Production & Industrial Engineering

General Engineering

Vol. V : Basic Thermodynamics

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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General Engineering : Vol. V – Basic Thermodynamics

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Basic Thermodynamics

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VOLUME V

General Engineering

Basic Thermodynamics

INTRODUCTION

The most of general sense of thermodynamics is the study of energy and its relationship to the properties of matter. All activities in nature involve some interaction between energy and matter. Thermodynamics is a science that governs the following:

- Energy and its transformation
- Feasibility of a process involving transformation of energy
- Feasibility of a process involving transfer of energy
- Equilibrium processes

More specifically, thermodynamics deals with energy conversion, energy exchange and the direction of exchange.

5.1 Application of Thermodynamics

All natural processes are governed by the principles of thermodynamics. However, the following engineering devices are typically designed based on the principles of thermodynamics.

Automotive engines, turbines, compressors, pumps, fossil and nuclear power plants, propulsion systems for the aircrafts, separation and liquification plant, refrigeration, air-conditioning and heating devices.

The principles of thermodynamics are summarized in the form of set of axioms. These axioms are known as four thermodynamic laws :

- **The Zeroth Law** deals with thermal equilibrium and provides a means for measuring temperatures.
- **The First Law** deals with the conservation of energy and introduces the concept of internal energy.
- **The Second Law** of thermodynamics provides with the guidelines on the conversion of internal energy of matter into work. It also introduces the concept of entropy.
- **The Third Law** of thermodynamics defines the absolute zero of entropy. The entropy of a pure crystalline substance at absolute zero temperature is zero.

5.2 Different Approaches in the Study of Thermodynamics

Thermodynamics can be studied through two different approaches:

(1) Macroscopic approach and

(2) Microscopic approach

1. **Macroscopic Approach :** Consider a certain amount of gas in a cylindrical container. The volume (V) can be measured by measuring the diameter and the height of the cylinder. The pressure (P) of the gas can be measured by a pressure gauge. The temperature (T) of the gas can be measured using a thermometer. The state of the gas can be specified by the measured P, V and T. The values of these variables are space averaged characteristics of the properties of the gas under consideration. In classical thermodynamics, we often use this macroscopic approach. The macroscopic approach has the following features.
   - The structure of the matter is not considered.
   - A few variables are used to describe the state of the matter under consideration.
   - The values of these variables are measurable following the available techniques of experimental physics.
2. **Microscopic Approach :** On the other hand, the gas can be considered as assemblage of a large number of particles each of which moves randomly with independent velocity. The state of each particle can be specified in terms of position coordinates (x_i, y_i, z_i) and the momentum components (p_{xi}, p_{yi}, p_{zi}). If we consider a gas occupying a volume of 1 cm^3 at ambient temperature and pressure, the number of particles present in it is of the order of 10^{20} . The same number of position coordinates and momentum components are needed to specify the state of the gas. The microscopic approach can be summarized as :
   - A knowledge of the molecular structure of matter under consideration is essential.
   - A large number of variables are needed for a complete specification of the state of the matter.

5.3 Concept of System and Surrounding

5.3.1 System

A thermodynamic system is defined as a definite quantity of matter or a region in space upon which attention is focused in the analysis of a problem. We may want to study a quantity of matter contained with in a closed rigid walled chambers, or we may want to consider something such as gas pipeline through which the matter flows. The composition of the matter inside the system may be fixed or may change through chemical and nuclear reactions. A system may be arbitrarily defined. It becomes important when exchange of energy between the system and the everything else outside the system is considered. The judgement on the energetics of this exchange is very important.

5.3.2 Surroundings

Everything external to the system is surroundings. The system is distinguished from its surroundings by a specified boundary which may be at rest or in motion. The interactions between a system and its surroundings, which take place across the boundary, play an important role in thermodynamics. A system and its surroundings together comprise a universe.

Types of Systems

Two types of systems can be distinguished. These are referred to, respectively, as closed systems and open systems or control volumes. A closed system or a control mass refers to a fixed quantity of matter, whereas a control volume is a region in space through which mass may flow. A special type of closed system that does not interact with its surroundings is called an **Isolated system** .

Two types of exchange can occur between the system and its surroundings :

1. energy exchange (heat or work) and
2. exchange of matter (movement of molecules across the boundary of the system and surroundings).

Based on the types of exchange, one can define :

- **isolated systems :** no exchange of matter and energy
- **closed systems :** no exchange of matter but some exchange of energy
- **open systems :** exchange of both matter and energy

If the boundary does not allow heat (energy) exchange to take place it is called adiabatic boundary otherwise it is diathermal boundary.

5.4 Property

To describe a system and predict its behaviour requires a knowledge of its properties and how those properties are related. Properties are macroscopic characteristics of a system such as mass, volume, energy, pressure and temperature to which numerical values can be assigned at a given time without knowledge of the past history of the system. Many other properties are considered during the course of our study.

- The value of a property of a system is independent of the process or the path followed by the system in reaching a particular state.
- The change in the value of the property depends only on the initial and the final states.

The word state refers to the condition of a system as described by its properties.

Mathematically, if p is a property of the system, then the change in the property in going from the initial state 1 to the final state 2 is given by

$$\int_1^2 dp = p_2 - p_1$$

If $p = p(x, y)$ then,

$$dp = \left(\frac{\partial p}{\partial x}\right)_y dx + \left(\frac{\partial p}{\partial y}\right)_x dy = adx + bdy$$

where, $$a = \left(\frac{\partial p}{\partial x}\right)_y \text{ and } b = \left(\frac{\partial p}{\partial y}\right)_x$$

If $$\left(\frac{\partial a}{\partial y}\right)_x = \left(\frac{\partial b}{\partial y}\right)_x$$

then dp is said to be an exact differential, and p is a point function. A thermodynamic property is a point function and not a path function. Pressure, temperature, volume or molar volume are some of the quantities which satisfy these requirements.

5.4.1 Intensive and Extensive Properties

There are certain properties which depend on the size or extent of the system, and there are certain properties which are independent of the size or extent of the system. The properties like volume, which depend on the size of the system are called extensive properties. The properties, like temperature and pressure which are independent of the mass of the system are called **intensive properties**. The test for an intensive property is to observe how it is affected when a given system is combined with some fraction of exact replica of itself to create a new system differing only by size. Intensive properties are those which are unchanged by this process, whereas those properties whose values are increased or decreased in proportion to the enlargement or reduction of the system are called extensive properties.

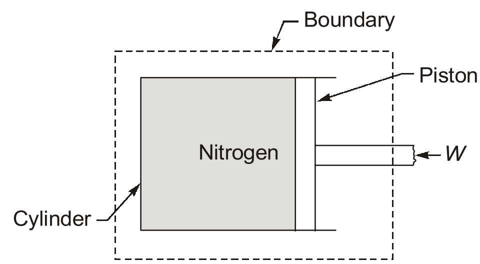
Assume two identical systems S_1 and S_2 as shown in figure. Both the systems are in identical states.

Let S_3 be the combined system. Is the value of property for S_3 same as that for S_1 (and S_2)?

Example 5.7 0.3 kg of nitrogen gas at 100 kPa and 40°C is contained in a cylinder. The piston is moved compressing nitrogen until the pressure becomes 1 MPa and temperature becomes 160°C. The work done during the process is 30 kJ. Calculate the heat transferred from the nitrogen to the surroundings. c_v for nitrogen = 0.75 kJ/kgK.

Solution:

Mass of nitrogen, m = 0.3 kg



Temperature before compression = 40°C or 313 K

Temperature after compression = 160°C or 433 K

The work done during the compression process,

$$W = -30 \text{ kJ}$$

According to first law of thermodynamics,

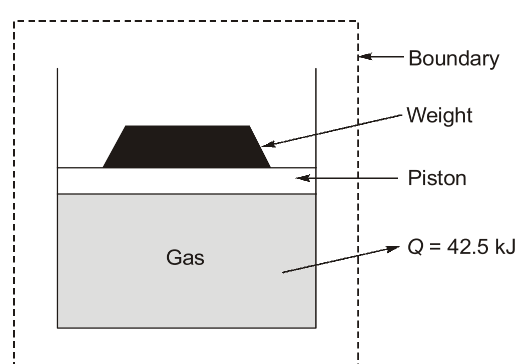
$$Q = \Delta U + W = (U_2 - U_1) + W = mc_v(T_2 - T_1) + W$$

$$= 0.3 \times 0.75(433 - 313) - 30 = -3 \text{ kJ}$$

Hence, heat 'rejected' during the process = 3 kJ.

Example 5.8 When a stationary mass of gas was compressed without friction at constant pressure its initial state of 0.4 m^3 and 0.105 MPa was found to change to final state of 0.20 m^3 and 0.105 MPa. There was a transfer of 42.5 kJ of heat from the gas during the process. How much did the internal energy of the gas change?

Solution :



Initial state :

Pressure of gas, p_1 = 0.105 MPa

Volume of gas, V_1 = 0.4 m^3

Final state

Pressure of gas, p_2 = 0.105 MPa

Volume of gas, V_2 = 0.20 m^3

Process used : Constant pressure

Heat transferred, Q = –42.5 kJ (–ve sign indicates that heat is rejected)

Change in internal energy, $\Delta U = U_2 - U_1$:

First law for a stationary system in a process gives

$$Q = \Delta U + W$$

$$Q_{1-2} = (U_2 - U_1) + W_{1-2} \quad \text{...(i)}$$

Here $$W_{1-2} = \int_{V_1}^{V_2} pdV = p(V_2 - V_1)$$

Change in internal energy, $\Delta U = U_2 - U_1$:

First law for a stationary system in a process gives

$$Q = \Delta U + W$$

or $$Q_{1-2} = (U_2 - U_1) + W_{1-2} \quad \text{...(i)}$$

Here, $$W_{1-2} = \int_{V_1}^{V_2} pdV = p(V_2 - V_1)$$

$$= 0.105(0.20 - 0.40) \text{ MJ} = -21 \text{ kJ} \quad [\because 1 \text{ MJ} = 10^3 \text{ kJ}]$$

Substituting this value of W_{1-2} in equation (i), we get

$$-42.5 = (U_2 - U_1) - 21$$

$\therefore$ $$U_2 - U_1 = -42.5 + 21 = -21.5 \text{ kJ}$$

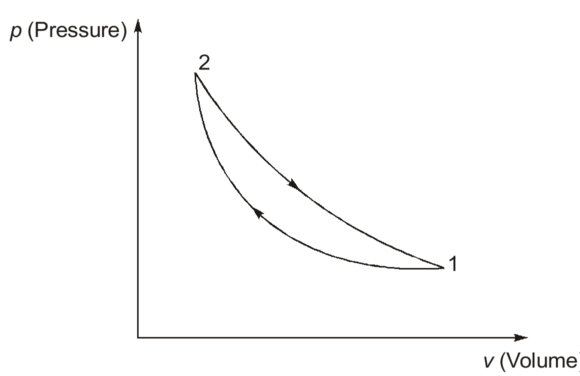
Hence 'decrease' in internal energy = 21.5 kJ.

Example 5.9 A cylinder containing the air comprises the system. Cycle is completed as follows :

(i) 82000 N-m of work is done by the piston on the air during compression stroke and 45 kJ of heat are rejected to the surroundings.

(ii) During expansion stroke 100000 N-m of work is done by the air on the piston. Calculate the quantity of heat added to the system.

Solution :



Compression stroke. Process 1-2 :

Work done by the piston on the air,

$$W_{1-2} = -82000 \text{ N-m } (= -82 \text{ kJ})$$

Heat rejected to the system, $$Q_{1-2} = -45 \text{ kJ}$$

Now, $$Q_{1-2} = (U_2 - U_1) + W$$

$$-45 = (U_2 - U_1) + (-82)$$

$\therefore$ $$(U_2 - U_1) = 37 \text{ kJ} \quad \text{...(i)}$$

Expansion stroke. Process 2–1 :

Work done by air on the piston,

$$W_{2-1} = 100000 \text{ N-m} (= 100 \text{ kJ})$$

Now, $$Q_{2-1} = (U_1 - U_2) + W$$
$$= -37 + 100 \text{ kJ} = 63 \text{ kJ}$$

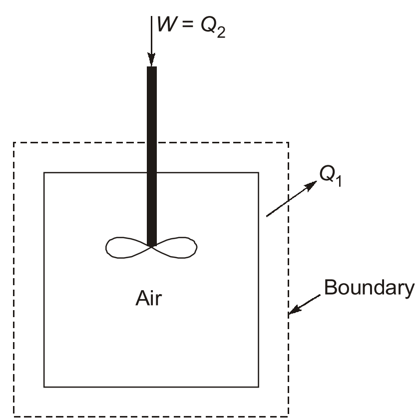
Hence, quantity of heat added to the system = 63 kJ.

Example 5.10 A tank containing air is stirred by a paddle wheel. The work input to the paddle wheel is 9000 kJ and the heat transferred to the surroundings from the tank is 3000 kJ, Determine :

(i) Work done;

(ii) Change in internal energy of the system.

Solution :



Work input to the paddle wheel = 9000 kJ

Heat transferred to the surroundings from the tank = 3000 kJ

As it is a closed system, the first law of thermodynamics can be written as

$$U_1 - Q + W = U_2 \quad \text{...(i)}$$

The work eaters into the tank in the form of energy only so this should he considered as heat input.

$$Q = Q_1 - Q_2 = 3000 - 9000 = -6000 \text{ kJ}.$$

(i) Since volume does not change (being constant volume process)

∴ Work done, $W = 0$

Putting the value of $W = 0$ in equation (i), we get

(ii) $$U_1 - (-6000) + 0 = U_2$$

∴ $$U_2 - U_1 = 6000 \text{ kJ}$$

Hence, change in internal energy (increase) = 6000 kJ.

5.11.1 Statements of Second Law

There are two statements of the second law of thermodynamics, the Kelvin-Planck statement, and the Clausius statement.

The Kelvin-Planck statement pertains to heat engines. The Clausius statement pertains to refrigerators/heat pumps.

- Kelvin-Planck statement of second law

  It is impossible to construct a device (engine) operating in a cycle that will produce no effect other than extraction of heat from a single reservoir and convert all of it into work.

  Mathematically, Kelvin-Planck statement can be written as :

  $$W_{cycle} \le 0 \text{ (for a single reservoir)}$$

- Clausius statement of second law

  It is impossible to transfer heat in a cyclic process from low temperature to high temperature without work from external source.

5.11.2 Reversible and Irreversible Process

A process is reversible with respect to the system and surroundings if the system and the surroundings can be restored to their respective initial states by reversing the direction of the process, that is, by reversing the heat transfer and work transfer. The process is irreversible if it cannot fulfill this criterion.

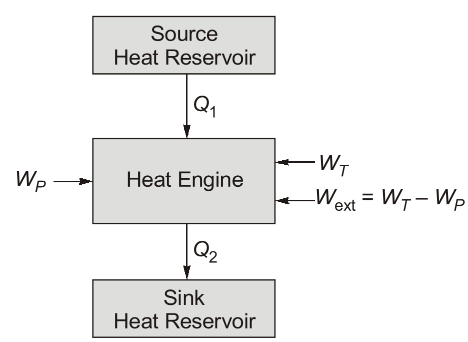
5.11.3 Heat Reservoirs

A heat reservoir is defined as a body of infinite heat capacity, which is capable of absorbing or rejecting an unlimited quantity of heat without suffering any change in its temperature.

Let Q_1 is the heat transferred to the system from source Q_2 is heat rejected from system.

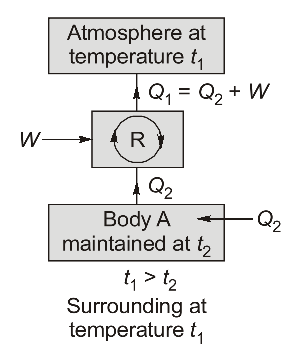
Figure show cyclic heat engine exchanging heat with source and a sink and producing

$$W_{net} = W_T - W_P$$



5.12 Refrigerator

A refrigerator is a device which, operating in a cycle, maintains a body at a temperature lower than the temperature of the surroundings. Let the body A be maintained at t_2, which is lower than the ambient temperature t_1. Even though A is insulated there will always be heat leakage Q_2 into the body from the surroundings by virtue of the temperature difference. In body A, Q_2 and W are of primary interest, there is a performance parameter in a refrigerator cycle, called coefficient of performance (COP) defined as



$$\text{COP} = \frac{\text{Desired effect}}{\text{Work input}} = \frac{Q_2}{W}$$

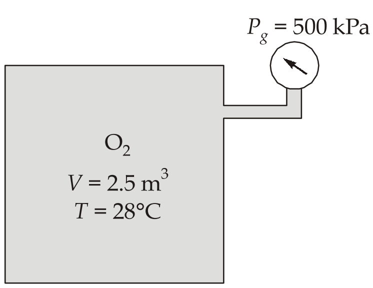
Since, $$Q_1 = Q_2 + W$$

$\therefore$ $$[\text{COP}]_{net} = \frac{Q_2}{Q_1 - Q_2} \qquad \text{...(i)}$$

Q.15 A gas is compressed from an initial volume of 0.42 m^3 to a final volume of 0.12 m^3. During the quasi-equilibrium process, the pressure changes with volume according to the relation $P = aV + b$, where a = –1200 kPa/m^3 and b = 600 kPa. The work done during this process is
(a) 82.8 kJ (b) –82.8 kJ
(c) 84.09 kJ (d) –84.09 kJ

Q.16 The air in the car tyre is initially at 2 bar and –5°C. After driving the car for a while, the temperature increases to 5°C. The new pressure in the tyre is __________ kPa. (Correct to 1 decimal place)

Q.17 The pressure gauge on a 2.5 m^3 oxygen tank reads 500 kPa. Then the amount of oxygen (kg) in the tank ______. (Correct up to two decimal places) if the temperature is 28°C and the atmospheric pressure is 97 kPa.



Student's Assignments 2

Q.18 A certain amount of gas is compressed from 1 bar and 0.1 m^3 to 5 bar and 0.03 m^3. The process is according to $PV^n = k$. What is the magnitude and direction of work?
(a) 14.706 kJ (on the gas)
(b) 17.046 kJ (on the gas)
(c) 14.706 kJ (by the gas)
(d) 17.046 kJ (by the gas)

Q.19 One kg of air is subjected to the following processes:
1. Air expands isothermally from 6 bar to 3 bar.
2. Air is compressed to half the volume at constant pressure.
3. Heat is supplied to air at constant volume till the pressure becomes threefold.

In which of the above processes, the change in entropy will be positive.
(a) 1 and 2 (b) 2 and 3
(c) 1 and 3 (d) 1, 2 and 3

Q.20 Entropy of a saturated liquid at 227°C is 2.6 kJ/kg-K. Its latent heat of vapourization is 1800 kJ/kg, then the entropy of saturated vapour at 227°C will be:
(a) 2.88 kJ/kg-K (b) 6.2 kJ/kg-K
(c) 7.93 kJ/kg-K (d) 10.53 kJ/kg-K

Q.21 The entropy of a mixture of pure gases is the sum of the entropies of constituents evaluated at
(a) temperature and pressure of the mixture
(b) temperature of the mixture and the partial pressure of the constituents
(c) temperature and volume of the mixture
(d) pressure and volume of the mixture

Q.22 At certain temperature, a hypothetical substance has h_f = 230 kJ/kg and latent heat of vapourization as 2135 kJ/kg, the enthalpy of its vapour liquid mixture of 0.97 quality fraction is (kJ/kg)
(a) 2536.73 (b) 2307.21
(c) 2295.73 (d) 2300.95

Q.23 A spherical balloon has a diameter of 25 cm and contains air at a pressure of 150 kPa. The diameter of the balloon increases to 30 cm in certain process. During this process the pressure of gas inside the balloon is proportional to the diameter of the balloon. What is the work done by the air inside the balloon during this process?
(a) 2 kJ (b) 5 kJ
(c) 3 kJ (d) 1 kJ

Q.24 An insulated rigid tank contains 0.9 kg of air at 150 kPa and 20°C. A paddle wheel is rotated inside the tank until temperature rises to 55°C. If surrounding air is at T_0 = 20°C. The energy destroyed is [Take c_v of air = 0.718 kJ/kgK]
(a) 21.4 kJ (b) 1.2 kJ
(c) 22.6 kJ (d) 30.3 kJ

Q.25 A heat engine operates between three thermal reservoirs. It absorbs 258 kJ of energy as heat from a reservoir at 52°C and rejects 100 kJ and 88 kJ of energy as heat to reservoirs at 27°C and

2°C, respectively. It delivers 70 kJ of work. This heat engine,

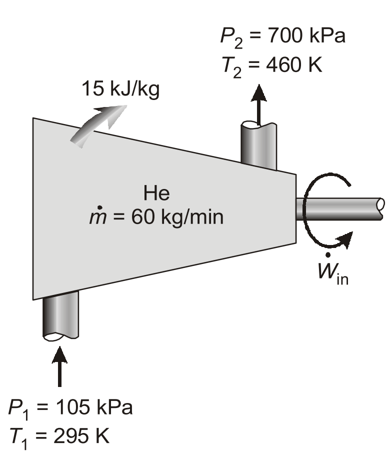
(a) violates the first law of thermodynamics only
(b) violates the 2nd law of thermodynamics but satisfy the first law
(c) satisfy the first law but violates the 2nd law of thermodynamics
(d) satisfy both the laws

Q.26 A body of mass 2.5 kg and c_p = 1.00 kJ/kgK is available at 600 K. If the atmosphere is at 300 K. The maximum work obtainable from the body by interacting with atmosphere is________ kJ.

Q.27 A heat engine receives half of its heat supply at 1000 K and half at 500 K, while rejecting heat to the sink at 300 K. The maximum thermal efficiency of the engine is ________%

Q.28 Block *A* of mass 5 kg and temperature 300°C. Block *B* of mass 10 kg and temperature –50°C. These two blocks consist of an isolated system. Heat capacities of block *A* and *B* be 1.0 and 0.4 kJ/kgK. The irreversibility of the system is________kJ.

Q.29 Helium is to be compressed from 105 kPa and 295 K to 700 kPa and 460K. A heat loss of 15 kJ/kg occurs during the compression process. Neglecting kinetic energy changes, the power input (in kW) required for a mass flow rate of 60 kg/min _______. (Correct up to two decimal places) Assume specific heat at constant pressure for helium as 5.1926 kJ/kgK.



ANSWERS

1. (d)	**2.** (a)	**3.** (a)	**4.** (a)	**5.** (a)
6. (b)	**7.** (18.04)	**8.** (939)	**9.** 10.5	**10.** (48)
11. (1300)	**12.** (15)	**13.** (d)	**14.** (b)	**15.** (b)
16. (207.4)	**17.** (19.08)	**18.** (a)	**19.** (c)	**20.** (b)
21. (b)	**22.** (d)	**23.** (d)	**24.** (a)	**25.** (c)
26. (230.14)	**27.** (55)	**28.** (276)	**29.** (871.78)	

HINTS

1. (d)
The mixture of air and liquid air is not a pure substance, because the relative proportions of oxygen and nitrogen differ in gas and liquid phases in equilibrium.

2. (a)

$$DOF = 0$$

Gibbs phase rule fails at critical point.

3. (a)
At steady state fluid properties doesn't change with respect to time at any given point.

4. (a)
If temperature is constant, *U* will remain unchanged as internal energy for an ideal gas is the function of temperature only.

6. (b)
Now, $\quad DH_{oil} = DH_{water}$

$$\Rightarrow \dot{m}_{oil}\left[1.68(T_1 - T_2) + 10.5 \times 10^{-4} \times \left(T_1^2 - T_2^2\right)\right]$$

$$= \dot{m}_{water} \times c_{p_w}\,[T_1 - T_2]_{water}$$

$$\Rightarrow 3\left[1.68(90-30) + 10.5 \times 10^{-4}\left(90^2 - 30^2\right)\right]$$

$$= \dot{m}_{water} \times 4.18 \times (70 - 25)$$

$$\Rightarrow \quad \dot{m}_{water} = 1.73 \text{ kg/s}$$

7. 18.04 (17.0 to 19.0)
Gas constant, $R = c_p - c_v$

$$= 1.968 - 1.507$$

$$= 0.461 \text{ kJ/kgK}$$

Molecular weight,

$$\mu = \frac{\bar{R}}{R} = \frac{8.314}{0.461} = 18.04 \text{ g/gmol}$$

8. (939)
Pressure, P = Constant

$$V \propto T$$

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

$$\frac{V_1}{4V_1} = \frac{303}{T_2}$$

$$T_2 = 1212\text{ K}$$
$$= 939\,°\text{C}$$

9. **10.5 (10 to 11)**

Paddle wheel work = Torque × Angular displacement

$$= 100 \times 60 \times 2 \times 2p \times 10^{-3}$$
$$W = 75.4\text{ kJ}$$

Heat gained by the air = Paddle wheel work (for insulated tank)

$$mC_V\Delta T = W$$

$$\Delta T = \frac{W}{mC_V} = \frac{75.4}{10 \times 0.718}$$
$$= 10.5°\text{C}$$

10. **48 (47.5 to 48.5)**

For a steady flow process

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + z_1\right) + \dot{Q} = \dot{m}\left(h_2 + \frac{V_2^2}{2} + z_2\right) + \dot{W}$$

$$\dot{W} = \dot{m}\left(h_1 - h_2 + \frac{V_1^2 - V_2^2}{2} + z_1 - z_2\right) + \dot{Q}$$

$$= 3\,(-18 + 3) - 3$$
$$= -45 - 3 = -48\text{ kW}$$

(–ve sign indicates that work is given to the compressor)

11. **(1300)**

Power production, $W = 1200$ MW

Heat given, $\dot{Q}_g = 900 \times 10^7$ kJ/h = 2500 MW

Heat rejected, $Q_R = \dot{Q}_g - W = 2500 - 1200$

$$= 1300\text{ MW}$$

12. (15)

Availability, $W_{out} = (h_1 - h_2) - T_0(s_1 - s_2)$

$$= (300 - 150) - 300(1.25 - 0.8)$$
$$= 15\text{ kJ/kg}$$

13. **(d)**

$$S_2 - S_1 = \int_1^2 \frac{dQ}{T} + S_{gen}$$

For internally reversible, $S_{gen} = 0$

So, $$S_2 - S_1 = \begin{cases} = 0 \\ > 0, \\ < 0 \end{cases}$$

$$\left[\text{Depending on} \int_1^2 \frac{dQ}{T}\right]$$

14. **(b)**

Power consumed by fan,

$$E_1 = 25\text{ W}$$

Power delivered to air,

$$E_2 = \frac{1}{2}\dot{m}v^2 = \frac{1}{2}0.8 \times 8^2$$
$$= 25.6\text{ W}$$

Since $E_2 > E_1$, this fan violates the first law of thermodynamics. Hence the claim of inventor is impossible.

15. **(b)**

The boundary work can determined by

$$W = \int_1^2 PdV = \int_1^2 (aV + b)dV$$

$$= a\frac{V_2^2 - V_1^2}{2} + b(V_2 - V_1)$$

$= \left(-1200\text{kPa/m}^3\right)\dfrac{(0.12^2 - 0.42^2)\text{m}^6}{2} + (600$ kPa$)(0.12 - 0.42)$ m^3

$$= -82.8\text{ kJ}$$

16. **(207.4) (207 to 208)**

Assuming ideal gas behavior of air inside tyre and the volume of tyre will remain constant, we get,

∴ $$V = C$$

Hence, $$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$\frac{2}{268} = \frac{P_2}{278}$$

∴ $$P_2 = 2.0746\text{ bar}$$

or $$P_2 = 207.4\text{ kPa}$$

17. **(19.08)(19.06 to 19.20)**

The gas constant of oxygen is $R = \dfrac{8.314}{32}$ kPa m^3/kgK = 0.2598 kPa m^3/kgK

The absolute pressure of O_2 is

$$P_{abs} = P_{gauge} + P_{atm}$$
$$= 500 + 97 = 597\text{ kPa}$$

Treating O_2 as an ideal gas, the mass of O_2 in tank is determined to be

$$m = \frac{PV}{RT} = \frac{(597\text{ kPa})(2.5\text{m}^3)}{(0.2598\text{kPa m}^3/\text{kgK})(28+273)\text{K}}$$

$= 19.086$ kg

18. (a)

Displacement work,

$$W_{1\text{-}2} = \frac{P_1V_1 - P_2V_2}{n-1}$$

$$P_1V_1^n = P_2V_2^n = C$$

$$\frac{P_1}{P_2} = \left(\frac{V_1}{V_2}\right)^n$$

Taking logarithm on both side,

$$\ln\left(\frac{P_1}{P_2}\right) = n\ln\left(\frac{V_2}{V_1}\right)$$

$$n = \frac{\ln\left(\frac{1}{5}\right)}{\ln\left(\frac{0.03}{0.1}\right)} = 1.33677 \approx 1.34$$

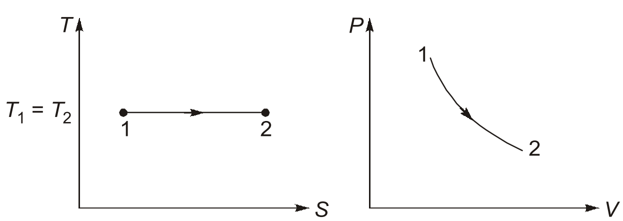
$$W_{1\text{-}2} = \frac{1\times10^5\times0.1 - 5\times10^5\times0.03}{1.34-1}$$

$= -14706$ Joule $= -140706$ kJ

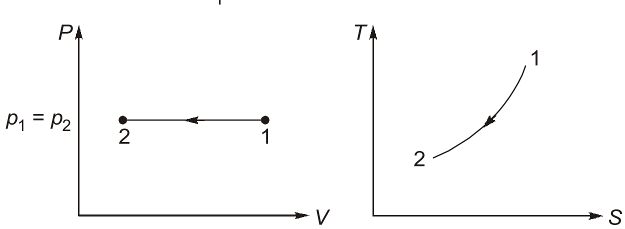
i.e., Work done on the gas = 14.706 kN

19. (c)

(i) Air expands isothermally from 6 bar to 3 bar



(ii) Air is compressed to half the volume at constant pressure



(iii) Heat is supplied to air at constant volume till pressure become three fold

$$p_2 = 3p_1$$

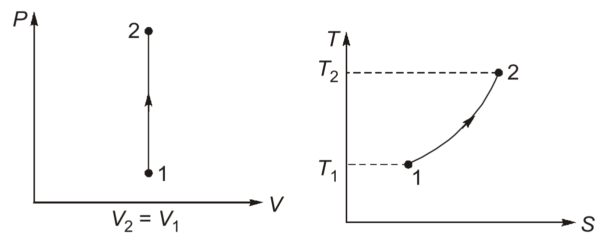
$$\frac{p_2}{p_1} = 3$$

V = Constant

$p \propto T$

$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

$$\frac{T_2}{T_1} = \frac{p_2}{p_1} = \frac{3p_1}{p_1} = 3$$



$V_2 = V_1$

$T_2 = 3T_1$

20. (b)

Entropy of saturated vapour,

$$s_1 = s_f + \frac{h_{fg}}{T} = 2.6 + \frac{1800}{500}$$

$= 6.2$ kJ/kg-K

22. (d)

Enthalpy of vapour liquid mixture is,

$$h = h_f + xh_{fg} = 230 + 0.97\times2135$$

$= 2300.95$ kJ/kg

23. (d)

Given that, $P \,\alpha\, D$

$\Rightarrow$ $P = KD$

$\Rightarrow$ $K = \dfrac{P_1}{D_1} = \dfrac{150}{0.25} = 600$ kPa/m

$$V = \frac{4}{3}\pi R^3 = \frac{\pi D^3}{6}$$

$\Rightarrow$ $dV = \dfrac{\pi D^2}{2}dD$

$$W = \int_1^2 PdV = \int_1^2 (KD)\cdot\frac{\pi D^2}{2}dD$$

$$= \frac{\pi K}{8}\left[D_1^4 - D_2^4\right]$$

$$= \frac{600\pi}{8}[0.3^4 - 0.25^4]$$

$= 0.988$ kJ ≈ 1 kJ

24. (a)

$T_1 = 20°\text{C} = 293$ K,

$m = 0.9$ kg

$T_2 = 55°C = 328K$
$c_v = 0.718$ kJ/kgK
$T_0 = 20°C = 293$ K

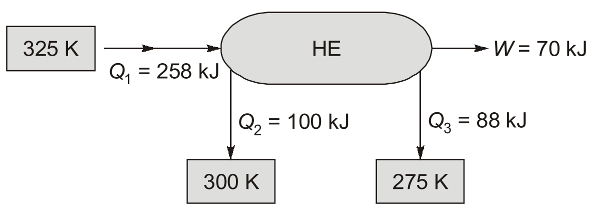
Exergy destroyed $= T_0\dot{S}_{gen}$

$$= T_0 m c_v \times \ln\frac{T_2}{T_1}$$

$$= 293 \times 0.9 \times 0.718 \ln\left(\frac{328}{293}\right)$$

$$= 21.365 \approx 21.4 \text{ kJ}$$

25. (c)



The first law of thermodynamics,

$$\oint dQ = \oint dW = 258 - 100 - 88$$

$$= 70 \text{ kJ}$$

Net-work delivered by the engine is 70 kJ. Hence the first law of thermodynamics is satisfied.

2nd law of thermodynamics (in the form of clausius inequality) gives

$$\oint \frac{dQ}{T} \le 0$$

$$\Rightarrow \quad \oint \frac{dQ}{T} = \frac{258}{325} + \frac{-100}{300} + \frac{-88}{275}$$

$$= 0.14 > 0$$

We find that the clausius inequality is not satisfied.

Hence, the 2nd law of thermodynamics is violated.

26. 230.14 (229 to 231)

Maximum work obtainable from a body and TER:

$$\Rightarrow W_{max} = m\left[c_p(T - T_0) + T_0 c_p \ln\left(\frac{T_0}{T}\right)\right]$$

$$= 2.5\left[1 \times (600 - 300) + 300 \times 1 \times \ln\left(\frac{300}{600}\right)\right]$$

$$= 230.14 \text{ kJ}$$

27. 55 (54 to 56)

Maximum efficiency is obtained when engine works on reversible cycle.

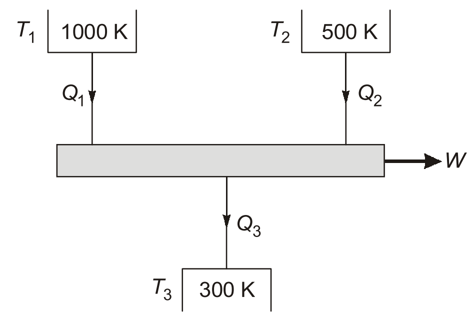
For maximum efficiency,

$$\Delta s_{\text{isolated system}} = 0$$

or, $$\oint \frac{dQ}{T} = 0$$

$$\Rightarrow \quad \Delta s = \sum\frac{Q}{T} + \left[\frac{-Q_3}{T_3}\right]$$

$$\Rightarrow \quad 0 = \frac{Q_1}{1000} + \frac{Q_2}{500} - \frac{Q_3}{300}$$



Now given, $Q_1 = Q_2 = Q$

$$\Rightarrow \quad \frac{Q_3}{300} = Q\left[\frac{1}{1000} + \frac{1}{500}\right]$$

$$\Rightarrow \quad \frac{Q_3}{Q} = \frac{300}{1000} + \frac{300}{500} = 0.9 \quad \text{...(1)}$$

Now, efficiency $= \dfrac{W}{Q_1 + Q_2} = \dfrac{W}{2Q}$

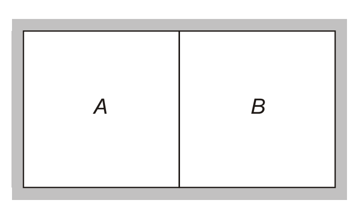
$$\eta_{max} = \frac{2Q - Q_3}{2Q_1} = 1 - \frac{Q_3}{2Q}$$

[using equation (1)]

$$= 1 - \frac{0.9}{2} = 0.55$$

28. 276 (275 to 277)

$m_A = 5$ kg; $m_B = 10$ kg
$T_A = 573$ K; $T_B = 223$ K
$c_A = 1$ kJ/kgK
$c_B = 0.4$ kJ/kgK



Let, T_f be final temperature,

By energy balance,

$$\Rightarrow \quad m_A c_A[T_A - T_f] = m_B c_B[T_f - T_B]$$

$$\Rightarrow 5 \times 1[573 - T_f] = 10 \times 0.4[T_f - 223]$$

$$\Rightarrow \quad T_f = 417.4\text{K}$$

$$S_{gen} = m_A c_A \ln\frac{T_f}{T_A} + m_B c_B \ln\frac{T_f}{T_B}$$

$= 5 \times 1 \ln\left(\frac{417.4}{573}\right) + 10 \times 0.4 \ln\left(\frac{417.4}{223}\right)$

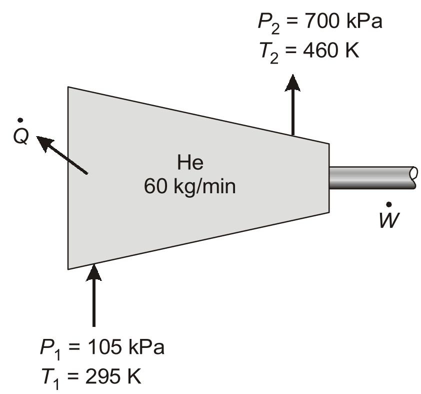
$= -1.58 + 2.507 = 0.92$ kJ/K

Irreversibility, $I = T_0 \Delta S = (273 + 27) \times 0.92$

$= 300 \times 0.92$

$= 276$ kJ

29. (871.78)(869.70 to 873.05)



From steady flow energy equation,

$$\dot{W}_{in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2$$

(Since $\Delta ke \simeq \Delta pe \simeq 0$)

$$\dot{W}_{in} - \dot{Q}_{out} = \dot{m}(h_2 - h_1) = \dot{m}c_p(T_2 - T_1)$$

Thus, $\dot{W}_{in} = Q_{out} + \dot{m}c_p(T_2 - T_1)$

$= \left(\frac{60}{60}\text{kg/s}\right)(15\text{kJ/kg}) + \left(\frac{60}{60}\text{kg/s}\right)(5.1926$ kJ/kgK$)(460 - 295)$K $= 871.779$ kW

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