LECTURE NOTES

ON

THERMALENGINEERING-II

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1. Performance of I.C. Engine

1.1 Mechanical Efficiency:

Mechanicalefficiencyisdefinedas**theratioof brakepower(deliveredpower)totheindicatedpower(powerprovidedtothepiston)**
Mathematically

$$\eta_m = \frac{B.P.}{I.P.}$$

Indicated thermal efficiency:

It is the ratio of the heat equivalent to one kW hour to the heat in the fuel per I.P. hour,
Mathematically,indicatedthermalefficiency,

$$\eta_i = \frac{\text{Heat equivalent to one kW hour}}{\text{Heat in fuel per I.P. hour}} = \frac{I.P. \times 3600}{m_f \times C}$$

Relative efficiency:

Relativeefficiencyisalsoknownasefficiencyratio.TherelativeefficiencyofanI.C.engineistheratiooftheindicatedthermalefficiencytotheairstandardefficiency.

Brake thermal efficiency:

Itistheratiooftheheatequivalent toonekWhourtotheheat inthefuelperB.P.hour.Mathematically,brakethermalefficiency,

$$\eta_b = \frac{\text{Heat equivalent to one kW hour}}{\text{Heat in fuel per B.P. hour}} = \frac{B.P. \times 3600}{m_f \times C}$$

Overall efficiency:

It is the ratio of the work obtained at the crankshaft in a given time to the energy supplied by the fuelduringthesametime. Mathematically,overall efficiency,

$$\eta_o = \frac{B.P. \times 3600}{m_f \times C}$$

B.P. =Brakepower inkW,
mf=Massoffuelconsumedinkg perhour,andC
=Calorificvalveoffuel inkJ /kg offuel.

Mean effective pressure:

The **mean effective pressure** (**MEP**) is a quantity relating to the operation of a reciprocating engineand is ameasureofanengine'scapacitytodoworkthatisindependentof enginedisplacement.
MathematicallyMEP=Workdone/Sweptvolume

Specific fuel consumption:

- The fuel consumption characterstics of an engine generally expressed in terms of specific fuelconsumptionperKw-hr
- Itisanimportantparameterthat reflectshowgoodtheengineperformanceis.
- Itisinverselyproportionaltothethermalefficiencyoftheengine.
- The brake-specific fuel consumption(bsfc) and indicated-specific fuel consumption(isfc) is the specificfuelconsumptiononthebasisofbrakepower(bp)andindicatedpower(ip)respectively.

$$sfc = \frac{Fuel\ consumption\ per\ unit\ time}{power}$$

1.2 Air–fuelratio:

Air-fuel ratio is commonly used in the gas turbineindustry as well as in government studies of internalcombustionengine,andreferstotheratioofairtothefuel.

Internal combustion engines burn fuel to create kinetic energy. The burning of fuel is basically the reaction offuel with oxygen in the air. The amount of oxygen present in the cylinder is the limiting factor for the amount offuel that can be burnt. If there's too much fuel present, not all fuel will be burnt and un-burnt fuel will bepushedout throughtheexhaustvalve.

The carburettor controls the fuel/air mixture on a motorbike, and you often hear 'lean' and 'rich' being used todescribethefuel/airmixture. Let'slookatwhat effectthisratiohasontheengine.
Firstly, there's a theoretically optimal fuel/air mixture. This is called the **stoichiometric** mass/volume and it tellsyou how much air (ie. oxygen) you need to completely burn an amount of fuel. **Ifyou have less air than this,the mixture is rich.** **If you have too much air, the mixture is lean.** You can look at it in terms of fuel. Too muchfuel givesarichmixture,toolittlegivesaleanmixture.

ForExample:
15.0:1= Lean
14.7:1= Stoichiometric
13.0:1=Rich

The stoichiometric mass is related to the carbon/hydrogren ratio in your fuel. This makes sense, since eachcarbon atom needs two oxygen atoms to make CO2, and each hydrogren needs on average half an oxygenatom. So you can presumably just add up the number of carbon and hydrogen atoms and do a bit of maths toworkouthowmanyoxygenatomsyou'regoingtoneed.

If you have the 'perfect' amount ofoxygen for yourpetrolyou canexpectto getabout45 mega-joules ofenergy for every kilogram of petrol you've got. However, *engines aren't perfectly efficient.* For a start, to get themaximum amount of work out of the explosion, you'd have to let the gases expand until they'vecooled downto the surrounding air temperature (look up Carnot cycles somewhere). In a real engine, the gases only get toexpandaslongasthepistonismovingdown.Whentheexhaustportopens,andthepistonmovesuptoputtheexhaustgasesout,thegasesarestill hot.That'swhytheexhaustpipegetshot!

Calorific value of fuel:

Calorificvalueisdefinedas**theamountofheatenergyreleasedduringcompletecombustionofaunitmassofafuel**.Itis expressedinkJ/kg.

Grosscalorificvalue(GCV) orHigherHeatingValue(HCV)istheamountofheat releasedbythecompletecombustion of a unit of fuel. It assumes all water vapour produced during combustion process is fullycondensed.
Net Calorific Value (NCV) or lower heating value (LHV) or lower calorific value (LCV) is determined bysubtracting the heat of vaporization of the water vapour from the higher heating value. It assumes watervapour leaves with the combustion products without fully being condensed. Fuel should be purchased based onNCV.

1.2 Workout problems to determine efficiencies and specific fuel consumption:

Problem 48.1: A two stroke cycle internal combustion engine has a mean effective pressure of 6 bar. The speed of the engine is 1000 r.p.m. I: diameter of piston and stroke are 110 mm and 140 mm respectively, find the indicated power developed.

Solution:

Given: No. of strokes per cycle for the engine, $S = 2$;

Actual mean effective pressure, $p_{am} = 6$ bar;

Engine speed, $N = 1000$ r.p.m;

Diameter of the piston, $D = 110$ mm $= 0.11$ m;

Stroke length, $L = 140$ mm $= 0.14$ m;

No. of cylinders = 1;

No. of missed cycle, $n_{mc} = 0$;

Determine the indicated power developed, I.P.:

Formula: Indicated power developed, $IP = \frac{100.p_{am}.L.A.(\frac{2N}{S} - n_{mc})}{60} \times$ (No. of cylinders), kW

$$= \frac{100.p_{am}.L.A.(\frac{2N}{S})}{60} \times \text{(No. of cylinders)} \qquad [\because n_{mc} = 0]$$

Answer: Indicated power, **I.P** $= \frac{100.p_{am}.L.A.(\frac{2N}{S})}{60} \times$ (No. of cylinders)

$$= \frac{100 \times 6 \times 0.14 \times \frac{\pi}{4} \times (0.11)^2 \times \frac{2 \times 1000}{2}}{60} \times 1 = \mathbf{13.3\ kW}$$

Problem 48.3: A rope brake was used to measure the brake power of a single cylinder, four stroke cycle petrol engine. It was found that the torque due to brake load is 175 N-m and the engine makes 500 r. p.m. Determine the brake power developed by the engine.

Solution:

Given: Torque due to brake load, $T = 175$ N-m .

Engine speed, $N = 500$ r.p.m.

Determine the brake power, B.P. ;

Formula: Brake power, B.P. $= \frac{2\pi NT}{1000 \times 60}$

Answer: Brake power, B.P. $= \frac{2\pi NT}{1000 \times 60} = \frac{2\pi \times 500 \times 175}{1000 \times 60} = \mathbf{9.16\ kW}$

Questionsforexercise/assignment:

Shortquestions

1. DefineMechanicalefficiency?
2. Defineindicatedpower?
3. Definebrakepower?
4. Definespecificfuelconsumption?
5. DefineAirfuelratio?

Longquestions

1. **WriteshortnotesonAir-fuelratio?**
2. **FindoutmechanicalefficiencyandfrictionalpoweroffourstrokepetrolenginewithIP60 KWANDBP25kw?**

2Air compressor

2.1 Functions of air compressor and its industrial uses:

All air compressors perform the same basic function — they increase the pressure and reduce the volume of agas,likeair.

Compressedairisusedfor:

- Packingandpalletingproducts.
- Closingandcheckingdevices.
- Fillingequipmentfordrinks.
- Coolingandfreezingproducts.

Compressors are used throughout industry to provide shop or instrument air; to power air tools, paint sprayers,and abrasive blast equipment; to phase shift refrigerants for air conditioning and refrigeration; to propel gasthroughpipelines;etc

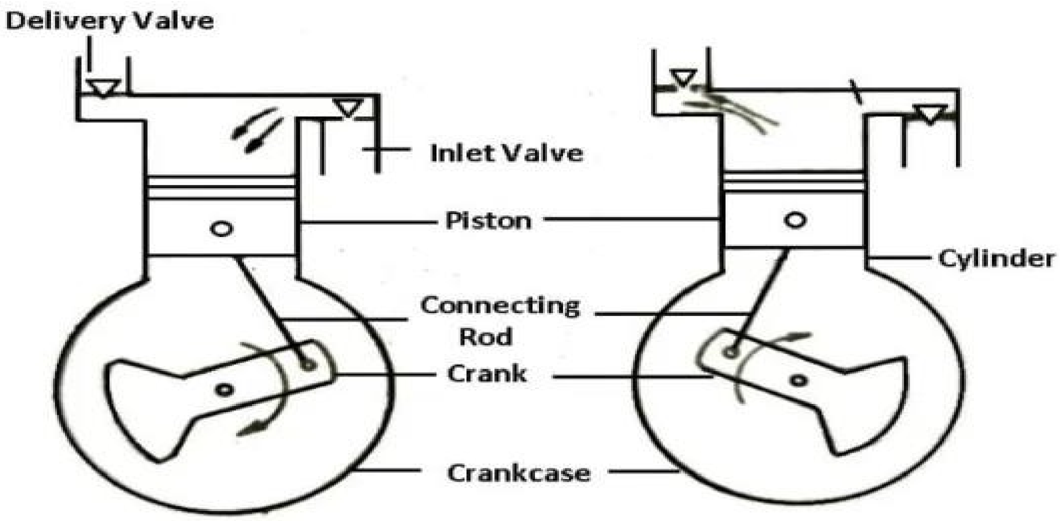
2.2 Classifications of air compressor

Followingarethetypesofaircompressors:

1. Reciprocatingaircompressor
2. Rotaryaircompressor
3. Centrifugalaircompressor
4. Axialaircompressor

2.3 Describe parts and working principle of reciprocating air compressor:

A reciprocating air compressor is a type of positive displacement compressor that uses a piston. The piston isdrivenbythecrankshafttotransferthehigh-pressuregasesintothecylinder.



Reciprocating Air Compressor

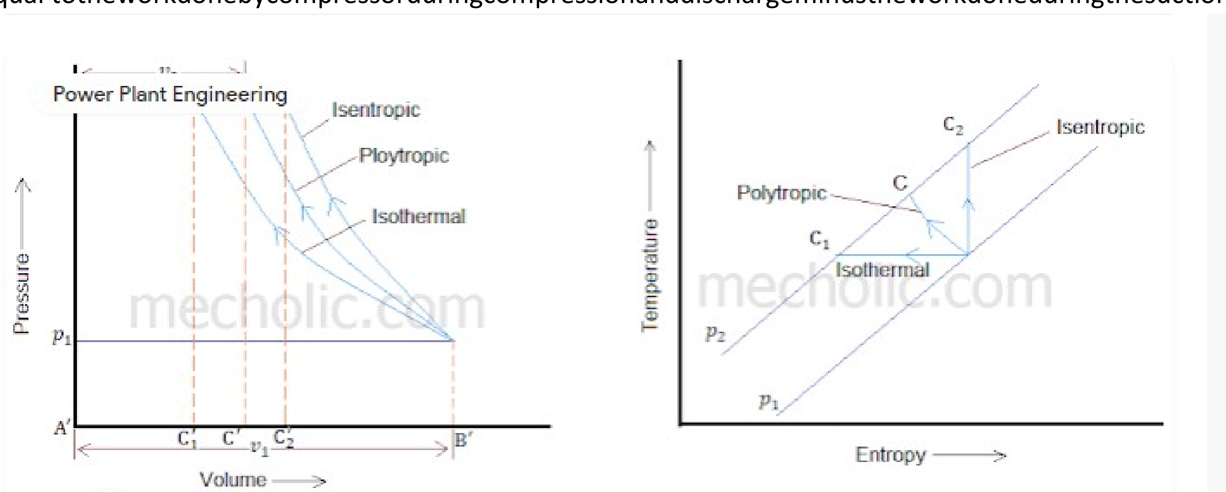
In these types of air compressors, initially, the gas enters from the suction manifold. This gas is flowing throughacompressioncylinderwhereitgetscompressedbyanattachedpiston.Itisdriveninareciprocatingmotion bytheapplicationofacrankshaft, anditisreleased. Atypicalreciprocatingcompressoriscommonlyusedinautomotiveindustriestogenerate5 to30horsepower.A large type of reciprocating compressor creates up to 1000 horsepower that equals 750 KW, and it is used inthe large petroleum iWhen compared to a regular diaphragm compressor, it has a longer lifespan and requiresquiet maintenance because of continuous use. A reciprocating compressor is used in gas pipelines, chemicalplants,airconditioning,andrefrigerationplants.ndustry.

2.4 Terminology ofaircompressor:

Bore:**boreisthediameterof thecircularopeningatitsend**
Stokelength:Thestrokelengthis**howfarthepistontravelsinthecylinder**
FAD stands for **Free Air Delivery**, and this is the volume of compressed air that an air compressor willactuallydischargeasaresult ofthecompressionprocess.CFM(FAD)istypicallyathirdlessthanCFM(Displacement)
Vometricefficiency:
The volumetric efficiency represents **the efficiency of a compressor cylinder to compress gas**. Itmay be defined as the ratio of the volume of gas actually delivered to the piston displacement,correctedtosuctiontemperatureandpressure

2.5 Derive the workdone for single stage and two stage compressor with or without clearance volume:

The working of reciprocating compressor includes three operations, suction, compression, and discharge ofcompressed fluid. thus there are three work is included in a cycle of reciprocating compressor, work of pistonduring the suction of fluid/ refrigerant, work of piston during the compression of fluid as well as work duringthe discharge of compressed fluid. Mathematically the work done by the reciprocating compressor is equal totheworkdonebycompressorduringcompressionanddischargeminustheworkdoneduringthesuctionfluid.



Considerasinglestage,singleactingreciprocatingcompressorwithoutclearancevolume.Thefollowingfigureshows the PV and TS diagram of this compressor. The compression process may be isentropic, polytropic, orisothermal

Let p_1= Suction pressure (pressure before compression)v_1=Suctionvolume
T_1=Suction temperature
p_2, v_2, T_2 are the corresponding pressure, volume, and temperature after compression.riscompressionratio(p_1/p_2)
Workdoneduringisothermalcompression

ThelineABrepresentssuctionoffluid,areaunderAB(ieABB'A')representworkdoneduringthesuctionprocess

$W_1=p_1v_1$

BC_1 represent compression of fluid when piston moving from bottom dead center to top dead center. Whenthepressureinsidethecylinderreachesp_2,thedischargevalveopens.Furthermovementpistontowardsthe topdeadcentercausethecompressedairtodischarge. C_1D representdischargingoffluid.

WorkdoneduringcompressionisW$_2$=AreaofBC_1C_1'B'

$$W_2 = p_1 v_1 \log_e \left(\frac{v_1}{v_2}\right)$$

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Work done during discharge W_3= Area

C_1DA'C_1'W_3=p_2v_2

Workdonebythecompressorduringtheonecompletecycleofoperationisequalto $W=W_3+W_2-W_1$

$$W = p_2 v_2 + p_1 v_1 \log_e \left(\frac{v_1}{v_2}\right) - p_1 v_1$$

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Since$p_1v_1=p_2v_2$

$$W = p_1 v_1 \log_e \left(\frac{v_1}{v_2}\right)$$

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$$= 2.3\, p_1 v_1 \log \left(\frac{v_1}{v_2}\right)$$

But$p_1v_1=mRT_1$and

$$\frac{v_1}{v_2} = \frac{p_2}{p_1} = r$$

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$$W = 2.3\, mRT_1 \log r$$

Workdoneduringpolytropiccompression(PV^n=constant)
TheworkdoneduringthecompressionisequaltoareaunderBCC'B'

$$W_2 = \frac{p_2 v_2 - p_1 v_1}{n-1}$$

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Workdone$W=W_3+W_2-W_1$

$$W = p_2 v_2 + \frac{p_2 v_2 - p_1 v_1}{n-1} - p_1 v_1$$

$$= \frac{(n-1)p_2 v_2 + p_2 v_2 - p_1 v_1 - (n-1)p_1 v_1}{n-1}$$

$$= \frac{n}{n-1}(p_2 v_2 - p_1 v_1)$$

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$$= \frac{n}{n-1} p_1 v_1 \left(\frac{p_2 v_2}{p_1 v_1} - 1\right)$$

Forpolytropiccompression $p_1v_1^n=p_2v_2^n$,nisploytropic index

$$\frac{v_2}{v_1} = \left(\frac{p_1}{p_2}\right)^{\frac{1}{n}}$$

Putthe valueof v_2/v_1inequationofworkdone

$$W = \frac{n}{n-1} p_1 v_1 \left(\frac{p_2}{p_1}\left(\frac{p_1}{p_2}\right)^{\frac{1}{n}} - 1\right)$$

$$= \frac{n}{n-1} mRT_1 \left(\frac{p_2}{p_1}\left(\frac{p_2}{p_1}\right)^{\frac{-1}{n}} - 1\right)$$

$$= \frac{n}{n-1} mRT_1 \left(\left(\frac{p_2}{p_1}\right)^{\frac{-1}{n}+1} - 1\right)$$

$$= \frac{n}{n-1} mRT_1 \left(\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right)$$

since

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

The above equation will become

$$= \frac{n}{n-1} mRT_1 \left(\frac{T_2}{T_1} - 1\right)$$

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

Work done during isentropic compression

The curve BC_2 Shows isentropic compression. The equation for work done during isentropic compression is similar to that of during polytropic compression.

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

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Here γ is isentropic index.

since

$$\gamma = \frac{c_p}{c_v}$$

and

$$c_p - c_v = R = c_p \frac{\gamma - 1}{\gamma}$$

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Here c_p and c_v are specific heats

$$W = \frac{\gamma}{\gamma - 1} mc_p \left(\frac{\gamma - 1}{\gamma}\right)(T_2 - T_1)$$

$$W = mc_p(T_2 - T_1)$$

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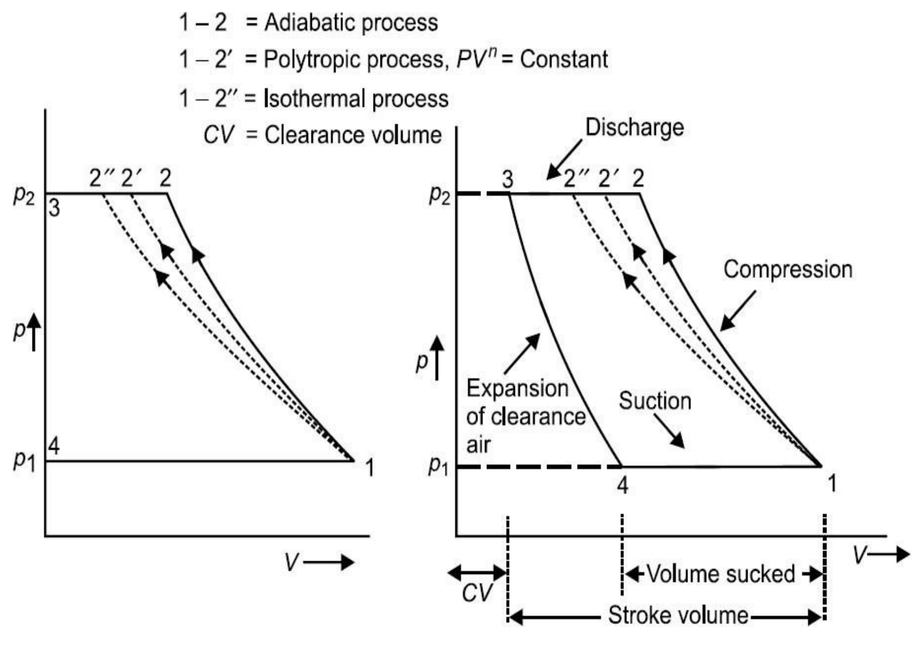
Derivetheworkdonefortwostagecompressorwithorwithoutclearancevolume:

ThermodynamicAnalysisofReciprocatingCompressor

Compressionofairincompressormaybecarriedoutinthreedifferentwaysofthermodynamicprocesses such as isothermal compression, polytropic compression or adiabatic compression. Figure (2)shows the thermodynamic cycle involved in compression. Clearance volume is provided in reciprocatingcompressor.Purposeofclearancevolumeincylinderistwofold.Oneistoaccommodatevalvemec hanismandanotheroneistopreventcollisionofpistonwithcylinderhead.

On *p-V* diagram process 4–1 shows the suction process followed by compression during 1–2, dischargeprocess2–3andexpansionofclearaneair3-4(ifclearancevolumeisprovided).



(a) (b)

Fig. (2)Compressioncycleon*p-V*diagram(a)withoutclearancevolume(b)withclearancevolume

Air enters compressor at pressure $p_1$and is compressed up to p_2. Compression work requirement can beestimated from the area bounded by the curves comprising the cycle. Area on *p*–*V* diagram shows thatwork requirement shall be minimum with isothermal process $1 - 2''$. Work requirement is maximum withprocess 1–2 i.e. adiabatic process. As an engineer one shall attempt to minimise the requirement ofcompression-work. Therefore, ideally compression should occurisothermally for minimum work input.In practice,itisnotpossibletorealiseisothermalcompression.Reasonismaintainingconstanttemperature during compression is very difficult. Generally, compressors run at substantially high speedwhile isothermal compression requires compressor to run at very slow speed so that heat producedduringcompressionisdissipatedoutandtemperatureremainsconstant.Highrunningspeedofcompressorlead compression process near to adiabatic or polytropic process. It is thus obvious that actual compressionprocess should be compared with isothermal compression process. A mathematical parameter calledisothermal efficiency is defined for quantifying the degree of deviation of actual compression process(adiabatic or polytropic process) from idealcompression process (isothermalcompression process).Isothermal efficiency is defined as the ratio of isothermal work to actual indicated work in reciprocatingcompressor.

$$IsothermalEfficiency = \frac{IsothermalWork}{ActualIndicatedWork}$$

Compressionprocessfollowingthreedifferentprocessesisalsoshownon*T*-*s*diagraminFig. (3).

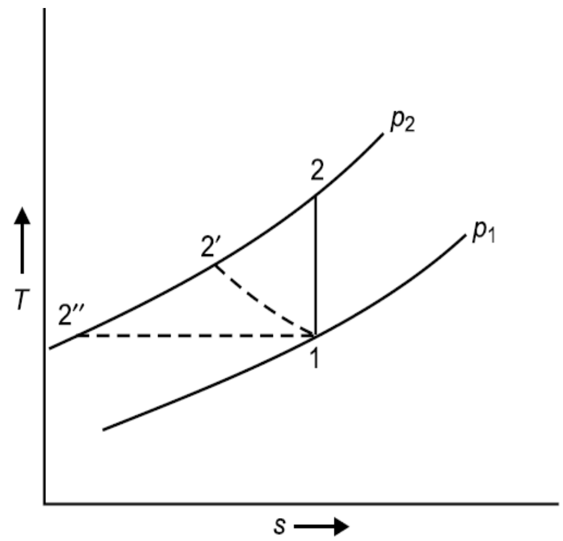


Fig.(3)Compressionprocesson*T*-*S*diagram.

CompressionWork,(withoutclearancevolume)-Assumingcompressionprocessfollow

$$W_c = \text{Area on } p\text{-}V \text{ diagram}$$

$$= \left[p_2V_2 + \left(\frac{p_2V_2 - p_1V_1}{n-1}\right)\right] - p_1V_1$$

$$= \left(\frac{n}{n-1}\right)[p_2V_2 - p_1V_1]$$

$$= \left(\frac{n}{n-1}\right)(p_1V_1)\left[\frac{p_2V_2}{p_1V_1} - 1\right]$$

$$W_c = \left(\frac{n}{n-1}\right)(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]$$

$$\boxed{W_c = \left(\frac{n}{n-1}\right)(mRT_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]}$$

$$W_{c,\ iso} = p_2V_2 + p_1V_1 \ln r - p_1V_1$$

polytropicprocessi.e.pV^n=C

or, $$\boxed{W_c = \left(\frac{n}{n-1}\right) mR\ (T_2 - T_1)}$$

Incaseofcompressorhavingisothermalcompressionprocess,*n=1*i.e.p_1V_1=p_2V_2

$$W_{c,\ \text{iso}} = p_1 V_1 \ln r, \text{ where } r = \frac{V_1}{V_2}$$

Incase,compressorfollowadiabaticcompressionprocess,$n=\gamma$

$$W_{c,\ \text{adiabatic}} = \left(\frac{\gamma}{\gamma - 1}\right) mR\ (T_2 - T_1)$$

Or,

$$W_{c,\ \text{adiabatic}} = mC_p\ (T_2 - T_1)$$

$$W_{c,\ \text{adiabatic}} = m\ (h_2 - h_1)$$

Henceisothermalefficiency

$$\eta_{\text{iso}} = \frac{p_1 V_1 \ln r}{\left(\frac{n}{n-1}\right)(p_1 V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]}$$

As an engineer one should attempt to design a compressor which efficiency approaches 100%,thereby meaning that actual work of compression should approach isothermal work of compression.Thiscanbeachievedbyadoptingfollowingmethod

I. Providefinsoverthesurfaceofcylinder. Finsfacilitatequickheattransferfromair(whichisbeingcompressed)toatmosphere.
II. Water jacket may be provided around compressor cylinder so that heat can be picked by coolingwatercirculatingthroughwaterjacket.
III. Watermayalsobeinjectedattheendofcompressionprocessinordertocooltheairbeingco mpressed.
IV. In case of multistage compression in different compressors operating serially, the air leavingone compressor may be cooled up to ambient state or somewhat high temperature beforebeinginjectedintosubsequentcompressor.

Allthesemethodsrestrictthetemperatureriseduringcompression.Henceactualcompressionprocessapproachestoisothermal compression.

Compression Work, (with clearance volume)- With clearance volume the cycle is represented onFig.(2-b).Theworkdoneforcompressionofairpolytropicallycanbegivenbytheareaenclosedincycle1–2–3–4.

$$W_{c,\text{ with CV}} = \text{Area}1234$$

$$= \left(\frac{n}{n-1}\right)(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right] - \left(\frac{n}{n-1}\right)(p_4V_4)\left[\left(\frac{p_3}{p_4}\right)^{\frac{(n-1)}{n}} - 1\right]$$

$$W_{c,\text{ with }CV} = \left(\frac{n}{n-1}\right)(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right] - \left(\frac{n}{n-1}\right)(p_1V_4)\cdot\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]$$

$$\boxed{W_{c,\text{ with }CV} = \left(\frac{n}{n-1}\right)p_1\cdot\left[\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right]\cdot(V_1 - V_4)}$$

$$\boxed{W_{c,\text{ with }CV} = \left(\frac{n}{n-1}\right)p_1V_d\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]}$$

This($V1$–$V4$),sayV_d,isactuallythevolumeofairinhaledinthecycleanddeliveredsubsequently.

Assumingairbehavesasaperfectgas. Nowtemperatureandpressurecanberelatedas

$$\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} = \frac{T_2}{T_1} \quad \text{And} \quad \left(\frac{p_4}{p_3}\right)^{\frac{(n-1)}{n}} = \frac{T_4}{T_3} \Rightarrow \left(\frac{p_1}{p_2}\right)^{\frac{(n-1)}{n}} = \frac{T_4}{T_3}$$

Substituting,

$$W_{c,\text{ with }CV} = \left(\frac{n}{n-1}\right)(m_1RT_1 - m_2RT_4)\left[\frac{T_2}{T_1} - 1\right]$$

Ideallythereshall benochangeintemperatureduringsuctionanddeliveryi.e.T_1=T_4&T_2=T_3.Aboveequationcanbewrittenas

$$W_{c,\text{ with }CV} = \left(\frac{n}{n-1}\right)(m_1RT_1 - m_2RT_1)\left[\frac{T_2 - T_1}{T_1}\right]$$

Or

$$\boxed{W_{c,\text{ with }CV} = \left(\frac{n}{n-1}\right)(m_1 - m_2)R(T_2 - T_1)}$$

Where(m_1-m_2)indicatesthemassofairsuckedordelivered.Forunitmassofairdeliveredtheworkdoneperkgofair canbegivenas,

$$W_{c,\text{ with } CV} = \left(\frac{n}{n-1}\right) R(T_2 - T_1), \text{ per kg of air}$$

Thus from above expressions it is obvious that the clearance volume reduces the effective sweptvolumei.e.themassof airhandledbuttheworkdoneperkgof airdeliveredremainsunaffected.

Powerrequiredtorunthecompressor

Forsingleactingcompressor,

$$\text{Power required} = \left[\left(\frac{n}{n-1}\right)p_1(V_1 - V_4)\left\{\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right\}\right] \times N$$

$$\text{for double acting compressor, power} = \left[\left(\frac{n}{n-1}\right)p_1(V_1 - V_4)\left\{\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\right\}\right] \times 2N$$

Questionsforexercise/assignment:

1. **DefineFAD?**
2. **Defineboreandstrokelengthofcompressor?**
3. **Mentiondifferentindustrialuseofcompressor?**
4. **Classifycompressor?**
5. **DrawPV&TSdiagramofsinglestagereciprocatingcompressor?Long**

questions

1. **Deriveworkdoneofsinglestagereciprocatingaircompressor?**
2. **Deriveworkdoneoftwostagereciprocatingaircompressor?**

References:

1. https://www.theengineerspost.com/types-of-air-compressors/
2. https://www.mecholic.com/2019/03/work-done-by-reciprocating-compressor.html#:~:text=Mathematically%20the%20work%20done%20by,during%20the%20suction%20of%20fluid.&text=p2%2C%20v2%2C%20T,volume%2C%20and%20temperature%20after%20compression.

3. Propertiesofsteam

3.1 Differencebetweengasandvapour:

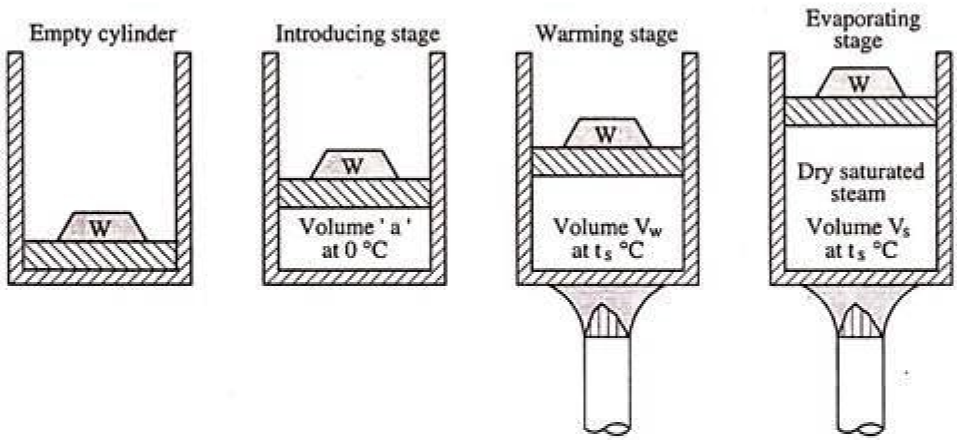
Vapour	Gas
Vapour is a mixture of two or more different phases at room temperature, these phases are liquid and gaseous phases.	Gas usually contains a single thermodynamic state at room temperature.
Vapour has a collection of particles without any definite shape when observed under a microscope.	Gas does not have a definite shape when it is observed under a microscope.
Vapour consists of random molecules and atoms moving randomly about.	Gas also consists of random molecules and atoms moving about randomly.
Vapour is not a state of matter, unlike gases.	Gases are a state of matter.

3.2 Formationofsteam:

GenerationofOneKg ofSteamataGivenPressurefromWaterInitiallyAt0°C:

Let us decide upon the pressure under which one kg of water is to be heated. After fixing the pressurewecanknowthesaturationtemperatureforthispressurefromsteamtablesandthus,watershouldbe heatedtothistemperaturebeforesteamwill begenerated.

illustratesthethreestagesintheformationof steam,atsomeconstantpressure,namely:



Stages of steam formation
FIG. 3-7

(1) IntroducingStage:

During this stage 1 kg of water at 0°C is pumped into the cylinder against an absolute pressure P, the pressure ofsteam generation. This pressure is caused by the weight placed on piston and pressure of atmosphere. The energyexpended by the pump to deliver 1 kg of water of volume 'a' m^3 at 0°C equals P × a (joules). This energy appears aspressureenergyofthewaterinthecylinder andcouldbemadetodoworkbyvirtueofits pressure.

(2) WarmingStage:

During this stage heat is added to the water so that its temperature from 0°C is raised tot_s (the temperature atwhich steamwillbegin to formunderabsolute pressure P)and to increasethevolume of1 kg ofwater from'a' to v_f,where v_f is the volume of1 kg ofwaterat the temperaturet_s and absolute pressure P.The heatsupplied during thiswarming stage is called Sensible Heat because it can be detected by the sense of touch and produces a riseintemperature(t_s–0)°C to be seen on a thermometer.

hesensible heatsuppliedinthewarmingstageisusedfortwo purposes:

(i) Toincrease the temperature of1 kg ofwaterfrom0°C to t_s.Thisheatisutilizedfor increasing the internalenergyofwater.

(ii) Todo externalworkdw(v_f– a)Joulesin increasing thevolume ofwater from'a' to v_f againstthe absolute pressure Pwhich actsconstantlyon the piston.

ByFirstLawof Thermodynamics asappliedtonon-flowprocess,heatsupplied=change ininternalenergy+external workdone bywater.

∴Sensible heat=hf—(u_f–u_o)+P(v_f–a).

Ifthechangesininternalenergyarereckonedfrom0°C,u_0 willbezeroandwegetsensible heat-h_f =u_f +P(v_f–a).

(3) EvaporatingStage:

During this stage further heat is supplied to 1 kg of water at t_{sat}, the saturation temperature corresponding to theconstant pressure P. The volume changes from v_f to v_g. During this stage heat is added at constant temperatureandthisheatisutilizedinchangingthestateofwater. Theexternal workdoneduringthisstage=$P(v_g–v_f)$. Because the heat added during this stage cannot be recorded by a rise in temperature on the thermometer, it iscalledLatentHeat(hiddenheat)orheatofvaporizationi.e.,hf_g.

Thelatentheatis,therefore,usedfor twopurposes:

(i) To overcometheinternalmolecularresistanceofthewaterbychangingitfromwaterintosteam.

(ii) Toforcebackthepistontoincreasethevolumefromthatofwatertothatofsteam.

By First Law of Thermodynamics as applied to non-flow process, heat supplied = change in internal energy +externalworkdone.

∴Heatofvaporization=$h_{fg}=(u_g–u_f)+P(v_g–v_f)$.

Thus,weseethatenergyissuppliedinthreestages togeneratesteamatapressurePfromwaterat0°C.

3.4 PropertiesofSteam*:*

The properties of steam are interrelated. If we know certain properties, the other properties may befound out. For example, if the pressure of saturated steam is observed by the pressure gauge, itstemperature can be found from steam tables in which the results of various experiments have beentabulated.

All other properties of a given mass of steam can be known when any two properties such as thepressureanddrynessfractionofsteam forsaturatedsteamandpressureanddegreeofsuperheatforsuperheatedsteam areknown.

If the steam is dry and saturated then only pressure should be known to determine all the properties.Thus, in order to observe the above two properties of steam, pressure gauges and steam calorimeters orthermometersareusedatsuitablepoints.

DrynessFractionofSaturatedSteam:

We have seen that steam in contact with water contains liquid particles in suspension. Thus, the steamconsists of dry saturated steam and water particles in suspension. The dryness fraction of steam isdefined as the ratio of the mass of dry steam in a certain quantity of steam to the mass of total wetsteam. Itisgenerally denotedbytheletterx.

Thedrynessfractionofawetsteam mayalsobedefinedastheamountofdrysteaminunitamountofwetsteam. If1kg ofwetmercuryvapourcontains0.12kgofdropletsofliquidmercury,ithasadrynessfractionof(1–0.12)=0.88.

UseofSteam Tables:

The values tabulated in the steam tables are determined accurately by experiments. These values formthebasisformanycalculationsconcernedwithsteamengineering. Thesetablesaretobeusedbecause vapours do not obey general gas law. The values given in the tables are for one kg of dry saturatedsteambutthesevaluescanalsobeemployedforwetsteamcalculations.

In order to determine the properties of steam at some intermediate pressure between those given intables, we interpolate assuming the linear relation between these values. The method is very simple andatthesametimeaccurate.

SensibleHeat:

If is denoted by the letter h_f in steam tables. It is the quantity of heat in kJ required to raise thetemperature of 1 kg of water from 0°C to the saturation temperature at which water begins to boil atthegivenpressureP. Thepressuresaregiveninbar($10^5 N/m^2$)absolute.

Inchanging watertosteamunderconstantpressure,thetemperatureofwatermustbebroughtuptoitsboiling point at the given pressure before it can evaporate. Sometimes sensible heat is called the liquidheat or liquid enthalpy. Sensible heat of water h_f may be found approximately by multiplying its specificheatbyitssaturationtemperature.

Actually the specific heat of water is not constant but it increases with increase in the saturationtemperature i.e., with increase in the pressure. The value of h_f given in the steam tables accounts for thevariationinthespecificheatofwater.

Itisalways,preferabletorefertothetablesforaccuratevalues.Itshouldbenotedthatenthalpyvaluesgiven in tables are not absolute values. These are simple changes in values from the reference state. Itvalues of enthalpy will be positive and below the reference state values of enthalpy if given will benegative. A similar situation arises with temperature measurements. It should be noted that withvapours,otherthansteam, tablesarepreparedhaving theirownreferencestates.

LatentHeatofVaporization:

It is denoted by the letter h_{fg}in steam tables. It is the quantity of heat required to convert 1 kg of waterat saturation temperature for a given pressure to one kg of dry saturated steam, at that pressure. Thevalue of latent heat of vaporization decreases as the pressure increases and it becomes zero when thecritical pressureisreached.

The enthalpy of a vapour depends on how the vapour is heated. The enthalpy given in the tables is forheatingatconstantpressure.

$H_{sat}=h_g=h_f+h_{fg}$.

EnthalpyofSteam:

EnthalpyofWetSteam:

If the dryness fraction of steam is known, with the help of steam tables we can getthevalue oftotalheatfor wetsteam bythe formula givenbelow:

$H_{wet}=h_f+xh_{fg}$

where H_{wet} =enthalpyof1 kg ofwetsteam h_f

=sensible heatof1 kg ofsteam

x=drynessfraction ofsteam

and h_{fg}=enthalpyofvaporization1 kg ofdrysaturated steam.

EnthalpyofSuperheatedSteam:

From dry saturated condition a vapour receives superheat and its temperature rises above saturationtemperature t_{sat}. It has now entered the superheat phase. The enthalpy added during the superheatphase is the superheat enthalpy. The total enthalpy of superheated vapour will be the sum of theenthalpyofdrysaturatedvapourandthesuperheatenthalpy.

When steam is superheated, its temperature is known and when its pressure isknown the enthalpy of 1 kg of steam can be obtained by the use of the formula givenbelow:

$H_{sup}=h_f+h_{fg}+Cp(t_{sup}–t_{sat})$

where H_{sup} = enthalpy of 1 kg of superheated

steamh_f=sensible heatof1kg ofsteam

h_{fg}=enthalpyofvaporization1kgofdrysaturatedsteam

C_p = mean specific heat of superheated steam at constant

pressuret_{sup}=temperatureofsuperheatedsteam

and t_{sat} = saturation temperature corresponding to the pressure of steam

generation.Sinceweknowthat-

$h_g=h_f+h_{fg}$

where h_g is the enthalpy of one kg of dry saturated steam, the above formula can be written as$H_{sup}=h_g+C_p(t_{sup}–t_{sat})$.

The difference (t_{sup} – t_{sat}) is called the degree of superheat, e.g., steam at a pressure of 10 bar has asaturation temperature of 179.9°C and if the temperature of steam is 200°C the degree of superheat is200–179.9=20.1°C.

The value of mean specific heat of superheated steam C_p depends upon the degree of superheat and thepressure of steam generation. The average value of C_p for superheated steam is 2.0934 kJ/kg-K.

ThevaluesofhforagivenvalueofpressurePandtemperaturet_{sup}.

3.5 UseofsteamtableandMollierchartforunknown properties:

SteamTables

Extensivepropertiesatsaturatedliquidandsaturated vaporstate

In steam tables, extensive properties at saturated liquid and at saturated vapor for 1 kg of liquid/vaporare given as shown in Table 21.1(a) and Table 21.1(b). In Table 21.1(a) these properties are listed withreferencetosaturation temperatureandinTable21.1(b)withreferencetosaturationpressure.
Therefore, it is more convenient to use Table 21.1(a) when temperature is given and Table 21.1(b) whenpressure is given. In both the tables, the values of specific volume (v_f), enthalpy (h_f), and entropy (s_f) ofwaterinsaturatedliquidstateandvaluesofspecificvolume(v_g),enthalpy(h_g),andentropy(s_g)ofsteamin saturated vapor state are directly noted down. The values of internal energy (u_f) of water in saturatedliquid state and values of internal energy (u_g) of steam in saturated vapor state are calculated by usingfollowingrelations.

$u_f=h_f-pv_f$ and $u_g=h_g-pv_g$

Extensivepropertiesofwetsteami.e.intheliquid+vaporregion

Forwetsteam, thevaluesofspecificvolume(v),internal energy(u),enthalpy(h),andentropy(s)arecalculatedwiththefollowingrelations.

$v=x.v_g+(1-x).v_f$

or $v=v_f+x.v_{fg}$ where $v_{fg}=v_g-v_f$

For substances such as water, at pressures far below the critical point, the specific-volume (v) equationsmayoftenbesimplifiedto

$v=x.v_g$

because v_f isverysmall incomparisonto v_g.Thisisnot ofcoursepermissiblewhenxisverysmall.

$h=x.h_g+(1-x).h_f=h_f+x.h_{fg}$ where h_{fg}(Latentheatofevaporation)=(h_g-h_f)

$u=h-p.v$

$s=x.s_g+(1-x).s_f=s_f+x.s_{fg}$ where $s_{fg}=s_g-s_f$

Intheaboveequations,all thepropertiesofwaterinsaturatedliquidstateandsteaminsaturatedvaporstate are found as discussed in the previous section of “Extensive properties at saturated liquid andsaturatedvaporstate”.

Extensivepropertiesinsuperheatedvaporstate(vaporregion)

The properties of superheated steam are given as shown in Table 21.2 (a, b, c) separately. They dependnot only on pressure but also on the superheating temperature T_{sup}. The values of specific volume ofsuperheated steam (v_{sup}), enthalpy of superheated steam (h_{sup}), and entropy of superheated steam (s_{sup})aredirectlynoteddownfromTable21.2(a), Table21.2(b)andTable21.2(c),respectively.Thevaluesofinternalenergyofsuperheatedsteam(u_{sup})iscalculatedbyusingthefollowingrelation.

$u_{sup}=h_{sup}-pv_{sup}$

Steam tablesforsaturatedwaterandsteam(temperature)

Tempera-ture in °C	Absolute Pressure in bar	Specific Volume in m³/kg		Specific Enthalpy in kJ/kg			Specific Entropy in kJ/kg °K			Tempera-ture in °C
		Water	Steam	Water	Evaporation	Steam	Water	Evaporation	Steam	
(t)	(p)	(v_f)	(v_g)	(h_f)	(h_{fg})	(h_g)	(s_f)	(s_{fg})	(s_g)	(t)
0	0.006 11	0.001 000	206.16	0.0	2 501.6	2 501.6	0.000	9.158	9.158	0
1	0.006 57	0.001 000	192.61	4.2	2 499.2	2 503.4	0.015	9.116	9.131	1
2	0.007 06	0.001 000	179.92	8.4	2 496.8	2 505.2	0.031	9.074	9.105	2
3	0.007 58	0.001 000	168.17	12.6	2 494.5	2 507.1	0.046	9.033	9.079	3
4	0.008 13	0.001 000	157.27	16.8	2 492.1	2 508.9	0.061	8.592	9.053	4

Table 21.1 (b). Steam tables for saturated water and steam (pressure)

Absolute Pressure in bar	Tempera-ture in °C	Specific Volume in m³/kg		Specific Enthalpy in kJ/kg			Specific Entropy in kJ/kg °K			Absolute Pressure in bar
		Water	Steam	Water	Evaporation	Steam	Water	Evaporation	Steam	
(p)	(t)	(v_f)	(v_g)	(h_f)	(h_{fg})	(h_g)	(s_f)	(s_{fg})	(s_g)	(p)
0.006 1	0.000	0.001 000	206.16	0.0	2 501.6	2 501.6	0.000	9.158	9.158	0.006 1
0.010	6.980	0.001 000	129.21	29.3	2 485.0	2 514.4	0.106	8.871	8.977	0.010
0.015	13.01	0.001 001	88.351	54.6	2 470.8	2 525.4	0.195	8.635	8.830	0.015
0.020	17.51	0.001 001	67.012	73.5	2 460.2	2 533.6	0.261	8.464	8.725	0.020
0.025	21.09	0.001 002	54.340	88.4	2 451.8	2 540.2	0.312	8.333	8.645	0.025
0.030	24.10	0.001 003	45.670	101.0	2 444.6	2 545.6	0.354	8.224	8.578	0.030

Steamtablesforsaturatedwaterandsteam(pressure)

Absolute Pressure in bar	Tempera-ture in °C	Specific Volume in m³/kg		Specific Enthalpy in kJ/kg			Specific Entropy in kJ/kg °K			Absolute Pressure in bar
		Water	Steam	Water	Evaporation	Steam	Water	Evaporation	Steam	
(p)	(t)	(v_f)	(v_g)	(h_f)	(h_{fg})	(h_g)	(s_f)	(s_{fg})	(s_g)	(p)
0.006 1	0.000	0.001 000	206.16	0.0	2 501.6	2 501.6	0.000	9.158	9.158	0.006 1
0.010	6.980	0.001 000	129.21	29.3	2 485.0	2 514.4	0.106	8.871	8.977	0.010
0.015	13.01	0.001 001	88.351	54.6	2 470.8	2 525.4	0.195	8.635	8.830	0.015
0.020	17.51	0.001 001	67.012	73.5	2 460.2	2 533.6	0.261	8.464	8.725	0.020
0.025	21.09	0.001 002	54.340	88.4	2 451.8	2 540.2	0.312	8.333	8.645	0.025
0.030	24.10	0.001 003	45.670	101.0	2 444.6	2 545.6	0.354	8.224	8.578	0.030

Steamtablesforspecificvolumeofsuperheatedsteam

Absolute Pressure in bar (p)	Saturation Temperature in °C (t_s)	Specific Volume (v) in m³/kg at Various Temperatures in °C										
		100	150	200	250	300	350	400	500	600	700	800
0.02	17.5	86.08	97.63	109.2	120.7	132.2	143.8	155.3	178.4	201.5	224.6	247.6
0.04	29.0	43.03	48.81	54.58	60.35	66.12	71.89	77.66	89.20	100.7	112.3	123.8
0.06	36.2	28.68	32.53	36.38	40.23	44.08	47.93	51.77	59.47	67.16	74.85	82.54
0.08	41.5	21.50	24.40	27.28	30.17	33.06	35.94	38.83	44.60	50.37	56.14	61.91
0.10	45.8	17.20	19.51	21.83	24.14	26.45	28.75	31.06	35.68	40.30	44.91	49.53

Steamtablesforenthalpyofsuperheatedsteam

Absolute Pressure in bar (p)	Saturation Tempurature in °C (t_s)	Enthalpy (h) in kJ/kg at Various Temperatures in °C										
		100	150	200	250	300	350	400	500	600	700	800
0.02	17.5	2 688.5	2 783.7	2 880.0	2 977.7	3 076.8	3 177.5	3 279.7	3 489.2	3 705.6	3 928.8	4 158.7
0.04	29.0	2 688.3	2 783.5	2 879.9	2 977.6	3 076.8	3 177.4	3 279.7	3 489.2	3 705.6	3 928.8	4 158.7
0.06	36.2	2 688.0	2 783.4	2 879.8	2 977.6	3 076.7	3 177.4	3 279.6	3 489.2	3 705.6	3 928.8	4 158.7
0.08	41.5	2 687.8	2 783.2	2 879.7	2 977.5	3 076.7	3 177.3	3 279.6	3 489.1	3 705.5	3 928.8	4 158.7
0.10	45.8	2 687.5	2 783.1	2 879.6	2 977.4	3 076.6	3 177.3	3 279.6	3 489.1	3 705.5	3 928.8	4 158.7

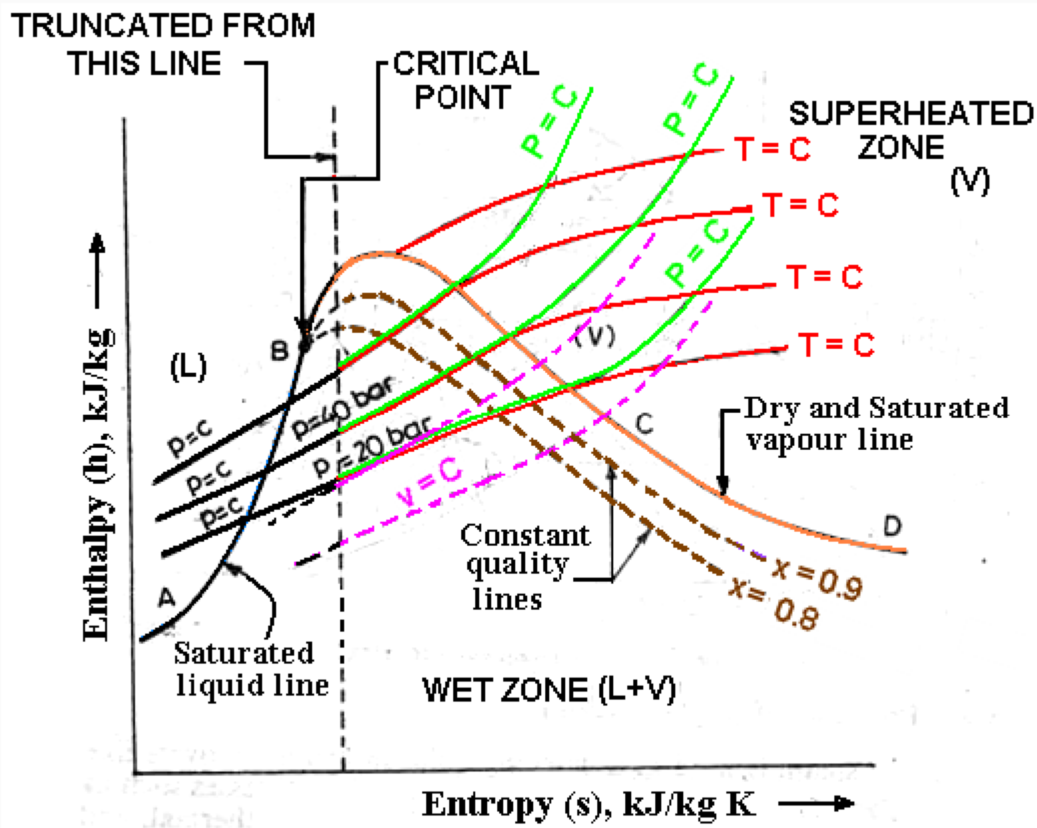
Steamtablesforentropyofsuperheatedsteam

Absolute Pressure in bar (p)	Saturation Temperature in °C (t_s)	Entropy (s) in kJ/kg °K at Various Temperatures in °C										
		100	150	200	250	300	350	400	500	600	700	800
0.02	17.5	9.193	9.433	9.648	9.844	10.025	10.193	10.351	10.641	10.904	11.146	11.371
0.04	29.0	8.873	9.113	9.328	9.524	9.705	9.874	10.031	10.321	10.585	10.827	11.051
0.06	36.2	8.685	8.925	9.141	9.337	9.518	9.686	9.844	10.134	10.397	10.639	10.864
0.08	41.5	8.552	8.792	9.008	9.204	9.385	9.554	9.711	10.001	10.265	10.507	10.731
0.10	45.8	8.449	8.689	8.905	9.101	9.282	9.450	9.608	9.898	10.162	10.404	10.628

MollierorEnthalpy-Entropy(h-s)diagram:

The Mollier diagram is a is plot of enthalpy (h) versus entropy (s) as shown in Fig.It is also known as theh-s diagram. This diagram has a series of **constant temperature lines**, **constant pressure lines**, **constantquality lines**, and **constant volume lines**. The Mollier diagram is used only when quality is greater than50% and for superheated steam. For any state, atleast two properties should be known to determinetheotherunknownpropertiesofsteamatthatstate.

The commercially available Mollier diagram is truncated from a point beyond the critical point i.e. itshows only a portion of this diagram which is drawn in colors. In such truncated diagram property ofliquidcannotberead.



TRUNCATED FROM THIS LINE
CRITICAL POINT
P = C
P = C
P = C
SUPERHEATED ZONE
(V)
T = C
T = C
T = C
T = C
(L)
B
(V)
p=c
p=c
p=c
p=40 bar
p=20 bar
v = C
C
Dry and Saturated vapour line
D
Constant quality lines
x = 0.9
x = 0.8
A
Saturated liquid line
WET ZONE (L+V)
Enthalpy (h), kJ/kg
Entropy (s), kJ/kg K

3.6 Flowandnonflowprocessesof vapour:

Theboundaryofanon-flowprocesscanbefixed,movingorimaginary.
These are compression and expansion processes on gases in a cylinder with complete leak proof.
Inthesethereisonlyenergytransferwithzeromasstransfer.
Thesenonflowprocessescan bethefollowings:

(i) constant

pressureprocessWhileheatingatco

nstantpressuredU =δq—pdv

Inanisobariccompression,heatisstoredintheformofenthalpy.(notet

heuseofδanddintheequation).

δisusedwithheatsuppliedorrejected

dforchangeinaquantitysuchasvolumeorinternal energy

(ii) constantvolumeprocess

δq=dU sinceδW=0

During a iso-choric (Constant volume) process, work done is zero and the total energy changesintointernal energy

(iii) constanttemperatureprocess
δq=δWsincedU =0.
(iv) reversibleadiabaticprocess
Duringareversibleadiabaticprocess,thereisnofriction.
No heat is supplied or rejected. Therefore δW = dU since
δQ=0Aprocesswithnoheatgainorheatlossisanadiabatic process.
(v) poly-tropicprocess
Duringapoly-tropicprocess,δQ=δW–worklostinfriction
pV^n=C isamathematicalformofapoly-tropicprocessinwhichnoparameterisconstant.
(vi) constantinternalenergyprocess

Whengravity,magnetic,electrical,motionandcapillaryeffectsarenegligible.Thenthetotalenergy(E)isequalt otheinternal energy(U).

FlowProcesses
Flowprocessisoneinwhichthereisenergyandmasstransferacrosstheboundaryofthesystem.Allflowsy stemsareOPENsystemssinceenergyandworkcrosstheirboundaries.
Followingaretheflowprocesses.
(i) frominletofcompressortoitsoutletinarefrigeration system

work Done in a poly-tropic compression (Open system)$W=\int -vdp=n(p_2v_2-p_1v_1)/(n-1)$
workDoneinapoly-tropiccompression(closedsystem)

$W=\int pdv=(p_2v_2-p_1v_1)/(n-1)$
Workdoneinanopensystemisntimestheworkdoneinaclosedsystem

(ii) Throughanozzle
(iii) flowacrossaturbine
(iv) *Flowinapipe*

Flowprocessesareoftwo

types.SteadyFlowSystem

When properties are constant with respect to time it is called a steady flow systems. All theexperimentaldataisrecordedundersteadyflowconditions.Steadyflowenergyequationisaheatbalancefo rthesystem.

NonSteadyFlowSystem

When properties vary with respect to time it is called a non-steady flow systems. Nothing useful can befoundunderunsteadyflowconditions.

3.7 RepresentationofPV,TS&HSdiagram:

ConstantPressureProcess:

(a) **p-v,T-s,andh-sRepresentation**.Assumethatsteamundergoesaconstantpressureheatingprocess from its initial state to final state.Let the initial condition of steam be in the wetregion as point 1 at pressure $p_1$having dryness fraction $x_1$and the final condition in thesuperheat region as point 2 at pressure p_2(= p_1) and super heating temperature $t_{sup,2}$asshowninFig.22.1onp-v, T-sandh-sdiagrams.

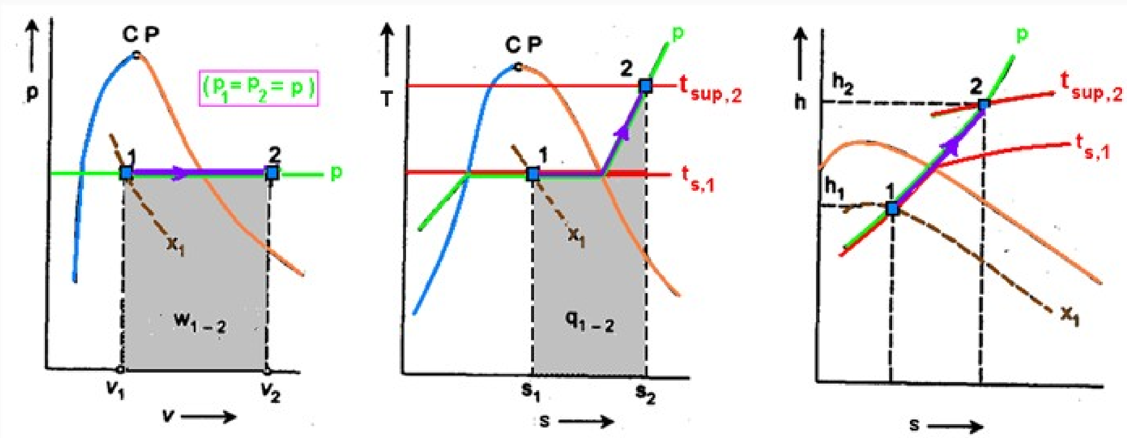


Fig. 22.1. Constant pressure heating process of steam

ConstantVolumeProcess:

(a) p-v, T-s and h-s

Representation: Assume that steamundergoesaconstantvolumecoolingprocessfromtheinitialconditionofsu

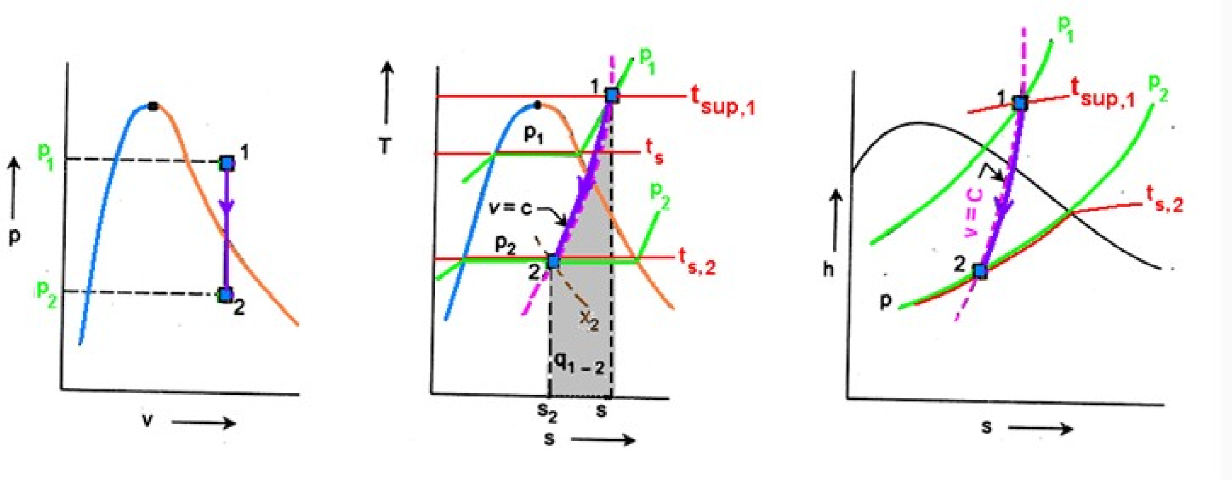


Fig. 22.2. Constant volume cooling process of steam

IsothermalProcess:

a)p-v, T-s and h-s Representation: Assume that steam undergoes an isothermal expansion processfrom the initial condition of wet steam at pressure $p_1$and dryness fraction $x_1$to the finalcondition

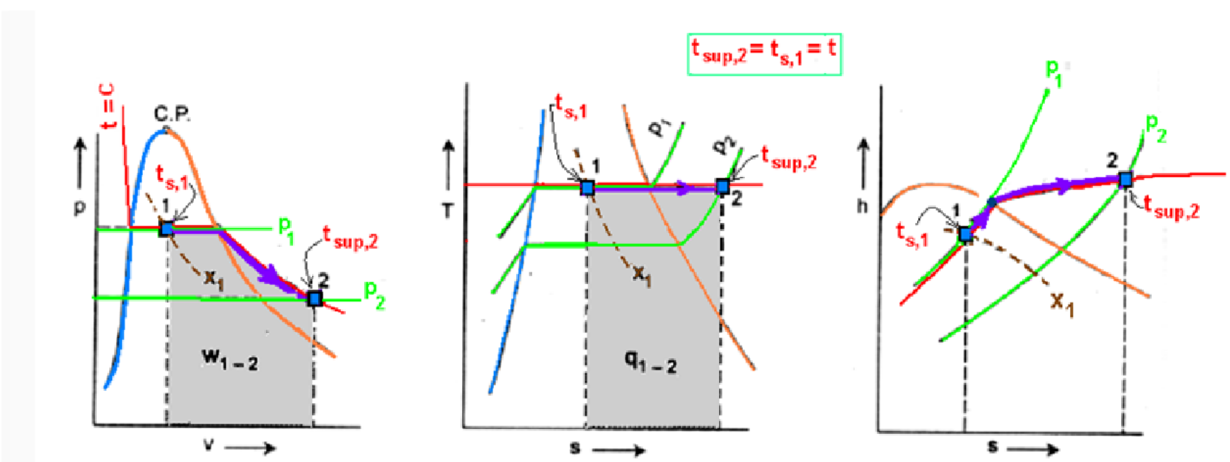


Fig. 22.4. Isothermal process

PolytropicProcess:

(a) p-v Representation: Assume that steam undergoes a polytropic expansion process following the law$pv^n = c$ from pressure p_1 to p_2. It is to be noted that steam does not behave as perfect gas obeying pv

ThrottlingProcess:

As described earlier, the throttling process involves passing of a higher pressure fluid through a narrowconstriction resulting in reduction in pressure and temperature, increase in specific

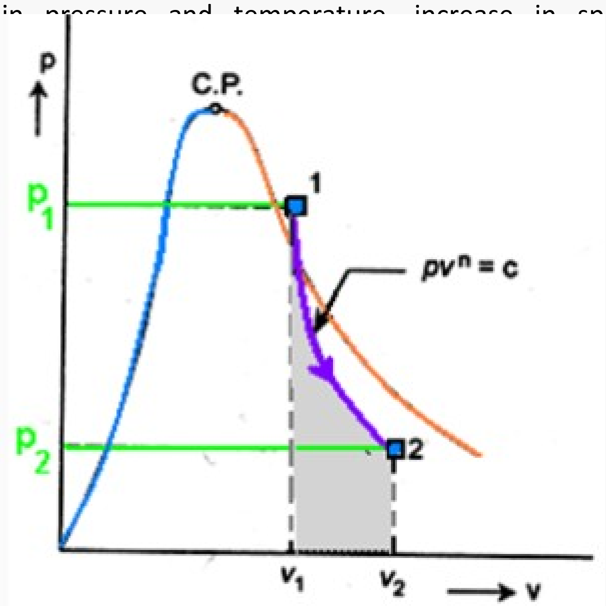


Fig. 22.5. Polytropic process

Theprocessisadiabaticandnoheatflowfromortothesystembutitnotreversible.

Examples: Steamstopvalveandthrottlevalveinstalledattheentryofsteamturbineinpowerplants.Whenflowof steamtakesplacethroughthesevalves,throttlingprocessoccurs.

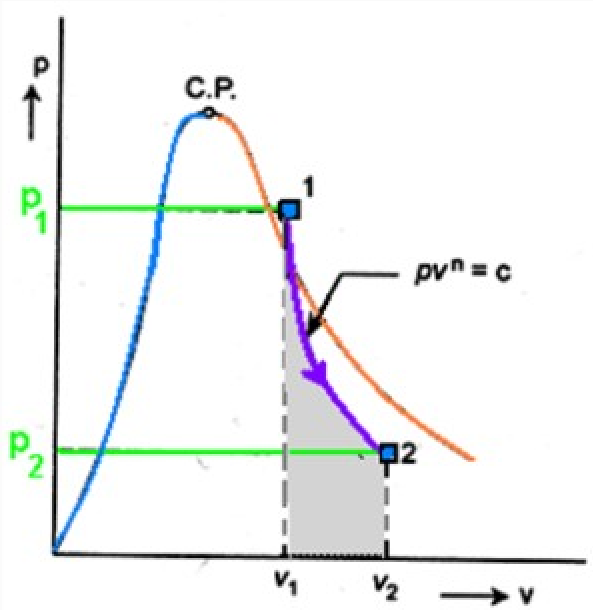


Fig. 22.5. Polytropic process

***3.8* Simplenumerical:**

Problem 1: Find the enthalpy of 1 kg of steam at 12 bar when,

- (a) steam is dry saturated,
- (b) steam is 22% wet and
- (c) superheated to 250°C.

Assume the specific heat of the superheated steam as 2.25 kJ/kgK

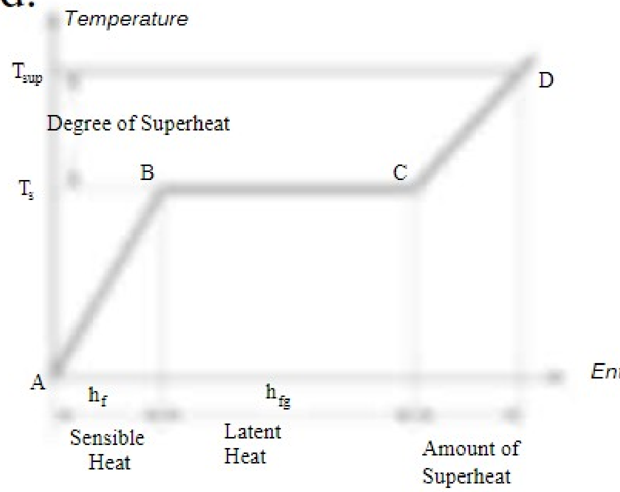
- Solution: From the steam tables at 12 bar, the following values are noted.

T_{sat} = 188°C

h_f = 798.43 kJ/kg

h_{fg} = 1984.3 kJ/kg

Now,



(a) Enthalpy of Dry saturated Steam:

$$hg = h_f + h_{fg}$$

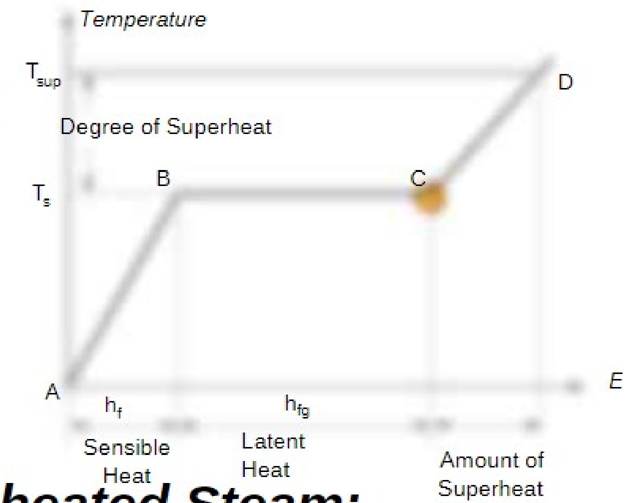
$$= 798.43 + 1984.3 \text{ kJ/kg}$$

$$= 2782.73 \text{ kJ/kg}$$

- ***(b) Enthalpy of Wet Steam:***

When the steam is 22% wet, it will be 78% dry. Therefore the dryness fraction x = 0.78

$$h_x = h_f + x\, h_{fg}$$
$$= 2346.18 \text{ kJ/kg}$$



- ***(c) Enthalpy of Superheated Steam:***
- $h_{sup} = h_f + h_{fg} + C_{sup}(T_{sup} - T_{sat})$
- $= 2922.23 \text{ kJ/kg}$

Questionsforexercise/assignment:

Shortquestions

1. **Diffferencebetweengasandvapour?**
2. **Definesensibleheat?**
3. **Definelatentheat?**
4. **Define**

enthalpy?Long
questions

1. **Brieflyexplainformationofsteam?**

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4.SteamGenerator

4.1 ClassificationandtypesofBoiler

TYPESOFBOILERS
Theboilerscanbeclassifiedaccordingtothefollowingcriteria.Accordingtoflowofwaterandhot gases.
1.Watertube.

2. Firetube.Inwatertubeboilers,watercirculatesthroughthetubesandhotproductsofcombustionflowove rthesetubes.

In fire tube boiler the hot products of combustion pass through the tubes, which are surrounded, bywater. Fire tube boilers have low initial cost, and are more compacts. But they are more likely toexplosion, water volume is large and due to poor circulation they cannot meet quickly the change insteam demand. For the same output the outer shell of fire tube boilers is much larger than the shell ofwater-tube boiler. Water tube boilers require less weight of metal for a given size, are less liable toexplosion, produce higher pressure, are accessible and can response quickly to change in steamdemand. Tubes and drums of water-tube boilers are smaller than that of fire-tube boilers and due tosmaller size of drum higher pressure can be used easily. Water-tube boilers require lesser floor space.Theefficiencyofwater-tubeboilersismore.

Watertubeboilersareclassifiedasfollows.1.Horizontalstraighttubeboilers

(a)Longitudinaldrum(b)Cross-drum.

2. Benttubeboilers

(a)Twodrum(b)Threedrum(c) Lowheadthreedrum(d)Fourdrum.

3. Cyclonefiredboilers

Variousadvantagesofwatertubeboilersareasfollows.

(i) Highpressureoftheorderof140kg/cm2canbeobtained.
(ii) Heatingsurfaceislarge. Thereforesteamcanbegeneratedeasily.
(iii) Largeheatingsurfacecanbeobtainedbyuseoflargenumberoftubes.
(iv) Because of high movement of water in the tubes the rate of heat transfer becomes largeresultingintoagreaterefficiency.

Firetubeboilersareclassifiedasfollows.l.Externalfurnace:

(i) Horizontalreturntubular
(ii) Shortfirebox

(iii) Compact.

2.Internalfurnace:

(i) Horizontaltubular

(a)Shortfirebox(b) Locomotive(c)Compact(d)Scotch

(ii) Verticaltubular.

(a)Straightverticalshell,verticaltube(b)Cochran(verticalshell)horizontaltube.

Variousadvantagesoffiretubeboilersareasfollows.(i)Lowcost(ii)Fluctuation

sofsteamdemandcanbemeteasily

(iii) Itiscompactinsize.

Accordingtopositionoffurnace.

(i) Internallyfired(ii)Externallyfired

In internally fired boilers the grate combustion chamber are enclosed within the boilershellwhereasincaseofextremelyfiredboilersandfurnaceandgrateareseparatedfromthe boilershell.

4.2 ImportanttermsforBoiler

Followingareimportanttermsusedinsteamboilers:

1. BoilerShell
2. CombustionChamber
3. Grate
4. Furnace
5. Heatingsurface
6. Mountings
7. Accessories

4.3 ComparisonbetweenFireTubeandWaterTubeBoiler

Sr. No.	Fire tube boiler	Water tube boiler
1	Hot flue gases are passed through the one or more tubes that heat the water in a container	Water is passed through the tubes which is heated by hot gases
2	initially, it takes time to start steam generation after firing the boiler	It takes less time for steam generation after firing the boiler
3	rate of steam generation is lower	rate of steam generation is higher
4	This boiler generator low-pressure steam up to 20 bar.	This boiler generates high-pressure steam up to 200 bar.
5	Suitable for heating in chemical processes and also used as process steam	Suitable for high capacity power generation
6	It has less risk of accidents	Higher risk of an accident because of higher operating pressure
7	The initial cost is less	Higher initial cost
8	The size of the boiler is larger for the same rate of steam generation.	the size of the boiler is small as compared to fire tube boiler for the same rate of steam generation
9	It takes more floor area	It takes less floor area
10	it requires less skilled operators for its operation	It requires a skilled operator for its operation

4.4 DescriptionandworkingofCochranBoiler

CochranBoiler

Cochran Boiler is a multi-tubular vertical fire tube boiler having a number of horizontal firetubes.Itisthemodificationof asimpleverticalboiler wheretheheatingsurface hasbeen increased by means of a number of fire tubes. The efficiency of this boiler is much better than thesimpleverticalboiler.

PartsofCochranBoiler:

ACochranBoilerisconsistedoffollowingparts:

1. Shell
2. Grate
3. CombustionChamber
4. Firetubes
5. Firehole
6. Firebox (Furnace)
7. Chimney
8. ManHole
9. Fluepipe
10. FireBrickLining
11. FeedCheck Valve
12. BlowOffValve
13. AshPit
14. SmokeBoxDoor
15. Anti Priming Pipe
16. Crown
17. PressureGauge
18. SafetyValve
19. Water LevelIndicator
20. WaterLevelGauge
21. Fusible Plug
22. Stop Valve

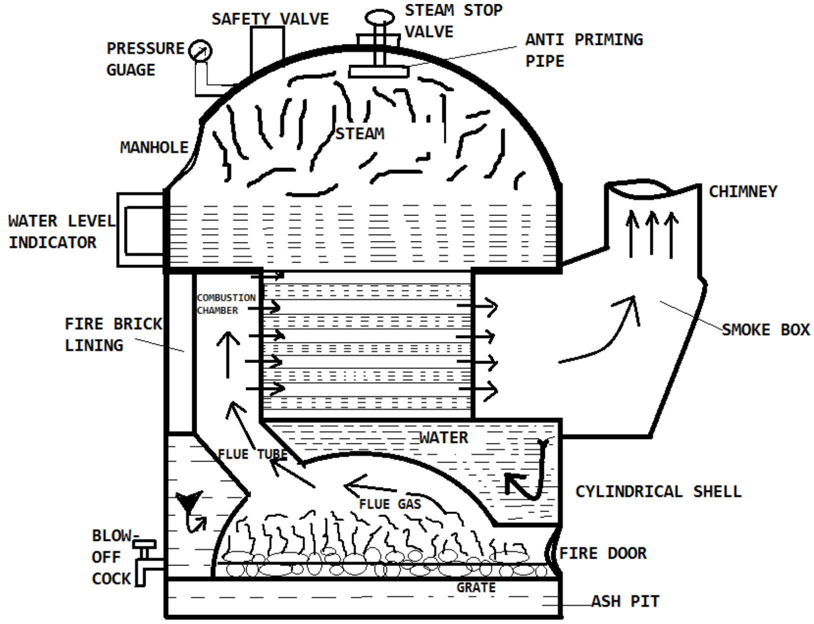


FIG: COCHRAN BOILER

1Shell:

The main body of the boiler is known as a shell. It is hemispherical on the top, where space is providedforsteam.

Thishemispherical top givesa highervolumeto arearatio whichincreasesthe steamcapacity.

#2Grate:

In the grate section, solid fuel is stored, it is designed so well that air can easily flow through it, and alsothe ashesfall fromthegrate quite easily.Inthissection,thefireisplaced.

#3CombustionChamber:

It is lined with fire bricks on the side of the shell to prevent overheating of the boiler. Hot gases enter thefire tubes from the flue pipe through the combustion chamber. The combustion chamber is connected tothefurnace.

#4FireTubes:

There are various fire tubes whose one end is connected to the furnace and other to the chimney.Sevaralhorizontal firetubesare provided toincreased the heating surface.

#5FireHole:

Thesmallholeisprovided atthebottomofthe combustionchamberto placefuel isknown asafire hole.

#6FireBox(Furnace):

Itworksasa mediator offiretubesandcombustion chamber.

Itisalsodome-shapedliketheshellsothatthegasescanbedeflectedback tilltheyarepassedoutthrough theflue pipetothe combustion chamber.

#7Chimney:

Itisprovidedfor theexitofflue gasesto theatmospherefromthesmokebox.

#8ManHole:

Itisprovidedfortheinspectionand repair oftheinteriorofttheboilershell.

#9FluePipe:

Itisashortpassage connectingthefireboxwiththe combustionchamber.

#10FireBrickLining:

ItisaspecialtypeofbricklinguseinCochranBoilertoreduce theconvectionofheatfrom theoutersurface ofthe boiler.FireBrickisgenerallymade offireclay.

#11FeedCheckValve:

Itisused tocontrol theflowofwaterinside the boiler,italso helpstorestrictthe backflowofwater.

#12BlowOffValve:

Itisused to blowoffthe settledown impurities,mud,and sedimentspresentinthe boiler water.

#13AshPit:

Itisachamberinsidea boilerwhere ashesarestored.

#14SmokeBoxDoor:

Itisusedto cleanthe smokeboxdepositsmaterials.

#15AntiPrimingPipe:

Sometimes water droplets come out with the steam, so to prevent the droplets from carried out by thesteamtheAntiPrimingPipeisused.

#16Crown:

Itishemisphericaldome-shapedsectionof aboiler, whereburningof fuelhappens.

#17PressureGauge:

Itmeasuresthepressureofsteam insidetheboiler.

#18SafetyValve:

Itblowsofftheextrasteamwhenthesteampressureinsidetheboilerreachesabovesafetylevel.

#19WaterLevelIndicator:

Thepositionofthewater levelintheCochranboilerisindicatedbythewater levelindicator.

#20WaterLevelGauge:

Itglasstubefitted outsideoftheboilerto checkthewaterlevelinsidetheboiler.

#21FusiblePlug:

It is one type of safety measure. If the inside temperature of the boiler cross the limit, then for safetypurpose thisFusiblePlugmeltsand thewatercomesintothe boilerfurnace andextinguish thefire.

#22StopValve:

Stopvalveisused totransfersteam to thedesiredlocationwhen itisrequired.Otherwise,itstopsthesteam in the boiler.

WorkingPrincipleofCochranBoiler:

TheCochran boilerworksassame asotherfiretube boiler.

First,Thecoal isplacedatthegratethroughthefirehole.

Then the air is entering into the combustion chamber through the atmosphere and fuel is sparked throughfirehole.

Then flue gases start flowing into the hemispherical dome-shaped combustion chamber. This flue gasesfurthermovesinto thefire pipes.

Heatisexchangedfromfluegasesto the waterinto thefire tubes.

Thesteamproducecollectedintotheuppersideoftheshellandtakenoutby whentherequiredpressuregenerated.

Theflue gasesnow send to the chimneythrough afireboxwhere itleavesinto theatmosphere.

Now, this process repeats and runs continuously. The steam generates used into the small industrialprocessed.

ApplicationsofCochranBoiler:

TheapplicationofCochranboilerare:

- Varietyofprocessapplicationsindustries.
- Chemicalprocessingdivisions.
- PulpandPapermanufacturingplants.
- Refiningunits.

Besides, they are frequently employed in power generation plants where large quantities of steam(ranging up to 500 kg/s) having high pressures i.e. approximately 16 megapascals (160 bar) and hightemperaturesreaching up to 550°C are generallyrequired.

FeaturesofCochranboiler:

ThesearesomefeaturesofCochranBoiler:

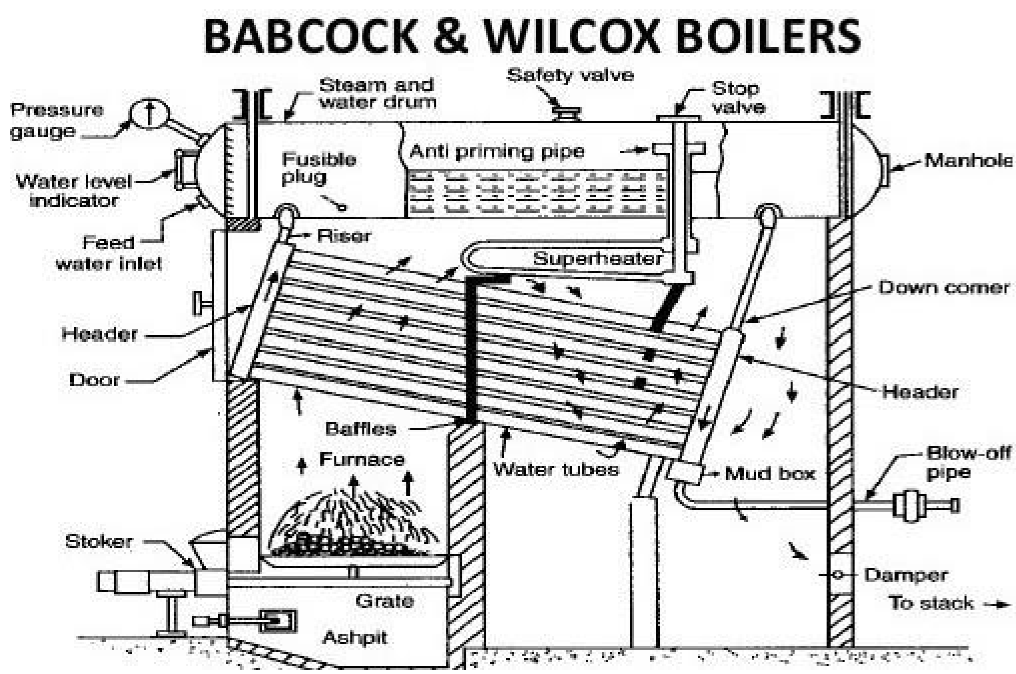
- IntheCochranboiler,anytypeoffuelcanbeused.
- Itisbestsuitablefor smallcapacityrequirements.
- It givesabout70%thermalefficiencywithcoalfiringandabout75%thermalefficiencywithoilfiring.
- The ratio ofthe grateareatothe heating surface areavariesfrom10:1 to25:1.

DescriptionandworkingofBabcockandWilcoxBoiler:

BabcockandWilcoxBoilerParts:

ABabcockandWillcoxBoilerPartsorConstructionconsistsof:

- *Drum*
- *WaterTubes*
- *UptakeandDowntakeheader*
- *Grate*
- *furnace*
- *Baffles*
- *Superheater*
- *Mudbox*
- *InspectionDoor*
- *WaterLevelIndicator*
- *Pressure Gauge*



Drum:

Thisisahorizontalaxisdrumwhichcontainswaterandsteam.

Watertubes:

Water tubes are placed between the drum and furnace in an inclined position (at an angle of 10 to 15degrees) to promote watercirculation.

UptakeandDowntakeHeader:

Thisispresentatthefrontendoftheboilerandconnected tothefrontendofthe drum.Ittransportsthesteam fromthe watertubesto the drum.and

Thisispresentattherear endoftheboilerandconnectsthewater

tubestotherearendofthedrum.Itreceiveswaterfromthe drum.

Grate:

Coalisfedtothegratethroughthefiredoor.

Furnace:

Thefurnaceiskeptbelowtheuptake-header.

Baffles:

Thefire-brick baffles,twoinnumber,areprovidedtodeflectthehotfluegases.

Superheater:

It increases the temperature of saturated steam to the required temperature before discharging it from thesteamstopvalve.

MudBox:

Thisisused to collectthemud presentinthe water.

Mudboxisprovidedatthebottomendofthedown-takeheader.

InspectionDoor:

Inspectiondoorsareprovidedforcleaningandinspectionofthe boiler.

WaterLevelIndicator:

Thewaterlevelindicatorshowsthelevelofwaterwithinthedrum.

PressureGauge:

Thepressuregaugeisusedtocheckthepressureofsteamwithintheboiler drum.

WorkingPrincipleofBabcockandWilcoxBoiler:

The working of Babcock and Wilcox boiler is first the water starts to come in the water tubes from thedrumthroughdowntakeheader withthehelpofaboilerfeedpumpwhichcontinuestofeedthewateragainstthe drumpressure.

The water present in the inclined water tubes gets heated up by the hot flue gases produced by theburningofcoalonthefire grate.

These fuel gases are uniformly heated the water tube with the help of a baffle plate which works deflectthefluesgasuniformthroughoutthetubeswhichabsorbedtheheatingmaximumfrom thefluegases.

As the hot flue gases come in contact with water tubes, It exchanges the heat with heater and convertsintothe steam.

Continuous circulation of water from the drum to the water tubes and water tubes to the drum is thusmaintained.

Thecirculationofwaterismaintainedbyconvectivecurrentandit'sknownasNaturalCirculation.

The Steam generated is moved upward, due to density difference and through the up-take header, it getscollected atthe uppersidein theboilerdrum.

Anti-primingpipeinsidethedrumwhichworksseparatesthemoisturefrom thesteamandsendsit'stothesuperheater.

The superheater receives the water-free steam from an anti-priming pipe. It increases the temperature ofthesteamtothedesired levelandtransfersitto themain steamstopvalveoftheboiler.

Thesuperheatedsteamstopvalveiseither collectedinasteam drumorsendit'sinsidethesteamturbineforelectricitygeneration.

ApplicationsBabcockandWilcoxBoiler:

The main application Babcock and Wilcox boiler to produce **high-pressure steam in power generationindustries**.

4.6BoilerMountingsandaccessories

BoilerMountings

Thesearethefittings,whicharenecessarilymountedontheboileritselfandmandatorilyrequiredforthesafeandproperoperationofboiler.Variousboilermountingsarebeingdiscussedhereonebyone.

1 Waterlevelindicator

Function

Water level indicator is fitted outside the boiler shell to indicate the water level in the boiler through aglass tube. In any type of boiler, water should remain at the designed level. If the water falls below thelevel due to change of phase into steam and simultaneously fresh water does not fill in by some reason,thehotsurfacemayexposetosteamonlyandoverheat.Thisisbecausetheheattransfersco-efficientof steamis very less as compared to water.Due to overheat, damage of tube surface may occur.Toavoid this situation, level of water in the boiler needs to be constantly monitored & maintained by boileroperatorbykeepingwatchonwaterlevel indicator.

Construction

As shown in the , two horizontal tubes made of gun metal extend from the boiler shell in such a waythat top one is connected to steam space and bottom one is connected to water space of the boiler.These are connected at the other end by a vertical glass tube contained in a hollow casting in such away that water and steam come out in the glass tube and their interface is visible through it. Each gunmetal tube is also provided with a cock to control the flow of water/steam to the glass tube. One draincock is fitted atthe bottom for cleaning purpose.The horizontal metal tubes also contain one metalball each which normally rests on a hemispherical groove in the tubes. In case the water/steam rushwith high speed as may be if glass tube breaks by accident, this ball lifts up from its normal position andblockaholewhichconnectsthemetaltubewithglasstubeandstopstheflow.

Working

Working of water level indicator or water gauge is very simple. When the cocks are opened, boilingwater and steam from the boiler shell flow into the hard glass tube and maintain the same level as in theboiler which is visible to operator. When the water level falls down beyond a safe limit, operator mayswitchonthefeedpumptofillmorewaterintheboilershell.Inthewaterandsteampassagesinthegunmetaltubes,ametalballrestinthecavitymadeinthepassage.Incaseofbreakageofglasstubesby accident, water and steam contained at high pressure in the boiler rush with high speed towardsbroken glass tube due to large pressure difference between inside and outside of boiler. Due to this, theball resting in the cavity made in the passage lifts and rushes towards the end of gun metal tube andblocks the passage of steam or water flow. Then immediately the cock can be closed and glass tube canbereplacedsafely.

2 PressureGauge

Function

A pressure gauge is used to indicate the pressure of steam in the boiler. It is generally mounted on thefront top of the boiler. Pressure gauge is of two types as (i) Bourdon Tube Pressure Gauge (ii) Diaphragmtype pressure gauge. Both these gauges have a dial in which a needle moves over a circular scale undertheinfluenceofpressure.Atatmosphericpressureitgiveszeroreading.Somegaugesindicateonlythe positive pressure but some are compound and indicate negative pressure or vacuum also. Looking at thegauge, boiler operator can check the safe working pressure of the boiler and can take necessary steps tokeep the pressure within safe limits. If pressure increases and crosses the safe limit due to any reason,the boiler shell material may fail and it can burst causing damage to life and property. Thus it is veryimportanttoconstantlymonitorpressureinaboilerwiththehelpofpressuregauge.

Construction&working

Abourdontubepressuregaugeisnormallyused,theconstructionofwhichisshowninthe

The bourdon tube is an elliptical spring material tube made with special quality bronze. One end of tubeis connected to gauge connector and other end is closed and free to move. A needle is attached to thefree end of tube through a small gear mechanism. With the movement of tube under pressure, needlerotates on the circular scale. The movement of tube & hence needle is proportionate to the rise inpressureandsocalibratedwithscale.

The pressure gauge connector is attached to the boiler shell through a U-tube siphon and three waycocks. In the U-tube, condensate remains filled and so live steam does not come in direct content ofbourdon tube but it push or exert pressure on the condensate which further stretch bourdon tube.Steam is not allowed a direct contact with the gauge due to high temperature effect on the pressurerecording.Thethreewaycockisusedtogiveanentireconnectionforinspector�spressuregauge.

3 Springloadedsafetyvalve

Function

Spring loaded safety valve is a safely mounting fitted onthe boiler shelland isessentially required onthe boiler shell to safeguard the boiler against high pressure. It is a vital part of boiler and always be ingood working condition to protect the boiler from bursting under high pressure and so to save life andproperty.

Construction

As shown in figit consists of two openings or valve seats which are closed by two valves attached to asingle lever. The lever is pivoted at one end and attached to a spring at the middle. The spring is fixed atthe bottom end with the overall body of valve. Due to spring force, the liver and hence valves remainseated on the valve seats and do not allow the steam to escape. When the pressure force of steamexceeds the spring pulling force, valve & lever are lifted and steam escape thus decreasing the pressurebelow the safe limit. On decreasing the pressure valves sit again on their seats and thus stop the steamflowfromtheboiler. Sometimes,thelevermayalsobeliftedmanuallytoreleasesteamifrequired.

4 Fusibleplug

Function

Thefunctionoffusibleplugistoprotecttheboilerfromdamageduetooverheatingofboilertubesbylowwaterlevel
.

Construction

As shown in Fig., it is simply a hollow gun metal plug screwed into the fire box crown. This hollow gunmetal plug is separated from the main metal plug by an annulus fusible material. This material isprotectedfromfiresidebymeansofaflange.

Working

When the water in the boiler is at its normal level, fusible plug remains submerged in water and itstemperature does not exceed its melting temperature, because its heat is transferred to water easily. Ifunder some unwanted condition, water level comes down to unsafe limit; fusible plug is exposed tosteam in place of water. On the other side it is exposed to fire. So its temperature exceeds its meltingpoint due to very low heat transfer to steam and it melts down. Immediately steam and water underhighpressurerushtothefireboxandextinguishthefire.

5 Blow-off-cock

Function

It is a controllable valve opening at the bottom of water space in the boiler and is used to blow off somewater from the bottom which carries mud or other sediments settled during the operation of boiler. It isalsousedtocompletelyemptythewaterwhentheboiler isshutoffforcleaningpurposeorforinspectionandrepair.

Constructionandworking

The construction is as shown in **fig.** It has a casing having a passage with one side flange to connect withboiler shell. The passage is blocked by a cone shape plug having a cross rectangular hole. Sealing is madewith a top and bottom asbestos packing filled in grooves on plug. The shank of the plug passes through agland and stuffing box in the cover. On the top portion of the shank a box spanner can be fitted to rotatethe shank and plug by 90^0 to either open or close the blow-off-cock. The working is also clearly visible onplayingtheanimation.

6 Feed-check-valve

Function

The feed check valve is fitted in the feed water line of the boiler after the feed pump. Its function is toallow the water to flow in the boiler when the discharge pressure of feed pump is more than the insidesteam pressure of boiler and prevent the back flow in case the feed pump pressure is less than boilerpressure.Feedcheckvalveisfittedslightlybelowthenormalwaterlevel intheboiler.

Construction

The construction of feed check valve is as shown in fig 25.6 In the casing of valve there is a check valvewhich can move upor downon its seatunderthe pressure of water. When supply pressure of feedwater acting at the bottom of check valve is more, valve lifts up and allows the water to fill in the boiler.Whensupplypressuredropsbystoppingoffeedpump,theboilerpressureactsonthetopofvalveanditsits onitsgunmetalseatand stopsbackflowoftheboilerwateroutoftheboilershell.

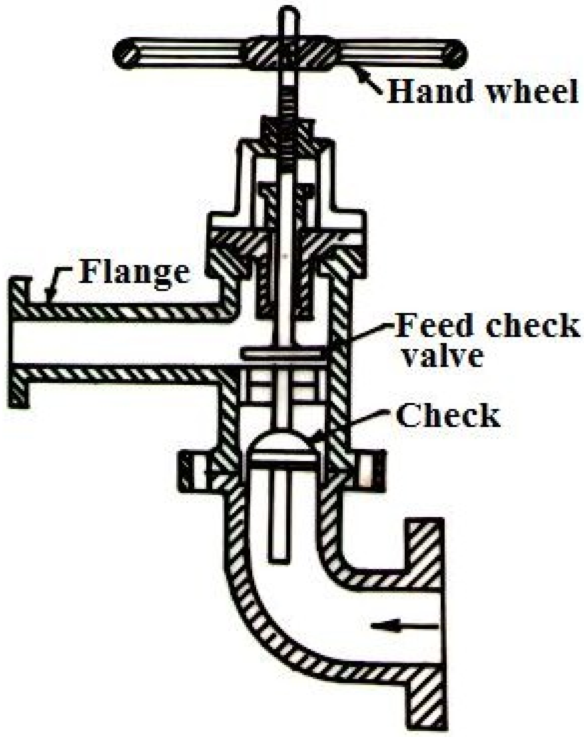


Fig.6Feedcheckvalve

7 Steamstop valve

Function

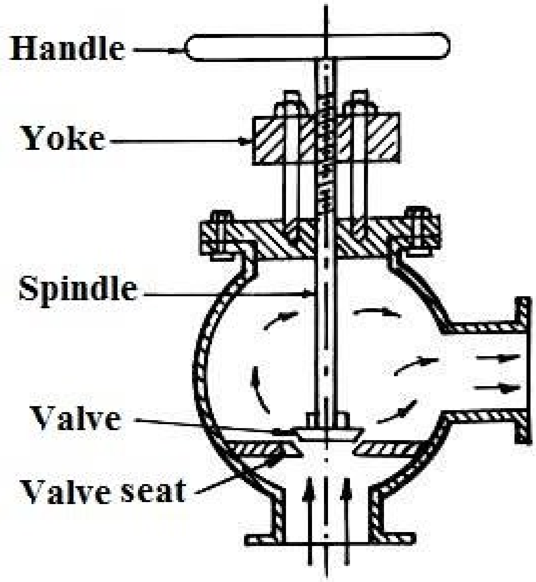
It is fitted over the boiler in between the steam space and steam supply line. Its function is to regulatethesteamsupplyfromboilertothesteamline.

Constructionandworking

The construction of steam stop valve is as shown in fig 25.7. Its casing has a L-shaped steam flowpassage.Itconsistsofavalveandvalveseattostoporallow

thesteamflow.

The valve is attached to a spindle and handle. Spindle passes through packing in the stuffing box toprevent leakage. The spindle has external threads in the top portion and moves in the internal threatsof a fix nut. By rotating clockwise and anticlockwise the spindle and valve moves down and up thusclosingoropeningthevalves.



Steamstop valve

BoilerAccessories

Boiler accessories are the components which are attached to the boiler (Not mounted on it) andare essentially for working of boiler and for increasing its efficiency. Various boiler accessoriesare discussedasbelow

1Feed pump

Feed pump is placed nearby the boiler and is used to feed water to boiler working at a highpressure. The job of feed pump is not just put the water in the boiler but as boiler is working athigh pressure, discharge pressure of feed pump must be sufficiently higher than this to push thewaterinsidetheboiler.

Construction&working

The feed pump used in boiler is of two types (i) Reciprocating type (ii) Rotary type. Both thesetypes are positive displacementtype to discharge againsthigh pressure.The discharge pressureof a single stage centrifugal pump is not high enough to overcome the high pressure of boiler somultistage centrifugalpumpisusedas a boilerfeedpump.

In stationary low pressure boiler used in processing industries, a multistage centrifugal pump runby an electrical motor is more suitable. In multistage centrifugal pump, a number of centrifugalcasing are so attached toeach other that the **impeller** of each is mounted on the same shaftrunby an electrical motor and discharge of 1st stagegoes to2nd stage and of 2nd to3rd stage and soon.Asshowninfig,ineachstagethepressureofwatergoesonincreasinganddischarge pressureoffinalstageissohighastoovercometheinternalpressureofboiler.Thesespumpshaveindependen tworkingandhave smoothoperation.

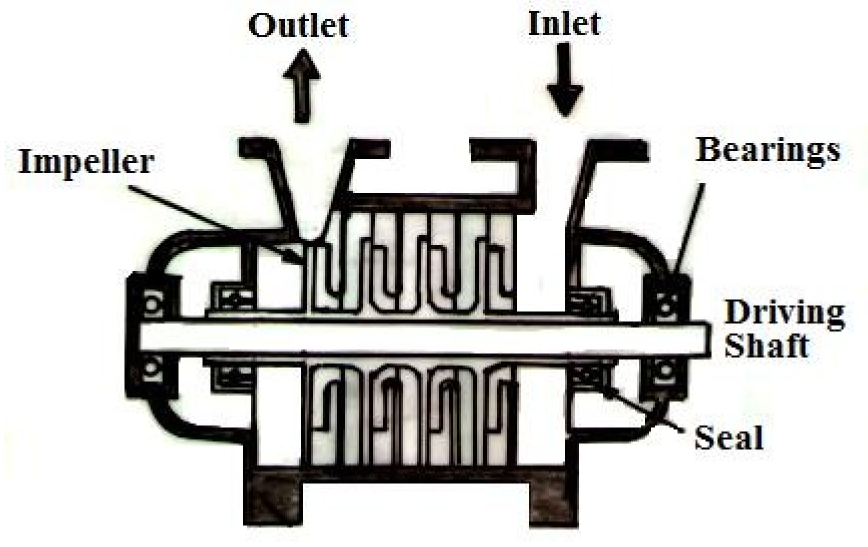


Fig.Multistagecentrifugalpumps

2. Economizer

Function

An economizeris a specially constructed heat exchangerfor harnessing the heatenergy ofoutgoing flue gases and utilizing itin preheating of boiler feed water. It saves the heat energyandsothefueland decreasestheoperatingcost ofboilerbyincreasingitsthermalefficiency.

Construction&working

Economizersareoftwo typesas(i)Externaltype(ii)Internaltype.Theexternaltypeeconomizeris constructed and installed apart from the boiler and the flue gases from the boiler are directed toflow through it before escaping through chimney. A vertical tube external economizer is showninfig.

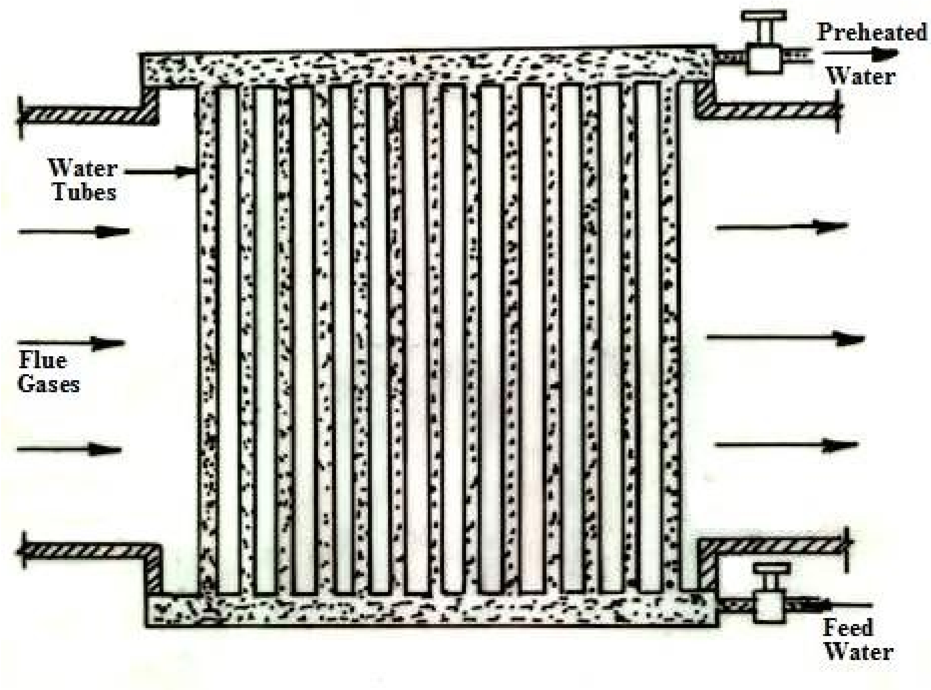


Fig.Externaleconomizer

It is employedfor boilers of medium pressure range. Here a number of vertical tubes made ofcast iron are connected to common headers at the bottom and top. Feed water flow into thebottom header and then through the vertical tubes flow out from the top header. Hot flue gasesescaping from the boiler are directed to flow across the outside surface of tubes thus indirectlyheating the feed water flowing inside. To avoid deposit of soot over the tube surface, tubularscrapers are fitted over the tubes. These are operated by chain and pulley system and whilemoving up and down slowly scrap the soot over the wall of tubes and soincrease the heattransfer rate.An internaltubeeconomizerisfittedinsidetheboilerandisan integralpartofit.

AdvantagesofEconomizer

1. Stressesproducedintheboilermaterialduetotemperaturedifferenceofboilermaterialandfeedwater arereducedbecause ofincreaseinfeedwatertemperature.
2. Evaporative capacity of boiler increases as less heat will be required to generate steam if feedwatertemperatureis alreadyhighduetopreheating.
3. Overallefficiencyofboilerincreases because ofmore steamproducedperkgoffuelburnt.

3. AirPre-heater

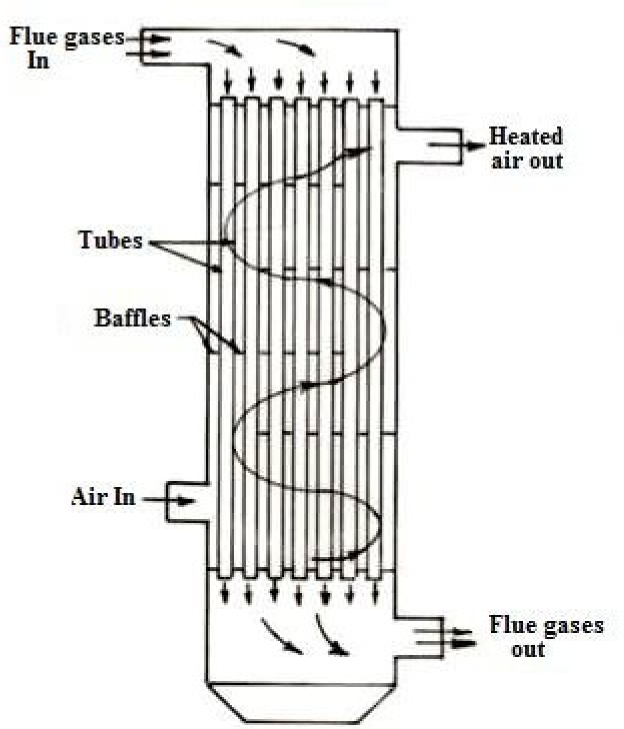


Fig.AirPre-heater(TubularType)

Function

Thefunctionofairpre-heateristofurtherutilizetheheatoffluegasesaftercomingoutofeconomizertopreheatthe airusedinfurnace oroilburner.

Construction

It is a plate type or tubular type or storage heat exchanger, in which flue gases pass through thetubes on one side of plate and air pass on other side. In storage type a rotor fitted with mesh ormatrix alternatively come in the passage of flue gases and air thus exchanging heat. A tubulartypeair-heateris as shown infig25.10

4Superheater

Thefunction of superheateris toincreasethetemperature of steam beyondits saturationtemperature. It is a type of heat exchanger. Hot flue gases coming out of burner are first directedthrough super heater before the boiler. The main advantage of superheating of steam comes inpowerplants,wheresteamisexpandedthroughaturbine.Butinaprocessingindustrysuperheatingisrequiredonlytoavoidcondensationinpipes.Thussuperheaterhaslessadvantageoruse ina processingindustryandmanytimesnotusedbut notalways.

Questionsforexercise/assignment:

Shortquestions

1. Defineboiler?
2. Definegrate?
3. Mentiontwodifferentmountingsusedwithboiler?
4. Definefiretubeboiler?
5. Defineairpreheater?

Longquestions

1. DescribetheconstructionandworkingofCochranboiler.
2. DescribetheconstructionandworkingofBabcock-wilcoxboiler.
3. BrieflyexplainBurdontubepressuregauge.

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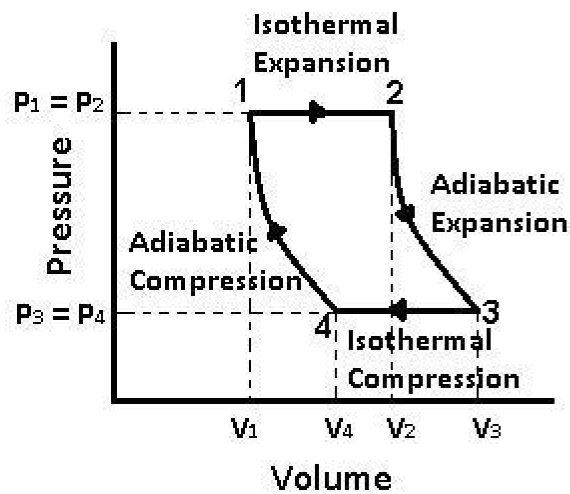
5 Steampowercycle

5.1 CarnotVapourCycle

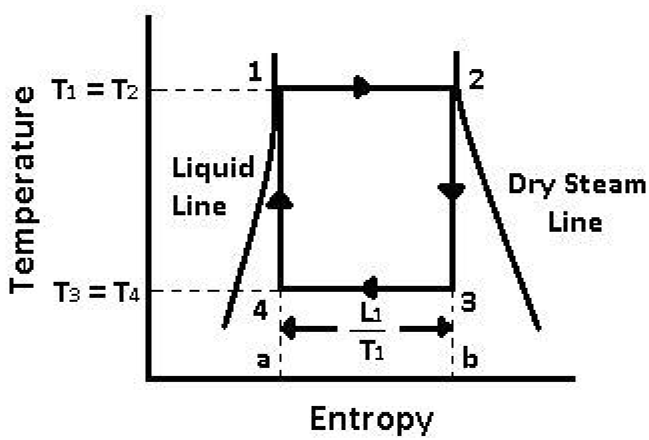
In a vapour cycle, all the theory remains the same as thermodynamic cycleexcept the workingsubstance,which issteam.Thesteammaybeinanyform,i.e.wet,dryorsaturatedorsuperheated.

ACarnotcyclesteamasaworkingsubstanceisrepresentedonthep-vandT-sdiagramin

CarnotVapourCycleP-VDiagram



CarnotVapourCycleT-SDiagram



5.2 CarnotVapourCycleProcesses

Thecycleiscompletedbythefollowingfourprocesses:

- 1-2Process(IsothermalExpansion)

- 2-3Process(AdiabaticExpansion)
- 3-4Process(IsothermalCompression)
- 4-1Process(AdiabaticCompression)

1. Process1-2(IsothermalExpansion)

- Thewaterisisothermallyconvertedintodrysaturatedsteam,ataconstanttemperature(T1)andpressure(p1).
- Drystateofsteamisexpressedinpoint2.
- ItmeansthatthetemperatureT2(i.e.,atpoint2)andpressurep2(i.e.,atpoint2)isequaltotemperatureT1andpressurep2respectively.
- Thisisothermalexpansionisrepresentedbycurve1-2onp-vandT-sdiagraminthefigure.
- Weknowthattheheatisabsorbedbywaterduringitsconversionintodrysteamisitslatentheat(L1).

$$\therefore \text{Change of entropy}$$

$$= (s_2 - s_1)$$

Wealsoknowthatthearea12baintheT-sdiagramrepresentstheheatabsorbedtosomescale,duringtheisothermalexpansion.

Heatabsorbedduringanisothermalexpansion(area12ba)

$$= (s_2 - s_1)T_1 \quad \dots \text{(i)}$$

2. Process 2-3(AdiabaticExpansion)

Thedrysteamnowexpandsadiabatically.Thepressureandtemperaturedropfromp2 top3 andT2toT3. As no heat is supplied or rejected during this process, there is no change of entropy. The adiabaticexpansionisrepresentedbythecurve2-3asshowninthefigure.

Readalso:ImportantTermsUsedInThermodynamics

3. Process3-4(IsothermalCompression)

- Thewetsteamisnowisothermallycompressedatconstanttemperature(T3)andpressure(p3).
- ItmeansthatthetemperatureT4(i.e.,atpoint4)andpressurep4(i.e.,atpoint4)isequaltothetemperatureT3andpressurep3respectively.

- Thisisothermalcompressionisrepresentedbythecurve3-4onp-vandT-sdiagramsasshown in the figure.

We know that area 3-4 in theT-sdiagramrepresentstheheatrejectedtosomescaleduringthe isothermal compression.

Heatrejectedduringisothermalcompression(area34ba)

$$= (s_2 - s_1)T_3 \quad \text{... (ii)}$$

4. Process4-1(AdiabaticCompression)

- The wet steam at point D is finally compressed adiabatically, till it returns back to its originalstate(point1).
- Thepressureandtemperaturerisefromp4top1andT4toT1respectively.
- Theadiabaticcompressionisrepresentedbythecurve4-1asshowninthefigure.
- Sincenoheatisabsorbedorrejected,thereforeentropyremainsconstant.Thiscompletesthecycle.

Weknowthatworkdoneduring the cycle

$$= \text{Heat absorbed} - \text{Heat rejected}$$

$$W = (s_2 - s)\, T_1 - (s_2 - s_1)T_3$$

$$= (s_2 - s_1)(T_1 - T_3)$$

AndtheefficiencyoftheCarnot cycle,

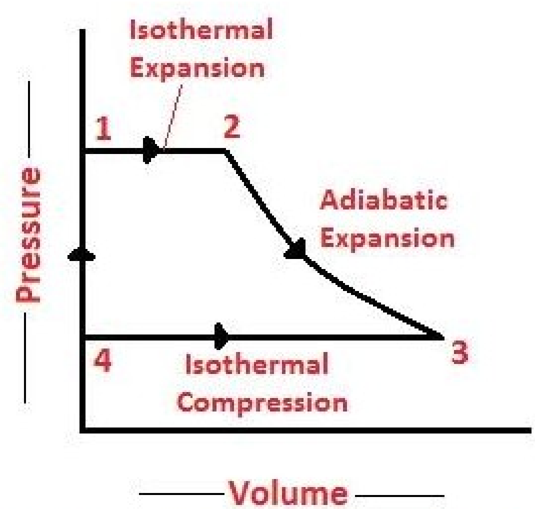
$$\eta_c = \frac{Work\ done}{Heat\ absorbed}$$

$$= \frac{(s_2 - s_1)(T_1 - T_3)}{(s_2 - s_1)} = \frac{T_1 - T_3}{T_1} = 1 - \frac{T_3}{T_1}$$

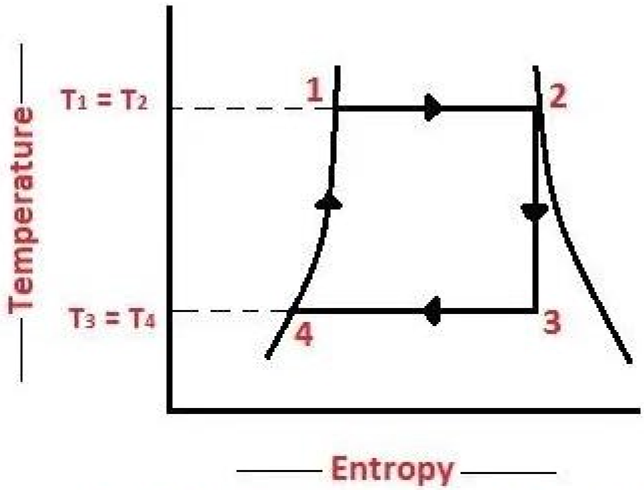
5.3 Rankine

Cycle5.3.1

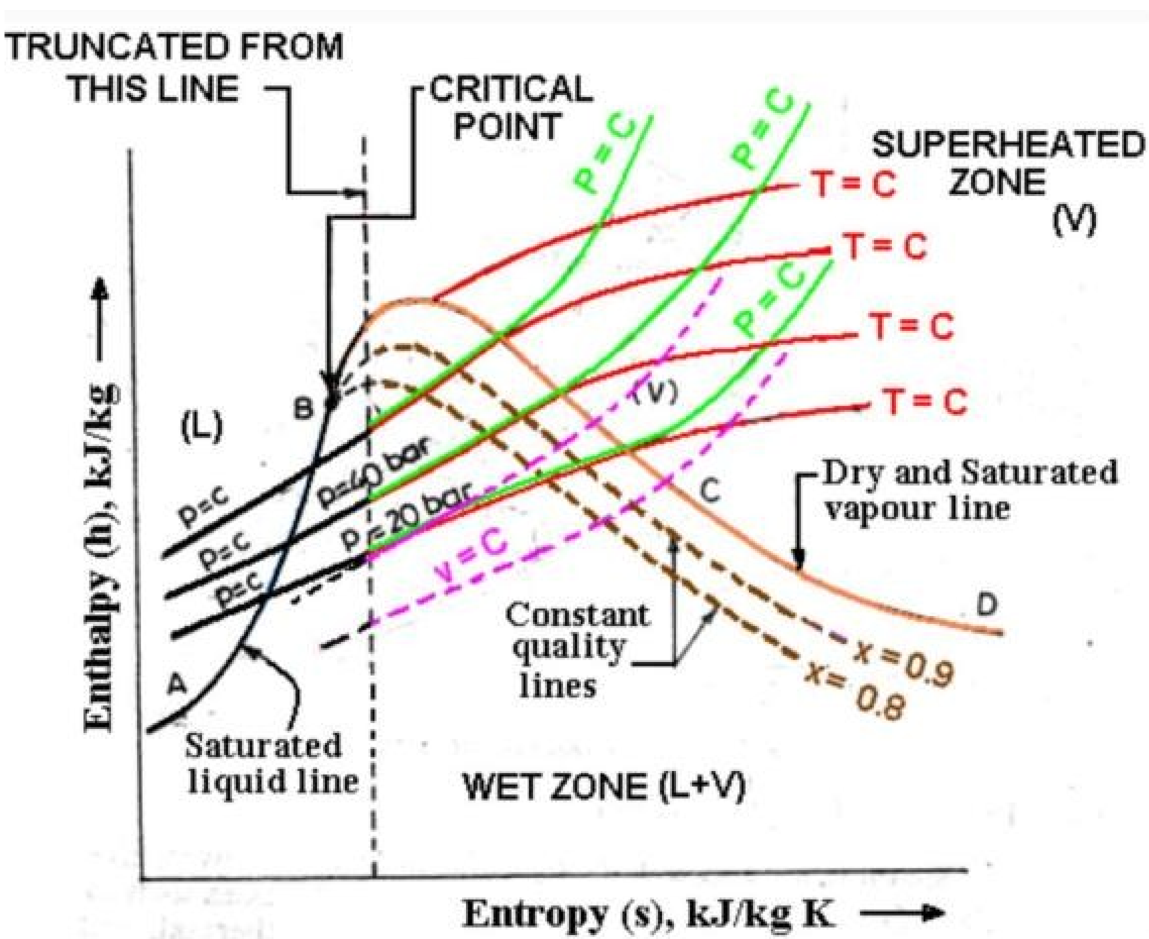
The **Rankine cycle** is a modified form of Carnot cycle,in which the isothermal compression (3-4) iscontinuedunitthesteamiscondensedintowater.ACarnotcycle,usingsteamasaworkingsubstance,isrepresentedorp-vandt-sdiagramasshowninthefigure.



P-v Diagram of Rankine Cycle



T-s Diagram of Rankine Cycle



ThefollowingarethefourstagesofanidealRankinecycle:

1. Isothermalexpansion
2. Adiabaticexpansion
3. Isothermalcompression
4. Warmingoperation

1. IsothermalExpansion

The water is isothermally converted into dry saturated steam at a constanttemperature(T1)andpressure (P1).Thedrystateofsteamisexpressedinpoint **2.** ItmeansthatthetemperatureT2(i.e.atpoint2)andpressureP2(i.e.atpoint2)ise qualtotemperatureT1andpressureP1respectively.

This isothermal expansion is represented by curve 1-2 in p-v and t-s diagrams inFig.Weknowthattheheatabsorbedduringisothermalexpansionbywaterdringitsco nversion

2. AdiabaticExpansion

The dry saturated steam now expands adiabatically. The pressure andtemperature fall from P2 and T2 to T3 respectively with a dryness fraction x2. Asnoheatissuppliedorrejectedduringthisprocess,thereisnochangeofentropy.Thea diabaticexpansionisrepresentedbythecurve2-3asshowninFig.

3. IsothermalCompression

Thewetsteamisnowisothermallycompressedatconstanttemperature(T3)andpressu re (p3) unit the whole steam is condensed into water. IT means that thetemperature T4 (i.e. at point 4) and pressure P4 is equal to the temperature T3andpressureP3respectively.

Theisothermalcompressionisrepresentedbycurve3-4onp-vandT-sdiagraminFig.Theheatrejectedbysteamisitslatentheat(equaltox3L3).

4. WarmingOperation

The water is now warmed at constant volume from temperature T4 to T1. Itspressure also rises from P4 to P1. The heat absorbed by water dring thisoperation is equal to the sensible heat or liquid heat corresponding to thepressureP1i.e.equaltosensibleheatatpoint1minussensibleheatatpoint4(i.e.equaltoh1-h4).

Butsensibleheat atpoint4isequaltoatpoint3.Thusheatabsorbedduringwarmingoperationequalto(h1-h3)

$$\therefore \textit{Heat absorbed during the complete cycle}$$

=Heatabsorbedduringisothermalexpansion+Heatabsorbedduringthewarmingoperation

$$= L_1 + (h_1 - h_2) = h_1 + L_1 - h_3$$

$$= H_1 - h_3 \quad (\because H_1 = h_1 + L_1) \quad \text{... (i)}$$

Andheatrejectedduringthecycle

$$= x_3 - L_3$$

$$\therefore \textit{Work done during the cycle}$$

= Heatabsorbed –Heatrejected

$$= (H_1 - h_3) - x_3.L_3 = H_1 - (h_3 + x_3.L_3)$$

$$= H_1 - H_3 \quad (\because H_3 = h_3 + x_3.L_3) \quad \text{... (ii)}$$

And efficiency(alsocalledRankineefficiency),

$$\eta = \frac{Work\ done}{Heat\ absorbed}$$

$$= \frac{H_1 - H_3}{H_1 - h_3} \quad \ldots (iii)$$

Questionsforexercise/assignment:

Shortquestions

1. DrawPV&TSdiagramofCarnotcycle?
2. DrawPV&TSdiagramofRankinecycle?

Longquestions

1. DescribetheCarnotcyclewithvaporwithhelpofPV,TS&HSdiagramsanddeduceaformulaf oritsthermalefficiency.
2. DescribetheRankinecyclewithvaporwithhelpofPV,TS&HSdiagramsanddeduceaformulaf oritsthermalefficiency.

Refernces:

- https://www.theengineerspost.com/carnot-vapour-cycle/
- https://www.theengineerspost.com/rankine-cycle/

6 HeatTransfer

6.1 ModesofHeatTreatment:

Thereisatotalof 3Modesof Heattransferwhichis:

1. **Conduction**
2. **Convectionand**
3. **Radiation**

1. Conduction:

In Conduction, the heat or energy is transferred by a direct contact like when any heated object youtouchwithyourhandtheconductionprocesstakeplace.

When we heat the Iron at one side the other side automatically gets heated because the moleculespresent in it travels to another side and heated that area too. So we can say Conduction is equal toDirectcontact.

Itisdefinedasthetransferofheatbymeansofmolecularagitationwithinamaterial withoutanymotionofthematerialasawhole

2. Convection:

Inconvection,theheat orenergyistransferredbymassmotionoffluidwhichmightbeairorwaterwhenheatedfluidiscausedtomoveawayfromthe sourceofheat-carryingenergywithit.

Example:

When the heat is provided to water at the bottom the pot is heated, the water particles move faster,and they also move farther apart. So now the heated water becomes less dense and we know the less-dense fluid will float on top of a more dense one. Now, the heated water rises in the pot. Thesurrounding cooler water flows into its place. This flow creates circular motion, known as convectioncurrents.

3. Radiation:

TheRadiationisdefinedasEverybodyemitsradiationintheformofanelectromagneticwaveorraysorparticles.I nthisprocessdoesnot requireamediumtotransfertheThermal(Heat)energy.

Example:

Insummerwhenyougointhefieldandforatimeyoustandthereyouwill feel heatupbecauseofsunemitstheheatandyourbodyskinreceives. Thatishowtheradiationprocessworks.

6.2 Fourierlaw ofheat conduction:

Fourier's law states that **the negative gradient of temperature and the time rate of heat transfer isproportional to the area at right angles of that gradient through which the heat flows**. Fourier's law istheothernameofthelawofheatconduction.

Fourier'slawdifferentialformisasfollows:

$$q = -k \nabla T$$

Where,

- qisthelocal heatfluxdensityinW.m^{2}
- kistheconductivityofthematerial inW.m^{-1}.K^{-1}
- ∇Tisthetemperaturegradientin K.m^{-1}

ThermalConductivity(k)

Thermal conductivity can be defined as **the rate at which heat is transferred by conduction through aunitcross-sectionareaof amaterial,whenatemperaturegradientexitsperpendiculartothearea**.

6.3 NewtonsLawofcooling:

Newton's law of cooling explains the rate at which an object/entity changes itstemperaturewhenitisexposedto radiation.Thischange isalmostproportional tothedifferencebetweentheobject’stemperatureanditssurroundings’temperature, given thatthisdifferenceisquitesmall.

6.4 Stefans-Boltzmannlawofradiation:

According to Stefan Boltzmann law, **the amount of radiation emitted per unit time from an area A of ablackbodyatabsolutetemperatureTisdirectlyproportionaltothefourthpowerofthetemperature**.

Mathematically **$W = \varepsilon\sigma T^4$**

whereemissivityεisequalto1forblackbodiesandlessthan1forgreybodies,σ beingtheStefanconstant.

Kirchoff'sLawofRadiation:

Atagiventemperature,**theratioof theemissivepowerof abodytoitsabsorptivepowerisconstantandisequaltotheemissivepowerof ablackbodyatthesametemperature**. aE=Eb.

6.5 Black bodyradiation

Blackbody radiation refers to **the spectrum of light emitted by any heated object**; common examplesincludetheheatingelementofatoasterandthefilamentofalightbulb.

Emissivity:

Emissivityisdefinedastheratiooftheenergyradiatedfromamaterial'ssurfaceto thatradiatedfromaperfect emitter, known as a blackbody, at the same temperature and wavelength and under the sameviewing conditions. It is a dimensionless number between 0 (for a perfect reflector) and 1 (for a perfectemitter).

Absorptivity:

Absorptivity is defined as **the fraction of the amount of incident radiation that is absorbedbythesurface**.

Transmissivity:

Thetransmissivity**describestheproportionofelectromagneticradiationwhichistransmittedthroughthe body, and has values between 0 and 1**. The remaining portion of the radiation is either reflected orabsorbedbythebody. Thisgivestherelationship:$\alpha+\rho+\tau=1$.

Questionsforexercise/assignment:

Shortquestions

1. DefineFourierlawofheatconduction?
2. DefineNewton’slawofcooling?
3. DifineKirchoff’slaw?
4. Defineabsorptivity?
5. Defineemissivity?

Longquestions

1. Statethemodesofheattransferandexplainit?
2. BrieflyexplainNewton’slawofcooling?
3. BrieflyexplainFourierlawofheatconduction?

References:

1. https://www.tutorialspoint.com/modes-of-heat-transfer-conduction-convection-and-radiation
2. https://byjus.com/physics/fouriers-law/
3. https://knowledge.carolina.com/physical-science/physics/newtons-law-of-cooling/
4. https://en.wikipedia.org/wiki/Stefan%E2%80%93Boltzmann_law
5. https://www.vedantu.com/question-answer/state-kirchhoffs-law-of-radiation-and-prove-it-class-11-physics-cbse-5f3f9f2a7367fe538f457be6

Previoussemester questionsforpractice

4TH SEM./MECH/MECH(IND INTG)/ MECH(MAINT)/
MECH(PROD)/ DME/MECH(SWICH)/ 2022(S)
Th4 Thermal Engineering-II

Full Marks: 80 Time- 3 Hrs

Answer any five Questions including Q No.1& 2
Figures in the right hand margin indicates marks

e. What is the difference between Reheat cycle and Regenerative cycle?

f. The thermal efficiency of a carnot heat engine is 60.5%. The minimum temperature of the cycle is 25^{0}c. Find the maximum temperature of the cycle. 171.71 k

g Deduce a formula for work done by a single stage single acting reciprocating air compressor when the law of expansion is PV^{n}=constant neglecting clearance.

3 Steam is being generated in a boiler under a pressure of 12bar. Find the enthalpy of 5kg of steam, when 10

(i) Steam is wet having dryness fraction of 0.75 11441.5

(ii) Temperature of steam is 300^{0c}. Take C_p= 2.1kJ/kg. 15100.105

4 Describe carnot cycle with vapour with the help of P-V, T-S and H-S diagrams and deduce a formula for itS thermal efficiency. 10

5 Describe the construction and working of Cochran boiler. 10

6 An engine uses 6.5kg of oil per hour of calorific value of 30,000kJ/kg. if the B.P of the engine is 22kw and mechanical efficiency 85%. Calculate 10

(i) Indicated thermal efficiency.

(ii) Brake thermal efficiency

(iii) Specific fuel consumption in kg/B.P/h.

7 Describe Rankine cycle with the help of P-V. T-S and H-S diagram and deduce a formula for its thermal efficiency considering feed pump work. 10