work done in isothermal process,

$$W_{3\text{-}1} = mRT \ln\left(\frac{V_1}{V_3}\right)$$

For polytropic process 2-3,

$$T_3V_3^{n-1} = T_2V_2^{n-1}$$

or
$$V_3 = V_2\left(\frac{T_2}{T_3}\right)^{\frac{1}{n-1}} = 0.07 \times \left(\frac{1408.08}{523}\right)^{\frac{1}{1.52-1}} = 0.47 \text{ m}^3$$

∴
$$W_{3\text{-}1} = 0.1316 \times 0.287 \times 523 \times \ln\left(\frac{0.026}{0.47}\right) = -57.18 \text{ kJ}$$

For an ideal gas internal energy change for an isothermal process = 0.

∴ From 1st law of thermodynamics,

$$Q = \Delta U + W = 0 + W$$

$\Rightarrow \quad Q_{3\text{-}1} = W_{3\text{-}1} = -57.18$ kJ

$\therefore$ Total heat transfer in the cycle

Heat received, $Q_{1\text{-}2} = $ **117.098 kJ**

Heat rejected, $Q_{3\text{-}1} + Q_{2\text{-}3} = $ **76.47 kJ**

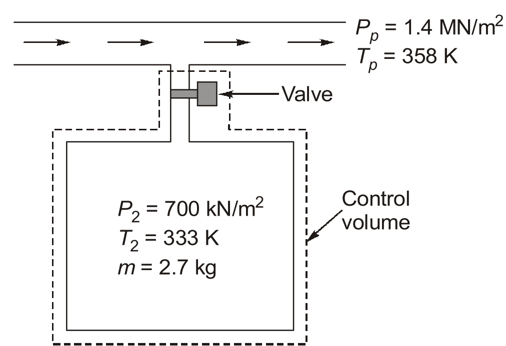
Net work output, $W_{net} = W_{1\text{-}2} + W_{2\text{-}3} + W_{3\text{-}1} = 33.44 + 64.31 - 57.18 = 40.57$ kJ

$\therefore$ Efficiency of cycle, $\eta = \frac{\text{Net work output}}{\text{Net heat supplied}} = \frac{W_{net}}{Q_{1-2}} = \frac{40.57}{117.098} = 0.3465 = $ **34.65%**

Q.3 A pressure vessel is connected, via a valve, to a gas main in which gas is maintained at a constant pressure and temperature of 1.4 MN/m^2 and 85°C respectively. The pressure vessels is initially evacuated. The valve is opened and a mass of 2.7 kg of gas passes into the pressure vessel. The valve is closed and the pressure and temperature of the gas in the pressure vessel are then 700 kN/m^2 and 60°C, respectively. Determine the heat transfer to or from the gas in the vessel. Determine the volume of gas before transfer.
For the gas, take c_p = 0.88 kJ/kgK, c_v = 0.67 kJ/kg K. Neglect the velocity of the gas in the main.
[CSE (Mains) 2004 : 30 Marks]

Solution:

Consider the pressure vessel and main connected by a valve as shown in figure.
Gas flows inside the vessel initially evacuated. Consider control volume as shown in figure.
Applying conservation of energy for variable flow process of this control volume,



$$\text{Rate of change of energy} = \frac{dE_v}{d\tau}$$

= Rate of inflow of energy – Rate of outflow of energy

$$\Rightarrow \quad \frac{dE_v}{d\tau} = h_p \frac{dm}{d\tau} + \frac{\delta Q}{d\tau}$$

$$\Rightarrow \quad \frac{du}{d\tau} = h_p \frac{dm}{d\tau} + \frac{\delta Q}{d\tau} \quad \text{(since velocity of pipe is negligible)}$$

Integrating, we get, $m_2 u_2 - m_1 u_1 = h_p (m_2 - m_1) + Q$

Initial mass of gas in control volume, $m_1 = 0$

Final mass of gas in control volume, $m_2 = 2.7$ kg

$\therefore$ Heat transfer to or from pressure vessel,

$$Q = m_2 u_2 - m_2 h_p = m_2 [c_v T_2 - c_p T_p] = 2.7 [0.67 \times 333 - 0.88 \times 358]$$
$$= -248.211 \text{ kJ}$$

$\therefore$ 248.21 kJ of heat is lost from the pressure vessel. Assume initial volume of gas in pipe before transfer is V_p. Since the gas can be assumed to follow ideal gas behaviour,

$$\frac{P_p V_p}{T_p} = \frac{P_2 V_2}{T_2} = mR = m(c_p - c_v)$$

or
$$V_p = \frac{T_p}{P_p} m(c_p - c_v) = \frac{358 \times 2.7 \times (0.88 - 0.67)}{1.4 \times 10^3} = \mathbf{0.145 \ m^3}$$

Hence, volume of gas before filling is 0.145 m^3.

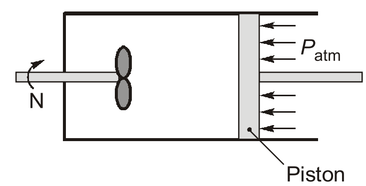
Q.4 A fluid, contained in a horizontal cylinder fitted with a frictionless leakproof piston, is continuously agitated by means of stirrer passing through the cylinder cover. The cylinder diameter is 0.40 m. During the stirring process lasting 10 minute, the piston slowly moves out a distance of 0.485 m against the atmosphere. The net work done by the fluid during the process is 2 kJ. The speed of the electric motor driving the stirrer is 840 rpm. Determine the torque in the shaft and the power output of the motor.

[CSE (Mains) 2007 : 20 Marks]

Solution:

Consider the system of fluid contained in the leakproof piston along with the stirrer. Work is being done by the piston on the fluid by stirring, through electric motor. As a result of this fluid moves out against atmospheric pressure and does work.

Work done by fluid against atmospheric pressure,



$$W_{atm} = \int PdV = P_{atm} \times (V_2 - V_1)$$
$$= (1.01325 \times 10^5) \times \frac{\pi D^2}{4}(\Delta x)$$
$$= 1.01325 \times 10^5 \times \frac{\pi \times 0.4^2}{4} \times 0.485$$
$$= 6.175 \times 10^3 \text{ J} = 6.175 \text{ kJ}$$

Net work done by the fluid, $W_{net} = W_{stirrer} + W_{atm}$

$$2 = W_{stirrer} + 6.175$$

or $W_{stirrer} = 2 - 6.175 = -4.175$ kJ

Sign is negative, since this work is done on the system.

Speed of rotation of motor, $\omega = \dfrac{2\pi N}{60} = \dfrac{2\pi \times 840}{60}$ rad/s = 87.965 rad/s

Power output of shaft $= \dfrac{W_{stirrer}}{t} = \dfrac{4.175}{10 \times 60} = 6.96 \times 10^{-3}$ kW = 6.96 W

Assume torque of motor as T Nm.

∴ Power of motor $= T\omega$

$$6.93 = T \times 87.965$$

or $T = \dfrac{6.96}{87.965}$ = **7.91×10^{-2} Nm**

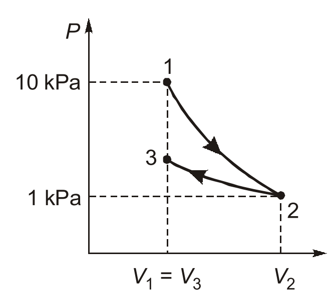
Q.5 (i) 0.5 m^3 of gas at 10 kPa and 130°C expands adiabatically to 1 kPa. It is then isothermally compressed to its original volume. c_p = 1.005 kJ/kgK and c_v = 0.718 kJ/kgK. Represent these processes on P-V diagram. Find final temperature and pressure of gas.

(ii) For compression work to be minimum, what should be process of compression? Is it used in practice?

[CSE (Mains) 2010 : 20 Marks]

Solution:

Consider the isothermal and adiabatic process as represented on P-V diagram in figure.

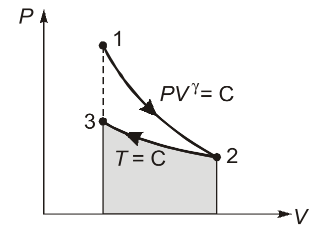


The ratio of specific heat,

$$\gamma = \frac{c_p}{c_v} = \frac{1.005}{0.718} \simeq 1.4$$

For process 1-2, Adiabatic expansion (reversible)

$$\therefore \quad T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 403\times\left(\frac{1}{10}\right)^{\frac{1.4-1}{1.4}} = 208.73 \text{ K}$$



Also $\quad PV^\gamma = \text{Constant}$

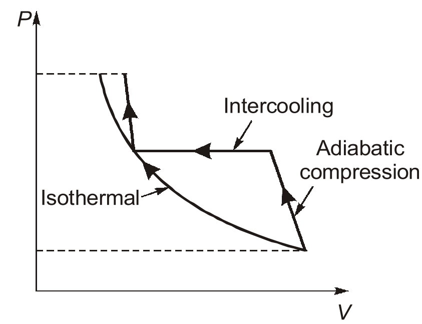
$$\Rightarrow \quad V_2 = V_1\left(\frac{P_2}{P_1}\right)^{1/\gamma} = 0.5\times\left(\frac{10}{1}\right)^{1/1.1} = 2.59 \text{ m}^3$$

For process 2-3, Isothermal compression

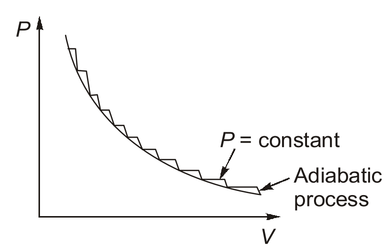
$$\therefore \quad T_3 = T_2 = 208.73 \text{ K}$$

$$PV = \text{Constant}$$

$$\Rightarrow \quad P_3 = \frac{P_2V_2}{V_3} = \frac{P_2V_2}{V_1} = \frac{1\times 2.59}{0.5} = \mathbf{5.18 \text{ kPa}}$$



As can be seen in figure, slope of an isothermal process is less than that of an isentropic/adiabatic process.
Hence area under the curve, which is equal to work done is minimum in case of an isothermal process.
∴ Isothermal process should be used in compression
In practice, for compression involving high compression ratios, adiabatic process with intercooling is employed. This method closely approaches as an isothermal process.
If process of adiabatic compression with intercooling is divided in very small pressure ratios, than adiabatic compression gives equivalent work of isothermal compression. That is why multistage compression is used in power plants.



Q.6 In the event of failure of heaters in a spacecraft, heat is lost by radiation at the rate of 100 kJ/hr while electronic instruments generate 75 kJ/hr inside the spacecraft. Initially the air inside the spacecraft is at 1 bar, 25°C with a volume of 10 m. How long it will take to reach air temperature of 0°C?
[CSE (Mains) 2012 : 12 Marks]

Solution:

Assumptions:
1. No leakage of air ,
2. No solar irradiation

Given: Net heat loss rate, $\dot{Q}$ = (100 – 75) = 25 kJ/hr, P_1 = 1 bar = 100 kPa, T_1 = 25°C, V = 10 m^3

As the process is isochoric i.e., $V = 0 \Rightarrow W = 0$,

By 1st law $\delta Q = \Delta U$ and $\Delta U = mc_v dT$

$$\therefore \quad \text{Total heat required, } Q = m\, c_v dT = m \times 0.718 \times 25$$

where,
$$m = \frac{P_1V_1}{RT_1} = \frac{100\times 10}{0.287\times 298} = 11.692 \text{ kg}$$

$$\therefore \quad Q = 11.692 \times 0.718 \times 25 = 209.877 \text{ kJ}$$

$$\text{Time} = \frac{Q}{\dot{Q}} = \frac{209.877}{25} = 8.395 \text{ hr.}$$

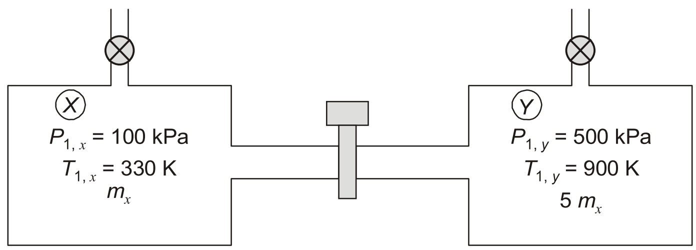
= **8 hour 23 minute 42 second**

Q.7 A certain amount of gas is filled in a tank *X* until its pressure is 100 kPa and temperature is 330 K. In another tank *Y*, 5 times the weight of gas in *X* is filled raising the pressure to 500 kPa and temperature 900 K. Both tanks *X* and *Y* are now connected through a tube having a valve which is closed. Assuming the gas is ideal and if the valve is opened till equilibrium state is achieved, find the ratio of the volumes of both tanks, equilibrium temperature and pressure. The tanks are insulated. For the gas, take: R = 0.296 kJ/kgK and c_v = 0.75 kJ/kgK.

[CSE (Mains) 2014 : 20 Marks]

Solution:

Assume final equilibrium pressure and temperature as P and T respectively.



Since gas in both compartments has been assumed to be an ideal gas, using ideal gas equation $PV = mRT$, we get

$$R = \frac{P_{1,x}V_x}{m_x T_{1,x}} = \frac{P_{1,y}V_y}{5m_x T_{1,y}}$$

$$\Rightarrow \quad \frac{100 \times V_x}{330} = \frac{500V_y}{5 \times 900} \Rightarrow \frac{V_x}{V_y} = \frac{11}{30}$$

After the valve has been opened and equilibrium achieved, final volume for gas

$$V_x + V_y = V_x + \frac{30\,V_x}{11} = \frac{41}{11}V_x$$

$$\text{Total mass} = m_x + 5\,m_x = 6\,m_x$$

$$R = \frac{P_{1,x}V_x}{m_x T_{1,x}} = \frac{P(41\,V_x / 11)}{6\,m_x T}$$

$$\Rightarrow \quad \frac{41P}{66T} = \frac{100}{330} \Rightarrow \frac{P}{T} = \frac{20}{41}$$

Heat exchange at constant volume takes place between the gas in tanks *X* and *Y*

and since $\delta W = 0$

$$\Delta Q = \Delta U$$

$$\Delta U = mc_v \Delta T$$

$\therefore$ Heat lost by tank, Y = Heat gained by tank X

$$5m_x c_v(900 - T) = m_x c_v(T - 330)$$

$$5(900 - T) = (T - 330)$$

or T = 805 K

Also, we have $\frac{P}{T} = \frac{20}{41}$

$$\Rightarrow \quad P = \frac{20}{41} \times 805 = \mathbf{392.7\ kPa}$$

$\therefore$ Final temperature and pressure are 805 K and 392.7 kPa respectively.

Q.8 The pressure in an automobile tyre depends on the temperature of the air in the tyre. When the air temperature is 25°C the pressure gauge reads 210 kPa. If the volume of the tyre is 0.025 m^3, determine the pressure rise in the tyre when the air temperature in the tyre rises to 50°C. Also, determine the amount of air that must be bled off to restore pressure to its original value at this temperature. Assume the atmospheric pressure is 100 kPa and gas constant of air, R = 0.287 kPa m^3/kgK.

[CSE (Mains) 2017 : 10 Marks]

Solution:

The absolute pressure in the tyre, $P_1 = P_{gauge} + P_{atm} = 210 + 100 = 310$ kPa

Gas constant of air, $R = 0.287$ kPa m^3/kg K

$$= 0.287\frac{\text{kN}}{\text{m}^2}\times \text{m}^3 \times \frac{1}{\text{kgK}} = 0.287 \text{ kJ/kgK}$$

As the air is an ideal gas, the final pressure in the tyre can be determined using the ideal equation as follows:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Since the volume in the tyre remains constant, $V_1 = V_2$.

$$P_2 = \frac{T_2}{T_1}P_1 = \frac{(273+50)}{(273+25)}\times 310 = \frac{323}{298}\times 310 = 336 \text{ kPa}$$

Pressure rise in the tyre, $\Delta P = P_2 - P_1 = 336 - 310 = 26$ kPa

$$\text{Initial mass, } m_1 = \frac{P_1V}{RT_1} = \frac{310\times 0.025}{0.287\times 298} = 0.0906 \text{ kg}$$

$$\text{Final mass, } m_2 = \frac{P_2V}{RT_2} = \frac{310\times 0.025}{0.287\times 323} = 0.0836 \text{ kg}$$

Amount of air to be bled off, $\Delta m = m_1 - m_2 = 0.0906 - 0.0836 = 0.0070$ kg

Q.9 The lighting needs of a classroom are met by 30 fluorescent lamps, each consuming 80 W of electricity. the light in the classroom are kept on for 12 hours a day and 250 days during a year. For a unit electricity cost of ₹ 7 per kWh, determine the annual energy cost of lighting for this classroom.

[CSE (Mains) 2018 : 10 Marks]

Solution:

Number of lamps = 30

Power consumed by each lamp = 80 W

Total power consumed = 30 × 80 = 2400 W = 2.4 kW

Tool of hours in a year = 12 × 250 = 3000 hrs.

Total energy consumption = Power × Time = 2.4 × 3000 kWh = 7200 kWh

Annual total cost = Total energy × Rate of energy

= 7200 × 7 = Rs.50400

Q.10 A 2 gm quantity of air undergoes the following sequence of quasi-static processes in a piston-cylinder arrangement:

(i) An adiabatic expansion in which the volume doubles.

(ii) A constant pressure process in which the volume is reduced to its initial value.

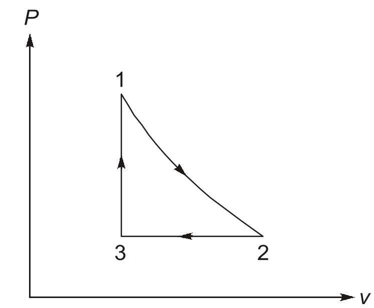
(iii) A constant volume compression back to the initial state.

The air is initially at 150°C and 5 atm. Calculate net work on the air in the sequence of processes.

[CSE (Mains) 2024 : 10 Marks]

Solution:

Given, m = 2 gm = 2×10^{-3} kg; T_1 = 150°C = 423 K; P_1 = 5 atm = 506.625 kPa; V_1 = V; V_2 = 2V



Pressure (1 - 2) adiabatic expansion

Now, $$V_1 = \frac{mRT_1}{P_1} = \frac{2\times10^{-3}\times0.287\times423}{506.625}$$

or $$V_1 = V = 4.7925 \times 10^{-4}\ \text{m}^3$$

We know, $$P_1V_1^{\gamma} = P_2V_2^{\gamma}$$

∴ $$P_2 = P_1\left(\frac{V_1}{V_2}\right)^{\gamma} = P_1\left(\frac{V}{2V}\right)^{1.4}$$

or $$P_2 = 506.625 \times (0.5)^{1.4} = 191.975\ \text{kPa}$$

∴ $$W_{1\text{-}2} = \frac{P_1V_1 - P_2V_2}{\gamma-1} = \frac{P_1V - 2P_2V}{0.4}$$

or, $$W_{1\text{-}2} = \frac{4.7925\times10^{-4}\left(506.625-2\times191.975\right)\times10^{3}}{0.4}$$

$$= 146.98 \simeq 147\ \text{J}$$

Pressure (2 - 3) Isobaric compression

$$W_{2\text{-}3} = P_2(V_3 - V_2) = P_2(V - 2V)$$

or $$W_{2\text{-}3} = -191.975 \times 4.7925 \times 10^{-4} \times 10^{3}$$

$$= -92\ \text{J}$$

Process (3 - 1) Isochoric process

$$W_{3\text{-}1} = 0\ \text{J}$$

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

$$= 147 + (-92) + 0$$

$$W_{net} = 55\ \text{J}$$

Now, Work done by the air = 55 J

Work done on the air = –55 J **Ans.**

2. First Law of Thermodynamics

Q.1 The ratio of heat transfer to work transfer in the process of an air compressor reciprocating type is 1 : 4. If the compression follows PV^n = constant, what is the value of n? Derive the equation that you use. In such a compression process the work required is 200 kJ/kg and the specific heat at constant volume is 0.75 kJ/kgK. What rise of temperature is expected at the end of compression process?

[CSE (Mains) 2001 : 20 Marks]

Solution:

Consider an air compressor reciprocating type as a closed system in which working fluid/gas is undergoing process $PV^n = C$.

$$\text{Work done in the process, } W = \int PdV = \int CV^{-n}dV = C\left[\frac{V^{-n+1}}{-n+1}\right]_{V_1}^{V_2} = \frac{P_1V_1 - P_2V_2}{n-1} = \frac{mR(T_1-T_2)}{n-1}$$

From 1st law of thermodynamics, $\delta Q = dU + \delta W$

$\Rightarrow$ $Q = mc_v(T_2 - T_1) + W$ (Since for an ideal gas $dU = mc_v dT$)

and $c_v = \dfrac{R}{\gamma - 1}$

$$= \frac{mR}{\gamma-1}(T_2 - T_1) - \frac{mR(T_2-T_1)}{n-1}$$

$$= \frac{mR(T_2-T_1)}{n-1}\left[\frac{n-\gamma}{\gamma-1}\right] = -W\left[\frac{n-\gamma}{\gamma-1}\right] = W\left[\frac{\gamma-n}{\gamma-1}\right]$$

$\therefore$ Ratio of heat transfer to work transfer $= \dfrac{Q}{W} = \left[\dfrac{\gamma-n}{\gamma-1}\right]$

$$\frac{Q}{W} = \left[\frac{\gamma-n}{\gamma-1}\right] = \frac{1}{4}$$

$$\frac{\gamma-n}{\gamma-1} = \frac{1}{4} \text{ or } 4\gamma - 4n = \gamma - 1$$

$$3\gamma - 4n = -1$$

$$3 \times 1.4 - 4n = -1$$

$$-4n = -5.2$$

or $n = 1.3$

Given: Work required in such a compression process, $w = -200$ kJ/kg

$$w = \frac{R[T_2 - T_1]}{1-n} = \frac{c_v(\gamma-1)dT}{1-n} \qquad c_v = \frac{R}{\gamma-1}$$

$$-200 = \frac{0.75 \times (1.4-1)}{1-1.3} \times dT$$

or $dT = 200$ K

Q.2 An engine using 10 moles of diatomic ideal gas works on the reversible cycle having the following processes:

(i) Adiabatic compression from 1 bar pressure and 300 K temperature to pressure of 9 times the initial value.

(ii) Constant pressure transformation upto temperature of 1000 K.

(iii) Adiabatic expansion upto 3 bars.

(iv) Constant pressure transformation such that temperature of 1000 K is reached,

(v) Adiabatic expansion,

(vi) Constant pressure transformation upto the original state.

For this engine,

(a) Represent the cycle on a p-v diagram.

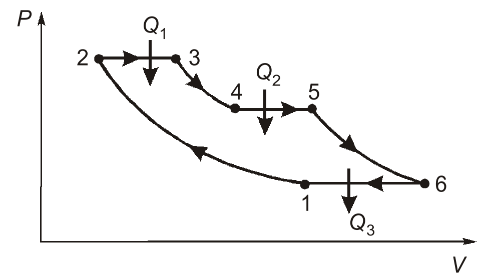
(b) Calculate pressure, temperature and volume at salient points.

(c) Calculate the efficiency of the engine summarizing results in a tabular form.

(d) Compare the efficiency of the engine operating on Carnot cycle between the same extreme temperature. Given comments.

[CSE (Mains) 2011 : 30 Marks]

Solution:



$$\gamma = 1+\frac{2}{F}$$

F = 5 for dia-atomic

The ratio of specific heats for a diatomic molecule is,

$$\gamma = \frac{c_p}{c_v} = \frac{7}{5} = 1.4$$

State 1: $P_1 = 1$ bar, $T_1 = 300$ K,

$n = 10$ moles

Since, $\bar{R} = 8.314$ J/mole K.

$$V = \frac{n\bar{R}T}{P} = \frac{10\times 8.31\times 300}{1\times 10^5} = 0.2493\ \text{m}^3$$

State 2: $P_2 = 9$ bar, $P_1 = 9$ bar

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 300(9)^{(1.4-1)/1.4} = 562\ \text{K}$$

$$V_2 = V_1\left(\frac{P_1}{P_2}\right)^{\gamma} = 0.2493\left(\frac{1}{9}\right)^{1.4} = 0.0115\ \text{m}^3$$

State 3: $T_3 = 1000$ K,

$P_3 = 9$ bar (given)

$$V_3 = \frac{T_3}{T_2}\times V_2 = \frac{1000}{562}\times 0.0115 = 0.0204\ \text{m}^3$$

State 4:

$$T_4 = T_3\left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}} = 1000\left(\frac{1}{3}\right)^{0.4/1.4} = 730.59\ \text{K}$$

$$V_4 = V_3\left(\frac{P_3}{P_4}\right)^{\gamma} = 0.0204\times(3)^{1.4} = 0.09497\ \text{m}^3$$

State 5: $T_5 = 1000$ K (given)

$P_5 = 3$ bar (isobaric process)

$$V_5 = \frac{T_5}{T_4}\times V_4 = \frac{1000}{730.59}\times 0.09497 = 0.130\ \text{m}^3$$

State 6: $P_6 = 1$ bar (given)

$$T_6 = T_5\left(\frac{P_6}{P_5}\right)^{\frac{\gamma-1}{\gamma}} = 1000\times\left(\frac{1}{3}\right)^{(1.4-1)/1.4} = 730.59\ \text{K}$$

$$V_6 = V_5\left(\frac{P_5}{P_6}\right)^{\gamma} = 0.130\times(3)^{1.4} = 0.6052\ \text{m}^3$$

Heat addition in process 2-3, 4-5, Q_1 and Q_2

Heat rejection in process 6 - 1, Q_3

$$Q_1 = c_p(T_3 - T_2) = 437.9\ c_p$$

$$Q_2 = c_p(T_5 - T_4) = 269.41\ c_p$$

$$Q_3 = c_p(T_6 - T_1) = 430.59\ C_p$$

$$\text{Efficiency, } \eta = \frac{Q_{in} - Q_{out}}{Q_{in}} = \frac{707.31 - 430.59}{707.31} = 0.3912 = 39.12\%$$

$$\text{Carnot efficiency} = 1 - \frac{T_{\min}}{T_{\max}} = 1 - \frac{300}{1000} = 0.70 = 70\%$$

Clearly given cycle has lesser efficiency than the carnot cycle because of following reasons:

1. Carnot cycle has isothermal heat addition and mean temperature of heat addition is higher in constant temperature heat addition.
2. This cycle contain external irreversibility in process (2-3), (4-5), (1-6). While Carnot cycle has all four processes, which are reversible and reversible cycle has higher efficiency than irreversible cycle.

Q.3 An insulated rigid tank is divided into two equal parts by a partition. Initially, one part contains 4 kg of an ideal gas at 800 kPa and 50°C, while the other part is evacuated. The partition is now removed and the gas expands into the entire tank. Determine the final temperature and pressure in the tank.

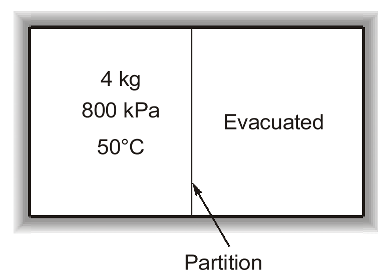
[CSE (Mains) 2017 : 10 Marks]

Solution:

Removing the partition is equivalent to allowing the partition to move in the right direction until the ideal gas fills the entire tank. As the right part of insulated tank is evacuated (i.e. there is vacuum), the resisting force in this would be zero. Since the resisting force is zero, the work done by the expanding gas is zero.

$V_1 = V_2 = \frac{V}{2}$

[V = Total volume]



As per first law of thermodynamics,

$$\delta Q = \delta W + \Delta U$$
$$\Delta U = 0$$

[$\delta Q = 0$ for insulated tank and $\delta W = 0$ for free expansion]

For an ideal gas,

$$u = f(T) \text{ only, so, } T_2 = T_1 = 50°\text{C}$$

As $T_2 = T_1$, the process is isothermal.

$$P_1V_1 = mRT_1 = P_2V_2 = mRT_2$$

$$P_2 = P_1\left(\frac{V_1}{V_2}\right) = P_1 \times \frac{1}{2} = \frac{800}{2} = 400 \text{ kPa}$$

Q.4 A 40 litres electrical radiator (heater) containing heating oil is placed in a 50 m^3 room. Both the room and the oil in the radiator are initially at 10°C. The radiator with a rating of 2.4 kW is now turned on. At the same time, heat is lost from the room at an average rate of 0.35 kJ/s. After some time, the average temperature for air in the room is 20°C and the oil in the radiator is 50°C. Take the density and the specific heat of the oil to be 950 kg /m^3 and 2.2 kJ/kg-K respectively. Determine how long the heater is kept on. Assume the room is well-sealed and ambient pressure is 1 bar.

[CSE (Mains) 2019 : 10 Marks]

Solution:

Given data:

Electrical radiator,

$$V = 40 \text{ litres}$$
$$\rho_{soil} = 950 \text{ kg/m}^3$$
$$c_{p,oil} = 2.2 \text{ kJ/kg-K}$$

Room,

$$\rho_{air} = 1.225 \text{ kg/m}^3 \text{ (Assumption)}$$

Heat needed fro the radiator Q_h

$$Q_h = c_{p,oil} \cdot M_{oil} \cdot \Delta T_h$$
$$= 2.2 \times (950 \times 0.04) \times (50 - 10) = 3344 \text{ kJ}$$

Heat needed for the room, Q_r

$$Q_r = M_{air} \cdot c_{p,air} \cdot \Delta T_r = (1.225 \times 50) \times 1.005 \times [20 - 10]$$
$$= 615.56 \text{ kJ}$$

∴ Total heat generated, $Q = Q_h + Q_r = 3344 + 615.56 = 3959.56$ kJ

Total heat exchange, $\dot{Q} = P - \dot{Q}_{out} = 2.4 - 0.35 = 2.05$ kN

Time 't' the heater needed to be on is

$$t = \frac{Q}{\dot{Q}} = \frac{3959.56}{2.05} = 1931.49 \text{ s}$$
$$= 32.19 \text{ minutes}$$

Q.5 Air enters the compressor of a gas turbine plant at ambient conditions of 100 kPa and 25°C with negligible velocity, and exits at 1 MPa and 347°C with a velocity of 90 m/s. The compressor is cooled at a rate of 1500 kJ/min and the power input to the compressor is 250 kW. Determine the mass flow rate of air through the compressor.
For air, consider c_p = 1.005 kJ/kg-K, c_v = 0.717 kJ/kg-K and R = 0.287 kJ/kg-K.

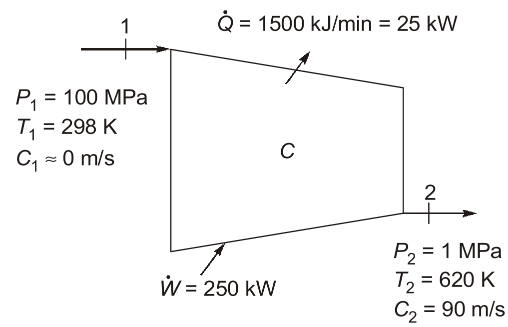
[CSE (Mains) 2020 : 10 Marks]

Solution:

Using conservation of energy assuming steady flow conditions,

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

$$\dot{m}h_1 + \dot{W} = \dot{m}\left(h_2 + \frac{C_2^2}{2}\right) + \dot{Q}$$



$$\dot{m}\left[(h_1 - h_2) - \frac{C_2^2}{2}\right] = \dot{Q} - \dot{W}$$

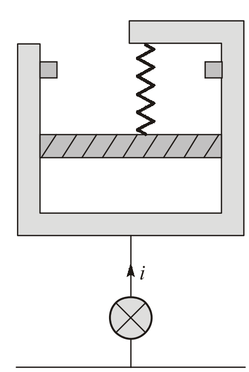
$$\dot{m}\left[c_p(T_1 - T_2) - \frac{90^2}{2} \times 10^{-3}\right] = 25 - 250$$

$$\dot{m}\left[1.005(298 - 620) - \frac{90^2}{2} \times 10^{-3}\right] = -225$$

$$\dot{m} \times -327.66 = -225$$

Mass flow rate of air, $\dot{m}$ = 0.6866 kg/s

Q.6 A frictionless piston/cylinder is loaded with a linear spring (as shown in the figure below) having a spring constant of 100 kN/m, and the piston cross-sectional area is 0.1 m². The cylinder having an initial volume of 20 L contains air at 200 kPa and ambient temperature 300 K.
There exists a stop in the cylinder which prevents its volume from exceeding 50 L. A valve connects the cylinder to an air supply line flowing air at 800 kPa, 325 K. The valve is now opened, allowing air to flow in until the cylinder pressure and temperature reach 800 kPa and 350 K respectively. The valve is then closed and the process ends. At the final state does the piston reach the stop? Calculate the heat transfer during the process. Take c_p = 1.005 kJ/kg-K and R = 0·287 kJ/kg-K for air.



[CSE (Mains) 2020 : 20 Marks]