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ESE – 2019
(MAINS)
Questions with Detailed Solutions

MECHANICAL ENGINEERING

PAPER – I

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MECHANICAL ENGINEERING

ESE _MAINS_2019_ (PAPER – 1)

PAPER REVIEW

Section – A consists of questions on Fluid Mechanics, Thermodynamics (Basic), Heat transfer, Refrigeration & Air conditioning and Internal Combustion Engines. Most of the questions on the above subjects are of medium difficultly level.

Section – B consists of questions on Hydraulic Machines, Power Plant Engineering, Turbomachinery and Renewable Sources of Energy. There are more questions on Power Plant Engineering and they are a bit difficult and lengthy as well.

Selection of questions play an important role in securing a good score. Based upon the above analysis it is observed that choosing 3 questions from Section – A will fetch a big advantage to the students.

SUBJECT WISE REVIEW

Subjects	Level	Marks
Basic thermodynamics	Medium	52
Refrigeration & Air conditioning	Medium	52
IC Engine	Hard	32
Power plant	Hard	92
Renewable sources of Energy	Medium	44
Heat transfer	Medium	32
Fluid Mechanics & Turbo machinery	Medium	176

Subjects Experts,

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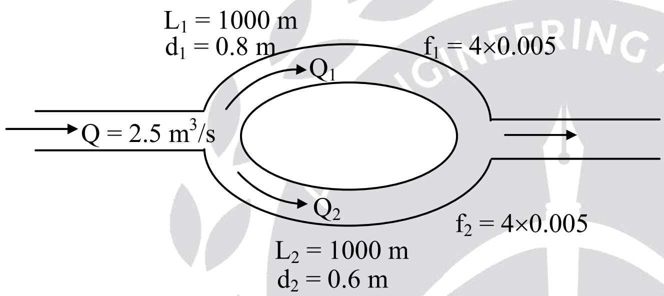
SECTION - A

01(a). A main pipe divides into two parallel pipes which again form as one pipe. The length and diameter of the first parallel pipe are 1000 m and 0.8 m respectively, while the length and diameter of the second parallel pipe are 1000 m and 0.6 m respectively. Find the rate of flow in each parallel pipe, if total flow in the main is 2.5 m^3/sec. The coefficient of friction for each parallel pipe is same and equal to 0.005. (12 M)

Sol: *Assumptions:* The flow is steady and incompressible.

Friction factor = 4 × coefficient of friction



Since the branching pipes are parallel,

$$h_{f1} = h_{f2}$$

or, $$\frac{f_1L_1Q_1^2}{12.1d_1^5} = \frac{f_2L_2Q_2^2}{12.1d_2^5}$$

$f_1 = f_2$ and $L_1 = L_2$ (Given)

$$Q_1^2 = \left(\frac{d_1}{d_2}\right)^5 Q_2^2$$

$$= \left(\frac{0.8}{0.6}\right)^5 Q_2^2 = 4.214Q_2^2$$

Or, $Q_1 = 2.0528\ Q_2$ .... (1)

Also, $Q_1 + Q_2 = 2.5$ m^3/s (given)

i.e., $Q_1 = 2.5 - Q_2$

From equation (1)

$2.5 - Q_2 = 2.0528\ Q_2$

Or, $$Q_2 = \frac{2.5}{3.0528} = 0.8189\,m^3/s$$

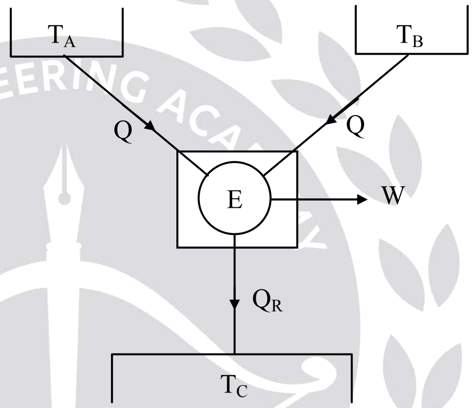
and $Q_1 = 1.6811$ m^3/s

01(b). A reversible engine works between three thermal reservoirs, A, B and C. The engine absorbs an equal amount of heat from the thermal reservoirs A and B kept at temperatures T_A and T_B respectively and rejects heat to the thermal reservoir C kept at temperature T_C. The efficiency of the engine is α times the efficiency of the reversible engine which works between the two reservoirs A and C.

Prove that: $\frac{T_A}{T_B} = (2\alpha - 1) + 2(1-\alpha)\frac{T_A}{T_C}$ **(12 M)**

Sol:

2^{nd} law $\oint \frac{dQ}{T} = 0$



$$\frac{Q}{T_A} + \frac{Q}{T_B} - \frac{Q_R}{T_C} = 0$$

$$Q\left[\frac{T_A + T_B}{T_A T_B}\right] = \frac{Q_R}{T_C}$$

$$\frac{Q_R}{Q} = T_C\left[\frac{T_A + T_B}{T_A T_B}\right]$$

$$\eta_e = 1 - \frac{Q_R}{2Q} = 1 - \frac{T_C}{2}\left[\frac{T_A + T_B}{T_A T_B}\right]$$

Efficiency is given as α times the efficiency of the reversible engine working between T_A & T_C

$$\alpha\left[1 - \frac{T_C}{T_A}\right] = 1 - \frac{T_C}{2}\left[\frac{T_A + T_B}{T_A T_B}\right]$$

$$\alpha - \alpha\frac{T_C}{T_A} = 1 - \frac{T_C}{2}\left[\frac{1}{T_A} + \frac{1}{T_B}\right]$$

$$\alpha - \alpha\frac{T_C}{T_A} = 1 - \frac{T_C}{2T_A} - \frac{T_C}{2T_B}$$

Multiply both side by T_A and divide by T_C

$$\alpha\frac{T_A}{T_C} - \alpha = \frac{T_A}{T_C} - \frac{1}{2} - \frac{1}{2}\frac{T_A}{T_B}$$

$$\frac{1}{2}\frac{T_A}{T_B} = \left(\alpha - \frac{1}{2}\right) + (1-\alpha)\frac{T_A}{T_C}$$

$$\frac{T_A}{T_B} = (2\alpha - 1) + 2(1-\alpha)\frac{T_A}{T_C}$$

01(c). With the help of a neat sketch, explain the working of a thermostatic expansion valve. How does it cope up with the variable load? (12 M)

Sol: ***Thermostatic expansion valve:***

- It is the most widely used expansion valve as it is adaptable to any type of refrigeration system. It has very feeler Bulbhigh efficiency as well.
- Though its name is thermostatic yet it is not actuated by the change in temperature of the evaporator. It is actuated by the superheat of the refrigerant leaving the evaporator.
- Its working is based on maintaining a constant degree of sufficient superheat at the evaporator outlet. The evaporators remain filled with the refrigerant under all conditions of load.
- The principle of the thermostatic expansion valve is shown in figure. It consists of pressure bellows/diaphragm, a needle and the seat, a feeler bulb and the adjustable spring.

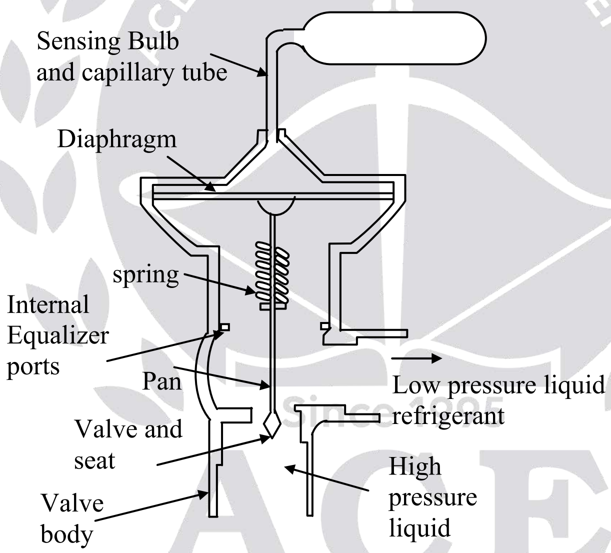


Fig: Thermostatic expansion valve

- The feeler bulb is fixed on the suction line at the outlet of the evaporator to sense the temperature changes of the refrigerant.
- The pressure of the feeler bulb liquid acts on one side of the bellows/diaphragm as it is connected to it by state of equilibrium because of the two opposing pressures.
- The valve setting gets disturbed, when the change in the degree of superheat is encountered, thereby it moves in the direction depending on which side the pressure is higher.
- Normally thermostatic expansion valves are adjusted for a 4.5 to 5.5^{0}C superheat.

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Regular Batches @ **Dilsukhnagar**	08th & 22nd July, 05th & 20th August 2019
Regular Batch @ **Kukatpally**	01st July 2019
Regular Batches @ **Pune**	01st & 15th July 2019
Weekend & Regular Batches @ **Chennai**	06th July 2019
Regular Batch @ **Bengaluru**	08th July 2019

ESE + GATE + PSUs – 2020

Regular Batch @ **Dilsukhnagar**	08th July 2019
Regular Batch @ **Pune**	01st July 2019

GATE + PSUs – 2021

Morning Batches @ **Abids**	12th July & 10th August 2019
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Morning & Evening Batches @ **Kukatpally**	12th July & 10th August 2019
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ESE + GATE + PSUs – 2021

Morning Batches @ **Abids**	12th July & 10th August 2019
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IES GENERAL STUDIES BATCH

Regular Batch @ **Abids**	12th July 2019
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GENCO / TRANSO / DISCOMS BATCH

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01(d). The fuel rod of a nuclear reactor is lagged with a tight fitting cladding material to prevent oxidation of the surface of the fuel rod by direct contact with the coolant. The heat generation occurs only in the fuel rod according to the following relation: $q_g = q_o\left[1-\frac{r^2}{R^2}\right]$.

Under steady state conditions, heat generated in the fuel rod is conducted through the cladding material and then dissipated to the coolant flowing around the cladding by convection.

Assuming that there is no contact resistance between the fuel rod and cladding, derive an expression for the heat flux through the fuel rod and cladding material. (12 M)

Sol: Given: $q_g = q_o\left[1-\frac{r^2}{R^2}\right]$

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial \Gamma}{\partial r}\right]+\frac{q_g}{k}=\frac{1}{\alpha}\frac{\partial T}{\partial t}$$

$$\frac{\partial}{\partial r}\left[r\frac{\partial T}{\partial r}\right]=\frac{-q_g r}{k}$$

$$\frac{\partial}{\partial r}\left[r\frac{\partial T}{\partial r}\right]=\frac{-q_o r}{k}\left[1-\frac{r^2}{R^2}\right]$$

$$\frac{d}{dr}\left[r\frac{dT}{dr}\right]=\frac{-q_g}{k}\left[r-\frac{r^3}{R^2}\right]$$

Integrating, $$r\frac{dT}{dr}=\frac{-q_g}{k}\left[\frac{r^2}{2}-\frac{r^4}{4R^2}\right]+c_1$$

$$r=o,\ \frac{dT}{dr}=0,\ c_1=0$$

$$r\frac{dT}{dr}=-\frac{q_g}{k}\left[\frac{r^2}{2}-\frac{r^4}{4R^2}\right]$$

$$\frac{dT}{dr}=\frac{-q_g}{rk}\left[\frac{r^2}{2}-\frac{r^4}{4R^2}\right]$$

$$\frac{dT}{dr}=\frac{-q_g r}{rk}\left[\frac{r}{2}-\frac{r^3}{4R^2}\right]$$

$$\frac{dT}{dr}=\frac{-q_g}{k}\left[\frac{r}{2}-\frac{r^3}{4R^2}\right]$$

On integration, $T = \frac{-q_g}{k}\left[\frac{r^2}{4} - \frac{r^4}{16R^2}\right] + c_2$ -----------(1)

At $r = R$,

$T = T_S$

$$T_S = \frac{-q_g}{k}\left[\frac{R^2}{4} - \frac{R^4}{16R^2}\right] + c_2$$

$$T_S = \frac{-q_g}{k}\left[\frac{R^2}{4} - \frac{R^2}{16}\right] + c_2$$

$$T_S = \frac{-q_g R^2}{k}\left[\frac{1}{4} - \frac{1}{16}\right] + c_2$$

$$T_S = \frac{-q_g R^2}{k}\left[\frac{3}{16}\right] + c_2$$

$$c_2 = T_S + \frac{q_g R^2 3}{16k}$$

Put c_2 in equation (1)

$$T = \frac{-q_g}{k}\left[\frac{r^2}{4} - \frac{r^4}{16R^2}\right] + T_S + \frac{3}{16}\frac{q_g R^2}{k}$$

$$T = T_S + \frac{3}{16}\frac{q_g R^2}{k} - \frac{q_g}{k}\left[\frac{r^2}{4} - \frac{r^4}{16R^2}\right]$$

$$q_{rod} = -k\left.\frac{dT}{dr}\right|_{r=R}$$

$$q_{rod} = -k\left[\frac{-q_g}{k}\left(\frac{r}{2} - \frac{r^3}{4R^2}\right)\right]_{r=R}$$

$$q_{rod} = -k\left[\frac{q_g}{k}\left[\frac{R}{2} - \frac{R^3}{4R^2}\right]\right]$$

$$q_{rod} = -k\left[\frac{-q_g}{k}\left[\frac{R}{2} - \frac{R}{4}\right]\right]$$

$$q_{rod} = q_g R\left[\frac{1}{2} - \frac{1}{4}\right]$$

$$q_{rod} = \frac{q_g k}{4}\ W/m^2$$

01(e). Compare compression ignition engine with spark ignition engine so far as the following points are concerned:

(i) Working cycle

(ii) Method of ignition

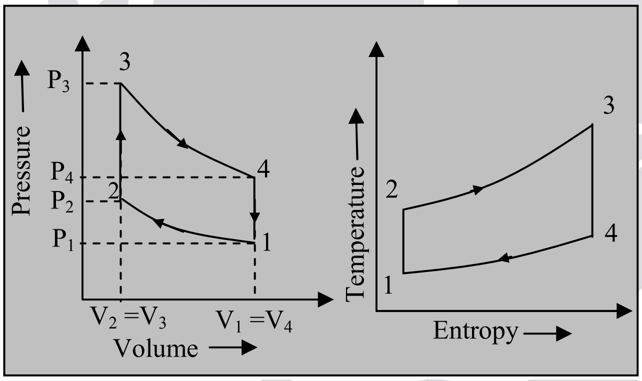
(iii) Method of fuel supply **(12 M)**

Sol:

(i) Working cycle of SI engine

Otto cycle:

The main drawback of the Carnot cycle is its impracticability due to high pressure and high volume ratios employed with comparatively low mean effective pressure. Nicolaus Otto(1876), proposed a constant – volume heat addition cycle which forms the basis for the working of today's spark-ignition engines. The cycle is shown on *P-V* and *T*-s diagrams in the following figures



The process 1-2 represents isentropic compression of the air when the piston moves from bottom dead centre to top dead centre.

The process 2-3 heat is supplied reversibly at constant volume. This process corresponds to spark-ignition and combustion in the actual engine.

The process 3 - 4 represents isentropic expansion

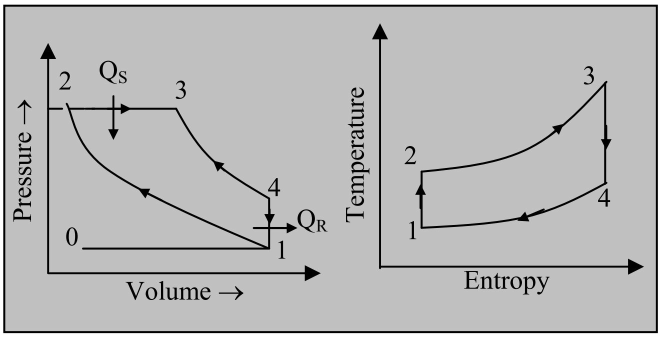
The process 4 - 1 represent constant volume heat rejection.

Working cycle of CI engine :

Diesel Cycle:

The Diesel cycle is shown on P-V and T-s diagrams respectively

Diesel cycle consist of two reversible adiabatic, one reversible isobaric, and one reversible isochoric process.



Basic processes in diesel cycle

1 – 2 : Reversible adiabatic compression

2 – 3 : Constant pressure heat addition

3 – 4 : Reversible adiabatic expansion

4 –1 : Constant volume heat rejection

(ii) Method of Ignition in SI Engine :

An ignition system must provide the following basic requirements, a source of electric energy, a means for boosting the low voltage from the source to the very high voltage potential required to produce a high – tension across the spark plug gap that ignites, a means for timing and distributing the high voltage, i.e., distribute the high potential to each spark plug at the exact instant it is required in every cycle for each cylinder

- The battery and generator normally provide 6 to 12 volt potential direct current, while the magneto provides an alternating current of higher voltage.
- The relatively low voltage produced by the three different types of electric source must be boosted to a very high potential, 10,000 to 20,000 volts, in order to overcome the resistance of the spark gap and to release enough energy to initiate a self propagating flame front within the combustible mixture
- The low voltage form the source is raised in the secondary circuit by means of an ignition coil, breaker points, and condenser.
- The timing and distribution of the high potential to the proper spark plug at the exact instant it is required within each cylinder is accomplished by means of the distributor and breaker points

Method of Ignition in CI Engine :

- In CI engines the air fuel mixture is not homogeneous and the AFR in the various parts of the combustion chamber is different.
- As the combustion chamber contains compressed air at a temperature above the ignition temperature of the fuel, combustion occurs at many points within the chamber.
- As the fuel is injected, each minute droplet produced after atomization by the injector is enveloped by its own vapour, and after a small interval, combustion begins at the surface of this envelope.
- As stated in above section, the fuel is not injected all at once but continues over a number of degrees of crank angles(upto about 35 degree, depending upon speed and size of engine).
- The first droplets of fuel entering the cylinder come in contact with air whose temperature is only a little above the ignition temperature and hence the beginning of the burning process takes a little time.
- The droplets which enter later find the air already heated to a temperature much above the ignition temperature due to burning of the earlier droplets and begin to burn almost immediately as they enter the cylinder, but the last droplets to enter find some difficulty in burning as much of the oxygen in the air has been consumed.

  Therefore, to ensure proper combustion of the fuel, sufficient mixing of the fuel and air is necessary by dispersion of the fuel and turbulence of the air

(iii) Method of fuel supply in SI engine

An engine is generally operated at different loads and speeds. For this, proper air-fuel mixture should be supplied to the engine cylinder. Fuel and air are mixed to form three different types of mixtures.

i) Chemically correct mixture

ii) Rich mixture and

(iii) Lean mixture

Chemically correct or stoichiometric mixture is one in which there is just enough air for Complete combustion of the fuel.

For example, to burn one kg of octane (C_8H_{18}) completely 15.12 kg of air is required. Hence chemically correct A/F ratio for C_8H_{18} is 15.12:1; usually approximated to 15:1. This chemically correct mixture will vary only slightly in numerical value between different hydrocarbon fuels. It is always computed from the chemical equation for complete combustion for a particular fuel. Complete combustion means all carbon in the fuel is converted to CO_2 and all hydrogen to H_2O.

A mixture which contains less air than the stoichiometric requirement is called a rich mixture (example, A/F ratio of 12:1, 10:1 etc.).

A mixture which contains more air than the Stoichiometric requirement is called a lean mixture (example, A/F ratio of 17:1, 20:1 etc.)

There is however, a limited range of A/F ratios in a homogeneous mixture, only within which combustion in an SI engine will occur. Outside this range, the ratio is either too rich or too lean to sustain flame propagation. This range of useful A/F ratio runs from approximately 9:1 (rich) to 19:1 (lean) as indicated in the figure.

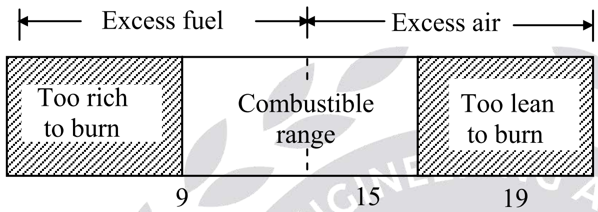


Fig: Air - fuel ratio

The carburetor should provide an A/F ratio in accordance with engine operating requirements and this ratio must be within the combustible range.

Method of fuel supply in CI engine

Fuel injection in CI engines:

The fuel injection in CI engines consists of fuel supply tank, filters, lines, fuel pump, and fuel injector.

- The function of the fuel injection system is to supply correct quantity of fuel and inject it at the correct time without after – dribbling, atomize the fuel properly, and ensure that the fuel spray penetrates the desired areas of the combustion chamber.
- CI engine fuel injection system may be of two types – air injection, airless or solid injection.
- In air – injection, the fuel is injected into the cylinder by means of compressed air at about 7 MPa. Though this system was used in early years, it is seldom used now.
- Advantages of this system are good atomization and distribution, and possibility of using high viscosity, less expensive fuel.
- Disadvantages are complication of the engine with high pressure multi stage air compressor which absorbs a part of engine power.
- Now a days the airless or solid injection is used, and this system consists of two main parts – a high pressure fuel pump (15 – 30 MPa) and a fuel injector.

- Depending upon the arrangement of the fuel pumps and injectors, solid injection system may be classified as:
  (i) common rail system,
  (i) unit injector system,
  (ii) individual pump and injector system.

02(a). A jet of water is discharging at 25 kg/sec from a nozzle of 25 mm diameter. The jet from the nozzle is directed towards a window of a building at a height of 30 m from the ground. Assuming the nozzle discharge to be a height of 2 m from the ground, determine the greatest distance from the building where the foreman can stand, so that the jet can reach the window. (20 M)

Sol: *Assumptions:*

(i) Air resistance is neglected.

(ii) The flow is steady and incompressible.

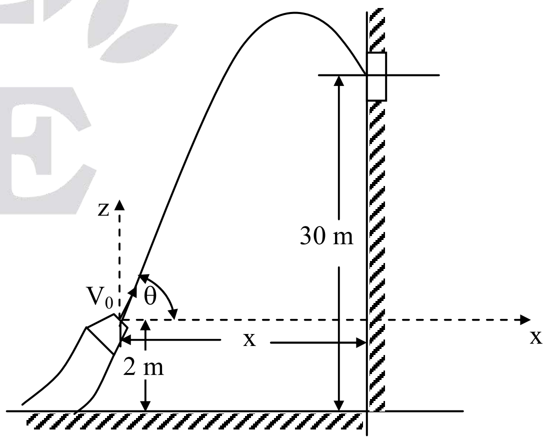
Given:

$\dot{m} = 25\,\text{kg/s}$, $d_j = 25$ mm

$$V_0 = \frac{\dot{m}}{\rho A_j} = \frac{25 \times 4}{10^3 \times \pi \times 0.025^2} = 50.93 \text{ m/s}$$

$$x = (V_0 \cos\theta)t \quad \ldots\ldots (i)$$

and $$z = (30-2) = (V_0 \sin\theta)t - \frac{1}{2}gt^2 \quad \ldots\ldots (ii)$$



From equation (i)

$$\cos\theta = \frac{x}{V_0 t}$$

$$\sin\theta = \sqrt{1-\cos^2\theta} = \sqrt{1-\left(\frac{x}{V_0 t}\right)^2}$$

Substituting this value in Equation (ii), we get

$$28 = \left(V_0\sqrt{1-\frac{x^2}{V_0^2 t^2}}\right)t - \frac{1}{2}gt^2 = \sqrt{V_0^2 t^2 - x^2} - \frac{1}{2}gt^2$$

Or, $$28 + \frac{1}{2}gt^2 = \sqrt{V_0^2 t^2 - x^2}$$

$$\left[28+\frac{1}{2}gt^2\right]^2 = V_0^2t^2 - x^2$$

Or, $$x = \sqrt{V_0^2t^2 - \left(28+\frac{1}{2}gt^2\right)^2} \quad \text{.......... (iii)}$$

and $$\frac{dx}{dt} = \frac{2V_0^2t - 2\left(28+\frac{1}{2}gt^2\right)(gt)}{2\sqrt{V_0^2t^2 - \left(28+\frac{1}{2}gt^2\right)^2}}$$

For maximum x, $\frac{dx}{dt} = 0$

Hence, $$V_0^2t - \left(28+\frac{1}{2}gt^2\right)gt = 0$$

$$V_0^2t = 28gt + \frac{1}{2}g^2t^3$$

$$V_0^2 = 28g + \frac{1}{2}g^2t^2$$

Or, $$t^2 = \frac{\left(V_0^2 - 28g\right)\times 2}{g^2}$$

$$t = \sqrt{\frac{\left(50.93^2 - 28\times 9.81\right)\times 2}{9.81^2}} = 6.942 \text{ s}$$

Thus, the greatest distance from the building where the foreman can stand, is [from equation (iii)]

$$x = \sqrt{50.93^2 \times 6.942^2 - \left(28+\frac{1}{2}\times 9.81\times 6.942^2\right)^2} = 234.75 \text{ m}$$

02(b). Two rigid tanks shown in Figure 2 (b) each contain 10 kg of N_2 gas at 1000 K, 500 kPa. They are now thermally connected to a reversible heat pump, which heats one and cools the other with no heat transfer to the surroundings. When one tank in heated to 1500 K, the process stops. Find the final (P, T) in both tanks and the work input to the heat pump, assuming constant heat capacities.

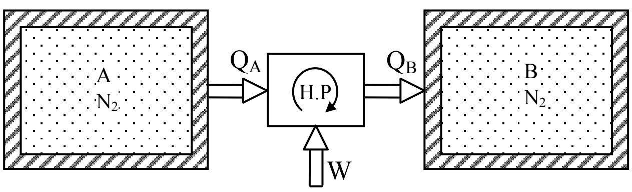


Figure 2(b)

(20 M)

Sol: Given: $P_{A,1}$, $P_{B,1}$, $T_{A,1}$, $T_{B,1}$, $T_{B,2}$

Assumptions: Nitrogen can be treated as an ideal gas. System is closed.

Second Law:

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_i - S_e + S_{gen}$$

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T}\,(\to 0) + S_i\,(\to 0) - S_e\,(\to 0) + S_{gen}\,(\to 0)$$

$$S_2 - S_1 = 0$$

$m_A(s_2 - s_1)_A + m_B(s_2 - s_1)_B = 0$

$$0 = m_A\left[c_v \ell n\left(\frac{T_{A,2}}{T_{A,1}}\right) + R\ell n\left(\frac{v_{A,2}}{v_{A,1}}\right)\right] + m_B\left[c_v \ell n\left(\frac{T_{B,2}}{T_{B,1}}\right) + R\ell n\left(\frac{v_{B,2}}{v_{B,1}}\right)\right]$$

$$0 = m_A\left[c_v \ell n\left(\frac{T_{A,2}}{T_{A,1}}\right) + R\ell n\left(\frac{v_{A,2}}{v_{A,1}}\right)(\to 0)\right] + m_B\left[c_v \ell n\left(\frac{T_{B,2}}{T_{B,1}}\right) + R\ell n\left(\frac{v_{B,2}}{v_{B,1}}\right)(\to 0)\right]$$

$$m_A = m_B$$

$$0 = c_v \ell n\left(\frac{T_{A,2}}{T_{A,1}}\right) + c_v \ell n\left(\frac{T_{B,2}}{T_{B,1}}\right)$$

$$0 = \ell n\left(\frac{T_{A,2}}{T_{A,1}}\right) + \ell n\left(\frac{T_{B,2}}{T_{B,1}}\right)$$

$$\ell n\left(\frac{T_{A,2}}{T_{A,1}}\right) = -\ell n\left(\frac{T_{B,2}}{T_{B,1}}\right)$$

$$T_{A,2} = T_{A,1}\left(\frac{T_{B,1}}{T_{B,2}}\right) = 1000\text{K}\frac{1000\text{K}}{1500\text{K}}$$

$$T_{A,2} = 667 \text{ K}$$

Now find pressures $R = \frac{Pv}{T} = \frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2}$

Volume is fixed, $P_2 = P_1 \frac{T_2}{T_1}$

$$P_{2,B} = 500\,\text{kPa}\,\frac{1500\,\text{K}}{1000\,\text{K}} = 750\,\text{kPa}$$

$$P_{2,A} = 500\,\text{kPa}\,\frac{667\,\text{K}}{1000\,\text{K}} = 333\text{ kPa}$$

Apply first law to find work

$U_2 - U_1 = Q_{12} - W_{12}$

$W_{12} = U_1 - U_2$

$W_{12} = m_A (u_1 - u_2)_A + m_B(u_1 - u_2)_B$

$W_{12} = m_A c_v(T_1 - T_2)_A + m_B c_v(T_1 - T_2)_B$

$$W_{12} = (10\,kg)0.745\frac{kJ}{kgK}(667\,K - 1000\,K) + (10\,kg)0.745\frac{kJ}{kgK}(1500\,K - 1000\,K)$$

$W_{12} = 1244$ kJ

02(c) Water is flowing steadily over a smooth flat plate with a velocity of 2 m/sec. The length of the plate is 30 cm. Calculate

(i) The thickness of the boundary layer 10 cm from the leading edge of the plate;

(ii) The rate of growth of the boundary layer at 10 cm from the leading edge; and

(iii) The drag coefficient on one side of the plate.

Assume parabolic velocity profile.

Kinematic viscosity of water, $\nu = 1.02 \times 10^{-6}$ m^2/sec.

Derive the expressions used in the calculation. (20 M)

Sol: *Assumptions:*

(i) The flow is steady, incompressible and two-dimensional in x-y plane.

(ii) The boundary layer remains laminar, over the range of interest.

Given:

Smooth flat plate

$U_\infty = 2$ m/s;

L = 30 cm

$\nu = 1.02 \times 10^{-6}$ m^2/s

Velocity profile is parabolic

i.e., $$\frac{u}{U_\infty} = 2\left(\frac{y}{\delta}\right) - \left(\frac{y}{\delta}\right)^2$$

The momentum thickness is evaluated as:

$$\theta = \int_0^\delta \frac{u}{U_\infty}\left(1 - \frac{u}{U_\infty}\right)dy = \int_0^\delta \left[2\frac{y}{\delta} - \left(\frac{y}{\delta}\right)^2\right]\left[1 - \frac{2y}{\delta} + \frac{y^2}{\delta^2}\right]dy$$

$$= \int_0^\delta \left[2\frac{y}{\delta} - \frac{4y^2}{\delta^2} + \frac{2y^3}{\delta^3} - \frac{y^2}{\delta^2} + \frac{2y^3}{\delta^3} - \frac{y^4}{\delta^4}\right]dy$$

$$= \int_0^\delta \left[2\frac{y}{\delta} - \frac{5y^2}{\delta^2} + \frac{4y^3}{\delta^3} - \frac{y^4}{\delta^4}\right]dy$$

Integrating the above relation, we get

$$\theta = \left[\frac{y^2}{\delta} - \frac{5}{3}\frac{y^3}{\delta^2} + \frac{y^4}{\delta^3} - \frac{1}{5}\frac{y^5}{\delta^4}\right]_0^\delta$$

$$= \delta - \frac{5}{3}\delta + \delta - \frac{1}{5}\delta$$

$$\theta = 2\delta - \frac{5}{3}\delta - \frac{1}{5}\delta = \frac{2}{15}\delta \quad \text{………... (i)}$$

Using von-Karman M.I. equation,

$$\frac{d\theta}{dx} = \frac{\tau_0}{\rho U_\infty^2} \quad \text{………. (ii)}$$

where, $\tau_0 = \mu \left.\frac{\partial u}{\partial y}\right|_{y=0} = \mu \frac{\partial}{\partial y}\left[2\frac{y}{\delta} - \frac{y^2}{\delta^2}\right]_{y=0} U_\infty$

$$= \frac{\mu U_\infty \times 2}{\delta} \quad \text{…………………..... (iii)}$$

Thus, from equations (i), (ii) and (iii)

$$\frac{d}{dx}\left(\frac{2}{15}\delta\right) = \frac{2\mu U_\infty}{\delta \times \rho U_\infty^2} = \frac{2\mu}{\rho\delta U_\infty}$$

$$\frac{2}{15}\frac{d\delta}{dx} = \frac{2\mu}{\rho\delta U_\infty}$$

$$\delta\frac{d\delta}{dx} = \frac{15\mu}{\rho U_\infty} \quad \text{....................... (iv)}$$

Integrating,

$$\frac{\delta^2}{2} = \frac{15}{\rho}\frac{\mu}{U_\infty}x + c$$

But at $x = 0,\ \delta = 0 \Rightarrow c = 0$

Thus, $\frac{\delta^2}{x^2} = 30\frac{\mu}{\rho x U_\infty} = \frac{30}{Re_x}$

$$\Rightarrow \quad \delta = \frac{\sqrt{30}\,x}{\sqrt{Re_x}} = \frac{5.477\,x}{\sqrt{Re_x}} \quad \text{.................. (v)}$$

(i) At x = 10 cm, $Re_x = \dfrac{2\times 0.1}{1.02\times 10^{-6}} = 196078.43$

$$\delta_{x=10\,cm} = \frac{5.477\times 0.1}{\sqrt{196078.43}}$$

$$= 1.237 \times 10^{-3}\ m$$

Or, $\delta_{x\,=\,10\,cm} = 1.237$ mm

(ii) The rate of growth of the boundary layer, $\dfrac{d\delta}{dx} = \dfrac{15\nu}{U_\infty}\times\dfrac{1}{\delta}$

$$\left.\frac{d\delta}{dx}\right|_{x=10\,cm} = \frac{15\nu}{U_\infty}\times\frac{1}{\delta_{x=10\,cm}}$$

$$= \frac{15\times 1.02\times 10^{-6}}{2}\times\frac{1}{1.237\times 10^{-3}}$$

$$= 6.1843 \times 10^{-3}\ m/m$$

(iii) We know that drag coefficient, C_D can be expressed as: (from Equations (iii) & (v)

$$C_{D,x} = \frac{\tau_0}{\frac{1}{2}\rho U_\infty^2} = \frac{2\mu U_\infty}{\delta\times\frac{1}{2}\rho U_\infty^2} = \frac{4\mu\sqrt{Re_x}}{\rho U_\infty\times 5.477x}$$

$$C_{D,x} = \frac{4\mu}{\rho U_\infty\times 5.477}\sqrt{\frac{U_\infty}{\nu}}.x^{-1/2}$$

$$C_{D,L} = \frac{1}{L}\int_0^L c_{D,x}dx = \frac{1}{L}\times\frac{4\mu}{\rho U_\infty\times 5.477}\left[2x^{\frac{1}{2}}\right]_0^L\times\sqrt{\frac{U_\infty}{\nu}}$$

$$= \frac{8\mu}{L\rho U_\infty\times 5.477}\sqrt{\frac{U_\infty L}{\nu}}$$

$$C_{D,L} = \frac{1.46}{\sqrt{Re_L}}$$

where $Re_L = \dfrac{U_\infty L}{\nu} = \dfrac{2\times 0.3}{1.02\times 10^{-6}} = 588235.29$

Thus, the drag coefficient on one side of the plate is

$$C_D = \frac{1.46}{\sqrt{588235.29}} = 1.904\times 10^{-3}$$

03(a). A four-stroke cycle gasoline engine has six single-acting cylinders of 8 cm bore and 10 cm stroke. The engine is coupled to a brake having a torque radius of 40 cm. At 3200 rpm, with all cylinders operating, the net brake load is 350 N. When each cylinder in turn is rendered inoperative, the average net brake load produced at the same speed by the remaining 5 cylinders is 250 N. Estimate the indicated mean effective pressure of the engine. With all cylinders operating, the fuel consumption is 0.33 kg/min; calorific value of fuel is 43 MJ/kg; the cooling water flow rate and temperature rise is 70 kg/min and 10°C respectively. On test, the engine is enclosed in a thermally and acoustically insulated box through which the output drive, water, fuel, air and exhaust connections pass. Ventilating air blown up through the box at the rate of 15 kg/min enters at 17°C and leaves at 62°C. Draw up a heat balance of the engine stating the items as a percentage of the heat input.

(20 M)

Sol: 4 Stroke cycle :

Torque radius, r = 0.4 m

No. of cylinders = 6 = x

Diametre = d = 0.08 m,

Length = l = 0.1 m,

Speed = N = 3200 rpm

Net brake load = 350 N = W

Net brake load with each cylinder cut off = W_1 = 250 N

Fuel consumption = $\dot{m}_f$ = 0.33 kg/min

Calorific value of fuel = CV = 43000 kJ/kg

Cooling water flow rate = $\dot{m}_w$ = 70 kg/min

Temperature rise of cooling water = ΔT = 10°C

Air entering the box = $\dot{m}_a$ = 15 kg/min

Temperature of air entering box = T_e = 290 K

Temperature of air leaving box = T_l = 273 + 62 = 335 K

Brake power with all cylinder firing

$$B = \frac{2\pi NT}{60000} = \frac{2\pi N\,W\,r}{60000} = \frac{2\pi \times 3200 \times 350 \times 0.4}{60000} = 49.89\text{ kW}$$

Brake power with first cylinder cut off

$$B_1 = \frac{2\pi N W_1 r}{60000} = \frac{2\pi \times 3200 \times 250 \times 0.4}{60000} = 33.49 \text{ kW}$$

$B_1 = B_2 = B_3 = B_4 = B_5 = B_6 = 33.49$ kW

IP = x B – $(B_1 + B_2 + ... + B_6)$ = 6×46.89 – (6× 33.49) = 80.38 kW

$$IP(kW) = \frac{p_{mi} L A N x}{120}$$

$$80.38 = \frac{p_{mi} \times 0.1 \times \frac{\pi}{4} \times (0.08)^2 \times 3200 \times 6}{120}$$

$$p_{mi} = \frac{80.38 \times 120}{\frac{\pi}{4} \times (0.08)^2 \times 3200 \times 6 \times 0.1} = 999.95 \text{ kPa} \approx 10 \text{ bar}$$

(A) Heat supplied by fuel = $\dot{m}_f(kg/min) \times CV(kJ/kg)$

= 0.33 × 43000 = 14190 kJ/min

(B) Heat converted to brake power = 46.89 kW = 46.89 × 60 = 2813.4 kJ/min

(C) Heat carried away by cooling coater

$= \dot{m}_w(kg/min) \times c_{pw}(kJ/kgK) \times (\Delta T)$

= 70 × 4.2 × 10 = 2940 kJ/min

(D) Heat carried away by ventilating air

$= \dot{m}_a(kg/min) \times c_{pa}(T_\ell - T_e)$

= 15×1.005 × (335 - 290) = 678.375 kJ/min

(E) Friction, radiation and other exhaust losses = A – (B + C + D)

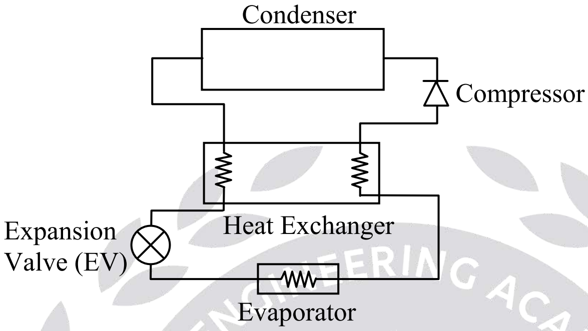
= 14190 – (2813.4 + 2940 + 678.375)

= 7758.225 kJ/min

Heat Balance Sheet :

Description	**kJ/min**	**%**	**Description**	**kJ/min**	**%**
A	14190	100	B	2813.4	19.83
			C	2940	20.71
			D	678.375	4.78
			E	7758.23	54.67
Total	**14190**	**100**		**14190**	**100**

03(b). A simple saturation refrigeration cycle uses R134a as refrigerant. The refrigeration system operates at 40°C condenser temperature and –16°C evaporation temperature respectively. If a liquid vapour heat exchanger is installed in the above simple saturation refrigeration cycle, find the COP and power per ton of refrigeration. The outlet vapour of heat exchanger is 15°C temperature.



(20 M)

Sol:

$c_{pl} = 1.498$ kJ/kgK

$s_6 = 1.7379$ kJ/kgK ,

$s_2' = 1.711$ kJ/kgK ,

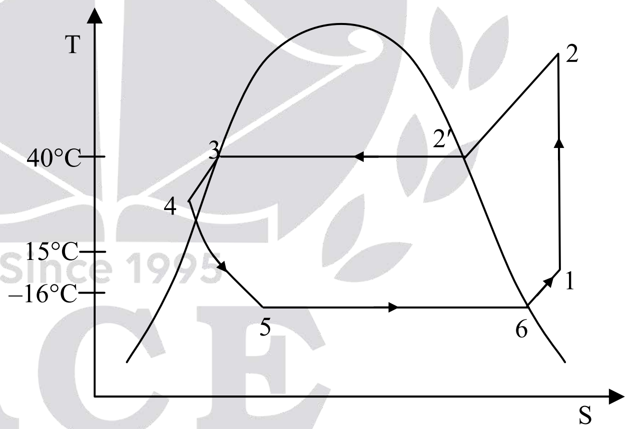
$h_6 = 256.41$ kJ/kg,

$h_2' = 419.43$ kJ/kgK ,

$h_3 = 256.41$ kJ/kg,

$c_{pv_2} = 1.145$ kJ/kgK

$c_{pv_1} = 0.831$ kJ/kgK



$$h_1 = h_6 + c_{pv_1}(T_1 - T_6)$$

$$= 389.02 + 0.831\ (15 - (-16)) = 414.78 \text{ kJ/kg}$$

$$s_1 = s_6 + c_{pv_1}\ \ell n\left(\frac{T_1}{T_6}\right)$$

$$= 1.7379 + 0.831\ \ell n\left(\frac{288}{257}\right)$$

$$= 1.8325 \text{ kJ/kgK}$$

$s_1 = s_2 = 1.8325 > 1.7111\ (s_2')$

After compression, in superheated state.

$$s_1 = s_2' + c_{pv_2}\ \ell n\left(\frac{T_2}{T_2'}\right)$$

$$1.8325 = 1.7111 + 1.145\ \ell n\left(\frac{T_2}{313}\right)$$

$$\ell n\left(\frac{T_2}{313}\right) = \frac{1.8325 - 1.7111}{1.145} = 0.106$$

$T_2 = 313\ e^{0.106} = 348$ K

$h_2 = h_2' + c_{pv_2}\left(T_2 - T_2'\right)$

$= 419.43 + 1.145\ (348 - 313)$

$= 459.5$ kJ/kg

Heat gained in superheating = Heat loss in subcooling

$h_1 - h_6 = h_3 - h_4$

$414.78 - 389.02 = c_{pl}\ (T_3 - T_4)$

$414.78 - 389.02 = 1.498\ (40 - T_4)$

$$T_4 = 40 - \frac{414.78 - 389.02}{1.498} = 22.8°C$$

$h_4 = h_3 - (h_1 - h_6)$

$= 256.41 - (414.78 - 389.02)$

$= 230.65$ kJ/kg

$h_4 = h_5 = 230.65$ kJ/kg

$$COP = \frac{h_6 - h_5}{h_2 - h_1}$$

$$= \frac{389.02 - 230.65}{459.5 - 414.78}$$

$$= \frac{158.37}{44.72} = 3.54$$

$$\frac{HP}{TR} = \frac{4.72}{COP} = \frac{4.72}{3.54} = 1.33$$

03(c). Moist air at 28°C DBT and 20.6 WBT and 101.325 kPa barometric pressure flows over a cooling coil and leaves it at a state of 10°C DBT and with specific humidity 7.046 gm/kg of dry air.

(i) If the air is required to offset a sensible heat gain of 2.35 kW and a latent heat gain of 0.31 kW in a space to be air-conditioned, calculate the mass of dry air which must be supplied to the room in order to maintain a DBT of 21°C in the room.

(ii) What will be the relative humidity in the room?

(iii) If a sensible heat gain diminishes by 1.175 kW but latent heat gain remains unchanged, at what temperature and moisture content must the air be supplied to the room?

Take specific capacity of air as 1.012 kJ/kg K, latent enthalpy of water at 21°C is 2454 kJ/kg. Show the processes on the psychrometric chart. (20 M)

Sol: From chart,

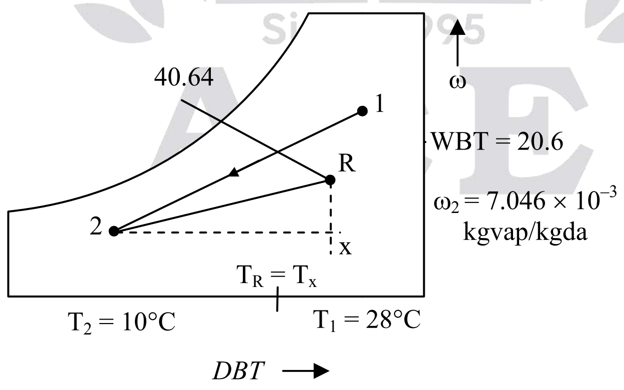
$\omega_1 = 0.0122$,

$h_1 = 60$ kJ/kg d.a

$$h_2 = c_{pa}(T_2 - 0) + \omega_2\left[(h_{fg})_{0C} + c_{pv}(T_2 - 0)\right]$$

$= 1.012\ (10 - 0) + 0.007046\ [2500 + 1.88\ (10 - 0)]$

$= 27.87$ kJ/kg



Room total heat load = 2.35 + 0.31 = 2.66 kW

$$\dot{m}_a(\text{kg/sec})(h_x - h_2)\left(\frac{\text{kJ}}{\text{kgK}}\right) = \text{RSHL(kW)}$$

$$\dot{m}_a(\text{kg/sec})\,(c_{Phs})\left(\frac{\text{kJ}}{\text{kgK}}\right)(T_x - T_2) = \text{RSHL(kW)}$$

$c_{p_{hs}} = c_{Pa} + \omega_2 \times c_{P_v}$

$= 1.012 + 7.046 \times 10^{-3} \times 1.88$

$= 1.0252$ kJ/kgK

$\dot{m}_a(\text{kg/sec})(T_x - T_2)c_{p_{hs}} = \text{RSHL}(\text{kW})$

$\dot{m}_a(21-10)\times 1.0252 = 2.35$

(i) Mass of dry air supply to room,

$$\dot{m}_a = \frac{2.35}{11\times 1.0252} = 0.2084\,\text{kg/sec}$$

$\dot{m}_a(h_R - h_2) = \text{RTHL}(\text{kW})$

$0.2084\,(h_R - 27.87) = 2.66$

$$h_R = 27.87 + \frac{266}{0.2084}$$

$= 40.64$ kJ/kg d.a

(ii) Relative humidity in room,

At 40.64 kJ/kgda and DBT , $T_R = 21°C$

From chart,

$\omega_R = 0.0074$ kgvap/kgda

$\phi_R = 48\%$

(iii) $T_R = 21°C$,

$\omega_R = 0.0074$,

$\phi_R = 48\%$,

$h_R = 40.64$ kJ/kgda

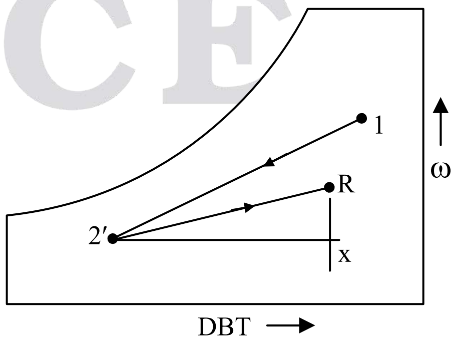
$T_X = T_R = 21°C$

RSHL = 2.35 - 1.175 = 1.175 kW

RLHL = 0.31 kW

RTHL = RSHL + RLHL

= 1.175 + 0.31 = 1.485 kW



$\dot{m}_a(h_R - h_x) = \text{RLHL}(\text{kW})$

$0.2084\,(40.64 - h_x) = 0.31$

$$h_x = 40.64 - \frac{0.31}{0.2084} = 39.15 \text{ kJ/kgda}$$

$$\dot{m}_a\left(h_x - h_2'\right) = \text{RSHL}(\text{kW})$$

0.2084 (39.15 – h_2') = 1.175

$$h_2' = 39.15 - \frac{1.175}{0.2084} = 33.51 \text{ kJ/kgda}$$

On the vertical from R mark h_x and fix the state "x" and horizontal from x will give the intersection point 2′ the supply state of air to the room.

From chart,

T_2' = 15.5°C

$\omega_2' = \omega_x = 0.007$

$c_{p_{hs}} = c_{pa} + \omega_2' c_{pv}$

$= 1.012 + 0.007 \times 1.88$

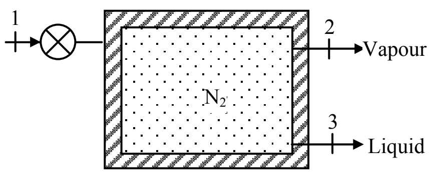
$= 1.02516$ kJ/kgK

$$\dot{m}_a(\text{kg/sec})\left(c_{p_{hs}}\right)\left(\frac{\text{kJ}}{\text{kgK}}\right)\left(T_x - T_2'\right) = \text{RSHL}(\text{kW})$$

0.2084 (1.02516) (21 – T_2') = 1.175

$$T_2' = 21 - \frac{1.175}{0.2084 \times 1.025156} = 15.5°\text{C}$$

04(a). A geothermal source provides 10 kg/s of hot water at 500 kPa, 150°C flowing into a flash evaporator that separates vapour and liquid at 200 kPa. Find the three fluxes of availability (inlet and two outlets) and the irreversibility rate. Take ambient temperature as 25°C.



(Refer Table A placed at the end of booklet) **(20 M)**

Sol: From steam table,

Properties of saturated water at pressure, P_1 = 500 kPa

Enthalpy of liquid, $h_1 = h_f$ = 632.18 kJ/kg

Entropy of liquid, $s_1 = s_f$ = 1.8417 kJ/kg

At P_2 = 200 kPa & x = 1

Enthalpy of water vapour, $h_2 = h_g = 2706.63$ kJ/kg

Enthalpy of water, $h_3 = h_f = 504.68$ kJ/kg

$s_2 = s_g = 7.1271$ kJ/kgK

$s_3 = s_f = 1.530$ kJ/kgK

At ambient condition, ($T_0 = 25°C$)

Saturated water :

$h_o = 104.87$ kJ/kg

$s_o = 0.3673$ kJ/kgK

Mass balance:

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3$$

Energy balance :

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_3 h_3$$

$$h_1 = x\, h_2 + (1 - x)\, h_3$$

$$x = \frac{h_1 - h_3}{h_2 - h_3}$$

Here the fraction of vapour coming out from the flash chamber is x enthalpy at state 1 is h_1 , enthalpy at state 2 is h_2 and enthalpy at state 3 is h_3.

$$x = \frac{632.18 - 504.68}{2706.63 - 504.68} = 0.0579$$

Now mass of vapour

$$x = \frac{\dot{m}_2}{\dot{m}_1}$$

$$\dot{m}_2 = x\,\dot{m}_1$$

$$\dot{m}_2 = 0.0579 \times 10 = 0.579 \text{ kg/s}$$

Mass of liquid,

$$\dot{m}_3 = (1 - x)\dot{m}_1$$

$$= (1 - 0.0579) \times 10 = 9.421 \text{ kg/s}$$

Apply entropy generation equation for the control mass

$$\dot{m}_1 s_1 + s_{gen} = \dot{m}_2 s_2 + \dot{m}_3 s_3$$

$$s_{gen} = \dot{m}_2 s_2 + \dot{m}_3 s_3 - \dot{m}_1 s_1$$

s_{gen} → entropy generation for entire process

s_{gen} = (0.579 × 7.127) + (9.421 × 1.53) – (10×1.8417)

= 0.124 kW/K

Availability at state 1

$$\psi_1 = \dot{m}_1\left[(h_1 - h_0) - T_o(s_1 - s_o)\right]$$

= 10 [(632.18 – 104.87) – 298(1.8417 – 0.3673)]

= 877.2 kW

Availability at state 2

$$\psi_2 = \dot{m}_2\left[(h_2 - h_0) - T_o(s_2 - s_o)\right]$$

= 0.579 [(2706.63 – 104.87) – 298(7.1271 – 0.3673)]

= 339.5 kW

Availability at state 3

$$\psi_3 = \dot{m}_3\left[(h_3 - h_0) - T_o(s_3 - s_o)\right]$$

= 9.421 [(504.68 – 104.87) – 298(1.53 – 0.3673)]

= 500.7 kW

Now,

Irreversibility, I = $\psi_1 + \psi_2 + \psi_3$

= 877.2 – 339.5 – 500.7

I = 37 kW

04(b). Air at a mean velocity of 20 m/sec flows through a 2 cm diameter tube whose surface is maintained at 200°C. The temperature of air as it enters the tube at inlet is 20°C and leaves the tube at 180°C. Determine

(i) The length of the tube required to heat the water from 20°C to 180°C, and

(ii) The pumping power required to maintain the flow.

Assume f = $0.3164/(Re_D)^{1/4}$.

Properties of air at the mean film temperature $\overline{T}_f$:

density = ρ = 0.8345 kg/m^3;

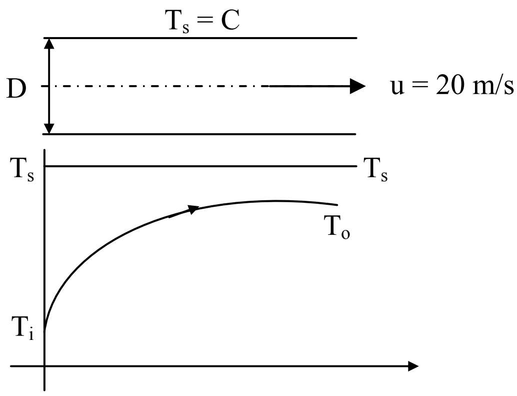
Specific heat = c_p = 1015 J/kg K;

Dynamic viscosity, μ = 2.3825 × 10^{-5} kg/m.s; P_r = 0.703;

Thermal conductivity, k = 0.034425 W/mK. (20 M)

Sol: D = 0.02 m, $T_S = 200°C$,

$T_i = 20°C$, $T_o = 180°C$



$$Re = \frac{\rho u D}{\mu} = \frac{0.8345\times 20\times 0.02}{2.3825\times 10^{-5}} = 14010.493$$

⇒ Flow is turbulent.

$$Nu = \frac{hD}{k} = 0.023 R_e^{0.8}\, Pr^{0.4}$$

$$\frac{h\times 0.02}{0.034425} = 0.023(14010.493)^{0.8}(0.703)^{0.4}$$

$$\frac{h\times 0.02}{0.034425} = 0.023\times 2075.69\times 0.8685$$

h = 71.36 W/m^{2}K

$$\dot{m} = \rho\frac{\pi}{4}D^2 u = 0.8345\times\frac{\pi}{4}(0.02)^2\times 20$$

$\dot{m}$ = 0.005243 kg/s

$$\frac{T_o - T_s}{T_i - T_s} = e^{\frac{-hpL}{\dot{m}c_p}}$$

$$\ell n\left[\frac{T_o - T_s}{T_i - T_s}\right] = \frac{-h\pi DL}{\dot{m}c_p}$$

$$\ell n\left[\frac{180-200}{20-200}\right] = \frac{-71.36\times\pi\times 0.02\times L}{0.005243\times 1015}$$

L = 2.667 m

$$f = \frac{0.3164}{(Re)^{\frac{1}{4}}} = \frac{0.3164}{(14010.493)^{\frac{1}{4}}}$$

f = 0.029081

$$h_f = \frac{\Delta P}{\rho g} = \frac{f L u^2}{2gD}$$

$$\Delta P = \frac{\rho f L u^2}{2D}$$

$$\Delta P = \frac{0.8345\times 0.029081\times 2.607\times(20)^2}{2\times 0.02}$$

ΔP = 632.669 N/m^2

$$\dot{V} = \text{flow rate} = A_c u = \frac{\pi}{4}D^2\times u$$

$$= \frac{\pi}{4}(0.02)^2 \times 20$$

$$= 0.006283 \text{ m}^3/\text{s}$$

Power required = $\Delta P \times \dot{V}$ = 632.669×0.006283 = 3.975 W

04(c). A single-cylinder, single-acting reciprocating compressor using R12 as refrigerant has a bore 80 mm and stroke 60 mm. The compressor runs at 1450 rpm. If the condensing temperature is 40°C, find the performance characteristics of the compressor when the suction temperature is –10°C. Specific heat of vapour at 40°C is 0.759 kJ/kg K. Assume the simple cycle of operation and no clearance. **(20 M)**

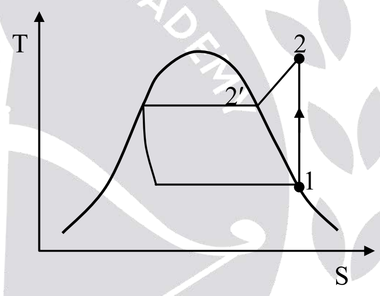
Sol: Single cylinder, Single acting.

Bore = d = 0.08 m,

Length = L = 0.06 m,

Speed = N = 1450 rpm,

c_{pv} = 0.759 kJ/kgK



v_1 = 0.7 m^3/kg,

h_1 = 183.2 kJ/kg,

h_2' = 203.2 kJ/kg

s_1 = 0.702 kJ/kgK,

s_2' = 0.6825 kJ/kgK

P_1 = 2.1912 bar,

P_2' = 9.607 bar

$s_1 = s_2 = 0.702 > s_2'$

Super heated state

$$s_1 = s_2 = s_2' + c_{pv}\, \ell n\left(\frac{T_2}{T_2'}\right)$$

$$0.702 = 0.6825 + 0.759\, \ell n\left(\frac{T_2}{313}\right)$$

$$\ell n\left(\frac{T_2}{313}\right) = \frac{s_1 - s_2'}{c_{pv}} = \frac{0.702 - 0.6825}{0.759} = 0.02569$$

$T_2 = 313\, e^{0.02569} = 321.15$ K

$h_2 = h_2' + c_{pv}\,(T_2 - T_2')$

$= 203.2 + 0.759\,(321.5 - 313)$

$= 209.39$ kJ/kg

Performance characteristics :

Work of compression $= h_2 - h_1$

$= 209.39 - 183.2 = 26.18$ kJ/kg

As clearance is zero, volumetric efficiency is 100 %.

$$\text{Mass flow rate} = \frac{\frac{\pi}{4} D^2 L N x}{60\, v_1}$$

$$= \frac{\frac{\pi}{4}\times(0.08)^2\times(0.06)\times 1450\times 1}{60\times 0.7} = 0.0104 \text{ kg/sec}$$

$$\text{Pressure ratio} = \frac{P_2}{P_1} = \frac{9.607}{2.1912} = 4.384$$

Compressor discharge temperature = 321.15 K = 48.15°C

SECTION - B

05(a). A single – cylinder, single-acting, square reciprocating pump has piston diameter and stroke length of 300 mm. The pump is placed such that the vertical distance between the center-line of the pump and sump level is 5 m. The water is being delivered at a height of 22 m above the centerline of the pump. The suction and delivery pipes are 8 m and 28 m long respectively, and diameter of both the pipes is 150 mm. If the pump is running at 30 rpm and coefficient of friction for suction and delivery pipe is 0.005, estimate the theoretical power required to drive the pump (kW). (12 M)

Sol: *Assumptions:*

(i) The motion of the plunger inside the cylinder is treated as a simple harmonic motion.

(ii) The crank rotates with a constant angular velocity ω rad/s.

(iii) The connecting rod is considered to be very long compared to crank radius.

Given data:

$D = 0.3$ m $= L$; $f = 4 \times 0.005 = 0.02$;

$H_s = 5$ m; $H_d = 22$ m;

$\ell_s = 8$ m; $\ell_d = 28$ m ;

$d_s = d_d = 0.15$ m ; $N = 30$ rpm;

$$A = \frac{\pi}{4} \times 0.3^2 = 0.0707\,m^2$$

Angular speed, $\omega = \dfrac{2\pi \times 30}{60} = 3.14\,rad/s$

$$\frac{A}{a_s} = \left(\frac{0.3}{0.15}\right)^2 = 4 \text{ and } \frac{A}{a_d} = 4$$

Average frictional head loss in the suction pipe,

$$h_{f\,sav} = \frac{2}{3} h_{fsm} = \frac{1}{3}\frac{f\ell_s}{gd_s}\left(\frac{A}{a_s}\omega r\right)^2$$

where h_{fsm} is the maximum frictional head loss in the suction pipe (at $\theta = 90°$)

$$= \frac{1}{3} \times \frac{0.02 \times 8}{9.81 \times 0.15}\left(4 \times 3.14 \times \frac{0.3}{2}\right)^2$$

$$= 0.1286 \text{ m}$$

Average frictional head loss in the delivery pipe.

$$h_{f\,dav} = \frac{2}{3}h_{fdm} = \frac{1}{3}\frac{f\ell_d}{gd_d}\left(\frac{A}{a_d}\omega r\right)^2 = 0.4503 \text{ m}$$

$$Q_t = \frac{ALN}{60} = \frac{0.0707 \times 0.3 \times 30}{60} = 0.0106 \text{ m}^3/\text{s}$$

Power required (theoretical)

$$P = \frac{\gamma ALN}{60}\left[H_s + H_d + \frac{2}{3}h_{fsm} + \frac{2}{3}h_{fdm}\right]$$

$$= 9.81 \times 0.0106\,[5 + 22 + 0.1286 + 0.4503]$$

$$= 2.869 \text{ kW} \cong 2.87 \text{ kW}$$

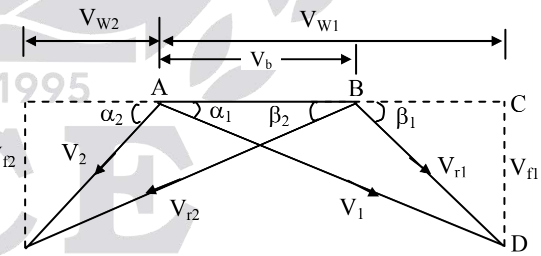
05(b). Show that the diagram work per unit mass of steam for maximum blading efficiency of a 50% reaction stage is V_b^2, where V_b is the mean blade velocity. (12 M)

Sol: α_1 = Nozzle angle at exit or fixed blade angle

α_2 = Entrance angle of fixed blade or Absolute velocity angle at outlet

β_1, β_2 = Blade or rotor or Vane angle at inlet & outlet respectively.

For 50% reaction turbine (Parson turbine)



$\therefore\ \alpha_1 = \beta_2, \quad V_1 = V_{r2}$

$\alpha_2 = \beta_1, \quad V_2 = V_{r1}$

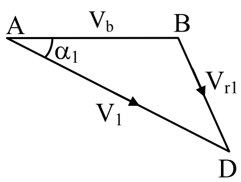
Power, $P = \dot{m} V_b (V_{w1} - V_{w2})$

Energy input, $\frac{V_1^2}{2} + \frac{V_{r2}^2 - V_{r1}^2}{2}$

But, $V_{r2} = V_1$

Energy input $= V_1^2 - \frac{V_{r1}^2}{2}$

$$\eta_{stage} = \frac{\dot{m} V_b (V_{w1} - V_{w2})}{\dot{m}\left(V_1^2 - \frac{V_{r1}^2}{2}\right)} = \frac{V_b (V_{w1} - V_{w2})}{V_1^2 - \frac{V_{r1}^2}{2}}$$



But, $V_{w1} = V_1 \cos\alpha_1$

$V_{w2} = V_b - V_{r2}\cos\beta_2$

i.e., $V_{w2} = V_b - V_1\cos\alpha_1$

Cosine rule :

$V_{r1}^2 = V_b^2 + V_1^2 - 2\, V_b\, V_1 \cos\alpha_1$

$W = V_b\,(V_{w1} - V_{w2})$

$\quad = V_b\,[V_1 \cos\alpha_1 - (V_b - V_1\cos\alpha_1)]$

$W = V_b\,(2V_1\cos\alpha_1 - V_b)$

Energy input :

$$= V_1^2 - \frac{V_{r1}^2}{2}$$

$$= V_1^2 - \left(\frac{V_b^2 + V_1^2 - 2\,V_b\,V_1\cos\alpha_1}{2}\right)$$

$$= \frac{1}{2}\left(V_1^2 - V_b^2 + 2\,V_b\,V_1\cos\alpha_1\right)$$

$$\eta = \frac{\text{Work}}{\text{Energy input}}$$

$$= \frac{V_b\,(2V_1\cos\alpha_1 - V_b)}{\frac{1}{2}\left(V_1^2 - V_b^2 + 2\,V_b\,V_1\cos\alpha_1\right)}$$

$$= \frac{\left(4\,V_b\,V_1\cos\alpha_1 - 2V_b^2\right)}{\left(V_1^2 - V_b^2 + 2\,V_b\,V_1\cos\alpha_1\right)}$$

$$\eta = \frac{4\,V_b\,V_1\cos\alpha_1 - 2\,V_b^2}{V_1^2 - V_b^2 + 2\,V_b\,V_1\cos\alpha_1}$$

Dividing by V_1^2

$$\eta = \frac{\dfrac{4V_b\cos\alpha_1}{V_1} - 2\left(\dfrac{V_b}{V_1}\right)^2}{1 - \dfrac{V_b^2}{V_1^2} + 2\dfrac{V_b}{V_1}\cos\alpha_1} = \frac{2\left[\dfrac{2V_b}{V_1}\cos\alpha_1 - \left(\dfrac{V_b}{V_1}\right)^2\right]}{1 - \left(\dfrac{V_b}{V_1}\right)^2 + 2\left(\dfrac{V_b}{V_1}\right)\cos\alpha_1}$$

Let, $a = \dfrac{V_b}{V_1}$

$$\eta = \frac{2\left(2a\cos\alpha_1 - a^2\right)}{1 - a^2 + 2a\cos\alpha_1} = \frac{2\left(2a\cos\alpha_1 - a^2 + 1 - 1\right)}{\left(2a\cos\alpha_1 - a^2 + 1\right)}$$

$$\eta = 2 - \frac{2}{\left(2a\cos\alpha_1 - a^2 + 1\right)}$$

For η_{max}, $2a\cos\alpha_1 - a^2 + 1$ should be maximum.

$$\frac{d}{da}\left(2a\cos\alpha_1 - a^2 + 1\right) = 0$$

$$2\cos\alpha_1 - 2a = 0$$

$$a = \cos\alpha_1 = \frac{V_b}{V_1}$$

Maximum efficiency :

$$\eta_{max} = 2 - \frac{2}{\left(2\cos^2\alpha_1 - \cos^2\alpha_1 + 1\right)}$$

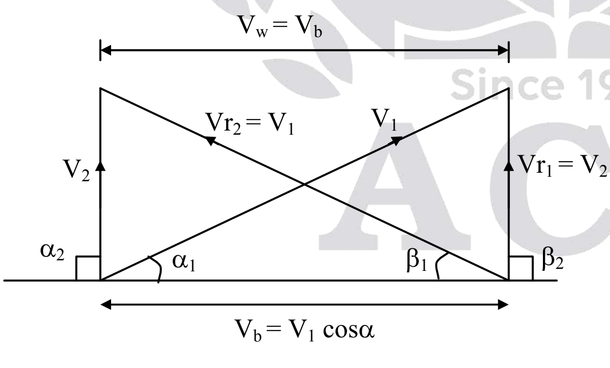
$$\eta_{max} = 2 - \frac{2}{\cos^2\alpha_1 + 1}$$

$$\eta_{max} = \frac{2\left(\cos^2\alpha_1 + 1\right) - 2}{\cos^2\alpha_1 + 1} = \frac{2\cos^2\alpha_1 + 2 - 2}{\cos^2\alpha_1 + 1}$$

$$\eta_{max} = \frac{2\cos^2\alpha_1}{\cos^2\alpha_1 + 1}$$

i.e., $$\eta_{max} = \frac{2V_b^{\ 2}}{V_b^{\ 2} + V_1^2}$$

The velocity diagram of 50 % reaction turbine with maximum blading efficiency is shown below.



The diagram work per kg of steam

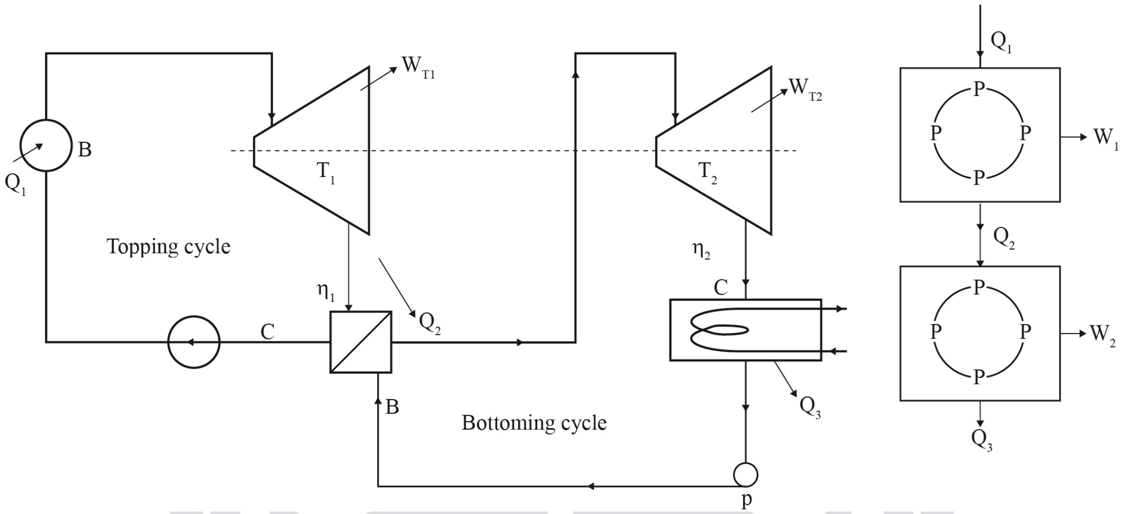
$$W_D = \Delta V_w\, V_b = 2\,(V_1\cos\alpha - V_b)\, V_b$$

From above equations, the diagram work per unit mass of steam for maximum blading efficiency,

$$W_D = (2V_b - V_b)\, V_b = V_b^2$$

05(c). Derive an expression for efficiency of a combined cycle where two thermodynamic cycles are coupled in series. The expression should be derived in terms of efficiencies of the coupled cycles. Conventional notations may be used. (12 M)

Sol: If two Rankine cycles with two different working fluids are coupled in series, the heat lost by one is absorbed by the other, as in the mercury-steam binary cycle. Let η_1 and η_2 be the efficiencies of the topping and bottom cycles, respectively, and η be the overall efficiency of the combined cycle.



$$\eta_1 = 1 - \frac{Q_2}{Q_1} \quad \text{and} \quad \eta_2 = 1 - \frac{Q_3}{Q_2}$$

$Q_2 = (1 - \eta_1)\, Q_1$

$Q_3 = Q_2\,(1 - \eta_2)$

$$\eta_1 = 1 - \frac{Q_3}{Q_1} = 1 - \frac{Q_2(1-\eta_2)}{Q_1} = \frac{Q_2(1-\eta_1)(1-\eta_2)}{Q_1}$$

$\eta = 1 - (1 - \eta_1)(1 - \eta_2)$

$1 - \eta = (1 - \eta_1)(1 - \eta_2)$

For n cycles coupled in series, the overall efficiency would be given by

$$1 - \eta = (1 - \eta_1)(1 - \eta_2)\ \ldots\ldots(1 - \eta_o)$$

$$1 - \eta = \prod_{i=1}^{n}(1 - \eta_i)$$

Total loss = product of losses in all the cycles in series.

For two cycles coupled in series,

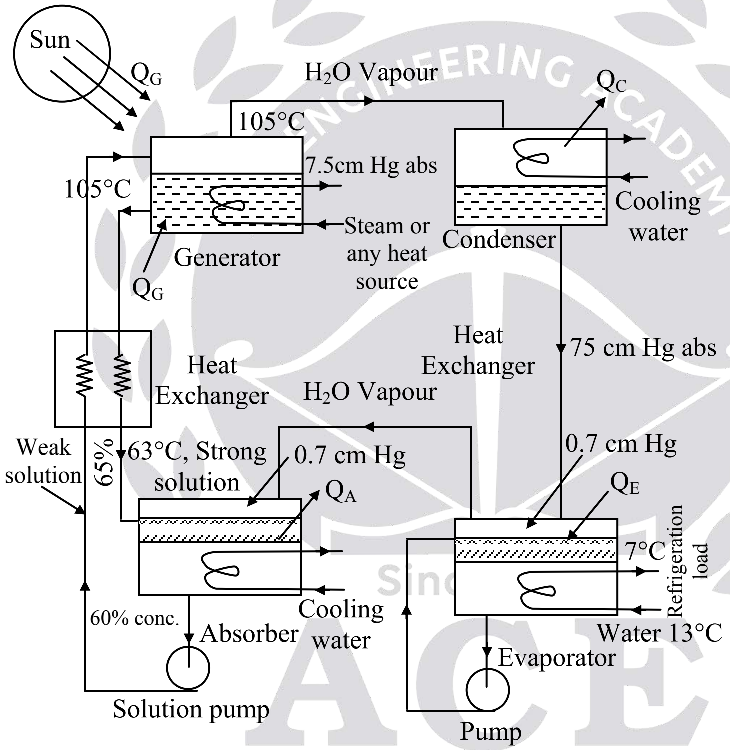
$$\eta = 1 - (1 - \eta_1 - \eta_2 + \eta_1\eta_2)$$

$$\eta = \eta_1 + \eta_2 - \eta_1.\eta_2$$

05(d). Explain with neat sketch how solar absorption refrigeration system works for space cooling. (12 M)

Sol: Refrigeration Cycles :

There is another absorption refrigeration system, namely, lithium bromide-water vapour absorption (figure). Here the refrigerant is water and the absorbent is the solution of lithium bromide salt in water. Since water cannot be cooled below 0^0C, it can be used as a refrigerant in air conditioning units. Lithium bromide solution has a strong affinity for water vapour because of its very low vapour pressure. It absorbs water vapour as fast as it is released in the evaporator.



While the vapour compression refrigeration system requires the expenditure of 'high-grade energy in the form of shaft work to drive the compressor with the concomitant disadvantage of vibration and noise, the absorption refrigeration system requires only 'low-grade' energy in the form of heat to drive it, and it is relatively silent in operation and subject to little wear. Although the COP = Q_E/Q_G is low, the absorption units are usually built when waste heat is available, and they are built in relatively bigger sizes. One current application of the absorption system that may grow in importance is the utilization of solar energy for the generator heat source of a refrigerator for food presentation and perhaps for comfort cooling.

05(e). How do fuel cells work? Explain the principle with the help of a sketch. (12 M)

Sol: FUEL CELL

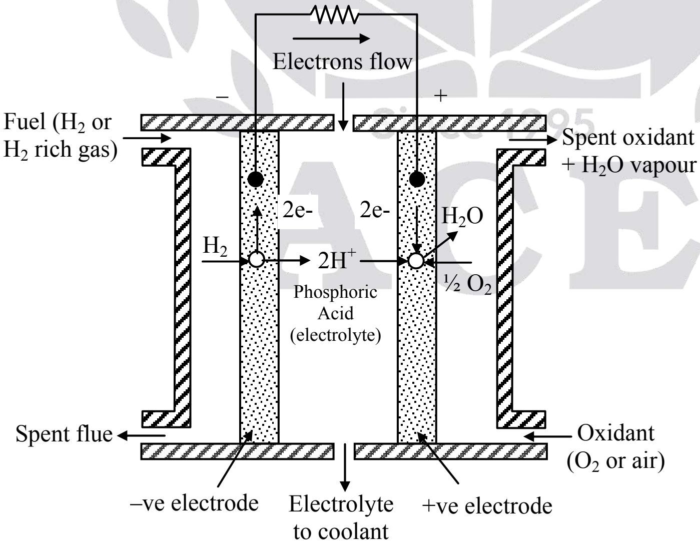
- A fuel Cell is a device that uses mainly hydrogen as a fuel and oxygen as a oxidant.
- This technology is based upon the simple combustion reaction,

  $2H_2 + O_2 \rightarrow 2H_2o$
- It converts chemical energy into electrical energy.

BASIC DESIGN OF FUEL CELL

- There are two electrodes on either side of an electrolyte.
- Electrode must be made by porous conducting material.
- Hydrogen and oxygen passes to collect charge over two different electrodes.
- By means of chemical reaction, electricity, heat and water are produced.
- Catalyst is also used to accelerate the reaction like platinum.
- Fuel Cell can be classified based on the type of electrolyte, type of the fuel and oxidant used, operating temperature range, Application basis etc.

Working Principle of Phosphoric Acid Fuel Cell :



Phosphoric Acid Fuel Cell

- Hydrogen fuel is supplied to the anode (Negative terminal)
- Oxygen is supplied to the Cathode (Positive terminal)
- At the anode $H_2 \rightarrow 2H^+ + 2e^-$

- Electrons reach cathode through the external load circuit.
- H^+ ions migrate from anode to cathode through the electrolyte.
- Now on cathode $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$
- By combining these equation water and electrical energy is obtained $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$
- The products depend on fuel and oxidant used.

06(a). A centrifugal pump has an impeller diameter at outlet as 1 m and delivers 1.5 m^3/s of water against a head of 100 m. The impeller is running at 1000 rpm. The width of the impeller is 85 mm. If the manometric efficiency is 85%, determine the type of impeller (forward, radial or backward curved), and the blade angle at outlet. Draw velocity triangle at outlet. (20 M)

Sol: *Assumptions:*

(i) The flow is steady.

(ii) The liquid is incompressible.

(iii) There are no irreversible losses through the impeller.

(iv) At the inlet the entry is shockless.

Centrifugal pump:

$D_2 = 1$ m; $Q = 1.5\ m^3/s$;

$H = 100$ m; $N = 1000$ rpm;

$B_2 = 85$ mm; $\eta_{man} = 0.85$

Type of impeller & β_2

$$u_2 = \frac{\pi D_2 N}{60} = \frac{\pi \times 1 \times 1000}{60} = 52.36\ m/s$$

Since, $\eta_{max} = \frac{gH_m}{u_2 V_{w2}}$

$$V_{w2} = \frac{gH_m}{u_2 \eta_{man}} = \frac{9.81 \times 100}{52.36 \times 0.85} = 22.042\ m/s$$

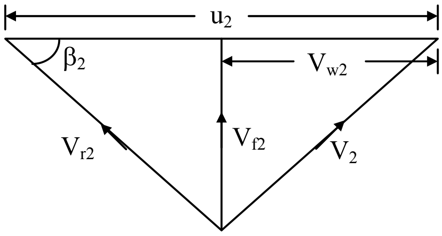
Since, $Q = \pi D_2 B_2 V_{f2}$

$$V_{f2} = \frac{Q}{\pi D_2 B_2} = \frac{1.5}{\pi \times 1 \times 0.085} = 5.617\ m/s$$

$$\tan\beta_2 = \frac{V_{f2}}{u_2 - V_{w2}} = \frac{5.617}{52.36 - 22.042} = 0.1853$$

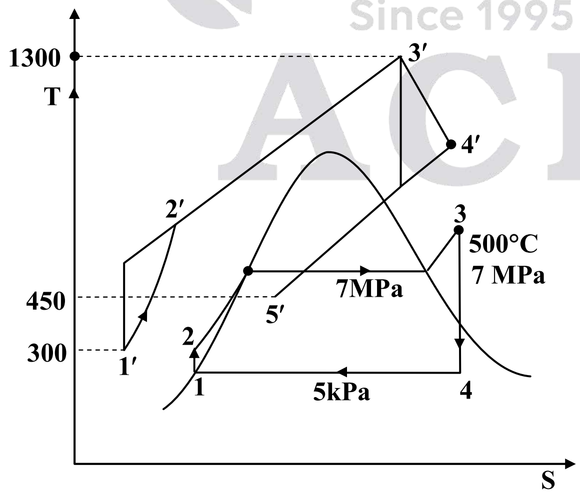
$\beta_2 = 10.497 \cong 10.5°$

Since $\beta_2 < 90°$, the blade type is backward curved.



Outlet velocity Δ

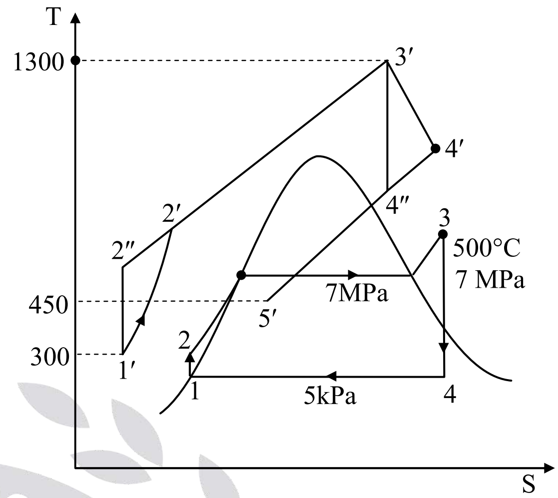
06(b). Consider the combined gas steam power cycle shown in the figure. The topping cycle is a gas turbine cycle that has a pressure ratio of 8. Air enters the compressor at 300 k and the turbine at 1300 k. The isentropic efficiency of the compressor is 80 percent, and that of the gas turbine is 85 percent. The bottoming cycle is a simple ideal Rankine cycle operating between the pressure limits of 7 MPa and 5 kPa. Steam is heated in a heat exchanger by the exhaust gases to a temperature of 500°C. The exhaust gases leave the heat exchanger at 450 k. Determine (i) the ratio of the mass flow rates of the steam and the combustion gases, and (ii) the thermal efficiency of the combined cycle.



Assume specific beat of gas as 1.005 kJ/kg K.

(20 M)

Sol: Pressure ratio $r_p = 8$;



$\eta_{comp} = 0.8$

$T_1' = 300K$

$T_2'' = T_1' \left(r_p\right)^{\frac{\gamma-1}{\gamma}} = 300(8)^{\frac{1.4-1}{1.4}} = 543.4 \text{ K}$

$T_2' = T_1' + \dfrac{T_2'' - T_1'}{\eta_{comp}}$

$= 300 + \dfrac{543.4 - 300}{0.8} = 604.25 \text{ K}$

$T_3' = 1300 \text{ K}$

Process 3′ to 4″

$Q = 0, \quad S = C, \eta_T = 0.85$

$T_4'' = \dfrac{T_3'}{\left(r_p\right)^{\frac{\gamma-1}{\gamma}}} = \dfrac{1300}{(8)^{\frac{1.4-1}{1.4}}} = 717.7$

$T_4' = T_3' - \eta_T\left(T_3' - T_4''\right)$

$= 1300 - 0.85(1300 - 717.7) = 805 \text{ K}$

$W_{comp} = c_{p_a}\left(T_{2'} - T_{1'}\right)$

$= 1.005(604.25 – 300) = 305.77 \text{ kJ/kg}$

$W_{turbine} = c_{p_a}\left(T_3' - T_4'\right) = 1.005(1300 - 805) = 497.48 \text{ kJ/kg}$

Heat given to steam by exhaust gases = $c_{p_a}\left(T_4' - T_5'\right)$

$= 1.005(805 - 450) = 356.78 \text{ kJ/kg}$

$P_1 = 5 \text{ kPa}$

$h_1 = 137.79 \text{ kJ/kg}$

$v_1 = 0.001005 \text{ m}^3\text{/kg}$

$h_2 - h_1 = v_f\left(P_{boiler} - P_{cond}\right) = 0.00105(7000 - 5)$

$h_2 = 137.79 + 0.001005(6995) = 145.14 \text{ kJ/kg}$

$h_3 = 3411.4 \text{ kJ/kg}$

$s_3 = 6.8$

$s_3 = s_4 = 6.8$ wet state

$s_3 = s_4 = s_{f_4} + x_4\left(s_{fg}\right)_4$

$6.8 = 0.4763 + x_4(7.9187)$

$$x_4 = \frac{6.8 - 0.4763}{7.9187} = 0.7985 \simeq 0.8$$

$$h_4 = h_{f4} + x\left(h_{fg}\right)_4 = 137.79 + (0.8)(2423.66) = 2076.72 \text{ kJ/kg}$$

Heat supplied to gas turbine

$$Q_{s_1} = h_3' - h_2'$$

$$= c_{p_a}\left(T_3' - T_2'\right)$$

$$= 1.005(1300 - 604.25) = 699.23 \text{ kJ/kg}$$

$(W_{net})_{turbine} = W_T - W_C = 497.48 - 305.77 = 191.71$ kJ/kg

$W_{pump} = h_2 - h_1 = 145.14 - 137.79 = 7.35$ kJ/kg.

$W_{turbine}$ (steam) $= h_3 - h_4$

$= 3411.4 - 2076.72 = 1334.68$ kJ/kg

$(W_{net})_{steam\ turbine} = W_T - W_P = 1334.68 - 7.35 = 1327.33$

Heat supplied to steam turbine = 1327.33 kJ/kg

$= h_3 - h_2$

$= 3411.4 - 145.14 = 3266.26$ kJ/kg

Heat rejected by gas turbine to steam turbine = 356.78 kJ/kg

Net heat supply to steam turbine = 3266.26 – 356.78 = 2909.48 kJ/kg

Net work of combined cycle = $\left(W_{net}\right)_{GT} + \left(W_{net}\right)_{ST}$

$= 191.71 + 1327.33 = 1519.04$ kJ/kg

Net heat supply to combined cycle = $\left(Q_s\right)_{GT} + \left(Q_s\right)_{ST}$

$= 699.23 + 2909.48 = 3608.71$ kJ/kg

$$\left(\eta_{th}\right)_{combined\ cycle} = \frac{\left(W_{net}\right)_{combined}}{\left(\text{Heat supply}\right)_{combined}} = \frac{1519.04}{3608.71} = 0.421 \text{ or } 42.1\%$$

Heat rejected by gases = Heat gained by steam

$$\dot{m}_g c_{p_a}\left(T_{4'} - T_{5'}\right) = \dot{m}_s\left(h_3 - h_2\right)$$

$$\frac{\dot{m}_s}{\dot{m}_g} = \frac{c_{p_a}\left(T_4' - T_5'\right)}{h_3 - h_2}$$

$$= \frac{1.005(805 - 450)}{(3411.4 - 145.14)}$$

$$= \frac{356.78}{3266.26} = 0.109$$

= 0.109 kg steam/kg gas

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06(c). What is Betz limit for wind turbines? Derive an expression for Betz limit for wind turbines. (20 M)

Sol: Betz limit :

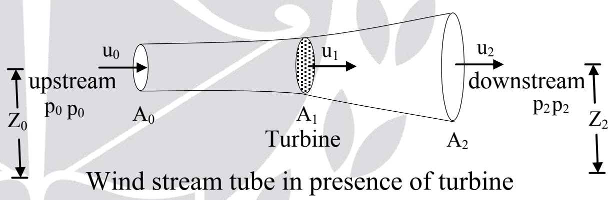
As wind energy is a low grade energy and by wind turbine, it is converted into high grade energy like electricity.

We know by thermodynamics second law that a low grade energy can not be fully converted into high grade energy.

So, Betz found a limit on the conversion of wind energy into electricity, which is known as Bets limit.

Betz model :

Unperturbed Wind stream tube in absence of turbine



Wind stream tube in presence of turbine

Betz model for expanding air-stream tube

where,

u_o = velocity of wind at upstream,

u_1 = velocity of wind at turbine.

u_2 = velocity of wind at down stream

A_0, A_1, A_2 = corresponding areas.

Assumption : Mass flow rate is constant.

Mass flow rate (incompressible fluid)

$$\dot{m} = \rho A_0 u_0 = \rho A_1 u_1 = \rho A_2 u_2 \quad \ldots\ldots (1)$$

ρ = density of air $\rightarrow$ unchanged

Force or thrust on Rotor (F) = $\dot{m}u_0 - \dot{m}u_2 \ldots (2)$

Power extracted by turbine

$$P_T = F.u_1 = \dot{m}(u_0 - u_2)\,u_1 \quad \ldots. (3)$$

Power extraction can also be written like difference in kinetic energy at the upstream and downstream.

$$P_T = \tfrac{1}{2}\dot{m}\left(u_0^2 - u_2^2\right) \quad \ldots\ldots.. (4)$$

(3) = (4)

$$u_1 = \left(\frac{u_0 + u_2}{2}\right) \quad \text{........ (5)}$$

Interference factor 'a' is defined as fractional wind speed decrease at the turbine.

$$a = u_0 - u_1 / u_0 \quad \text{........ (6)}$$

$$u_1 = (1 - a)\, u_0 \quad \text{......... (7)}$$

or $$a = (u_0 - u_2) / 2u_0 \quad \text{....... (8)}$$

a = induction / perturbation factor. By eq. (3)

$$P_T = (\rho\, A_1\, u_1)\,(u_0 - u_2)\, u_1$$

By eq. (6, 7, 8)

$$P_T = \rho \times A_1\,(1 - a)^2 \times u_0^2\,(2\,u_o) \times a$$

$$P_T = 4a\,(1 - a)^2 \left(\frac{1}{2}\rho A_1\, u_0^3\right) \quad \text{...... (9)}$$

$$P_T = C_P\, P_0$$

C_P = Power coefficient = Fraction of available power in the wind that can be extracted

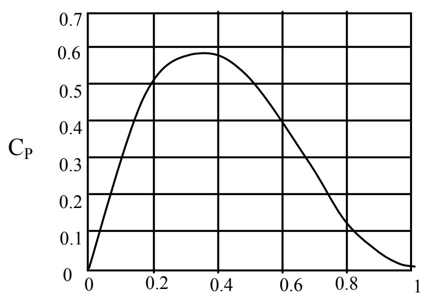
$C_P = 4a(1 - a)^2$

Maximum value of C_ρ can be

$$\frac{dC_p}{da} = 0 \Rightarrow a = \frac{1}{3}$$

$C_{P,max} = 0.593$

So According to Betz Model 59.3% is the maximum energy that can be extracted from wind.



Variation of Power coefficient (C_P) with interference factor (a)

07(a). A Pelton turbine with a wheel diameter of 1.5 m, operating with four nozzles, produces 16 MW of power. The turbine is running at 400 rpm and operating under a gross head of 300 m. Water is supplied through penstock of length 2 km. The coefficient of friction in penstock is 0.004. There is 10% of head loss taking place in the penstock. If the velocity coefficient is 0.97, blade velocity coefficient is 0.9, overall efficiency is 0.84 and Pelton bucket deflects the jet by 165%, determine

(i) Discharge through the turbine (m^3/s)

(ii) Penstock diameter (m)

(iii) Jet diameter (m)

(iv) Hydraulic efficiency of the turbine.

Draw velocity triangles. (20 M)

Sol: *Assumption: The flow is steady and incompressible.*

Given data:

$D = 1.5$ m; 4 nozzles

$P = 16$ MW; $N = 400$ rpm

$H_G = 300$ m; $L = 2$ km;

$H = H_G - (h_L)_{Penstock}$

$= 300 - 30 = 270$ m

$$V_1 = C_V\sqrt{2gH} = 0.97\sqrt{2\times 9.81\times 270} = 70.6 \text{ m/s}$$

$$u = \frac{\pi DN}{60} = \frac{\pi\times 1.5\times 400}{60} = 31.416 \text{ m/s}$$

$$\eta_0 = \frac{16\times 10^6}{\rho g Q H}$$

$$Q = \frac{16\times 10^6}{\eta_0 \rho g H} = \frac{16\times 10^6}{0.84\times 9810\times 270}$$

(i) Discharge through the turbine, $Q = 7.1913$ m^3/s

Discharge through one nozzle

$$q = \frac{7.1913}{4} \text{ m}^3/\text{s}$$

$$\frac{\pi}{4}d_j^2\times V_1 = \frac{7.1913}{4}$$

$$d_j = \sqrt{\frac{7.1913}{\pi \times 70.6}}$$

(iii) $d_j = 0.18 \text{ m} = 180 \text{ mm}$

(ii) $h_f = \frac{fLQ^2}{12.1D^5} = \frac{(0.004 \times 4) \times 2 \times 1000 \times (7.1913)^2}{12.1 \times D^5}$

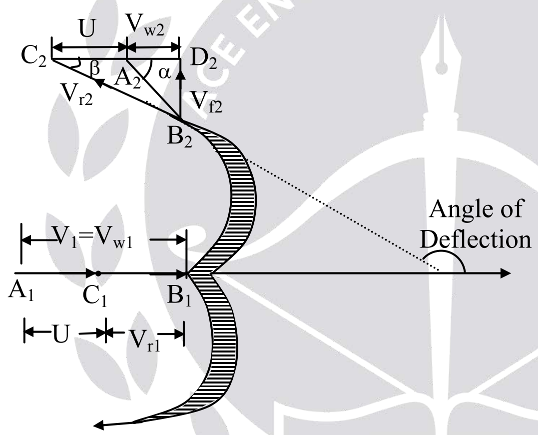
$\Rightarrow D = 1.354 \text{ m}$

(iv) $\eta_{hyd} = \frac{(V_1 - u)(1 + k\cos\beta)u}{gH}$

$$= \frac{(70.6 - 31.416)(1 + 0.9\cos 15°) \times 31.416}{9.81 \times 270}$$

$= 0.8688 = 86.88\ \%$

Velocity triangles are drawn as:



07(b). What do you mean by compounding in steam and gas turbines? What are the various methods of compounding in steam and gas turbines? Explain all the methods with neat sketch. (20 M)

Sol: Compounding of steam turbine :

- One of the chief objects in the development of the steam turbine is to reduce the speed of the rotor to practical limits.
- If the steam is expanded from the boiler pressure to the condenser pressure in a single stage, its velocity is liable to be supersonic, in which case pressure jumps may occur and reduce the efficiency.
- Also, if this high velocity is used up on a single-blade ring it produces a rotor speed of about 30,000 rev/min, which is too high for practical purposes.

- There are several methods of overcoming this high rotor speed, all of which utilize several blade rings. In all these methods there is a multiple system of rotors in series, keyed on a common shaft, and the steam pressure or the jet velocity is absorbed in stages as it flows over the rotor blades; this is known as compounding.

Compounding for Velocity:

- Rings of moving blades, separated by rings of fixed blades, are keyed in series on the turbine shaft.
- The steam is expanded through nozzles from boiler pressure to the condenser pressure, to a high velocity, and is then passed over the first ring of moving blades. Only a portion of this high velocity is absorbed by this blade ring, the remainder being exhausted on to the next ring of fixed blades.

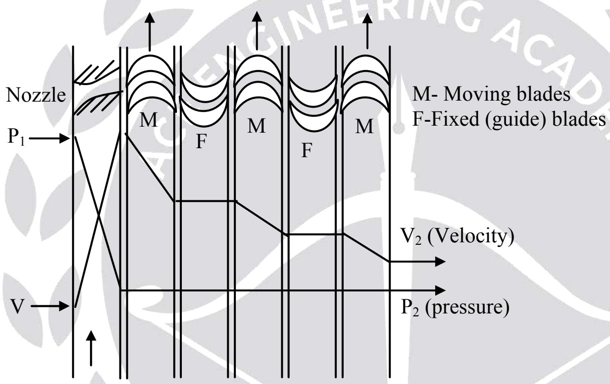


Fig: Compounding for velocity

Compounding for Pressure:

- In this type, rings of moving blades, each having a ring of fixed nozzles, are keyed to the turbine shaft in series.
- The total pressure drop of the steam does not take place in the first nozzle ring, but is divided up equally between all the nozzle rings.
- The steam from the boiler is passed through the first nozzle ring, in which it is only partially expanded. It then passes over the first moving blade ring, where nearly all of its velocity is absorbed. From this ring, it exhausts into the next nozzle ring and is again partially expanded, this absorbs a further portion of its total pressure drop.
- The velocity obtained from this second nozzle ring is absorbed by the next ring of moving blades. This process is repeated in the remaining rings until the whole of the pressure drop has been absorbed. Each pressure drop is known as a stage.
- This method of pressure compounding is used in the Rateau and Zoelly turbines.

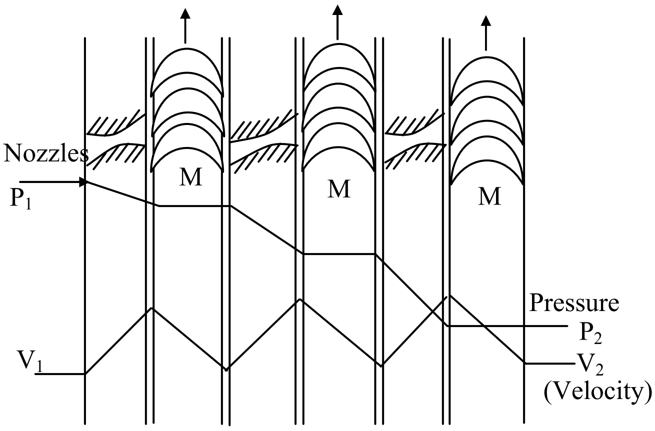


Fig: Pressure compounding

Pressure-Velocity Compounding:

- The total pressure drop of the steam is divided into stages, and the velocity obtained in each stage is also compounded.
- This has the advantage of allowing a bigger pressure drop in each stage, and consequently fewer stages are necessary.
- Hence, a shorter turbine will be obtained for a given total pressure drop.
- The curves of pressure and velocity for this type of compounding are shown in figure.
- It will be noticed that the diameter of the turbine is increased at each stage, this is to allow for the increasing volume of the steam at the lower pressures.
- A ring of nozzles must be fitted at the commencement of each stage. It will be seen from the curves that the pressure is constant during each stage, the turbine is therefore an impulse turbine.
- This method of pressure-velocity compounding is used in the Curtis turbine.

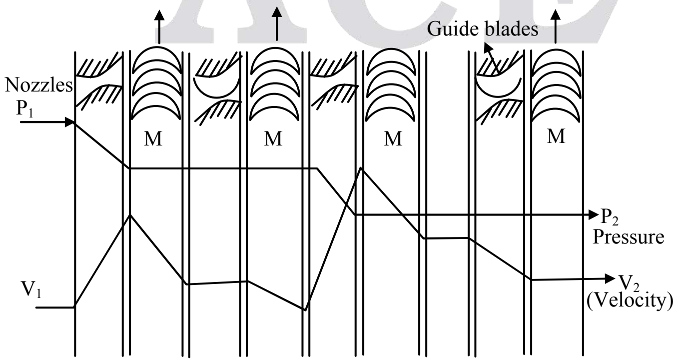


Fig: Velocity – Pressure compounding

Compounding in gas turbines :

Velocity compounding

One of the methods that is followed in multistage expansion in impulse turbine is to generate high velocity of fluid. This is done by expanding the gas through a large pressure drop in the nozzle blade row. The high velocity of fluid then transfers its energy in a number of stages by incorporating many rotor blade rows separated by rows of fixed guide blade. Since turbine is impulse type pressure of fluid remains constant after expansion in nozzle blade rows. Work done is in the ratio 9:7:5:3:1 in various rotor blade rows (5 numbers). Third stage in a three stage turbine produces only $1/9^{th}$ work total, hence more than three stages are not used in velocity compounding and it reduces length of turbine.

Pressure ratios used in gas turbines are much lower as compared to steam turbines. Losses in velocity stages are much higher compared to reaction stages hence velocity compounding has limited application in the field of gas turbines except in some special applications.

Major problems in velocity compounding :

- Nozzles are convergent and divergent type for high velocity hence more expensive and difficult in design.
- high velocity at nozzle exit leads to high cascade loss. Shock waves are generated if flow is supersonic which increases losses further.
-

Rateau stage or pressure compounding :

A high pressure ratio divides total pressure drop which is divided into a number of impulse stages. Due to lower pressure drops there are subsonic flows and such a stage does not suffer from disadvantages of velocity stages.

Multistage reaction turbines :

The gas pressure decreases continuously over both fixed and moving blades. As pressure drop is smaller in each stage as compared to impulse stages, gas velocities are relatively low and flow is accelerating throughout. This makes reaction stages aerodynamically more efficient though the tip leakage loss increases on account of relatively higher pressure difference across rotor blades.

07(c). A reaction steam turbine having diameter of 1400 mm is rotating at 3000 rpm. The turbine stages are designed in such a fashion that the enthalpy drop in both, rotor and stator, is same in each stage. If the speed ratio is 0.7 and blade angle at outlet is 20°, draw velocity triangles and determine degree of reaction, blade angle at inlet and diagram efficiency.

(20 M)

Sol: Diametre = 1.4 m,

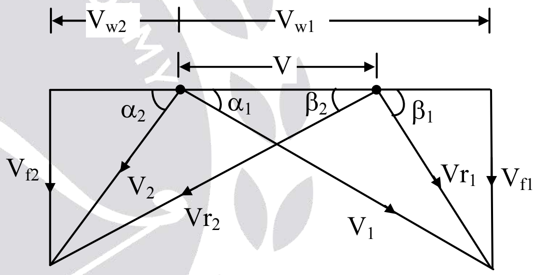
Speed = N = 3000 rpm,

$(\Delta h)_s = (\Delta h)_{rotor} = x$

Symmetrical turbine 50% reaction turbine. $\dfrac{U}{V_1} = 0.7$

Blade speed = $U = \dfrac{\pi DN}{60} = \dfrac{\pi \times 1.4 \times 3000}{60} = 219.8$ m/sec

Steam speed = $V_1 = \dfrac{U}{0.7} = \dfrac{219.8}{0.7} = 314$ m/sec



For 50% RT

$\alpha_1 = \beta_2 = 20°$

Exit angle of fixed blade = Exit angle of moving blade

$V_{w1} = V_1 \cos\alpha_1$

$= 314 \cos 20° = 295.06$ m/sec

$V_{f1} = V_1 \sin\alpha_1$

$= 314 \sin 20° = 107.394$ m/sec

$$\tan\beta_1 = \frac{V_{f1}}{V_{w1} - U} = \frac{107.394}{295.06 - 219.8} = 1.427$$

Inlet blade angle = $\beta_1 = \tan^{-1}(1.427) = 54.98° = \alpha_2$

$$\text{Diagram efficiency} = \frac{2\cos^2\alpha}{1+\cos^2\alpha}$$

$$= \frac{2\cos^2 20^\circ}{1+\cos^2 20^\circ} = 0.9378 = 93.78\%$$

$$\text{Degree of reaction} = \frac{(\Delta h)_{MB}}{(\Delta h)_{MB} + (\Delta h)_{FB}}$$

$$= \frac{x}{x + x} = 0.5$$

08(a). A single-stage air compressor delivers air at 6 bar. The pressure and temperature at the end of suction are 1 bar and 27°C. It delivers 1.5 m^3 of free air per minute when the compressor is running at 350 rpm. The clearance volume is 5% of stroke volume. The free air conditions are 1.013 bar and 15°C. The index of compression and expansion is 1.3. Find

(i) The volumetric efficiency,

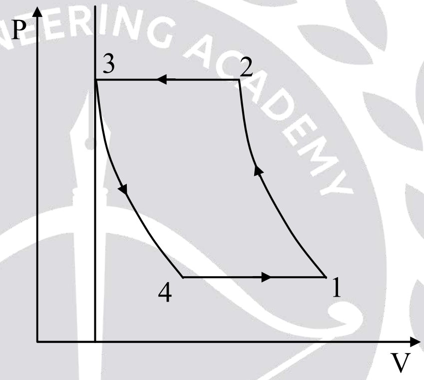
(ii) Bore and stroke of cylinder if both are equal,

(iii) The power required if the mechanical efficiency is 80%. (20 M)

Sol: Single stage

Single cylinder x = 1

Speed = N = 350 rpm



$$C = \frac{V_3}{V_S} = 0.05$$

n = 1.3

$$\frac{P_2}{P_1} = \frac{6}{1} = 6$$

P_1 = 100 kPa

T_1 = 273 + 27 = 300 K

$$\eta_{vol} = 1 + C - C\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} = 1 + 0.05 - 0.05\,(6)^{1/1.3} = 0.852$$

P_R = 101.3 kPa

T_R = 273 + 15 = 288 K

$\dot{V}_R = 1.5\ m^3/min$

$$\frac{P_R \dot{V}_R}{T_R} = \frac{P_1 \dot{V}_1}{T_1}$$

$$\dot{V}_1 = \frac{P_R V_R}{T_R} \times \frac{T_1}{P_1} = \frac{101.3 \times 1.5}{288} \times \frac{300}{100} = 1.583\ m^3/min$$

$$\left(\frac{\dot{V}_4}{\dot{V}_3}\right)^n = \left(\frac{P_3}{P_4}\right) \Rightarrow \dot{V}_4 = \dot{V}_3 (6)^{1/1.3}$$

$$\dot{V}_3 = 0.05\,V_s$$

$$\dot{V}_1 = \dot{V}_3 + \dot{V}_s$$

$$1.583 = \dot{V}_3 + \frac{1}{0.05}\dot{V}_3$$

$$\dot{V}_3 = 0.0754 \text{ m}^3/\text{min}$$

$$\dot{V}_4 = 0.0754 \times (6)^{\frac{1}{1.3}}$$

$$\dot{V}_4 = 0.299 \text{ m}^3/\text{min}$$

$$\therefore \ \dot{V}_1 - \dot{V}_4 = 1.284 \text{ m}^3/\text{min}$$

$$W_c(kW) = \left(\frac{n}{n-1}\right)P_1(\dot{V}_1 - \dot{V}_4)\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \left(\frac{1.3}{1.3-1}\right)100 \times \frac{1.284}{60}\left[(6)^{\frac{1.3-1}{1.3}} - 1\right] = 4.75 \text{ kW}$$

$$W_c(kW)_{Actual} = \frac{W_c(kW)}{\eta_m} = \frac{4.75}{0.8} = 5.93 \text{ kW}$$

Actual displacement = Displacement × η_{vol}

$$1.583 = \frac{\pi}{4}d^2 \times N.x \times \eta_{vol}$$

$$= \frac{\pi}{4}d^2 \times d \times 350 \times 1 \times 0.852$$

$$d^3 = \frac{4}{\pi} \times \frac{1.583}{0.852} \times \frac{1}{350} = 6.7624 \times 10^{-3}$$

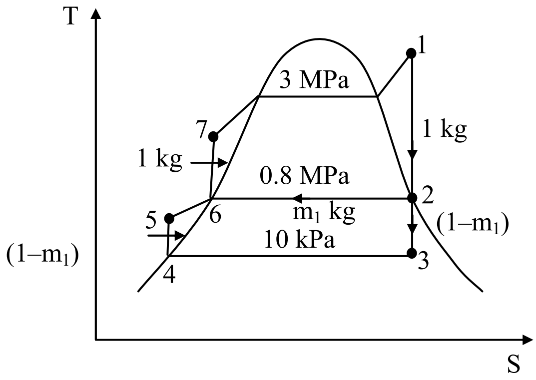
$$d = \sqrt[3]{6.7624 \times 10^{-3}} = 0.189 \text{ m}$$

Length = Diameter = 0.189 m

08(b). Consider the ideal steam regenerative cycle in which steam enters the turbine at 3 MPa, 300°C and exhausts to the condenser at 10 kPa. Steam is extracted from the turbine at 0.8 MPa and supplied to an open feed water heater. The feed water leaves the heater as saturated liquid. The appropriate pumps are used for the water leaving the condenser and feed water heater. If the mass flow rate through the boiler is 1 kg/s, determine the amount of steam extracted (kg/s), the total pump work (kW) and total turbine work (kW). Draw the schematic of this set-up.

(Refer Table A placed at the end of booklet) **(20 M)**

Sol:



$h_1 = 2993.48$ kJ/kg; $h_6 = 721.1$ kJ/kg

$s_1 = 6.5389$ kJ/kg.K; $v_6 = 0.001115$ m^3/kg

$h_4 = 191.81$ kJ/kg; $v_4 = 0.00101$ m^3/kg

$h_7 - h_6 = v_6[P_1 - P_2] = 0.001115[3000 - 800]$

$w_{p_2} = 2.453\,\text{kJ/kg}$

$h_7 = h_6 + w_{P_2} = 721.1 + 2.453 = 723.55$ kJ/kg

$h_5 - h_4 = v_4[P_2 - P_3] = 0.00101[800 - 10] \Rightarrow w_{P_1} = 00798$ kJ/kg

$h_5 = h_4 + w_{P_1} = 191.81 + 0.798 = 192.61$ kJ/kg

$s_1 = s_2 = s_{f_2} + x_2(s_{g_2} - s_{f_2})$

$6.5389 = 2.0461 + x_2\,(4.6166)$

$$x_2 = \frac{6.5389 - 2.0461}{4.6166} = 0.97$$

$h_2 = h_{f_2} + x_2(h_{fg2})$

$= 721.1 + 0.97(204804) = 2707.7$ kJ/kg

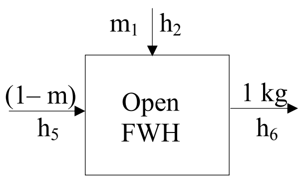
$s_1 = s_3 = s_{f_3} + x_3(s_{g_3} - s_{f_3})$

$6.5389 = 0.6492 + x_3\,(7.501)$

$$x_3 = \frac{6.5389 - 0.6492}{7.501} = 0.79$$

$h_3 = h_{f_3} + x_3(h_{f_g})_3$

$= 191.81 + 0.79 \times 2392.82 = 2082.14$ kJ/kg



Energy balance for FWH

$(1 - m_1)h_5 + m_1h_2 = 1\ h_6$

$m_1\ (h_2 - h_5) = h_6 - h_5$

$$m_1 = \frac{h_6 - h_5}{h_2 - h_5} = \frac{721.1 - 192.61}{2707.7 - 192.61} = \frac{528.49}{2515.09} = 0.21 \text{ kg}$$

$w_T = 1(h_1 - h_2) + (1 - m_1)\ (h_2 - h_3)$

$= 1(2993.48 - 2707.7) + (1 - 0.21)\ (2707.7 - 2082.14)$

$= 285.78 + 494.19$

$= 779.97$ kJ/kg

$w_P = (1 - m_1)w_{P_1} + 1(w_{P_2})$

$= (1 - 0.21)\ (0.798) + 1\ (2.453)$

$= 0.63 + 2.453 = 3.083$ kJ/kg

$w_{net} = w_T - w_P = 779.97 - 3.083$

$= 776.88$ kJ/kg

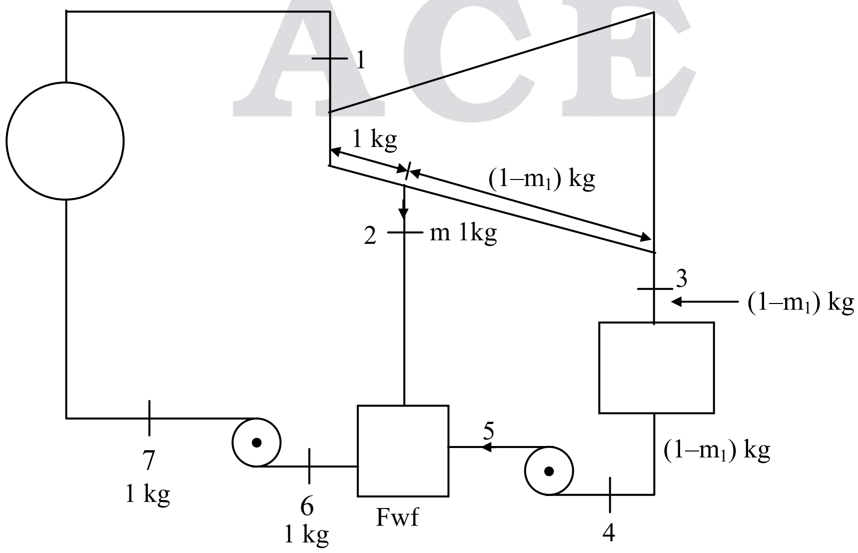
$Q_S = h_1 - h_7 = 2993.48 - 723.55 = 2269.93$ kJ/kg

$\dot{m}_s = 1 \text{ kg/sec}$

$\dot{m}_1 = 0.21 \text{ kg/sec}$

W_P (kW) = 3.083 kW

W_T (kW) = 779.97 kW



SCHEMATIC OF SETUP

08(c). A Brayton cycle works between 1 bar, 300 K and 5 bar, 1250 K. There are two stages of compression with perfect inter-cooling and two stages of expansion. The work out of first expansion stage is being used to drive the two compressors. The air from the first stage turbine is again heated to 1250 K and expanded. Calculate the power output of free power turbine and cycle efficiency without and with a perfect heat exchanger and compare them. Also calculate the percentage improvement in the efficiency because of the addition of heat exchangers. (20 M)

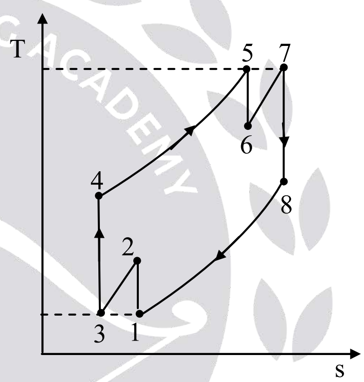
Sol:

$T_5 = T_7 = 1250$ K

$T_1 = 300$ K $= T_3$

$P_4 = P_5 = 5$ bar

$P_1 = 1$ bar



<u>**1-2-3-4-5-6-7-8**</u> Without heat exchanger

1-2 : $Q = 0$; $s = C$,

$$P_2 = P_3 = \sqrt{P_1 P_4} = \sqrt{1\times 5} = 2.236 \text{ bar}$$

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = 300\times\left(\frac{2.236}{1}\right)^{\frac{1.4-1}{1.4}} = 377.55 \text{ K}$$

3-4 : $Q = 0$; $s = C$, Perfect inter cooling

$T_1 = T_3 = 300$ K

$$T_4 = T_3\left(\frac{P_4}{P_3}\right)^{\frac{\gamma-1}{\gamma}} = 300\times\left(\frac{5}{2.236}\right)^{\frac{1.4-1}{1.4}} = 377.55 \text{ K}$$

High pressure turbine work = Work of compressor – I + Work of compressor – II

$$c_{pa}(T_5 - T_6) = c_{pa}(T_2 - T_1) + c_{pa}(T_4 - T_3)$$

$$T_5 - T_6 = (T_2 - T_1) + (T_4 - T_3)$$

$$1250 - T_6 = (377.55 - 300) + (377.55 - 300)$$

$$T_6 = 1250 - 155.1 = 1094.9 \text{ K}$$

5-6 : Q = 0 , s = C

$$\frac{T_5}{T_6} = \left(\frac{P_5}{P_6}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\frac{P_5}{P_6} = \left(\frac{T_5}{T_6}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1250}{1094.9}\right)^{\frac{1.4}{1.4-1}} = 1.5899$$

$$P_6 = \frac{P_5}{1.5899} = \frac{5}{1.5899} = 3.1448 \text{ bar}$$

7 -8 : Q = 0 ; s = C , $P_6 = P_7$

$$\frac{T_7}{T_8} = \left(\frac{P_7}{P_8}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_8 = \frac{T_7}{\left(\frac{P_7}{P_8}\right)^{\frac{\gamma-1}{\gamma}}} = \frac{1250}{\left(\frac{3.1148}{1}\right)^{\frac{1.4-1}{1.4}}} = 901 \text{ K}$$

$W_{net} = c_{pa} (T_7 – T_8)$

= 1.005 (1250 – 901) = 350.75 kJ/kg

Heat supplied = $c_{pa} (T_5 – T_4) + c_{pa} (T_7 – T_6)$

= 1.005 (1250 – 377.5 + 1250 – 1094.9)

= 1032.69 kJ/kg

$$\eta_{th} = \frac{W_{net}}{\text{Heat supplied}} = \frac{350.75}{1032.69} = 0.3396 = 33.96 \%$$

1-2-3-4-4′ - 5-6-7-8

With perfect Heat exchanger.

Heat rejected by exhaust gases used to heat compressed air with e = 1

$$\text{Effectiveness of HE} = e = \frac{(\Delta T)_{actual}}{(\Delta T)_{max}}$$

$$1 = \frac{T_4' - T_4}{T_8 - T_4}$$

$\Rightarrow$ $T_8 = T_4' = 901$ K

(W_{net}) of cycle with Heat exchange = c_{pa} $(T_7 - T_8)$

$$= 1.005\,(1250 - 901) = 350.75 \text{ kJ/kg}$$

Heat supplied with heat exchanger

$$= c_{pa}\,(T_5 - T_4') + c_{pa}\,(T_7 - T_6)$$

$$= c_{pa}\,(T_5 - T_4' + T_7 - T_6)$$

$$= 1.005\,(1250 - 901 + 1250 - 1094.9)$$

$$= 506.62 \text{ kJ/kg}$$

$$(\eta_{th})_{\text{with HE}} = \frac{W_{net}}{Q_s} = \frac{350.75}{506.62} = 0.6923 = 69.23\ \%$$

% improvement in efficiency

$$= \frac{(\eta_{th})_{\text{with HE}} - (\eta_{th})_{\text{without HE}}}{(\eta_{th})_{\text{without HE}}}$$

$$= \frac{69.23 - 33.96}{33.96} = 1.0386 \text{ or } 103.86\ \%$$

- Work output is same in both cases. Temperature at entry to combustion chamber is less in the case when there is no heat exchanger.
- Heat supplied is less in the case when there is heat exchanger.
- Thermal efficiency almost doubles with heat exchanger.

Saturation table of R134a

THERMODYNAMICS PROPERTIES OF R134a*

Temp. (°C)	Pressure MPa	Density (kg/m³) Liquid	Volume (m³/kg) Vapour	Enthalpy (kJ/kg) Liquid	Enthalpy (kJ/kg) Vapour	Entropy kJ/(kg-K) Liquid	Entropy kJ/(kg-K) Vapour	Specific Heat c_p, kJ/(kg-K) Liquid	Specific Heat c_p, kJ/(kg-K) Vapour	c_p/c_v Vapour
–103.30[a]	0.00039	1591.1	35.4960	71.46	334.94	0.4126	1.9639	1.184	0.585	1.164
–100.00	0.00056	1582.4	25.1930	75.36	336.85	0.4354	1.9456	1.184	0.593	1.162
–90.00	0.00152	1555.8	9.7698	87.23	342.76	0.5020	1.8972	1.189	0.617	1.156
–80.00	0.00367	1529.0	4.2682	99.16	348.83	0.5654	1.8580	1.198	0.642	1.151
–70.00	0.00798	1501.9	2.0590	111.20	355.02	0.6262	1.8264	1.210	0.667	1.148
–60.00	0.01591	1474.3	1.0790	123.36	361.31	0.6846	1.8010	1.223	0.692	1.146
–50.00	0.02945	1446.3	0.60620	135.67	367.65	0.7410	1.7806	1.238	0.720	1.146
–40.00	0.05121	1417.7	0.36108	148.14	374.00	0.7956	1.7643	1.255	0.749	1.148
–30.00	0.08438	1388.4	0.22594	160.79	380.32	0.8486	1.7515	1.273	0.781	1.152
–28.00	0.09270	1382.4	0.20680	163.34	381.57	0.8591	1.7492	1.277	0.788	1.153
–26.07[b]	0.10133	1376.7	0.19018	165.81	382.78	0.8690	1.7472	1.281	0.794	1.154
–26.00	0.10167	1376.5	0.18958	165.90	382.82	0.8694	1.7471	1.281	0.794	1.154
–24.00	0.11130	1370.4	0.17407	168.47	384.07	0.8798	1.7451	1.285	0.801	1.155
–22.00	0.12165	1364.4	0.16006	171.05	385.32	0.8900	1.7432	1.289	0.809	1.156
–20.00	0.13273	1358.3	0.14739	173.64	386.55	0.9002	1.7413	1.293	0.816	1.158
–18.00	0.14460	1352.1	0.13592	176.23	387.79	0.9104	1.7396	1.297	0.823	1.159
–16.00	0.15728	1345.9	0.12551	178.83	389.02	0.9205	1.7379	1.302	0.831	1.161
–14.00	0.17082	1339.7	0.11605	181.44	390.24	0.9306	1.7363	1.306	0.838	1.163
–12.00	0.18524	1333.4	0.10744	184.07	391.46	0.9407	1.7348	1.311	0.846	1.165
–10.00	0.20060	1327.1	0.09959	186.70	392.66	0.9506	1.7334	1.316	0.854	1.167
–8.00	0.21693	1320.8	0.09242	189.34	393.87	0.9606	1.7320	1.320	0.863	1.169
–6.00	0.23428	1314.3	0.08587	191.99	395.06	0.9705	1.7307	1.325	0.871	1.171
–4.00	0.25268	1307.9	0.07987	194.65	396.25	0.9804	1.7294	1.330	0.880	1.174
–2.00	0.27217	1301.4	0.07436	197.32	397.43	0.9902	1.7282	1.336	0.888	1.176
0.00	0.29280	1294.8	0.06931	200.00	398.60	1.0000	1.7271	1.341	0.897	1.179
2.00	0.31462	1288.1	0.06466	202.69	399.77	1.0098	1.7260	1.347	0.906	1.182
4.00	0.33766	1281.4	0.06039	205.40	400.92	1.0195	1.7250	1.352	0.916	1.185
6.00	0.36198	1274.7	0.05644	208.11	402.06	1.0292	1.7240	1.358	0.925	1.189
8.00	0.38761	1267.9	0.05280	210.84	403.20	1.0388	1.7230	1.364	0.935	1.192
10.00	0.41461	1261.0	0.04944	213.58	404.32	1.0485	1.7221	1.370	0.945	1.196
12.00	0.44301	1254.0	0.04633	216.33	405.43	1.0581	1.7212	1.377	0.956	1.200
14.00	0.47288	1246.9	0.04345	219.09	406.53	1.0677	1.7204	1.383	0.967	1.204
16.00	0.50425	1239.8	0.04078	221.87	407.61	1.0772	1.7196	1.390	0.978	1.209
18.00	0.53718	1232.6	0.03830	224.66	408.69	1.0867	1.7188	1.397	0.989	1.214
20.00	0.57171	1225.3	0.03600	227.47	409.75	1.0962	1.7180	1.405	1.001	1.219
22.00	0.60789	1218.0	0.03385	230.29	410.79	1.1057	1.7173	1.413	1.013	1.224
24.00	0.64578	1210.5	0.03186	233.12	411.82	1.1152	1.7166	1.421	1.025	1.230
26.00	0.68543	1202.9	0.03000	235.97	412.84	1.1246	1.7159	1.429	1.038	1.236
28.00	0.72688	1195.2	0.02826	238.84	413.84	1.1341	1.7152	1.437	1.052	1.243
30.00	0.77020	1187.5	0.02664	241.72	414.82	1.1435	1.7145	1.446	1.065	1.249

Temp. (°C)	Pressure Mpa	Density kg/m³ Liquid	Volume m³/kg Vapour	Enthalpy kJ/kg		Entropy kJ/(kg-K)		Specific Heat c_p, kJ/(kg-K)		c_p / c_v
				Liquid	Vapour	Liquid	Vapour	Liquid	Vapour	Vapour
32.00	0.81543	1179.6	0.02513	244.62	415.78	1.1529	1.7138	1.456	1.080	1.257
34.00	0.86263	1171.6	0.02371	247.54	416.72	1.1623	1.7131	1.466	1.095	1.265
36.00	0.91185	1163.4	0.02238	250.48	417.65	1.1717	1.7124	1.476	1.111	1.273
38.00	0.96315	1155.1	0.02113	253.43	418.55	1.1811	1.7118	1.487	1.127	1.282
40.00	1.0166	1146.7	0.01997	256.41	419.43	1.1905	1.7111	1.498	1.145	1.292
42.00	1.0722	1138.2	0.01887	259.41	420.28	1.1999	1.7103	1.510	1.163	1.303
44.00	1.1301	1129.5	0.01784	262.43	421.11	1.2092	1.7096	1.523	1.182	1.314
46.00	1.1903	1120.6	0.01687	265.47	421.92	1.2186	1.7089	1.537	1.202	1.326
48.00	1.2529	1111.5	0.01595	268.53	422.69	1.2280	1.7081	1.551	1.223	1.339
50.00	1.3179	1102.3	0.01509	271.62	423.44	1.2375	1.7072	1.566	1.246	1.354
52.00	1.3854	1092.9	0.01428	274.74	424.15	1.2469	1.7064	1.582	1.270	1.369
54.00	1.4555	1083.2	0.01351	277.89	424.83	1.2563	1.7055	1.600	1.296	1.386
56.00	1.5282	1073.4	0.01278	281.06	425.47	1.2658	1.7045	1.618	1.324	1.405
58.00	1.6036	1063.2	0.01209	284.27	426.07	1.2753	1.7035	1.638	1.354	1.425
60.00	1.6818	1052.9	0.01144	287.50	426.63	1.2848	1.7024	1.660	1.387	1.448
62.00	1.7628	1042.2	0.01083	290.78	427.14	1.2944	1.7013	1.684	1.422	1.473
64.00	1.8467	1031.2	0.01024	294.09	427.61	1.3040	1.7000	1.710	1.461	1.501
66.00	1.9337	1020.0	0.00969	297.44	428.02	1.3137	1.6987	1.738	1.504	1.532
68.00	2.0237	1008.3	0.00916	300.84	428.36	1.3234	1.6972	1.769	1.552	1.567
70.00	2.1168	996.2	0.00865	304.28	428.65	1.3332	1.6956	1.804	1.605	1.607
72.00	2.2132	983.8	0.00817	307.78	428.86	1.3430	1.6939	1.843	1.665	1.653
74.00	2.3130	970.8	0.00771	311.33	429.00	1.3530	1.6920	1.887	1.734	1.705
76.00	2.4161	957.3	0.00727	314.94	429.04	1.3631	1.6899	1.938	1.812	1.766
78.00	2.5228	943.1	0.00685	318.63	428.98	1.3733	1.6876	1.996	1.904	1.838
80.00	2.6332	928.2	0.00645	322.39	428.81	1.3836	1.6850	2.065	2.012	1.924
85.00	2.9258	887.2	0.00550	332.22	427.76	1.4104	1.6771	2.306	2.397	2.232
90.00	3.2442	837.8	0.00461	342.93	425.42	1.4390	1.6662	2.756	3.121	2.820
95.00	3.5912	772.7	0.00374	355.25	420.67	1.4715	1.6492	3.938	5.020	4.369
100.00	3.9724	651.2	0.00268	373.30	407.68	1.5188	1.6109	17.59	25.35	20.81
101.06[c]	4.0593	511.9	0.00195	389.64	389.64	1.5621	1.5621	∞	∞	∞

[a]Triple point [b]NBP [c]Critical point.

*Ashrae Handbook Fundamentals, 2005.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THERMODYNAMICS PROPERTIES OF R12*

Saturation Temp.	*Saturation Pressure*	*Saturated Liquid and Vapour*						*Vapour Superheated*			
								By 20		By 40°C	
t (°C)	p (bar)	v_f (kJ/kg)	v_g (m³/kg)	h_f (kJ/kg)	h_g (kJ/k)	s_f (kJ/kg-K)	s_g (kJ/kg-K)	h (kJ/kg)	s (kJ/kg-K)	h (kJ/kg)	s (kJ/kg-K)
–40	0.6417	0.66	0.2421	0	169.0	0	0.7274	180.8	0.7737	192.4	0.8178
–35	0.8069	0.67	0.1950	4.4	171.9	0.0187	0.7220	183.3	0.7681	195.1	0.8120
–30	1.0038	0.67	0.1595	8.9	174.2	0.0371	0.7171	185.8	0.7631	197.8	0.8068
–25	1.2368	0.68	0.1313	13.3	176.5	0.0552	0.7127	188.3	0.7586	200.4	0.8021
–20	1.5089	0.69	0.1089	17.8	178.7	0.0731	0.7088	190.8	0.7546	203.1	0.7979
–15	1.8256	0.69	0.0911	22.3	181.0	0.0906	0.7052	193.2	0.7510	205.7	0.7942
–10	2.1912	0.70	0.0767	26.9	183.2	0.1080	0.7020	195.7	0.7477	208.3	0.7909
–5	2.610	0.71	0.0650	31.4	185.4	0.1251	0.6991	198.1	0.7449	210.9	0.7879
0	3.086	0.72	0.0554	36.1	187.5	0.1420	0.6966	200.5	0.7423	213.5	0.7853
5	3.626	0.72	0.0475	40.7	189.7	0.1587	0.6942	202.9	0.7401	216.1	0.7830
10	4.233	0.73	0.0409	45.4	191.7	0.1752	0.6921	205.2	0.7381	218.6	0.7810
15	4.914	0.74	0.0354	50.1	193.8	0.1915	0.6902	207.5	0.7363	221.2	0.7792
20	5.673	0.75	0.0308	54.9	195.8	0.2078	0.6885	209.8	0.7348	223.7	0.7777
25	6.516	0.76	0.0269	59.7	197.7	0.2239	0.6869	212.1	0.7334	226.1	0.7763
30	7.450	0.77	0.0235	64.6	199.6	0.2399	0.6854	214.3	0.7321	228.6	0.7751
35	8.477	0.79	0.0206	69.5	201.5	0.2559	0.6839	216.4	0.7310	231.0	0.7741
40	9.607	0.80	0.0182	74.6	203.2	0.2718	0.6825	218.5	0.7300	233.4	0.7732
45	10.843	0.81	0.0160	79.7	204.9	0.2877	0.6812	220.6	0.7291	235.7	0.7724
50	12.193	0.83	0.0142	84.9	206.5	0.3037	0.6797	222.6	0.7282	238.0	0.7718
60	15.259	0.86	0.0111	95.7	209.3	0.3358	0.6777	226.4	0.7265	242.4	0.7706
70	18.859	0.90	0.0087	107.1	211.5	0.3686	0.6738	230.2	0.7240	246.2	0.7650

*Haywood R W, *Thermodynamics Tables in S.I. Units,* Cambridge University Press, 1968, P.22.

Superheated Water

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg-K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg-K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg-K
	P = 4.0 MPa (250.35°C)				P = 4.5 MPa (257.44°C)				P = 5.0 MPa (263.94°C)			
Sat.	0.04978	2601.7	2800.8	6.0696	0.04406	2599.7	2798.0	6.0198	0.03945	2597.0	2794.2	5.9737
275	0.05461	2668.9	2887.3	6.2312	0.04733	2651.4	2864.4	6.1429	0.04144	2632.3	2839.5	6.0571
300	0.05887	2726.2	2961.7	6.3639	0.05138	2713.0	2944.2	6.2854	0.04535	2699.0	2925.7	6.2111
350	0.06647	2827.4	3093.3	6.5843	0.05842	2818.6	3081.5	6.5153	0.05197	2809.5	3069.3	6.4516
400	0.07343	2920.8	3214.5	6.7714	0.06477	2914.2	3205.7	6.7071	0.05784	2907.5	3196.7	6.6483
450	0.08004	3011.0	3331.2	6.9386	0.07076	3005.8	3324.2	6.8770	0.06332	3000.6	3317.2	6.8210
500	0.08644	3100.3	3446.0	7.0922	0.07652	3096.0	3440.4	7.0323	0.06858	3091.8	3434.7	6.9781
600	0.09886	3279.4	3674.9	7.3706	0.08766	3276.4	3670.9	7.3127	0.07870	3273.3	3666.9	7.2605
700	0.11098	3462.4	3906.3	7.6214	0.09850	3460.0	3903.3	7.5647	0.08852	3457.7	3900.3	7.5136
800	0.12292	3650.6	4142.3	7.8523	0.10916	3648.8	4140.0	7.7962	0.09816	3646.9	4137.7	7.7458
900	0.13476	3844.8	4383.9	8.0675	0.11972	3843.3	4382.1	8.0118	0.10769	3841.8	4380.2	7.9619
1000	0.14653	4045.1	4631.2	8.2698	0.13020	4043.9	4629.8	8.2144	0.11715	4042.6	4628.3	8.1648
1100	0.15824	4251.4	4884.4	8.4612	0.14064	4250.4	4883.2	8.4060	0.12655	4249.3	4882.1	8.3566
1200	0.16992	4463.5	5143.2	8.6430	0.15103	4462.6	5142.2	8.5880	0.13592	4461.6	5141.3	8.5388
1300	0.18157	4680.9	5407.2	8.8164	0.16140	4680.1	5406.5	8.7616	0.14527	4679.3	5405.7	8.7124

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg-K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg-K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg-K
	P = 6.0 MPa (275.59°C)				P = 7.0 MPa (285.83°C)				P = 8.0 MPa (295.01°C)			
Sat.	0.03245	2589.9	2784.6	5.8902	0.027378	2581.0	2772.6	5.8148	0.023525	2570.5	2758.7	5.7450
300	0.03619	2668.4	2885.6	6.0703	0.029492	2633.5	2839.9	5.9337	0.024279	2592.3	2786.5	5.7937
350	0.04225	2790.4	3043.9	6.3357	0.035262	2770.1	3016.9	6.2305	0.029975	2748.3	2988.1	6.1321
400	0.04742	2893.7	3178.3	6.5432	0.039958	2879.5	3159.2	6.4502	0.034344	2864.6	3139.4	6.3658
450	0.05217	2989.9	3302.9	6.7219	0.044187	2979.0	3288.3	6.6353	0.038194	2967.8	3273.3	6.5579
500	0.05667	3083.1	3423.1	6.8826	0.048157	3074.3	3411.4	6.8000	0.041767	3065.4	3399.5	6.7266
550	0.06102	3175.2	3541.3	7.0308	0.051966	3167.9	3531.6	6.9507	0.045172	3160.5	3521.8	6.8800
600	0.06527	3267.2	3658.8	7.1693	0.055665	3261.0	3650.6	7.0910	0.048463	3254.7	3642.4	7.0221
700	0.07355	3453.0	3894.3	7.4247	0.062850	3448.3	3888.3	7.3487	0.054829	3443.6	3882.2	7.2822
800	0.08165	3643.2	4133.1	7.6582	0.069856	3639.5	4128.5	7.5836	0.061011	3635.7	4123.8	7.5185
900	0.08964	3838.8	4376.6	7.8751	0.076750	3835.7	4373.0	7.8014	0.067082	3832.7	4369.3	7.7372
1000	0.09756	4040.1	4625.4	8.0786	0.083571	4037.5	4622.5	8.0055	0.073079	4035.0	4619.6	7.9419
1100	0.10543	4247.1	4879.7	8.2709	0.090341	4245.0	4877.4	8.1982	0.079025	4242.8	4875.0	8.1350
1200	0.11326	4459.8	5139.4	8.4534	0.097075	4457.9	5137.4	8.3810	0.084934	4456.1	5135.5	8.3181
1300	0.12107	4677.7	5404.1	8.6273	0.103781	4676.1	5402.6	8.5551	0.090817	4674.5	5401.0	8.4925

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg-K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg-K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg-K
	P = 9.0 MPa (303.35°C)				P = 10.0 MPa (311.00°C)				P = 12.5 MPa (327.81°C)			
Sat.	0.020489	2558.5	2742.9	5.6791	0.018028	2545.2	2725.5	5.6159	0.013496	2505.6	2674.3	5.4638
325	0.023284	2647.6	2857.1	5.8738	0.019877	2611.6	2810.3	5.7596				
350	0.025816	2725.0	2957.3	6.0380	0.022440	2699.6	2924.0	5.9460	0.016138	2624.9	2826.6	5.7130
400	0.029960	2849.2	3118.8	6.2876	0.026436	2833.1	3097.5	6.2141	0.020030	2789.6	3040.0	6.0433
450	0.033524	2956.3	3258.0	6.4872	0.029782	2944.5	3242.4	6.4219	0.023019	2913.7	3201.5	6.2749
500	0.036793	3056.3	3387.4	6.6603	0.032811	3047.0	3375.1	6.5995	0.025630	3023.2	3343.6	6.4651
550	0.039885	3153.0	3512.0	6.8164	0.035655	3145.4	3502.0	6.7585	0.028033	3126.1	3476.5	6.6317
600	0.042861	3248.4	3634.1	6.9605	0.038378	3242.0	3625.8	6.9045	0.030306	3225.8	3604.6	6.7828
650	0.045755	3343.4	3755.2	7.0954	0.041018	3338.0	3748.1	7.0408	0.032491	3324.1	3730.2	6.9227
700	0.048589	3438.8	3876.1	7.2229	0.043597	3434.0	3870.0	7.1693	0.034612	3422.0	3854.6	7.0540
800	0.054132	3632.0	4119.2	7.4606	0.048629	3628.2	4114.5	7.4085	0.038724	3618.8	4102.8	7.2967
900	0.059562	3829.6	4365.7	7.6802	0.053547	3826.5	4362.0	7.6290	0.042720	3818.9	4352.9	7.5195
1000	0.064919	4032.4	4616.7	7.8855	0.058391	4029.9	4613.8	7.8349	0.046641	4023.5	4606.5	7.7269
1100	0.070224	4240.7	4872.7	8.0791	0.063183	4238.5	4870.3	8.0289	0.050510	4233.1	4864.5	7.9220
1200	0.075492	4454.2	5133.6	8.2625	0.067938	4452.4	5131.7	8.2126	0.054342	4447.7	5127.0	8.1065
1300	0.080733	4672.9	5399.5	8.4371	0.072667	4671.3	5398.0	8.3874	0.058147	4667.3	5394.1	8.2819

Saturated Water – Pressure Table

Press.	Sat. Temp.	Specific Volume m³/kg Sat. Liquid	Sat. Vapour	Internal Energy kJ/kg Sat. Liquid	Evap.	Sat. Vapour	Enthalpy kJ/kg Sat. Liquid	Evap.	Sat. Vapour	Entropy kJ/kg-K Sat. Liquid	Evap.	Sat. Vapour
P kPa	T_{sat} °C	v_f	v_g	u_f	u_{fg}	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
1.0	6.97	0.001000	129.19	29.302	2355.2	2384.5	29.303	2484.4	2513.7	0.1059	8.8690	8.9749
1.5	13.02	0.001001	87.964	54.686	2338.1	2392.8	54.688	2470.1	2524.7	0.1956	8.6314	8.8270
2.0	17.50	0.001001	66.990	73.431	2325.5	2398.9	73.433	2459.5	2532.9	0.2606	8.4621	8.7227
2.5	21.08	0.001002	54.242	88.422	2315.4	2403.8	88.424	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64,96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931
75	91.76	0.001037	2.2172	384.36	2111.8	2496.1	384.44	2278.0	2662.4	1.2132	6.2426	7.4558
100	99.61	0.001043	1.6941	417.40	2088.2	2505.6	417.51	2257.5	2675.0	1.3028	6.0562	7.3589
101.325	99.97	0.001043	1.6734	418.95	2087.0	2506.0	419.06	2256.5	2675.6	1.3069	6.0476	7.3545
125	105.97	0.001048	1.3750	444.23	2068.8	2513.0	444.36	2240.6	2684.9	1.3741	5.9100	7.2841
150	111.35	0.001053	1.1594	466.97	2052.3	2519.2	467.13	2226.0	2693.1	1.4337	5.7894	7.2231
175	116.04	0.001057	1.0037	486.82	2037.7	2524.5	487.01	2213.1	2700.2	1.4850	5.6865	7.1716
200	120.21	0.001061	0.88578	504.50	2024.6	2529.1	504.71	2201.6	2706.3	1.5302	5.5968	7.1270
225	123.97	0.001064	0.79329	520.47	2012.7	2533.2	520.71	2191.0	2711.7	1.5706	5.5171	7.0877
250	127.41	0.001067	0.71873	535.08	2001.8	2536.8	535.35	2181.2	2716.5	1.6072	5.4453	7.0525
275	130.58	0.001070	0.65732	548.57	1991.6	2540.1	548.86	2172.0	2720.9	1.6408	5.3800	7.0207
300	133.52	0.001073	0.60582	561.11	1982.1	2543.2	561.43	2163.5	2724.9	1.6717	5.3200	6.9917
325	136.27	0.001076	0.56199	572.84	1973.1	2545.9	573.19	2155.4	2728.6	1.7005	5.2645	6.9650
350	138.86	0.001079	0.52422	583.89	1964.6	2548.5	584.26	2147.7	2732.0	1.7274	5.2128	6.9402
375	141.30	0.001081	0.49133	594.32	1956.6	2550.9	594.73	2140.4	2735.1	1.7526	5.1645	6.9171
400	143.61	0.001084	0.46242	604.22	1948.9	2553.1	604.66	2133.4	2738.1	1.7765	5.1191	6.8955
450	147.90	0.001088	0.41392	622.65	1934.5	2557.1	623.14	2120.3	2743.4	1.8205	5.0356	6.8561
500	151.83	0.001093	0.37483	639.54	1921.2	2560.7	640.09	2108.0	2748.1	1.8604	4.9603	6.8207
550	155.46	0.001097	0.34261	655.16	1908.8	2563.9	655.77	2096.6	2752.4	1.8970	4.8916	6.7886
600	158.83	0.001101	0.31560	669.72	1897.1	2566.8	670.38	2085.8	2756.2	1.9308	4.8285	6.7593
650	161.98	0.001104	0.29260	683.37	1886.1	2569.4	684.08	2075.5	2759.6	1.9623	4.7699	6.7322
700	164.95	0.001108	0.27278	696.23	1875.6	2571.8	697.00	2065.8	2762.8	1.9918	4.7153	6.7071
750	167.75	0.001111	0.25552	708.40	1865.6	2574.0	709.24	2056.4	2765.7	2.0195	4.6642	6.6837

Saturated Water Pressure Entry Table A

Pressure	*Temp.*	Specific Volume, m³/kg			Internal Energy, kJ/kg		
		Sat. Liquid	*Evap.*	*Sat. Vapour*	*Sat. Liquid*	*Evap.*	*Sat. Vapour*
(kPa)	(°C)	v_f	v_{fg}	v_g	u_f	u_{fg}	u_g
0.6113	0.01	0.001000	206.131	206.132	0	2375.3	2375.3
1	6.98	0.001000	129.20702	129.20802	29.29	2355.69	2384.98
1.5	13.03	0.001001	87.97913	87.98013	54.70	2338.63	2393.32
2	17.50	0.001001	67.00285	67.00385	73.47	2326.02	2399.48
2.5	21.08	0.001002	54.25285	54.25385	88.47	2315.93	2404.40
3	24.08	0.001003	45.66402	45.66502	101.03	2307.48	2408.51
4	28.96	0.001004	34.79915	34.80015	121.44	2293.73	2415.17
5	32.88	0.001005	28.19150	28.19251	137.79	2282.70	2420.49
7.5	40.29	0.001008	19.23674	19.23775	168.76	2261.74	2430.50
10	45.81	0.001010	14.67254	14.67355	191.79	2246.10	2437.89
15	53.97	0.001014	10.02117	10.02218	225.90	2222.83	2448.73
20	60.06	0.001017	7.64835	7.64937	251.35	2205.36	2456.71
25	64.97	0.001020	6.20322	6.20424	271.88	2191.21	2463.08
30	69.10	0.001022	5.22816	5.22918	289.18	2179.22	2468.40
40	75.87	0.001026	3.99243	3.99345	317.51	2159.49	2477.00
50	81.33	0.001030	3.23931	3.24034	340.42	2143.43	2483.85
75	91.77	0.001037	2.21607	2.21711	394.29	2112.39	2496.67
100	99.62	0.001043	1.69296	1.69400	417.33	2088.72	2506.06
125	105.99	0.001048	1.37385	1.37490	444.16	2069.32	2513.48
150	111.37	0.001053	1.15828	1.15933	466.92	2052.72	2519.64
175	116.06	0.001057	1.00257	1.00363	486.78	2038.12	2524.90
200	120.23	0.001061	0.88467	0.88573	504.47	2025.02	2529.49
225	124.00	0.001064	0.79219	0.79325	520.45	2013.10	2533.56
250	127.43	0.001067	0.71765	0.71871	535.08	2002.14	2537.21
275	130.60	0.001070	0.65624	0.65731	548.57	1991.95	2540.53
300	133.55	0.001073	0.60475	0.60582	561.13	1982.43	2543.55
325	136.30	0.001076	0.56093	0.56201	572.88	1973.46	2546.34
350	138.88	0.001079	0.52317	0.52425	583.93	1964.98	2548.92
375	141.32	0.001081	0.49029	0.49137	594.38	1956.93	2551.31
400	143.63	0.001084	0.46138	0.46246	604.29	1949.26	2553.55
450	147.93	0.001088	0.41289	0.41398	622.75	1934.87	2557.62
500	151.86	0.001093	0.37380	0.37489	639.66	1921.57	2561.23
550	155.48	0.001097	0.34159	0.34268	655.30	1909.17	2564.47
600	158.85	0.001101	0.31457	0.31567	669.88	1897.52	2567.40
650	162.01	0.001104	0.29158	0.29268	683.55	1886.51	2570.06
700	164.97	0.001108	0.27176	0.27286	696.43	1876.07	2572.49
750	167.77	0.001111	0.25449	0.25560	708.62	1866.11	2574.73
800	170.43	0.001115	0.23931	0.24043	720.20	1856.58	2576.79

Saturated Water Pressure Entry

Table A

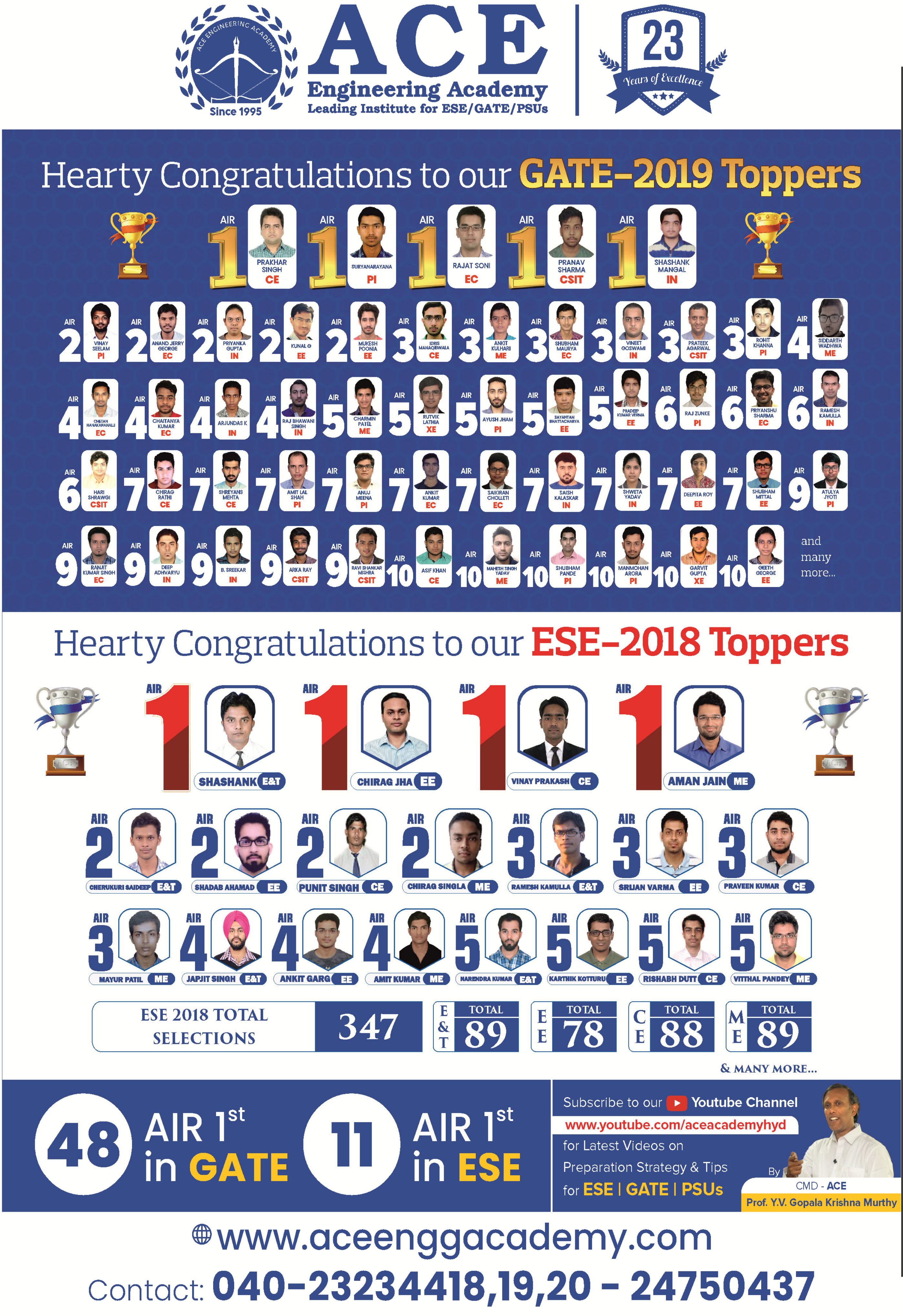
Pressure (kPa)	Temp (°C)	Enthalpy, kJ/kg Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapour h_g	Entropy, kJ/kg-K Sat. Liquid s_f	Evap. s_{fg}	Sat. Vapour s_g
0.6113	0.01	0.00	2501.3	2501.3	0	9.1562	9.1562
1.0	6.98	29.29	2484.89	2514.18	0.1059	8.8697	8.9756
1.5	13.03	54.70	2470.59	2525.30	0.1956	8.6322	8.8278
2.0	17.50	73.47	2460.02	2533.49	0.2607	8.4629	8.7236
2.5	21.08	88.47	2451.56	2540.03	0.3120	8.3311	8.6431
3.0	24.08	101.03	2444.47	2545.50	0.3545	8.2231	8.5775
4.0	28.96	121.44	2432.93	2554.37	0.4226	8.0520	8.4746
5.0	32.88	137.79	2423.66	2561.45	0.4763	7.9187	8.3950
7.5	40.29	168.77	2406.02	2574.79	0.5763	7.6751	8.2514
10	45.81	191.81	2392.82	2584.63	0.6492	7.5010	8.1501
15	53.97	225.91	2373.14	2599.06	0.7548	7.2536	8.0084
20	60.06	251.38	2358.33	2609.70	0.8319	7.0766	7.9085
25	64.97	271.90	2346.29	2618.19	0.8930	6.9383	7.8313
30	69.10	289.21	2336.07	2625.28	0.9439	6.8247	7.7686
40	75.87	317.55	2319.19	2636.74	1.0258	6.6441	7.6700
50	81.33	340.47	2305.40	2645.87	1.0910	6.5029	7.5939
75	91.77	384.36	2278.59	2662.96	1.2129	6.2434	7.4563
100	99.62	417.44	2258.02	2675.46	1.3025	6.0568	7.3593
125	105.99	444.30	2241.05	2685.35	1.3739	5.9104	7.2843
150	111.37	467.08	2226.46	2693.54	1.4335	5.7897	7.2232
175	116.06	486.97	2213.57	2700.53	1.4848	5.6868	7.1717
200	120.23	504.68	2201.96	2706.63	1.5300	5.5970	7.1271
225	124.00	520.69	2191.35	2712.04	1.5705	5.5173	7.0878
250	127.43	535.34	2181.55	2716.89	1.6072	5.4455	7.0526
275	130.60	548.87	2172.42	2721.29	1.6407	5.3801	7.0208
300	133.55	561.45	2163.85	2725.30	1.6717	5.3201	6.9918
325	136.30	573.23	2155.76	2728.99	1.7005	5.2646	6.9651
350	138.88	584.31	2148.10	2732.40	1.7274	5.2130	6.9404
375	141.32	594.79	2140.79	2735.58	1.7527	5.1647	6.9174
400	143.63	604.73	2133.81	2738.53	1.7766	5.1193	6.8958
450	147.93	623.24	2120.67	2743.91	1.8206	5.0359	6.8565
500	151.86	640.21	2108.47	2748.67	1.8606	4.9606	6.8212
550	155.48	655.91	2097.04	2752.94	1.8972	4.8920	6.7892
600	158.85	670.54	2086.26	2756.80	1.9311	4.8289	6.7600
650	162.01	684.26	2076.04	2760.30	1.9627	4.7704	6.7330
700	164.97	697.20	2066.30	2763.50	1.9922	4.7158	6.7080
750	167.77	709.45	2056.98	2766.43	2.0199	4.6647	6.6846
800	170.43	721.10	2048.04	2769.13	2.0461	4.6166	6.6627

Superheated Vapour Water **Table A**

Temp. (°C)	v (m³/kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg-K)	v (m³/kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg-K)
	300 kPa (133.55°C)				400 kPa (143.63°C)			
250	0.79636	2728.69	2967.59	7.5165	0.5951	2726.11	2964.16	7.3788
300	0.87529	2806.69	3069.28	7.7022	0.6548	2804.81	3066.75	7.5661
400	1.03151	2965.53	3274.98	8.0329	0.7726	2964.36	3273.41	7.8984
500	1.18669	3129.95	3485.96	8.3250	0.8893	3129.15	3484.89	8.1912
600	1.34136	3300.79	3703.20	8.5892	1.0056	3300.22	3702.44	8.4557
700	1.49573	3478.38	3927.10	8.8319	1.1215	3477.95	3926.53	8.6987
800	1.64994	3662.85	4157.83	9.0575	1.2372	3662.51	4157.40	8.9244
900	1.80406	3854.20	4395.42	9.2691	1.3529	3853.91	4395.06	9.1361
1000	1.95812	4052.27	4639.71	9.4689	1.4685	4052.02	4639.41	9.3360
1100	2.11214	4256.77	4890.41	9.6585	1.584	4256.53	4890.15	9.5255
1200	2.26614	4467.23	5147.07	9.8389	1.6996	4466.99	5146.83	9.7059
1300	2.42013	4682.99	5409.03	10.0109	1.8151	4682.75	5408.80	9.8780
	500 kPa (151.86°C)				600 kPa (158.85°C)			
Sat.	0.37489	2561.23	2748.67	6.8212	0.3157	2567.40	2756.80	6.7600
200	0.42492	2642.91	2855.37	7.0592	0.352	2638.91	2850.12	6.9665
250	0.47436	2723.50	2960.68	7.2708	0.3938	2720.86	2957.16	7.1816
300	0.52256	2802.91	3064.20	7.4598	0.43437	2801.00	3061.63	7.3723
350	0.57012	2882.59	3167.65	7.6328	0.47424	2881.12	3165.66	7.5463
400	0.61728	2963.19	3271.83	7.7937	0.51372	2962.02	3270.25	7.7078
500	0.71093	3128.35	3483.82	8.0872	0.59199	3127.55	3482.75	8.0020
600	0.80406	3299.64	3701.67	8.3521	0.66974	3299.07	3700.91	8.2673
700	0.89691	3477.52	3925.97	8.5952	0.74720	3477.08	3925.41	8.5107
800	0.98959	3662.17	4156.96	8.8211	0.82450	3661.83	4156.52	8.7367
900	1.08217	3853.63	4394.71	9.0329	0.90169	3853.34	4394.36	8.9485
1000	1.17469	4051.76	4639.11	9.2328	0.97883	4051.51	4638.81	9.1484
1100	1.26718	4256.29	4889.88	9.4224	1.05594	4256.05	4889.61	9.3381
1200	1.35964	4466.76	5146.58	9.6028	1.13302	4466.52	5146.34	9.5185
1300	1.45210	4682.52	5408.57	9.7749	1.21009	4682.28	5408.34	9.6906
	800 kPa (170.43°C)				1000 kPa (179.91°C)			
Sat.	0.24043	2576.79	2769.13	6.6627	0.19444	2583.64	2778.08	6.5864
200	0.26080	2630.61	2839.25	6.8158	0.20596	2621.90	2827.86	6.6939
250	0.29314	2715.46	2949.97	7.0384	0.23268	2709.91	2942.59	6.9246
300	0.32411	2797.14	3056.43	7.2327	0.25794	2793.21	3051.15	7.1228
350	0.35439	2878.16	3161.68	7.4088	0.28247	2875.18	3157.65	7.3010
400	0.38426	2959.66	3267.07	7.5715	0.30659	2957.29	3263.88	7.4650
500	0.44331	3125.95	3480.60	7.8672	0.35411	3124.34	3478.44	7.7621
600	0.50184	3297.91	3699.38	8.1332	0.40109	3296.76	3697.85	8.0289

Superheated Vapour Water Table A

Temp. (°C)	v (m³/kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg-K)	v (m³/kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg-K)
	2000 kPa (212.42°C)				2500 kPa (223.99°C)			
Sat.	0.09963	2600.26	2799.51	6.3408	0.07998	2603.13	2803.1	6.2574
250	0.11144	2679.58	2902.46	6.5452	0.08700	2662.55	2880.1	6.4084
300	0.12547	2772.56	3023.50	6.7663	0.09890	2761.56	3008.81	6.6437
350	0.13857	2859.81	3136.96	6.9562	0.10976	2851.84	3126.24	6.8402
400	0.15120	2945.21	3247.60	7.1270	0.12010	2939.03	3239.28	7.0147
450	0.16353	3030.41	3357.48	7.2844	0.13014	3025.43	3350.77	7.1745
500	0.17568	3116.20	3467.55	7.4316	0.13998	3112.08	3462.04	7.3233
600	0.19960	3290.93	3690.14	7.7023	0.15930	3287.99	3686.25	7.5960
700	0.22323	3470.99	3917.45	7.9487	0.17832	3468.80	3914.59	7.8435
800	0.24668	3657.03	4150.40	8.1766	0.19716	3655.30	4148.20	8.0720
900	0.27004	3849.33	4389.40	8.3895	0.21590	3847.89	4387.64	8.2853
1000	0.29333	4047.94	4634.61	8.5900	0.23458	4046.67	4633.12	8.4860
1100	0.31659	4252.71	4885.89	8.7800	0.25322	4251.52	4884.57	8.6761
1200	0.33984	4463.25	5142.92	8.9606	0.27185	4462.08	5141.70	8.8569
1300	0.36306	4678.97	5405.10	9.1328	0.29046	4677.80	5403.95	9.0291
	3000 kPa (233.90°C)				4000 kPa (250.40°C)			
Sat.	0.06668	2604.10	2804.14	6.1869	0.04978	2602.27	2801.38	6.0700
250	0.07058	2644.00	2855.75	6.2871	–	–	–	–
300	0.08114	2750.05	2993.48	6.5389	0.05884	2725.33	2960.68	6.3614
350	0.09053	2843.66	3115.25	6.7427	0.06645	2826.65	3092.43	6.5820
400	0.09936	2932.75	3230.82	6.9211	0.07341	2919.88	3213.51	6.7689
450	0.10787	3020.38	3344.00	7.0833	0.08003	3010.13	3330.23	6.9362
500	0.11619	3107.92	3456.48	7.2337	0.08643	3099.49	3445.21	7.0900
600	0.13243	3285.03	3982.34	7.5084	0.09885	3279.06	3674.44	7.3688
700	0.14838	3466.59	3911.72	7.7571	0.11095	3462.15	3905.94	7.6198
800	0.16414	3653.58	4146.00	7.9862	0.12287	3650.11	4141.59	7.8502
900	0.17980	3846.46	4385.87	8.1999	0.13469	3843.59	4382.34	8.0647
1000	0.19541	4045.40	4631.63	8.4009	0.14645	4042.87	4628.65	8.2661
1100	0.21098	4250.33	4883.26	8.5911	0.15817	4247.96	4880.63	8.4566
1200	0.22652	4460.92	5140.49	8.7719	0.16987	4458.60	5138.07	8.6376
1300	0.24206	4676.63	5402.81	8.9442	0.18156	4674.29	5400.52	8.8099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