ENGINEERINGTHERMODYNAMICS

(ME3391)

UNITI BASICS,ZEROTHANDFIRSTLAW

ReviewofBasics– Thermodynamicsystems,Propertiesandprocesses ThermodynamicEquilibrium - Displacement work - P-V diagram. Thermal equilibrium- Zeroth law – Concept of temperature and TemperatureScales.Firstlaw–applicationtoclosedandopensystems – steadyand unsteady flow processes.

UNITIISECONDLAWANDENTROPY9

Heat Engine – Refrigerator - Heat pump. Statements of second law and their equivalence &corollaries.Carnot cycle - Reversed Carnot cycle - Performance-Clausiusinequality.Conceptofentropy-T-sdiagram-Tds Equations - Entropy change for a pure substance.

UNITIIIAVAILABILITYANDAPPLICATIONSOFIILAW9

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UNITIVPROPERTIESOFPURESUBSTANCES 9

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Compressibility Chart. Maxwell relations - TdS Equations - heat capacitiesrelations-Energyequation,Joule-Thomsonexperiment - Clausius-Clapeyron equation.

UNIT I

BASICS,ZEROTHANDFIRSTLAW

Review of Basics – Thermodynamic systems, Properties and processes ThermodynamicEquilibrium - Displacement work - P-V diagram. Thermal equilibrium-Zerothlaw–ConceptoftemperatureandTemperatureScales.Firstlaw – application to closed and open systems – steadyand unsteady flow processes.

Nomenclature

A	area
C	velocity
$°C$	temperatureonthecelsius(orcentigrade)scale
c	specificheat
c_p	specificheatatconstantpressure
C_v	specificheatatconstantvolume
C_p	molarheatatconstantpressure
C_v	molarheatatconstantvolume
D, d	bore; diameter
H	enthalpy
h	specificenthalpy;heattransferco-efficient
P	power
N	rotationalspeed
K	temperatureonkelvinscale
L	stroke
M	molecularweight
m	mass
Q	heat,rateofheattransfer
q	rateofheattransferperunitarea
R	gasconstant
R_0	universalgasconstant
R	radius,expansionratio,compressionratio

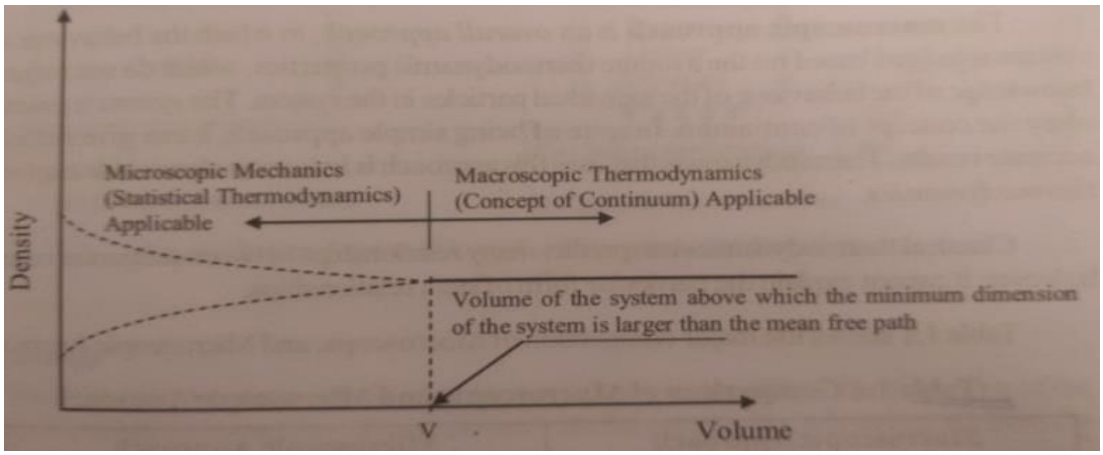
S	entropy
T	absolutetemperature;torque
U	internalenergy;overallheattransferco-efficient
u	specificinternalenergy
V	volume
v	specificvolume
W	work;rateofworktransfer;brakeload; weight
w	specificweight;velocityofwhirl
x	drynessfraction;lengthtivepressure,backpressure

Symbols α absorptivity γratioofspecificheats, $\frac{c_p}{c_v}$ ∈ emissivity;effectiveness ηefficiency θtemperaturedifference,angle ρ density σStefan-Boltzmannconstant φ relative humidity, angle.	Universalgasconstant,R_u=8.314 kJ/kmole − K Characteristicgasconstant,*c* $R_c=\frac{RU}{M}$ ForAirR=$\frac{8.314}{29}$=0.287kJ/kg-K ForwaterR=$\frac{8.314}{18}$=0.461kJ/kg-K UnitsofheatandworkiskJ UnitsofpressureisN/m^2 1 kPa= 10^3 Pa 1bar=1×10^5N/m^2 1bar=1×10^3kN/m^2

Thermodynamics is science which deals with the relations among heat, work and properties of system which are in equilibrium.

Thermodynamics=Thermo +dynamics
(Heat) (Motion)

concept of continuum is an a area that can keep being divided and divided infinitely ; no individual particles. It is a simplification that makes it possible to investigate the movement of matter on scales larger than the distance between particles.



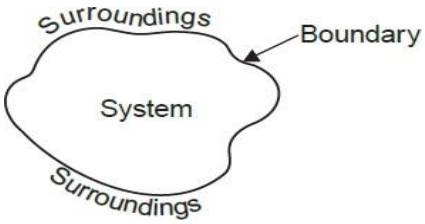
Concept of continuum is a kind of idealization of the continuous description of matter where the properties of the matter are considered as continuous functions of space variables.

THERMODYNAMICSYSTEMS

System, Boundary and Surroundings

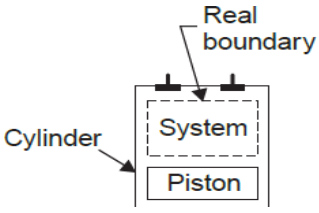
System:

A system is *a finite quantity of matter*



Boundary.

The *actual envelope enclosing the system* is the boundary of the system. The boundary may be fixed or it may move, as and when a system containing a gas is compressed or expanded.



Surroundings contain everything other then the system.

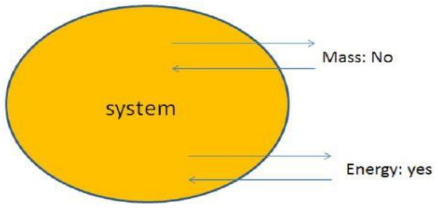
Universe: A system and surrounding to gether comprise a universe

Type of thermodynamic systems

1. **Closed System:**
2. **Open System**
3. **Isolated System**

Closed System:

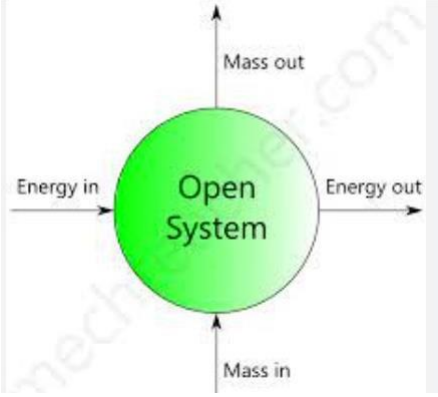
System does not permit any mass transfer.But only the energy transfer takes place.



Closed System

Open System

An **open system** both mass and energy transfer take place.



Isolated System: An isolated system ,which is not affected by surrounding is call isolated system.

Adiabatic System

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Homogeneous System

A system which consists of a single phase is termed as homogeneous system.Examples: Mixture of airandwatervapour,waterplusnitricacid and octane plus heptane.

HeterogeneousSystem

Asystem whichconsistsoftwoormorephasesiscalled a heterogeneous system. Examples :Water plus steam, ice plus water and water plus oil.

Thermodynamicpropertyand State(2marks)

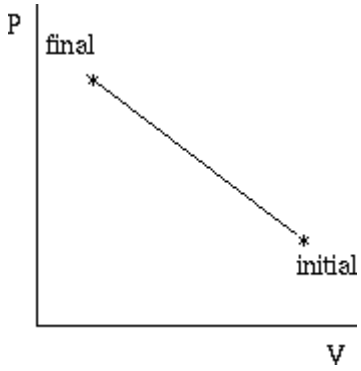
Thermodynamic property Any observable characteristics required to describetheconditionsorstateofa systemisknown asThermodynamic property of a system.

DifferentiateIntensiveandExtensiveProperty

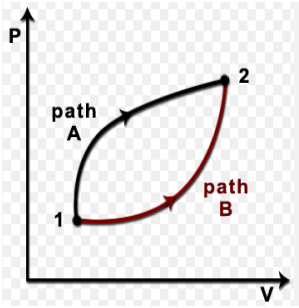
	Extensive properties	Intensiveproperties
massofa system	dependenton	independentof
additive.	yes,additive.	Notadditive.
Example:	mass(m),volume(V) ,Energy(E),Enthalp y(H)	Example:Pressure(P),Tempera ture(T),De nsity

.**State:** Istheconditionofthesystematanyparticularmoment.

- It isthecondition ofasystemasdefined bythevaluesofallit's properties.
- Itgivesacompletedescriptionofthesystem.
- Anyoperationinwhich oneormorepropertiesofasystemchange is called change of state .



Path:Athermodynamicpropertythatdependsonthepathbetween the initial and final state is known as the path function. The path functions depend on the path taken or covered between two (initial and final) states.



Phase. Aphaseisaquantityof matterwhichishomogeneousthroughout in chemical composition and physical structure

MACROSCOPICANDMICROSCOPICPOINTSOFVIEW

1. Macroscopicapproach—(*Macro*mean*big*or*total*)
2. Microscopicapproach—(*Micro*means*small*)

Detail	*Macroscopicapproach*	*Microscopicapproach*
approach	concernedwith *overallbehaviour*.	*structureofthe matter*
analysis	mathematicalformulae.	statisticalmethods
valuesof the properties	averagevalues.	*changesinproperties*
describea system	ewproperties areneeded.	Largenumberofvariables

THERMODYNAMICEQUILIBRIUM

A system is in ***thermodynamic equilibrium***if the temperature and pressureatallpointsaresame;thereshouldbenovelocitygradient;

1. **Thermalequilibrium.** Thetemperatureofthesystemdoesnotchange with time andhas same value at all points of the system.

2. **Mechanical equilibrium.** There are no unbalanced forces within the systemorbetweenthesurroundings.Thepressureinthesystemissameat all points and does not change withrespect to time

.

3. **Chemicalequilibrium.** Nochemicalreactiontakesplaceinthesystem and the chemicalcomposition which is same throughout the system does not vary with time.

THERMODYNAMICPROCESS

Pathand Process:

Theseriesofstatethrougha systempassesduringachangeofstateis Path of the system.

PROCESS:changeofstateundergonebyasystemfromone equilibrium state to another state.

Wecan allowoneofthepropertiestoremainaconstantduringaprocess.

Isothermal Constant Temperature (T)

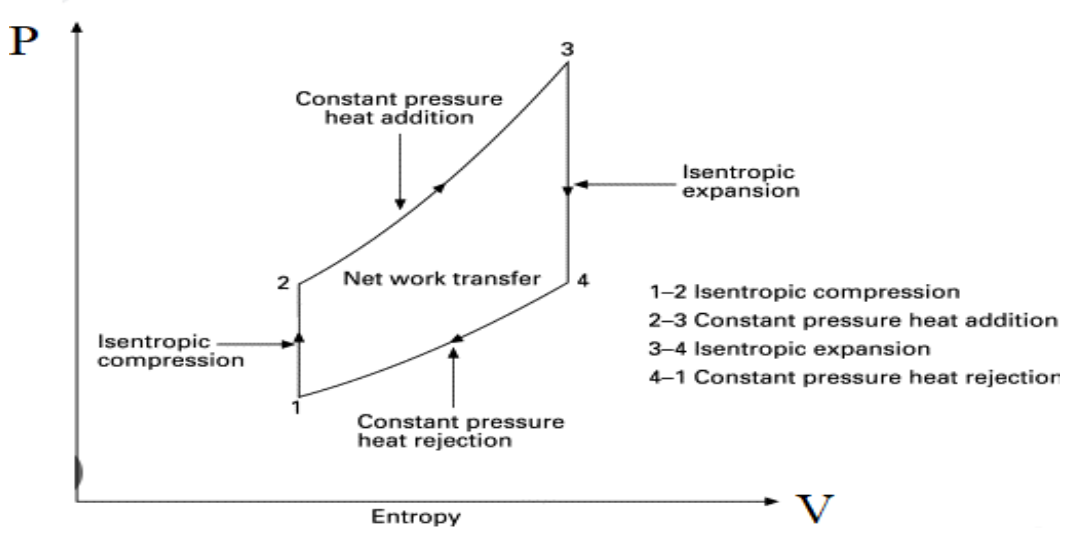
Isobaric Constant Pressure (P)

Isochoric Constant Volume (V)

Isentropic Constant Entropy (s)

IsenthalpicConstantEnthalpy(h)

Processoccurs:anenergytransferatasteadystate.



Aprocessmaybe

i)***non-flowprocess:****non-flow*inwhich afixed masswithinthedefined boundary isundergoing a change of state.

Example :Asubstancewhichisbeingheatedina closed cylinder undergoes

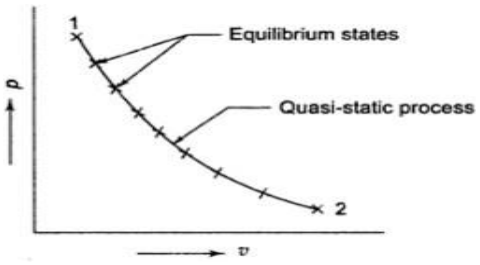
ii) flowprocessmassisenteringand leavingthroughtheboundary of an opensystem.

quasi-staticprocess

Aquasi-staticprocessisoneinwhichthedeviationfromthermodynamic equilibrium is infinitesimal.

Characteristics:

- refrredtoaslowprocess.
- happensataninfiniteslowrate,
- hasallofitsstaticinequilibrtum.
- thermodynamicequilibriumwithitssurroundingatalltimes

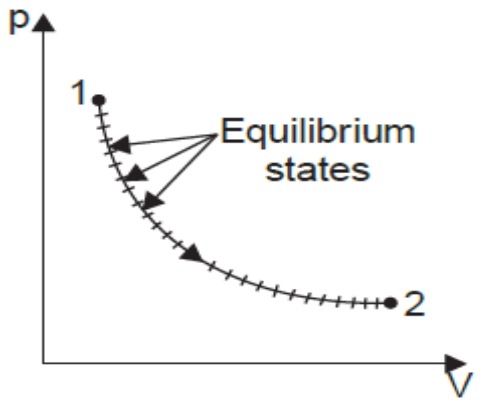


Non-Quasi-staticprocess.

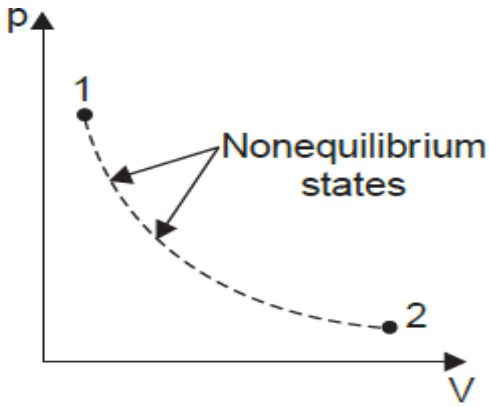
Ifaprocessiscarried outin suchawaythatateveryinstantthesystem departs finitely from thermodynamic equilibrium

REVERSIBLEandIRREVERSIBLEPROCESSES:

Reversible process. A reversible process (also some times known as quasi-staticprocess)isonewhichcanbestoppedatanystageand reversed so that the system and surroundings are exactly restored to their initial states. Thisprocesshasthefollowingcharacteristics:
1. Itmustpassthroughthesamestatesonthereversed path aswere initially visited on the forward path.
2. Thisprocesswhen undonewillleavenohistoryofevents inthe surroundings.
3. Itmustpassthroughacontinuousseriesofequilibriumstates.



Reversible process.



Irreversible process.

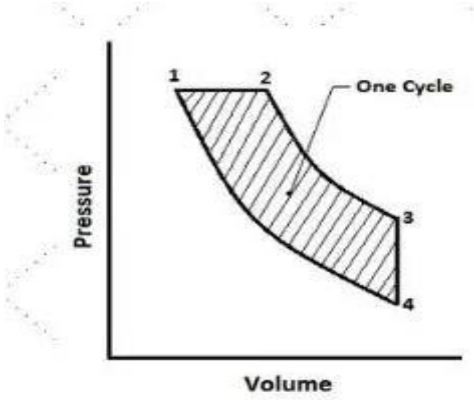
Examples.
(i) Frictionlessrelativemotion.
(ii) Expansionandcompressionofspring.

Irreversibleprocess.

An irreversibleprocess isonein whichheatistransferred throughafinite temperature.
Examples.
(i) Relativemotionwithfriction(ii)Combustion
(iii) Diffusion(iv)Freeexpansion
(v)Throttling(vi)Electricityflow

CYCLE

Thermodynamic cycle refers to number of processes in sequemce bringbackthesystemtoitsoriginalvolume, thenthesystemissaidtobe a **cycle.**



In figa systemstartsfromstate1and thenundergoes(1-2), (2-3), (3- 4) ,(4-1)

Anditsreturnsbaketoitsoriginalposition.

	PointFunction	Path Function
changeofthe path	isindependent	dependsonthepath
magnitudeof suchquantity	dependsonthestate.	areaunderthecurve
	Theseareexactdifferential.	inexactdifferential.
Ex:	likepressure(P), volume(V),Temp.(T),	Heatandwork

ENERGY,WORKANDHEAT

Energy: Energyisageneraltermembracingenergyintransitionand stored energy.

Work

Workissaidtobedonewhenaforcemovesthroughadistance.

$$W=F\times x \qquad N\text{-}m$$

Signconvention :

_ Ifthework isdone*by*thesystem *on*thesurroundings,*e.g.*, whena fluid expandspushing a piston outwards, the work is said to be *positive*.

Workoutputofthesystem*=+*W

_ Ifthework isdone*on*thesystem *by*thesurroundings,*e.g.*, whena force is applied to arotating handle, or to a piston to compress a fluid, the work is said to be *negative*.

Workinputtosystem =–W

Heatisthetransferof thermalenergybetweensystems,whileworkis the transfer of mechanical energy between two systems

Heatisdefined asformofenergythatcanbetransferred fromone system to another but there must be a temperature difference between these two systems.

Heatisusuallyrepresentedby'**Q**'in(kJ)

$$\int_1^2 \delta Q = Q_{1-2}$$

Signconvention :
Heatreceivedbythesystem=+Q
Heatrejectedorgivenupbythesystem=–Q.

	Heat	Work
Gradeofenergy	poor	high
source	Producedanywhere	requires
Convertedintoworks	friction	fully
Motionofmolecules	Radom	ordered
States	Formofenergy	Transferringenergy.

Zeroth law of thermodynamics' states that if two systems are each equalintemperaturetoa third,theyareequalintemperaturetoeach other.

a=bandb= c, thena= c.

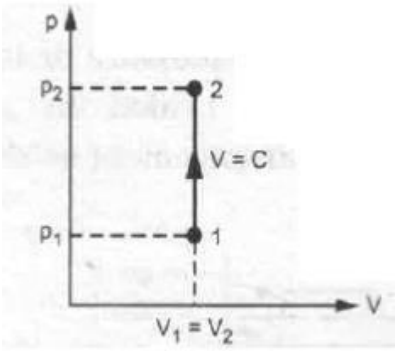
ApplicationofFirstLawtoNon-flow/Closedsystem

1. Constantvolumeprocess

2. Constantpressureprocess
3. Constanttemperatureprocess
4. Reversibleadiabaticprocess
5. Polytropicprocess

1.Constantvolumeprocess

If heatis suppliedat constantvolume thenthe pressureand temperatureofsystemwill increase but there is no any expansion or compression of gas



Work done d W=0

Generalgasequation $\frac{pV}{T}$=C

p,VandTrelations $\frac{p1}{T_1}=\frac{p2}{T_2}$

Heatsuppliedtothesystem=m$c_v(T_2-T_1)$

Change in internal energy(Changeinenthalpy)du =dQ = m $c_v(T_2-T_1)$

Changeinentropy

$\Delta S = mc_v \ln\left(\frac{T_2}{T_1}\right)$

Constantpressureorisobaricprocess

Generalvgasequation $\frac{pV}{T}$=C

p,VandTrelations $\frac{V1}{T_1}=\frac{V2}{T_2}$

Heatsuppliedtothesystem=m$c_p(T_2-T_1)$

Work done d W= p $(V_2 - V_1)$

Change ininternal energy (Changeinenthalpy)dh =d Q = m $c_p(T_2-T_1)$

Changeinentropy

$\Delta S = mc_p \ln\left(\frac{T_2}{T_1}\right)$

Constant temperature or isothermal process(Frictionless piston and cylinder**)**

Generalgasequation$\frac{pV}{T}$=C

p,VandTrelations $p_1V_1=p_2V_2$

Heatsupplied=workdelivered

dQ =dW= $p_1V_1\text{In}\left(\frac{V_2}{V_1}\right)=p_1V_1\text{In}\left(\frac{p_1}{p_2}\right)$

Changeininternalenergy(Change inenthalpy)

ΔU= 0

Changeinentropy

ΔS=mRIn $\left(\frac{V_2}{V_1}\right)$=mRIn $\left(\frac{p_1}{p_2}\right)$

ReverseAdiabaticProcess

{insulatedfrictionlesspistonandcylinderarrangement}

noheattransferdQ = 0

GeneralgasequationpV^{γ}=C

p,VandTrelations $p_1V_1^{\gamma}=p_2V_2^{\gamma}$

$\left(\frac{V_1}{V_2}\right)^{\gamma-1}=\left(\frac{P_2}{P_1}\right)^{\gamma-1}$

Heatdelivered

Q =0

Workoutputofthesystem

$dW=\frac{p_1V_1-p_2V_2}{\gamma-1}$

Changeinentropy

ΔS =0

PolytrophicProcess(non-flowpolytropicprocess**)**

Alltheprocesseslikeisobaric,isochoric,isothermal,adiabatic,etc. may be described byequation

pV^n=CWhere ‘n’=Indexofprocess.

If n=0, then pV^0=C p=C …Isobaric

If n= 1,then pV^1=C pV=C … Isothermal

If n=∞,then pV^{∞}=C V=C …Isochoric

If n =γ , thenpV^{γ}= C V=C…Isentropic

replaceγbyn.

p,VandTrelations $p_1V_1^n=p_2V_2^n$

$$\frac{T_2}{T_1}=\left(\frac{V_1}{V_2}\right)^{n-1}=\left(\frac{P_2}{P_1}\right)^{n-1}$$

Heattransfer

dQ =ΔU+dw

Changeininternalenergy(Changeinenthalpy)

$$\Delta U= mc_v(T_2-T_1)$$

Workoutputofthesystem

$$dw=\frac{p_1V_1-p_2V_2}{n-1}$$

Zerothlawof thermodynamics' statesthat IftwobodiesAandBare thermalequilibriumwith third systemCThen thebodiesAandBare thermal equilibrium with each other

a=bandb=c,thena= c.

SteadyFlowEnergyEquation[SFEE]

Considerasteadyflowopensystemasshown

Assumptions :

Thefollowingassumptionsaremadeinthesystemanalysis:

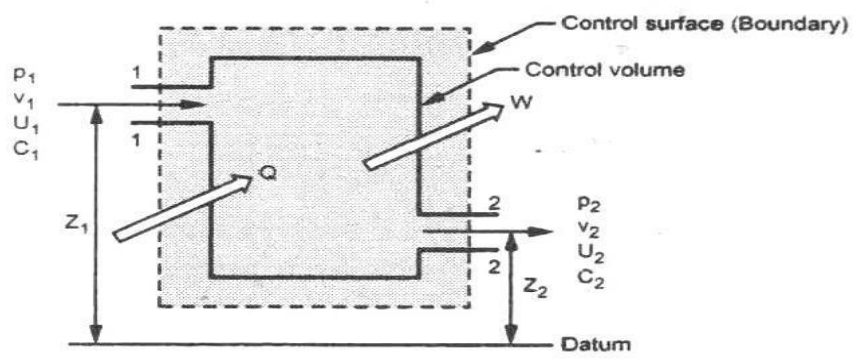
(i) Themassflowthroughthesystemremainsconstant.

(ii) Fluidisuniformin composition.

(iii) Theonlyinteractionbetweenthesystemandsurroundingsarework and heat.

(iv) Thestateoffluidatanypointremainsconstantwith time.

(v) Intheanalysisonlypotential,kineticandflowenergiesare considered.



where,*Q*=Heatsupplied(orenteringtheboundary)perkgoffluid,
W=Work done$^{kJ}/_{kg}$

C=Velocityoffluid ,
Z=Heightabovedatum,
p=Pressureofthefluid,
u=Internalenergyperkgoffluid,and
pv=Energyrequired for1kgoffluid.
This equation is applicable to any medium in

A₁and**A₂**bethecross-

sectionalareaatinletandoutlet**p₁**and**p₂**bethepressurea

tinletandoutlet.

$v_1$and$v_2$bethe specific volumeatinletandoutlet.

U₁and**U₂**betheinternalenergyatinletandoutlet.

C₁and**C₂**bethe velocity forfluid atinletandoutlet.

If**Q**istheamountofheatinteraction**W**istheworkoutput

Totalenergyenteringthesystem=P.E+K.E+I.E+F.E+Heatenergy

$$=gz_1+\frac{C_1^2}{2}+u_1+p_1v_1+Q$$

Totalenergylivingthesystem=P.E+K.E+I.E+F.E+Work

$$=gz_2+\frac{C_2^2}{2}+u_2+p_2v_2+W$$

Accordingtofirstlawofthermodynamics,

Totalenergy [enteringthesystem]=Totalenergy [leavingthesystem]

$$gz_1 + \frac{c_1^2}{2} + u_1 + p_1 v_1 + Q = gz_2 + \frac{c_2^2}{2} + u_2 + p_2 v_2 + W$$

$$\therefore [h = u + pv]$$

$$gz_1 + \frac{c_1^2}{2} + h_1 + Q = gz_2 + \frac{c_2^2}{2} + h_2 + W$$

Forenergyflowperunitofmass

$$m\left(gz_1 + \frac{c_1^2}{2} + h_1 + Q\right) = m\left(gz_2 + \frac{c_2^2}{2} + h_2 + W\right)$$

fortheunitofkJ/kg

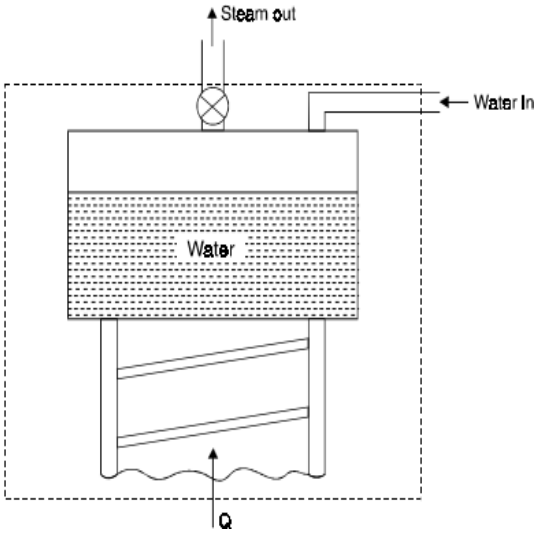
$$m\left(\frac{gz_1}{1000} + \frac{c_1^2}{2000} + h_1 + Q\right) = m\left(\frac{gz_2}{1000} + \frac{c_2^2}{2000} + h_2 + W\right)$$

ApplicationofSteadyFlowEnergyEquation

Boiler:(Steamgenerator)

Internalenergy(U)existsandflowenergyexistsduetomovementof water.theP.E(gz) and K.E($\frac{1}{2}c^2$)isisnegligible

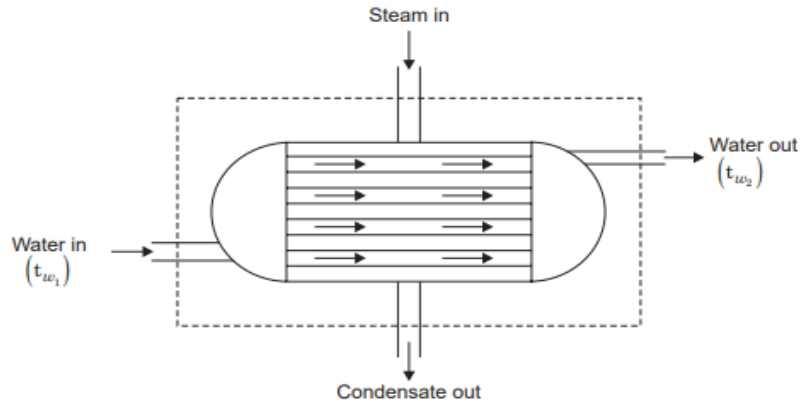
$$\therefore Q = (h_2 - h_1)\text{kJ}$$



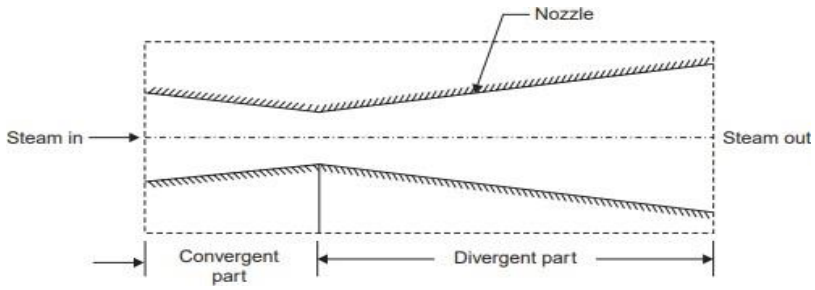
Condenser: Condenseristotransfertheheatfromsteamtocoolant.

Thereisnoworkdone,changeinP.E (gz)andK.E($\frac{1}{2}c^2$)isis negligible

$$Q=(h_2-h_1)\text{kJ}$$



Nozzle : Increasesthevelocityofkineticenergyoftheworking substance at the constant pressure drop.



Noworkdonebythesystem(W=0)

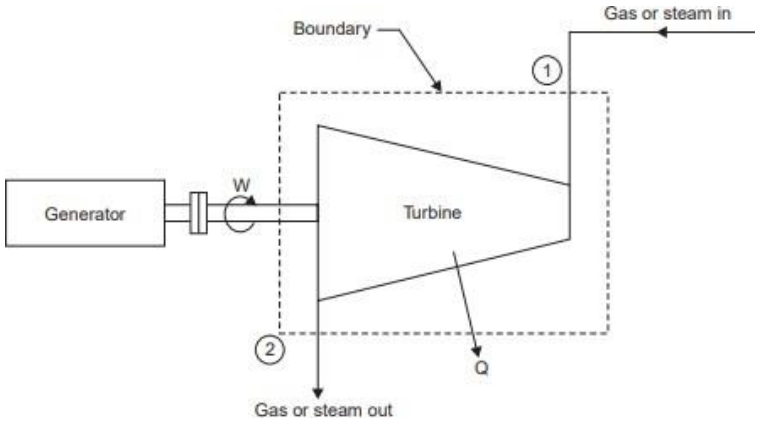
Thereisnoheattransfertakingplace(Q=0) There is no potential energy ($z_1 = z_2$)

$$\frac{C_1^2}{2}+h_1=\frac{C_2^2}{2}+h_2$$

Turbine:convertstheP.Eintomechanicalwork.

$z_1=z_2, C_1=C_2$

Turbineisfullyinsulated.Therefore,thereisnoheattransfer



Q=0

Aircompressor:

- **C**entrifugalCompressor

  No heat transfer

  changeinP.E(gz)andK.E($\frac{1}{2}C^2$)

  W=h_2-h_1

- ReciprocatingCompressor

  Applyingenergyequationtothesystem,

  :ΔP.E =0andΔK.E =0

  sincethesechangesarenegligiblecomparedwithotherenergies.∴

  h_1–Q=h_2–W ($-Wis$workdoneonthesystem)

Statethelimitationsoffirstlawofthermodynamics?

1. FirstLawplacesnorestrictiononthedirectionofaprocess.

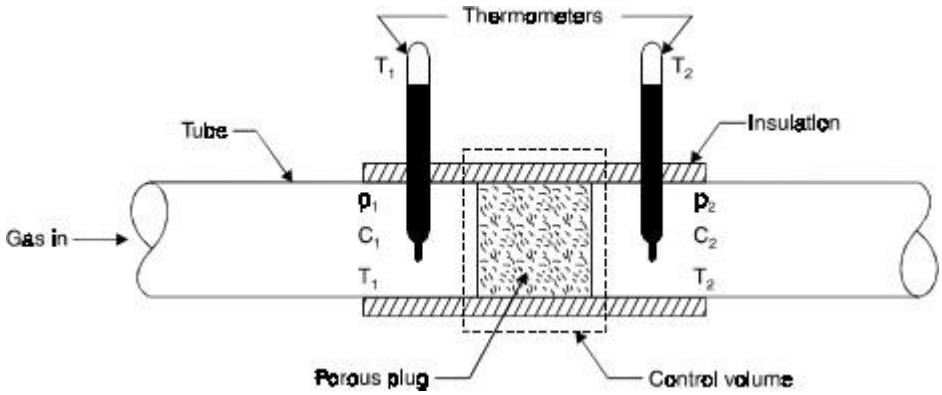
2. Itdoesnotensurewhethertheprocessisfeasibleornot.

3. This law does not differentiate heat and work. It is concerned with the quantity of energy and the transformation of energy from one form to anotherwithnoregardtoitsquality.THROTTLINGPROCESS ANDJOULE-THROTTLING PROCESS AND JOULE-THOMPSON POROUS PLUG EXPERIMENT

Throttlingprocessinvolvesthepassageofa higherpressurefluidthrough a narrow constriction. The effect is the reduction in pressure and increase in volume. This process is adiabatic as no heat flows from and to the

system,butitisnotreversible. Itisnotanisentropicprocess.Theentropy of the fluid actually increases.

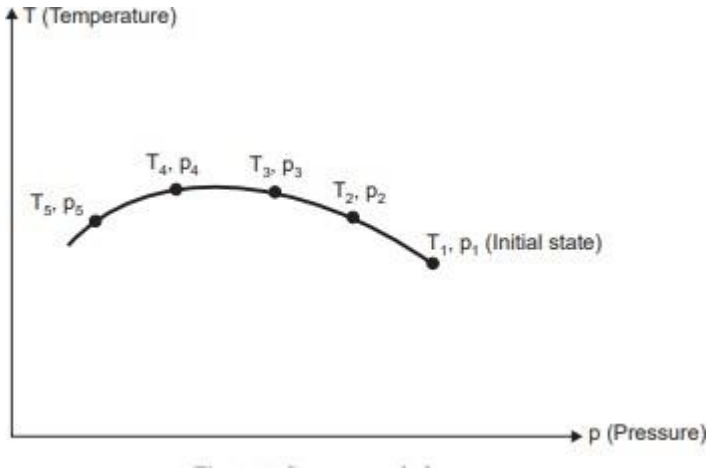
Suchaprocessoccursina flowthrough aporousplug,apartiallyclosed valve and a very narrow orifice.



Inthissystem,

Q=0(Systemisisolated)

W=0 (Thereisnoworkinteraction)



ΔPE=0 (Inletandoutletareatthesamelevel)

ΔKE=0(Kineticenergydoesnotchangesignificantly)

Energyequation to the system

$$h_1=h_2$$

Thisshowsthatenthalpyremainsconstantduringadiabaticthrottling process.

Thethrottlingprocessiscommonlyused forthefollowingpurposes: (i)For determining the condition of steam (dryness fraction).

(ii) Forcontrollingthespeedoftheturbine.

(i) Used inrefrigerationplantforreducingthepressureofthe refrigerant before entry into the evaporator

slopeiscalledJoule-Thompsonco-efficient,μandisgivenby

$$\mu=\left(\frac{\partial T}{\partial p}\right)_h$$

=0forideal gas.

Example : In a gas turbine unit, the gases flow through the turbine is 15 kg/sandthepowerdeveloped bytheturbineis12000kW. Theenthalpies of gases at theinlet and outlet are1260 kJ/kg and 400 kJ/kg respectively, and the velocity of gases at the inlet and outlet are 50 m/s and 110 m/s respectively.

Calculate :

i) Therateatwhichheatisrejectedtotheturbine,and

ii) Thearea oftheinlet pipegiventhat thespecificvolumeofthe gases at the inlet is 0.45 m3/kg.

Solution.

Rateofflowofgases,m=15 kg/s

Volume of gases at the inlet, v = 0.45 m3/kg

Powerdeveloped bytheturbine,P=12000kW

∴Work done,$W=\frac{12000}{15}$ =800kJ/kg

Enthalpyofgasesat theinlet,h_1=1260kJ/kg

Enthalpy of gases at the oulet, h_2 = 400 kJ/kg

Velocity of gases at the inlet, C_1 = 50 m/s

Velocity of gases at the outlet, C_2 = 110 m/s.

Heatrejected,Q:

Usingtheflowequation, $h_1+\frac{C_1^2}{2}+Q=h_2+\frac{C_2^2}{2}+W$

$$1260+\frac{50^2}{2\times1000}+Q=400+\frac{110^2}{2\times1000}+800$$

$$1260+1.25+Q=400+6.05+800$$

$$\therefore Q=-55.2\text{kJ/kg}$$

i.e.,Heatrejected=+55.2kJ/kg=55.2×15kJ/s=828kW. (Ans.)

(ii) Inletarea,A:

Usingtherelation, $m=\frac{C_A A}{v}=\frac{mv}{C}$

$$=\frac{0.45\times50}{50}0.135^2$$

Example:12kgofairperminuteisdeliveredbyacentrifugal air compressor. Theinlet and outlet conditionsofairareC_1 =12 m/s,p_1 =1 bar, v_1= 0.5 m3/kg and C_2= 90 m/s, p_2= 8 bar, v_2= 0.14 m^3/kg. The

increasein enthalpyofairpassingthroughthecompressoris150kJ/kg and heat loss to the surroundings is 700 kJ/min.

Find :(i)Motorpowerrequiredtodrivethecompressor;

(ii)Ratio of inlet to outlet pipe diameter.

Assumethatinletanddischargelinesareatthesamelevel. Solution.

Quantityofairdeliveredbythecompressor,m=^{12}=0.2$\frac{kg}{60}$/s.

Conditionsofairattheinlet1:

Velocity,C_1=12m/s

Pressure,p_1 =1bar=1 ×105 N/m^2 Specific

volume, v_1 = 0.5 m^3/kg

Conditionsofairattheoutlet2:

Velocity,C_2=90 m/s

Pressure,p_2 =8bar= 8×10^5N/m^2 Specific

volume, v_2 = 0.14 m^3/kg

Increaseinenthalpyofairpassingthroughthecompressor, (h_2 – h_1) = 150 kJ/kg

Heatlosttothesurroundings,Q=–700kJ/min=–11.67kJ/s.

(i) Motorpowerrequiredtodrivethecompressor:

Applying energy equation to the system,

$m(gz_1+\frac{C_1^2}{2}+h_1)+Q=m(gz_2+\frac{C_2^2}{2}+h_2)+W$

Forcompressor $z_1=z_2$

$W=m((h_1-h_2)+\frac{C^2-C^2}{\frac{1}{2\times1000}})+Q$

$= -42.46KJ/s \quad =42.46kW$

(ii) Ratioofinlettooutletpipediameter,$\frac{d1}{d_2}$

Themassofairpassingthroughthecompressorisgivenby

$m=\frac{A_1C_1}{V_1}=\frac{A_2C_2}{V_2}$

$\frac{A_1}{A_2}=\frac{C_2}{C_1}\times\frac{v_1}{v_2}=\frac{90}{12}\times\frac{0.5}{0.14}=26.78$

$(\frac{d_1}{d_2})^2=26.78$

$\frac{d_1}{d_2}$=5,175

A turbo compressor delivers 2.33 m3/s at 0.276 MPa, 43°C whichisheatedat thispressureto430°C and finallyexpanded in aturbinewhichdelivers1860kW.Duringtheexpansion,thereis a heat transfer of 0.09 MJ/s to the surroundings. Calculate the turbine exhaust temperature if changes in kinetic and potential energy are negligible.

t=93°C V=2.33m/s; p=0.276MPa;t=930°C

$\frac{dW}{dt}$=1860kW^{dQ}=$\frac{}{dt}$−0.09×1000KJ/s=−90kW

Constantpressureorisobaric process Generalgasequation$\frac{pV}{T}$=C p,VandTrelations $\frac{V1}{T_1}=\frac{V2}{T_2}$ Heatsuppliedtothesystem = $mc_p(T_2-T_1)$ Work done d W= p (V_2-V_1) Changeininternalenergy (Change in enthalpy) dh =d Q=$mc_p(T_2-T_1)$ Change in entropy ΔS=mc_p In $(\frac{T_2}{T_1})$	**Constant temperature or isothermal process** **(**Frictionless piston and cylinder**)** Generalgasequation$\frac{pV}{T}$=C p,VandTrelations $p_1V_1=p_2V_2$ Heatsupplied=workdelivered dQ =dW=$pV_{11}\text{In}(\frac{V_2}{V_1})$ =$pV_{11}\text{In}(\frac{p_1}{p_2})$ Change in internal energy(Changeinenthalpy) ΔU= 0 Changeinentropy ΔS=mRIn$(\frac{V_2}{V_1})$=mRIn$(\frac{p_1}{p_2})$
ReverseAdiabaticProcess {insulatedfrictionlesspistonand cylinder arrangement} noheattransferdQ = 0 GeneralgasequationpV^{γ}=C p,VandTrelations $pV^{\gamma}_{11}=pV^{\gamma}_{22}$ $(\frac{V_1}{V_2})^{\gamma-1}=(\frac{P_2}{P_1})^{\gamma-1}$	**Polytrophic Process(**non-flow polytropic process**)** All the processes like isobaric, isochoric, isothermal, adiabatic, etc.maybedescribedbyequation pV^n= C Where ‘n’ = Index of process. If n=0, then

Heatdelivered Q =0 Workoutputofthesystem dW=$\frac{p_1V_1-p_2V_2}{\gamma-1}$	pV^0=C p=C …Isobaric If n=1,thenpV^1=C pV=C …Isothermal If n=∞,thenpV^∞=C V=C **…**Isochoric If n=γ,thenpV^γ=C V =C…Isentropic

p,VandTrelations $p_1V_1^n=p_2V_2^n$

$$\frac{T_2}{T_1}=\left(\frac{V_1}{V_2}\right)^{n-1}=\left(\frac{P_2}{P_1}\right)^{n-1}$$

Heattransfer

dQ =ΔU+dw

Changeininternalenergy(Changeinenthalpy)

ΔU= mc_v(T_2-T_1)

Workoutputofthesystem

dw=$\frac{p_1V_1-p_2V_2}{n-1}$

Changeinentropy

ΔS =0

Zerothlawof thermodynamics' statesthat IftwobodiesAandBare thermalequilibriumwith third systemCThen thebodiesAandBare thermal equilibrium with each other

a=bandb=c,thena= c.

SteadyFlowEnergyEquation[SFEE]

Consider a steady flow open system as shown Assumptions :

Thefollowingassumptionsaremadeinthesystemanalysis:

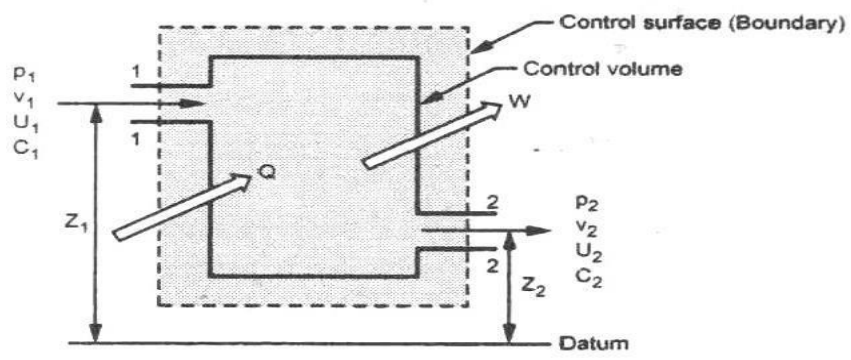
(i) Themassflowthroughthesystemremainsconstant.

(ii) Fluidisuniformincomposition.

(iii) Theonlyinteractionbetweenthesystemand surroundingsarework and heat.

(iv) Thestateoffluidatanypointremainsconstantwith time.

(v) Intheanalysisonlypotential,kineticandflowenergiesare considered.



where,*Q*=Heatsupplied(orenteringtheboundary)perkgoffluid,
W=Work done$^{kJ}/_{kg}$

C=Velocityoffluid ,
Z=Heightabovedatum,
p=Pressureofthefluid,
u=Internalenergyperkgoffluid,and
pv=Energyrequired for1kgoffluid.
This equation is applicable to any medium in

A₁and**A₂**bethecross-

sectionalareaatinletandoutlet**p₁**and**p₂**bethepressurea

tinletandoutlet.

$v_1$and$v_2$bethespecificvolumeatinletandoutlet.

U₁and**U₂**betheinternalenergyatinletandoutlet.

C₁and**C₂**bethevelocityforfluidatinletandoutlet.

If**Q**istheamountofheatinteraction**W**isthework output

Totalenergyenteringthesystem=P.E+K.E+I.E+F.E+Heatenergy

$$=gz_1+\frac{C_1^2}{2}+u_1+p_1v_1+Q$$

Totalenergylivingthesystem=P.E+K.E+I.E+F.E+Work

$$=gz_2+\frac{C_2^2}{2}+u_2+p_2v_2+W$$

Accordingtofirstlawofthermodynamics,

Totalenergy [enteringthesystem] = Totalenergy [leavingthesystem]

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

$$\therefore[h=u+pv]$$

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

Forenergyflowperunitofmass

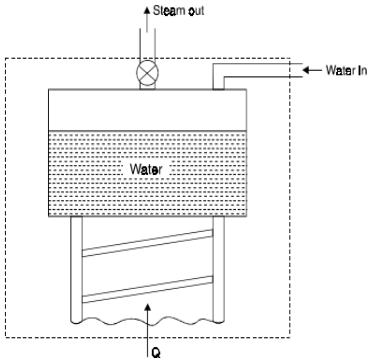
$$m\left(gz_1+\frac{C_1^2}{2}+h_1+Q\right)=m\left(gz_2+\frac{C_2^2}{2}+h_2+W\right)$$

fortheunitofkJ/kg

$$m\left(\frac{gz_1}{1000}+\frac{C_1^2}{2000}+h_1+Q\right)=m\left(\frac{gz_2}{1000}+\frac{C_2^2}{2000}+h_2+W\right)$$

ApplicationofSteadyFlowEnergyEquation

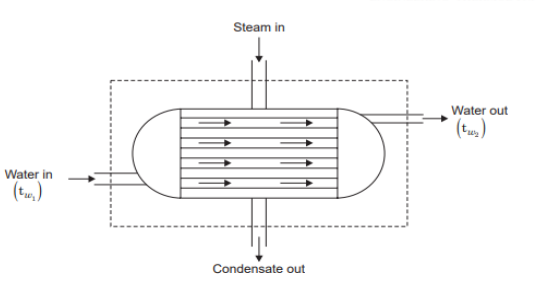
Boiler:(Steamgenerator)



Internal energy (U) exists and flow energyexistsduetomovementofwater. theP.E(gz)andK.E($\frac{1}{2}C^2$)isisnegligible

$$\therefore Q=(h_2-h_1)kJ$$

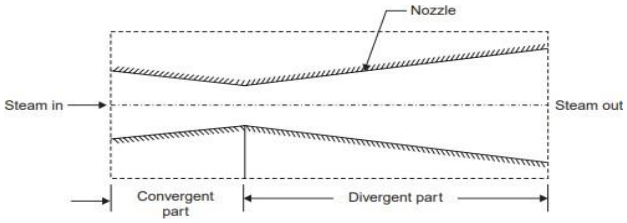
Condenser: Condenseristotransfer the heat from steam to coolant.



Thereisnoworkdone,changein P.E(gz) andK.E ($\frac{1}{2}C^2$)isisnegligible

$$Q=(h_2-h_1)kJ$$

Nozzle: Increasesthevelocityofkineticenergyoftheworking substance at the constant pressure drop.



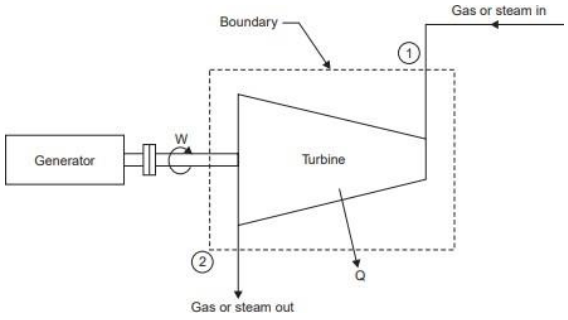
No work done by the system (W=0)

There is no heat transfer taking place (Q =0)

Thereisnopotentialenergy($z_1=z_2$)

$$\frac{c_1^2}{2}+h_1=\frac{c_2^2}{2}+h_2$$

Turbine:convertstheP.Einto mechanical work.



$z_1=z_2, C_1=C_2$

Turbineisfullyinsulated.There fore , there is no heat transfer

Q=0

Aircompressor:

- **C**entrifugalCompressor

  No heat transfer

  changeinP.E(gz)andK.E($\frac{1}{2}c^2$)

  $$W=h_2-h_1$$

- ReciprocatingCompressor

  Applyingenergyequationtothesystem,

  :ΔP.E=0andΔK.E=0

  sincethesechangesarenegligiblecomparedwithotherenergies.∴

  $h_1-Q=h_2-W$ $(-Wis$workdoneonthesystem)

Statethelimitationsoffirstlawofthermodynamics?

1. FirstLawplacesnorestrictiononthedirectionofaprocess.

2. Itdoesnotensurewhethertheprocessisfeasibleornot.

3. Thislawdoesnotdifferentiateheatand work.Itisconcerned with the quantity of energy and the transformation of energy from one form to another with no regard to its quality.

Example1:Afluidsystem,containedinapistonand cylindermachine, passes through a complete cycle of four processes. The sum of all heat transferredduringa cycleis–340kJ.Thesystemcompletes200cycles per min.

Completethe followingtableshowing themethodforeachitem,and compute the net rate of work output in kW.

Process	Q(kJ/min)	W(kJ/min)	ΔE(kJ/min)
1—2	0	4340	—
2—3	42000	0	—
3—4	–4200	—	–73200
4—1	—	—	—

Solution.

Sum of all heat transferred during the cycle = – 340 kJ.

Numberofcyclescompletedbythesystem=200cycles/min.

Totalheatenergy =–340×200=–68000kJ/min

Process1—2: Q = ΔE+ W =ΔE+ 4340 ∴ **ΔE=–4340kJ/min.**	**Process2—3:** Q= Δ E+W 42000=ΔE+0 **Δ E=42000 kJ/min.**	**Process3—4:** Q =ΔE+ W –4200=–73200+W **∴W=69000kJ/min.**

Process4—1:

ΣQ_{cycle}=–340kJ

$Q_{1-2}=Q_{2-3}+Q_{3-4}+Q_{4-1}$=–68000kJ/min

0+42000+ (–4200)+ Q_{4-1}=–68000Q_{4-1}=–105800kJ/min.

TotalinternalenergyΔUorΔE

∫dE=0,sincecyclicintegralofanypropertyis zero.

$\Delta E_{1-2}+\Delta E_{2-3}+\Delta E_{3-4}+\Delta E_{4-1}=0$

$-4340+42000+(-73200)+\Delta E_{4-1}=0$

$\therefore \Delta E_{4-1}=35540$ kJ/min.

$\therefore$ Workdown by system $W_{4-1}= Q_{4-1}-\Delta E_{4-1}$

$=-105800-35540=-141340$kJ/min

Example2:System of volume Vcontains amassm ofgasatpressure p andtemperatureT.Themacroscopicpropertiesofthesystemobeythe following relationship:

$$\left(p+\frac{a}{V^2}\right)(V-b)=mRT$$

Wherea,b,andRareconstants.
Obtain an expression for the displacement work done by the system duringaconstant-temperatureexpansionfromvolume V_1tovolumeV_2. Calculate the work done by a system which contains 10 kg of this gas expanding from 1$m^3$to 10 m^3at a temperature of293 K. Use the values a = 15.7 ×10 Nm^4 , b = 1.07 ×10$^{-2}m^3$, and R = 0.278 kJ/kg-K.

$$\left(p+\frac{a}{V^2}\right)(\mathbf{V}-b)=\mathbf{k(mRT)}$$

$\left(p+\frac{a}{V^2}\right)=\frac{k}{(\mathbf{V}-b)}$;p= $\frac{k}{(\mathbf{V}-b)}-\frac{a}{V^2}$

$\left(p_1+\frac{a}{V_1{}^2}\right)(V_1-b)=\left(p_2+\frac{a}{V_2{}^2}\right)(V_2-b)=\mathbf{k(mRT)}$

$\mathbf{W}=\int_1^2 p\,dV$

$$= \int_1^2\left(\frac{k}{(\mathbf{V}-b)}-\frac{a}{V^2}\right)$$

$$= \left[kIn(V-b)+\frac{a}{V}\right]$$

$=kIn\left(\frac{V_2-b}{V_1-b}\right)+a\left(\frac{1}{V_2}-\frac{1}{V_1}\right)$

Given m=10kg;T=293 K;R=0.278kJ/kg.K

$\therefore$ Constant k=10×293×0.278kJ=814.54kJ a =

15.7 × 10 Nm^4; b = 1.07 × 10^{-2}m^3

$\Rightarrow V_2$ =10m3,V_1 =1m^3

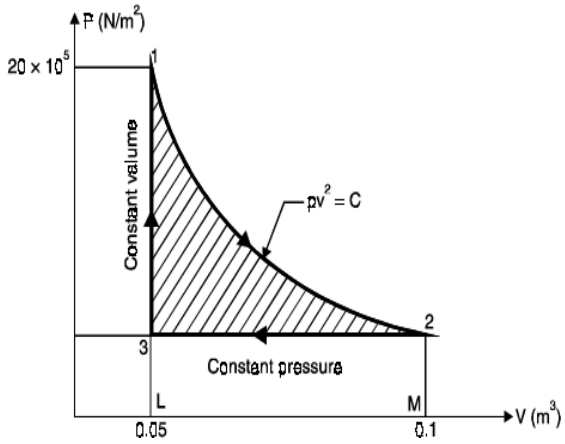
$=814.54\text{In}\left(\frac{10-1.07\times10^{-2}}{1-1.07\times10^{-2}}\right)+a\left(\frac{1}{10}-\frac{1}{1}\right)$

= 1742.14kJ

Example3:A cylinder contains 1 kg of a certain fluid at an initial pressureof20bar.Thefluidisallowedto expand reversiblybehinda piston according to a law

$$pV^2=\text{constant}$$

until the volume is doubled. The fluid is then cooled reversibly at constant pressure until the pistonregains its original position ; heat is then supplied reversibly with the piston firmly locked inposition until thepressure risestotheoriginal value of20bar.Calculatethe network done by the fluid, for an initial volumeof0.05 m³.



Massoffluid,m=1kg
p_1=20bar=20×10^5N/m^2
V_1=0.05m^3 $v_2=2V_1$

Consideringtheprocess1 $p_1{V_1}^2=p_2{V_2}^2$ $p_2=p_1\frac{{V_1}^2}{{V_2}^2}=p_1\frac{{V_1}^2}{2{V_1}^2}$ $=20\frac{V1}{2{V_1}^2}$:$\frac{20}{4}$=5bar	**Workdonebythefluidfrom1to2 W =** $\int_1^2 p\,dV$ $W_{1-2}=\int_{1V^2}^{2C}\underline{dv}$, whereC=$p_1{V_1}^2=20\times0.05^2$barm$^6_{0.1}$ $W_{1-2}=10^5\times20\times0.0025\left[\frac{1}{-V}\right]_{0.05}$ **=50000Nm**

Workdoneonfluidfrom2to3 (underconst.Pr..)

$$p_2(V_2-V_3)=10^5\times5\times(0.1-0.05)=25000\text{Nm}$$

Workdoneduringtheprocess3-1(*Volumeremainsconstant*)

W=0,

∴Networkdonebythefluid

Process1-2,2-3,3-1

=50000–25000+0

=25000Nm.(Ans.)

Example. Thefollowingequationgivestheinternalenergyofacertain substance

$$u=3.64pv+90$$

whereuiskJ/kg,pisinkPaandvisinm3/kg.

******Example4:A system composed of 3.5 kg of this substance expands from an initial pressure of 500 kPa and a volume of 0.25 m3 to a final pressure100kPainaprocessinwhich pressureandvolumeare related by***

$pv^{1.25}$=constant.

***(i) Iftheexpansionisquasi-static,*u=3.64 pV+90**

find Q,∆UandW fortheprocess.

(ii) Inanotherprocess,thesamesystem expandsaccordingtothesame pressure-volume relationship as in part and from the same initial state to the same final state as in part but the heat transfer in this case is 32 kJ.

Findtheworktransferforthisprocess.

(iii) Explainthedifferenceinworktransferinparts(i)and(ii).

Solution.

Internalenergyequation:u=3.64pv+90 Initial volume, $V_1 = 0.25\ m^3$

Initialpressure,p_1=500kPa

Final pressure, $p_2 = 100$ kPa

Process : $pv^{1.25}$ = constant.

$$pV_1^{1.25}=pV_2^{1.25}$$

$$V_2=V_1\left(\frac{p_1}{p_2}\right)^{\frac{1}{1.25}} \quad =0.25\left(\frac{500}{100}\right)^{\frac{1}{1.25}}$$

$=0.906m^3$

Now, u=3.64pv+90

$$\Delta u = u_2 - u_1$$

$$=3.64\ (p_2v_2 - p_1v_1)$$

$\therefore \Delta U = 3.64(p_2v_2 - p_1v_1)$

$\Delta U = 3.64(100\times10^3\times0.906 - 500\times10^3\times0.25)J[1Pa=1N/m^2]$

$= 3.64\times105\ (0.906 - 5\times0.25)J$

$= -3.64\times105\times0.344J = -125.2kJ$

i.e.,ΔU=–125.2 kJ.(Ans.)

Foraquasi-staticprocess Workdone

W

$$W = \int pdv = \frac{p_1V_1 - p_2V_2}{n-1}$$

$$= \frac{500\times10^3\times0.25 - 100\times10^3\times0.906}{(1.25-1)} = \frac{125-90.6}{0.25}$$

=137.6Kj

HeattransferQ

$\therefore Q = \Delta U + W$

$= -125.2 + 137.6 = 12.4Kj$

i.e.,Q=12.4kJ.(Ans.)

(ii)AtfinalstatesQ=32 kJ

$\therefore W = Q - \Delta U = 32 - (-125.2) = 157.2kJ.(Ans.)$

(iii)Theworkin(ii)isnotequal to$\int$pdVsince theprocessisnot quasi-static.

Example5: The properties of a system, during a reversible constant pressure nonflow process at p = 1.6 bar, changed from v_1= 0.3 m^3/kg, T_1=20°Ctov$_2$=0.55m3/kg,T_2=260°C.The specific heatofthe fluid is given by

$c_p = (1.5 + \frac{75}{T+45})$ ***kJ/kg°C,whereTisin°C.***

Determine:

(i)Heatadded/kg; (ii)Workdone/kg;

(iii) Change in internal energy/kg ; (iv)Changein enthalpy/kg.

Solution.

Initialvolume,$v_1 = 0.3m^3/kg$

Initial temperature, T_1 = 20°C
Finalvolume,v_2=0.55m3/kg
Finaltemperature, T_2 =260°C
Constantpressure,p=1.6bar=1.6× 10^5
Specificheatatconstantpressure,c_p=$(1.5+\frac{75}{T+45})$ TkJ/kg°C

(i) The **heatadded** perkgoffluidisgiven by

$$Q=\int_{T_1}^{T_2} C_p\,dT=\int_{20}^{260}\left(1.5+\frac{75}{T+45}\right)dT$$

$$=|1.5T+75\log(T+45)|_{20}^{260}$$

Heatadded=475.94kJ/kg.

(ii) Theworkdoneperkgoffluidisgivenby

$$W=\int_{v_1}^{v_2} p\,dv=p(v_2-v_1)$$

$$=1.6\times10^5(0.55-0.3)\text{N-m}$$

$$=40\times10^3\text{J}=40\text{kJ}$$

∴Workdone=40kJ/kg.(Ans.)

(iii) Changeininternalenergy,

$$\Delta u= Q-W=475.94-40$$

=435.94kJ/kg.(Ans.)

(iv) Changeinenthalpy,(fornon-flowprocess)

$$\Delta h=Q=475.94\text{kJ/kg.(Ans.)}$$

Example6:90kJ ofheatare supplied toa system ata constant volume. Thesystem rejects95kJofheatat constantpressureand18kJofwork is done on it. The system is brought to original state by adiabatic process. Determine:

(i) Theadiabaticwork;

(ii) The valuesofinternalenergyatall end statesifinitialvalueis 105 kJ.

Solution.

Heat supplied at constant volume = 90 kJ

Heatrejectedatconstantpressure=–95kJ

Workdoneonthesystem=–18 kJ

Initialvalueofinternalenergy,U_l=105 kJ

Processl–m(constantvolume)	**Processm–n(constantpressure)**
workdone=0 $Q_{l–m}=90=U_m–U_l$ $\therefore U_m=U_l+90=105+90$ **=195kJ**	$Q_{m–n}=(U_n–U_m)+W_{m–n}$ – 95 = $(U_n – U_m) – 18$ $\therefore U_n–U_m=–77$ kJ $U_n=195–77=118$kJ

$Q_{n–l}$=0beingadiabaticprocess

$\therefore \delta Q = 90 – 95 = – 5$ kJ

$\delta W=–18+W_{n–l}=–5$

$\therefore W_{n–l}= –5+18=13$kJ

Hence, $W_{n–l}$= 13kJ ;U_l=105kJ; U_m= 195kJ; U_n=118kJ. (Ans.)

= 475.94 kJ ∴ Heat added = 475.94 kJ/kg. (Ans.

Example7 : 0.1 m^3 of an ideal gas at 300 K and 1 bar is compressed adiabaticallyto8bar. Itisthencooledatconstantvolumeand further expanded isothermally so as to reach the condition from where it started. Calculate :

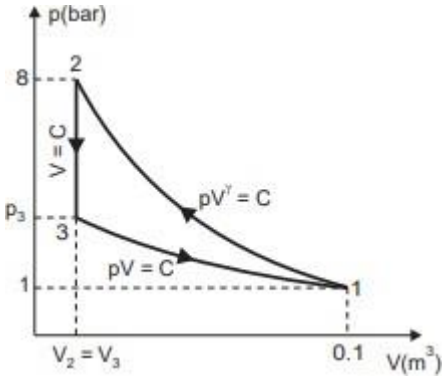
(i) Pressureattheendofconstantvolumecooling.

(ii) Changeininternalenergyduringconstantvolumeprocess.

(iii) Networkdoneandheattransferredduringthecycle.

Assume c_p= 14.3 kJ/kg K and c_v= 10.2 kJ/kg K.

Solution.Given :V_1 =0.1m^3; T_1 =300K; p_1=1bar; c_p = 14.3 kJ/kg K ; c_v = 10.2 kJ/kg K.



RefertoFig.

(i) Pressureattheendofconstantvolumecooling,p:

$$\gamma = \frac{c_p}{c_v} = \frac{14.3}{10.2} = 1.402$$

Characteristicgasconstant,R

$R = c_p - c_v = 14.3 - 10.2 = 4.1 kJ/kgK$

Consideringprocess1-2,

Rev.adiabatically

$p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$

$$\left(\frac{V_1}{V_2}\right)^{\gamma-1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1}$$

$$V_2 = V_1 \times \left(\frac{p_1}{p_2}\right)^{\frac{1}{\gamma}} = 0.1 \times \left(\frac{8}{1}\right)^{\frac{1}{1.402}}$$

$= 0.0227 m^3$

Also,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{8}{1}\right)^{\frac{1.402-1}{1.402}} = 1.815$$

$T_2 = T_1 \times 1.815 = 300 \times 1.815 =$ **544.5K**

Consideringprocess3–1,

$p_3 V_3 = p_1 V_1$

$$\therefore p_3 = \frac{p_1 V_1}{V_3} = \frac{1 \times 0.1}{0.0227} = 4.4 bar. (Ans.)$$

(ii) Changeininternalenergyduringconstantvolumeprocess,(U3–U2)

$$\text{Massofgas, } m = \frac{p_1 V_1}{RT_1} = \frac{(1 \times 10^5) \times 0.1}{4.1 \times 1000 \times 300} = 0.00813 kg$$

Change in internal energy during constant volume process 2–3,

$$U_3 - U_2 = mc_v(T_3 - T_2) = 0.00813 \times 10.2\ (300 - 544.5)$$

$(T_3 = T_1)$

= **–20.27kJ.**(Ans.)(–vesignmeansdecreaseininternalenergy)

iii)Networkdoneandheattransferredduringthecycle:

*Example8:**Amassofgasiscompressedina quasi-staticprocess from 80 kPa, 0.1 $m^3$to 0.4 MPa, 0.03 m^3. Assuming that the pressure and volume are related by pv^n = constant, find the work done by the gas system.***

solution: initialpressurep_1= 80kPa

InitialvolumeV_1=0.1m^3

Finalpressure(p_2)=0.4MPa=400kPa Final volume (V_2) = 0.03 m^3

Asp-Vrelation pV^n=C

$p_1V_1^n$=$p_2V_2^n$takin g $\log_e$ both side

nIn $(\frac{V_1}{V_2})$ =In $(\frac{P_1}{P_2})$

$$\mathbf{n= \frac{In(\frac{P_1}{P_2})}{In(\frac{V_1}{V_2})} = \frac{In(\frac{400}{80})}{In(\frac{0.1}{0.03})} = \frac{1.60944}{1.20397} =1.34}$$

$$\textbf{Work downW = dW } = \frac{p1V1-p2V2}{n-1} = \frac{80\times0.1-400\times0.03}{1.34-1}$$

$$=-11.764kJ$$

*Example9:**Amassofairisinitiallyat260°C and700kPa,andoccupies 0.028 m^3. The air is expanded at constant pressure to 0.084 m^3. A polytropic processwith n - 1.5 is then carried out followed by a constant temperature process which completes a cycle. All the process are reversible.***

i) Sketchthecycleinp-Vplanes.

ii) Findtheheatreceivedand heatrejectedinthecycleUi)Find the efficiency of the cycle

Sol. : Given : $T_1=T_3=260+273=533K$,

p_1p_2 = = 700 KPa= 700 kN/m^2

$V_1=0.028m^3$,V_2 =0.084m^3, pV^{15} =Constant (n=1.5given) process

1- 2=cont . pressure (p = C)

process2-3=polytropicprocess($Pv^{1.5}$ =constant) process

1- 3=cont .temperature(T= constant)

Calculatemassofair

Gasequation,P_1V_1=**mRT1**

$$m=\frac{p1V1}{mT_1}=\frac{700\times0.028}{0.287\times533}=$$ **0.1283 kg**

Heatsupplied onprocess1-2(cont.pressure) $P_1=P_2$

$$\frac{p_1V_1}{T_1}=\frac{p_2V_2}{T_2}$$

$$\frac{700\times0.028}{533}=\frac{700\times0.084}{T_2}$$

T_2=1599K

Heattransfer

Q= $mc_p(T_2-T_1)$

=01264×1.055×(1599−533)

$Q_{1\text{-}2}$=137.13kJ

Heattransferduringprocess2 -3

$$Q_{2\text{-}3}=m\,c_v\,(T_3-T_2)\left(\frac{n-\gamma}{n-1}\right)$$

$$=0.0128\times0.718\times\left(\frac{1.5-1.4}{1.5-1}\right)\times(533-1599)$$

$$=-19.594$$

Heattransferduringprocess3–1

$$\frac{P_2}{P_1}=\left(\frac{T_2}{T_1}\right)^{\frac{1.5}{1.5-1}}=$$

$$\frac{700}{p_3}=27$$

p_3=25,93kPa

HeattransferQ3-1=$mRT_1In\frac{P3}{P_1}$

$$=0.128\times0.287\times533In\frac{25.93}{700}$$

$= -64.53$ **kJ**(– v sign heatrejectedfromsystem)

Heat suppliedQS = 137.5Kj

Heat rejected$Q_R = Q_{R1} + Q_{R2}$

$=19.594 + 64.53$

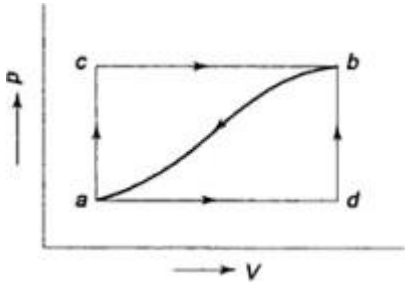
$=84.124$

Efficiencyofcycleη

$$\eta = \frac{Q_S - Q_R}{Q_S} = \frac{137.13 - 84.124}{13.713}$$

η= 38.654%

Example10A When a system is taken from state a to state b, in Fig. Ex. along path acb, 84 kJ of heat flow into the system, and the system does 32 kJ of work, (a) How much will the heat that flows into the system along path adb be, if the work done is 10.5 kJ? (b) When the system is returned from bto aalongthe curved path, the work doneonthe system is 21 kJ. Does the system absorb or liberate heat, and how much of the heat is absorbed or liberated? (c) If U_a= 0 and U_d= 42 kJ, find the heat absorbed in the processes ad and db.



Q_{acb}=84kJW_{acb}=32kJ

$Q_{acb} = U_b - U_a + W_{acb}$

$U_b - U_a = 84 - 32 = 52$kJ

$Q_{adb} = U_b - U_a + W_{adb}$

=52+10.5=62.5kJ

Q_{b-a}= U_a–U_b+ W_{b-a}

=–52–21=–73kJ

Thesystemliberates73kJofheat W_{adb}

= W_{ad}+ W_{db} = W_{ad} = 10.5k J

Q_{ad}=U_d–U_a+W_{ad}

= 42–0+10.5= 52.5kJ

S.F.E.E.

SteadyflowEnergyequation

$Q - W$=m[Δh+ΔK.E +ΔP.E]

ΔK.E= $\frac{C_1^2 - C_2^2}{2000KG}$ kJ,ΔP.E=g($\frac{z_1 - z_2}{1000}$) $\frac{kJ}{KG}$

Δh=($h_2 - h_1$)orc_p($T_2 - T_3$)orΔu+ΔpV

Massflowrate $\dot{m} = \frac{mass}{sec}$ kg/s.

Example1 :*10 kg of fluid per minute goes through a reversible steady flowprocess. Thepropertiesoffluidat the inletare :p_1=1.5bar,ρ_1=26 kg/m3, C_1 = 110 m/s and u_1= 910 kJ/kg andat the exit are p_2= 5.5 bar, ρ_2=5.5kg/m3, C_2=190m/sandu_2 =710kJ/kg.Duringthepassage, the fluid rejects 55 kJ/s and rises through 55 metres. Determine :*
(i) *Thechangeinenthalpy*(*Δh*);
(ii) *Workdoneduringtheprocess*(*W*).

Solution.
Flowoffluid =10kg/min

Propertiesoffluidattheinlet: *Pressure, p_1=1.5bar=1.5×105N/m^2 Density, ρ_1 = 26 kg/m^3 Velocity,C_1=110 m/s Internalenergy,u_1=910kJ/kg*	*Properties of the fluid at the **exit** : Pressure, p_2 = 5.5 bar = 5.5 × 10^5 N/m^2 Density,ρ_2 =5.5kg/m^3 Velocity, C_2 = 190 m/s*

Internalenergy,u_2=710kJ/kg

Heatrejectedbythefluid,Q=55kJ/s
Rise is elevation of fluid = 55 m.
(i) Thechangeinenthalpy,
Δh= Δu+ Δ(pv)

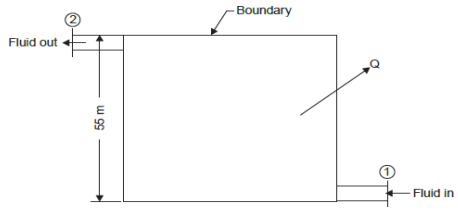
$\Delta(pv)=\frac{p2v2-p1v1}{1}$; $\frac{p2}{\rho_2}=\frac{p1}{\rho_1}(v=\frac{1}{\rho})$

$$\frac{5.5\times10^5}{5.5}-\frac{1.5\times\ 10^5}{26}$$

$= 1\times10^5-0.0577\times 10^5$

$=10^5\times0.9423$NmorJ=94.23kJ

$\Delta u=u_2-u_1=(710-910)=-200$kJ/kg
Substituting the value in eqn. (*i*), we get
$\Delta h=-200+94.23=$**–105.77kJ/kg.(Ans.)**



SteadyflowEnergyequation

$Q-\dot{}\ W$=m[Δh+ΔK.E +ΔP.E]

ΔK.E= $\frac{C_1^2-C_2^2}{2000KG}$kJ,ΔP.E=g($\frac{z_1-z_2}{1000}$) $\frac{kJ}{KG}$

/M-therm/Th4-4.pm5

Q=55kJ/s =$\frac{55}{\frac{10}{60}}$**=330kJ/kg**

Now,Δ$KE=\frac{C^2-C^2}{\frac{1\quad 2}{2000}}=\frac{190^2-110^2}{2000}$ =12000J
= 12kJ/kg
ΔPE =(Z_2–$Z1$)g= (55–0)×9.81NmorJ=539.5J
=0.54kJ/kg

Substitutingthevalueinsteadyflowequation, –
330 = 12 + 0.54 – 105.77 + *W*
***W* =–236.77kJ/kg.**
Workdonepersecond=–236.77×$\frac{10}{60}$==–39.46kJ/s
=–39.46kW. (Ans.)

Example 2:Air at a temperature of 15°C passes through a heat exchanger at a velocity of 30 m/s where its temperature is raised to 800°C. It then enters a turbine with the same velocity of 30 m/s and expands until the temperature falls to 650°C. On leaving the turbine,the air is taken at a velocity of 60 m/s to a nozzle where it expands until the temperature has fallen to 500°C. If the air flow rate is 2 kg/s, calculate(a)therateofheattransfertotheairintheheatexchanger,
(b) the poweroutput from the turbine assuming no heat loss, and (c)the velocity at exit from the nozzle, assuming no heat loss. Take theenthalpy of air as h = cj, where $c_p$is the specific heat equal to 1.005 kJ/kg K and t the temperature.

Solution*As shown in Fig. writing the S.F.E.E. for the heat exchanger and eliminating the terms not relevant,*

Inlet of heat exchanger	T_1=15+273=288k	c_1=30m/s
turbine	T_2=800+273=1073	c_2=30m/s
Nozzle inlet	T_3=650+273=923k	c_3=60m/s
Nozzleoutlet	T_3=500+273=773k	c_4=?

airflow ratew=2 kg/s,specificheatc_p=1.005

enthalpy of air as h = $c_p t$

Tofind:

(a) heattransfertotheairintheheatexchanger,

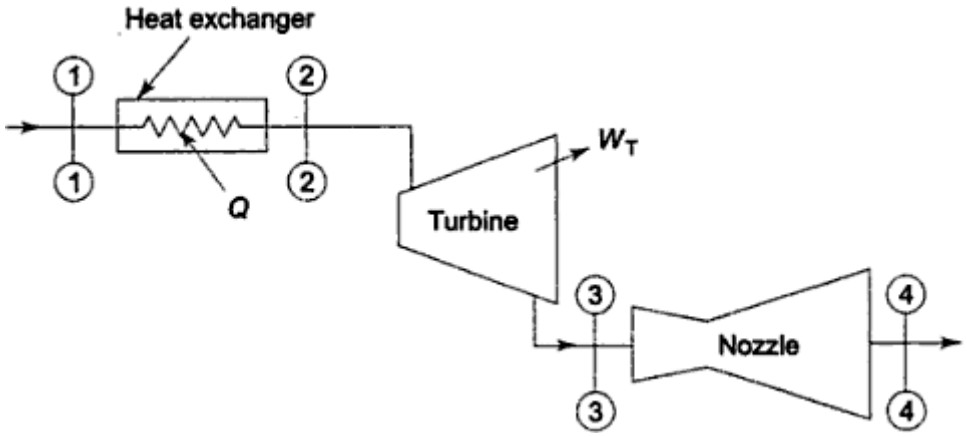
(b) thepoweroutput

(c) thevelocityatexitfromthenozzle

SteadyflowEnergyequation

$$m(gz_1+\frac{C_1^2}{2}+h_1)+Q=m(gz_2+\frac{C_2^2}{2}+h_2)+W$$

$Q-W$=m[Δh+ΔK.E +ΔP.E]



ΔK.E= $\frac{C_1^2 - C_2^2}{2000KG}$ kJ, ΔP.E=g($\frac{z_1 - z_2}{1000}$) $\frac{kJ}{KG}$

Inheatexchanger

$W_{1\text{-}2}=0$ $z_1=z_2$

SteadyflowEnergyequationreduces to

m($\frac{C_1^2}{2}$ $+h_1$)+Q=m($\frac{C_2^2}{2}$ $+h_2$)

Fromgiven data $c_1=c_2$ Q

$= m(h_2 - h_1)$; $m\, c_p(T_2 - T_1)$

$=mc_p(T_2 - T_1)$ $=2\times1.005\times(1073-288)$

$Q_{1\text{-}2}$=1577.85kw

Forturbine2-3

$Q_{2\text{-}3}$=0 $z_2=z_3$

SteadyflowEnergyequationreduces to

m($\frac{C_2^2}{2}$ $+h_2$)= m($\frac{C_3^2}{2}$ $+h_3$)+W

$\Delta h=(h_2-h_1)$ or $c_p(T_2-T_3)$ or $\Delta u+\Delta pV$

$W+(h_2-h_3)+(\frac{C_2^2}{2000} - \frac{C_3^2}{2000})$

$$\mathbf{W}+c_p(T_2-T_3);+(\frac{C_2^2}{2000}-\frac{C_3^2}{2000})$$

$$W+I.005(1073-923)+(\frac{30^2}{2000}-\frac{60^2}{2000})$$

W= 2988kW

Fornozzle3-4

Assumethat$Q_{3-4}=0$ $z_3=z_4$*(adiabaticnozzle)and*$W_{3-4}=0$

SteadyflowEnergyequationreduces to

$$c_p(T_3-T_4)+\frac{C_3^2-C_4^2}{2000}$$

$$1.005(923-773)+\frac{60^2-C_4^2}{2000}$$

$$\boldsymbol{C_4}\ \mathbf{=552.36}\frac{m}{s}$$

Example 3:In a gas turbine unit, the gases flow throughthe turbine is 15 kg/s and thepower developed by the turbine is 12000 kW. The enthalpiesofgasesattheinletandoutletare1260kJ/kgand400kJ/kg respectively, and the velocity of gases at the inlet and outlet are50 m/s and 110 m/s respectively. Calculate :
(i) Therateatwhichheatisrejectedtotheturbine,and
(ii) Theareaofthe inletpipegiventhatthespecificvolumeofthegases at the inlet is0.45 m3/kg.

Solution.Rate of flow of gases, m = 15 kg/s

Volume of gases at the inlet, v = 0.45 m^3/kg

Powerdevelopedbytheturbine, P=12000kW

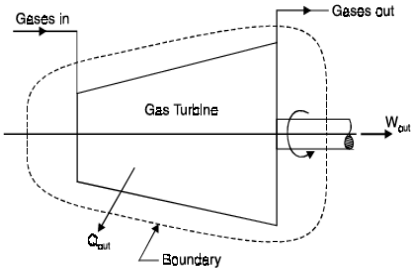
∴Workdone,W=$\frac{12000}{15}$=800kJ/kg

Enthalpyofgasesattheinlet,h_1 =1260kJ/kg

Enthalpy of gases at the oulet, h_2 = 400 kJ/kg

Velocity of gases at the inlet, C_1 = 50 m/s

Velocity of gases at the outlet, C_2 = 110 m/s.



SteadyflowEnergyequation

$$Q - W = m[\Delta h + \Delta K.E + \Delta P.E]$$

$\Delta h = (h_2 - h_1) = (400 - 1260) = -860 kJ/kg$

$\Delta P.E = 0$[***gasturbine*** $z_1 = z_2$]

$\Delta K.E = \frac{c_2^2 - c_1^2}{2000} kJ/kg$

$= \frac{110^2 - 50^2}{2000} = 4.8 kJ/kg$

$Q = 15\ (800 - 860 + 4.8) = 828 kJ/s$

Heatrejected=828kW. (Ans.)

ii)**Inletarea,A:**
Usingtherelation,

$\dot{m} = \frac{CA}{v}$

$$A = = \frac{\dot{m} v}{C} = \frac{0.45 \times 15}{50} = 0.135 m^2$$

A=0.135m2.(Ans.)

Example4:*Steamata6.87bar,205°C,entersinaninsulated nozzle with a velocity of50 m/s. It leaves at a pressure of 1.37 bar and a velocity of 500 m/s. Determine the final enthalpy of steam*.

Solution.Pressureofsteamattheentrance,p_1=6.87bar

Thevelocitywith whichsteamentersthenozzle, C_1 =50 m/s Pressure of steam at the exit, p_2 = 1.37 bar

Velocityofsteamattheexit, C_2=500 m/s.

Tofind:***finalenthalpyofsteam*.**

SteadyflowEnergyequation

$$Q - W = m[\Delta h + \Delta K.E + \Delta P.E]$$

Consideringthe*insulatednozzle*
— thereis*noworktransfer*(*i.e.,W*=0)
— thereis*noheattransfer*(*i.e.,Q*=0).
— thechangeinpotentialenergyisnegligible[*i.e.* $(Z_2 - Z_1)g = 0$].
Massflowratem=1

Equationbecome$\Delta h + \Delta K.E = 0$

Fromsteamtablecorrespondingto6.87bar, h_1=2850kJ/kg

$\Delta h = (h_2 - h_1) = (h_2 - 1260)$

$\Delta P.E = 0$[***gasturbine*** $z_1 = z_2$]

$$\Delta K.E = \frac{c_2^2 - c_1^2}{2000} kJ/kg$$

$$= \frac{500^2 - 50^2}{2000}$$

$$(h_2 - h_1) + \frac{c_2^2 - c_1^2}{2000}, (h_2 - 1260) + \frac{500^2 - 50^2}{2000}$$

h_2=2726.25kJ

Hencefinalenthalpyofsteam=2726.25kJ.(Ans.)

Example 5:12 kg of air per minute is delivered by a centrifugal air compressor. Theinlet and outlet conditionsofairare C1 =12 m/s, p1 = 1bar, v1=0.5m3/kgandC2 =90m/s,p2 =8bar,v2 =0.14m3/kg.The increase inenthalpy of air passing throughthe compressor is150 kJ/kg and heat loss to the surroundings is 700 kJ/min.Find : (i)Motor power required to drive the compressor ;
(ii)Ratioofinlettooutletpipediameter.
Assumethatinletanddischargelinesareatthesamelevel.
Solution. Quantityofairdeliveredbythecompressor,$m = \frac{12}{60} = 0.2$kg/s.

Conditionsofairattheinlet1:

Velocity,C_1=12m/s

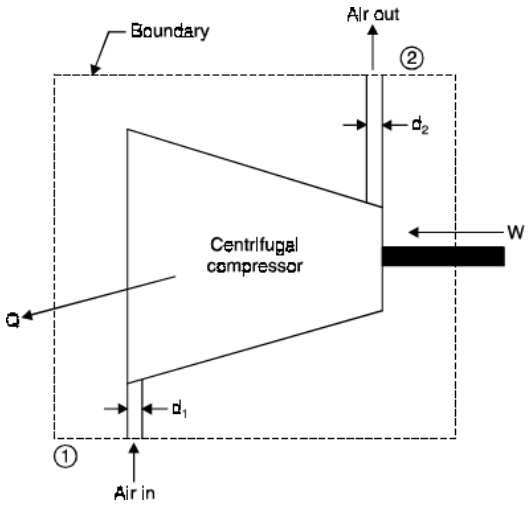
Pressure,p_1=1bar=1×10^5N/m^2

Specificvolume, v_1=0.5m^3/kg

Conditionsofairattheoutlet2:

Velocity,C_2=90m/s

Pressure,p_2 =8bar=8×10^{5}N/m^2



Specificvolume,v_2=0.14m^3/kg

Increaseinenthalpyofairpassingthroughthecompressor, (h_2 – h_1) = 150 kJ/kg

Heatlost tothesurroundings,

Q=–700kJ/min=–11.67kJ/s.

i) **Motorpowerrequiredtodrivethecompressor:**

SteadyflowEnergyequation

$$Q - W = m[\Delta h + \Delta K.E + \Delta P.E]$$

$$\Delta P.E = 0 \text{ [for } \textbf{compressor}\text{]}$$

$$Q - W = m[\Delta h + \Delta K.E]$$

$\Delta h = (h_2 - h_1)$;(h_2–h_1)=150kJ/kg

Δh=150kJ/kg

$$\Delta K.E = \frac{c_2^2 - c_1^2}{2000} kJ/kg$$

$$= \frac{12^2 - 90^2}{2000} = 3.978 kJ/kg$$

$$-11.67 - \dot{W} = 0.2[-150 + 3.978]$$

$$\dot{W} = = -42.46 kJ/s = -42.46 kW$$

Motor power required (or work done on the air) = 42.46 kW. (Ans.)

ii) **Ratio of inlet to outlet pipe diameter, $\frac{d1}{d_2}$**

The mass of air passing through the compressor is given by

$$m = \frac{CA}{v} \quad m = \frac{C_1 A_1}{v_1} = \frac{C_2 A_2}{v_2}$$

$$\frac{A_1}{A_2} = \frac{C_2}{C_1} \times \frac{v_1}{v_2} = \frac{90}{12} \times \frac{0.5}{0.14} = 26.78$$

$$\left(\frac{d_1}{d_2}\right)^2 = 26.78$$

Hence ratio of inlet to outlet pipe diameter = 5.175. (Ans.)

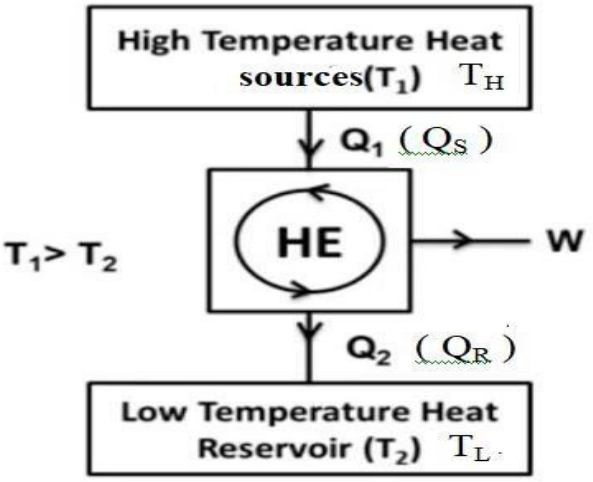
Unit-2

HeatEngine

HeatEngines:Heatengineisacyclicdevice,usedtoconvertheattowork.

Heatenginecanbecharacterizedbythefollowingpoints.

1. Theyreceiveheatfromahightemperaturesource(solarenergy,oil- furnace etc.)
2. They convert part of this heat to work (usually in the form of a rotating shaft)
3. Theyrejecttheremainingwasteheattoalowtemperaturesink(the atmosphere, rivers, etc)
4. Theyopertateonacycle.



Q_1= amount ofheatsuppliedtosteaminboilerfroma high-temperature source.

Q_2=amountofheatrejected fromsteamincondensertoalow temperature sink.

W=networkoutputofthisheatengine.

From firstlawof thermodynamics,

Heattransferfromsources $Q_1 = W + Q_2$

WorkdoneW=$Q_1 - Q_2$

$$\text{Thermalefficiency}(\eta) = \frac{\text{Networkoutput}}{\text{Totalheatinput}}$$

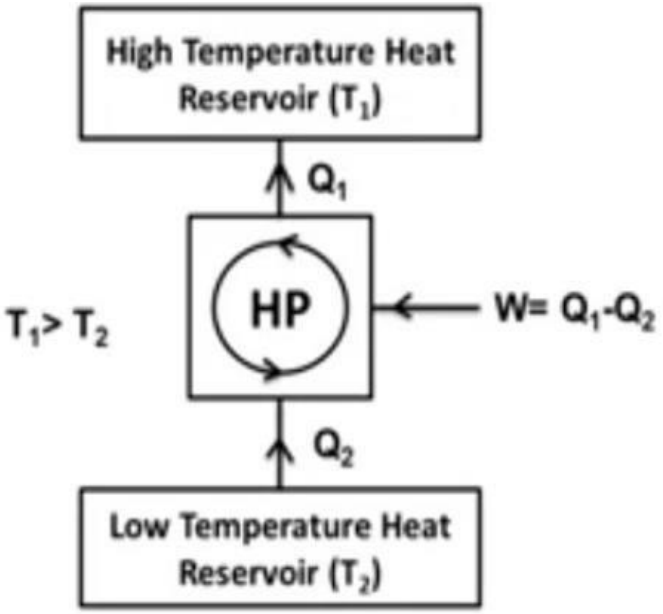
$$\eta_{th} = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$$

$$\eta_{th} = 1 - \frac{Q_2}{Q_1}$$

- ***Hence,efficiencyofheatengineisalwayslessunity.***

HeatPump

HeatPumps:Heatpumpsareanothercyclicdevices,usedtotransferheat from a low temperature medium to a high temperature medium. The objective of a heat pump is to maintain a heated space at a high temperature. This is accomplished by absorbing heat from a low temperature source, such as cold outside air in winter and supplying this heat to the high temperature medium such as a house.



$$\text{COP}_{HP} = \frac{\text{Desiredoutput}}{\text{Requiredinput}} = \frac{Q_1}{W}$$

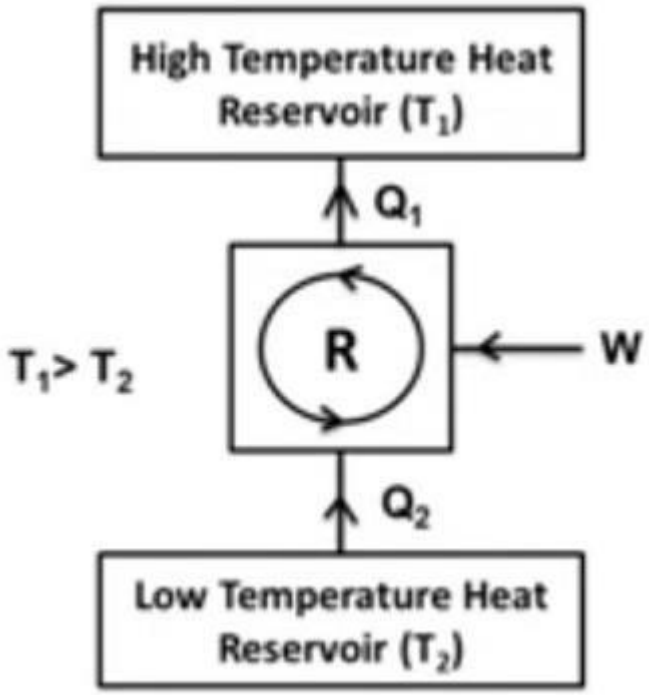
$$\text{COP}_{HP} = \frac{Q_1}{Q_1 - Q_2}$$

Forreversibleheatpump (carnot) $\frac{Q2}{Q_1} = \frac{T2}{T_1}$

$$\text{COP}_{HP(rev)} = \frac{Q_1}{Q_1 - Q_2} = \frac{T_1}{T_1 - T_2}$$

Refrigerator

Desiredeffectofrefrigeratoristocoolthegivenspaceby removing heat



$$\text{COP}_{Ref} = \frac{\text{Desiredoutput}}{\text{Requiredinput}} = \frac{Q_2}{W}$$

$$\text{COP}_{Ref} = \frac{Q_2}{Q_1 - Q_2}$$

Forreversibleheatpump (carnot) $\frac{Q2}{Q_1} = \frac{T2}{T_1}$

$$\text{COP}_{Rf(rev)} = \frac{Q_2}{Q_1 - Q_2} = \frac{T_2}{T_1 - T_2}$$

RelationbetweenCOP$_{HP}$and COP$_R$

$$\text{COP}_{HP} = \frac{\text{Desiredoutput}}{\text{Requiredinput}} = \frac{Q_1}{W} = \frac{Q_1}{Q_1 - Q_2}$$

$$\text{COP}_{Ref} = \frac{\text{Desiredoutput}}{\text{Requiredinput}} = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2}$$

Byequ:(1)–(2) $\text{COP}_{HP} - \text{COP}_{Ref} = \frac{Q_1}{Q_1 - Q_2} - \frac{Q_2}{Q_1 - Q_2} = 1$

COP$_{HP}$=COP$_R$+1

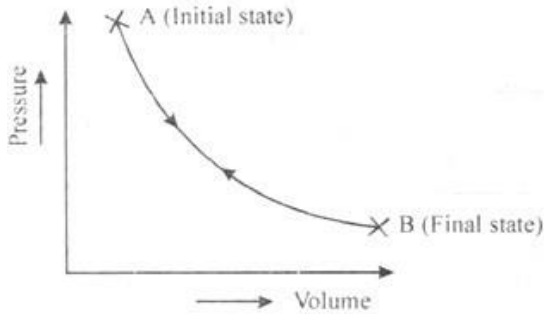
ReversibleProcessandIrreversibleProcess

A reversible process is one which is performed in such a way that both system and surroundings may be restored to their initial state,without producing any changes

Theassumptionsmadeforreversibleprocess

1. Thereversibleprocesshastobeaquasi-equilibriumprocess
2. Nofrictionisinvolvedintheprocess
3. Heat transfer occurs due to an infinitesimal temperature difference only
4. Unrestrainedexpansiondoesnotoccur.

The reversible process is purely an ideal process and it is an imaginary process which is used for theoritical calculations or ideal condition.



Irreversibility

Themixingoftwosubstancesandcombustionalsoleadstoirreversibility.Allspontaneous process are irreversible.

CausesofIrreversibility

Theirreversibilityofa processmaybeduetothefollowingreasons.

1) Lackofequilibriumduringtheprocess

i) HeattransferduetoLackofequilibrium

ii) Lackofpressureequilibriumwiththeinterior ofthesystemor between the system

iii) Freeexpansion

2. IrreversibilityduetoDissipativeeffects.

i) Friction

ii) Paddlewheelworktransfer

iii) Transferofelectricitythrougharesistor

Carnot Cycle: Carnot cycle is a reversible cycle that is composed of four reversible processes, two isothermal and two adiabatic.

¬Process1-2(ReversibleIsothermalHeat Addition)

$$Q_1 = w_{1-2} = mRT_1 \ln\left(\frac{V_2}{V_1}\right)$$

¬Process2–3(ReversibleAdiabaticExpansion)

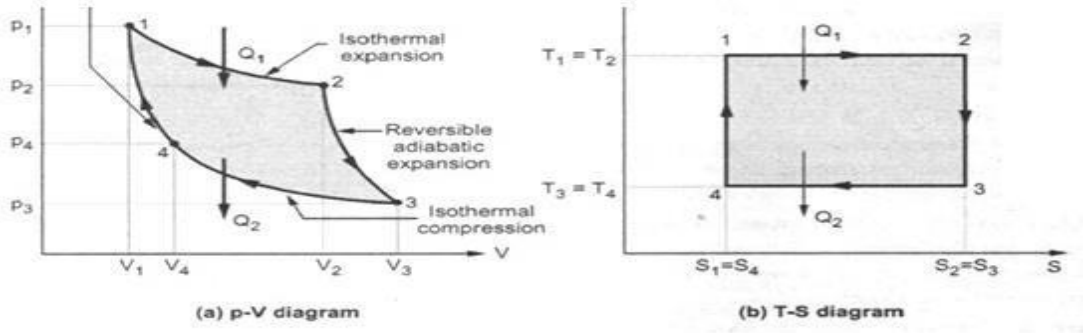
$$\frac{V_3}{V_4} = \frac{V_2}{V_1} \quad \therefore \quad \frac{Q_1}{T_1} = \frac{Q_2}{T_2} = \text{constant}$$

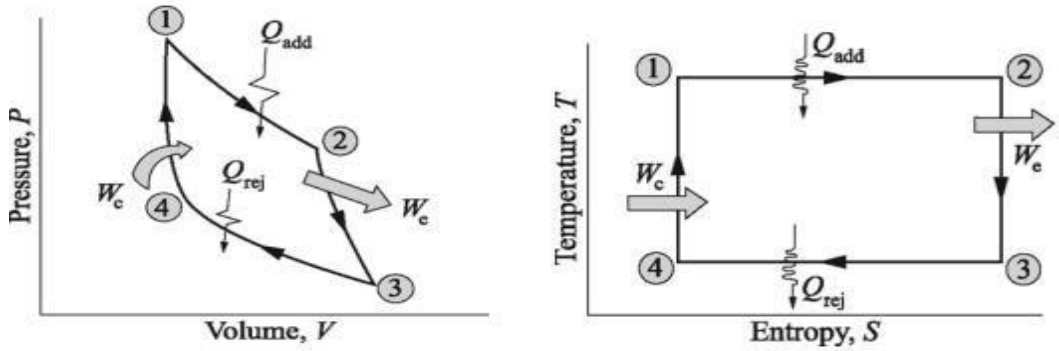
¬Process3–4(ReversibleIsothermalHeat Rejection)

$$Q_1 = w_{3-4} = mRT_2 \ln\left(\frac{V_3}{V_4}\right)$$

¬Process4–1(RevesibleAdiabaticCompression)

$$\frac{V_3}{V_4} = \frac{V_2}{V_1} \quad \therefore \quad \frac{Q_1}{T_1} = \frac{Q_2}{T_2} = \text{constant}$$





InIsothermalprocess

$P_1V_1 = P_2V_2$……(1)

AsB(V_2,P_2)andC(V_3,P_3liesonsameadiabatic

$P_2V_2^{\gamma}=P_3V_3^{\gamma}$……(2)

AgainCandDliesonsameIsothermalprocess

$P_3V_3^{\gamma}=P_4V_4^{\gamma}$

FinallyDand Aliesonsameadiabatic

$P_4V_4^{\gamma}=P_1V_1^{\gamma}$

Multiplying(1)(2)(3)and(4):

$$V_2^{\gamma-1}+V_4^{\gamma-1} = V_1^{\gamma-1}+V_3^{\gamma-1}$$

$$V_2V_4=V_1V_3$$

$$\frac{V_2}{V_1}=\frac{V_3}{V_4}$$

$$\log\frac{V_2}{V_1}=\log\frac{V_3}{V_4}$$

Dividing(4)and(2)

$$\frac{Q_1}{Q_2}=\frac{\text{KTlog}\frac{V_3}{V_4}}{KT\log\frac{V_1}{V_2}}$$

$$\frac{Q_1}{Q_2}=\frac{T_2}{T_1}$$

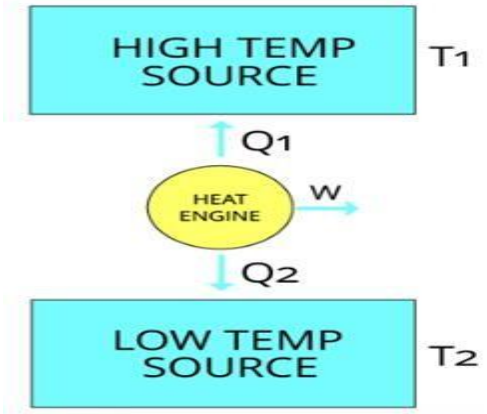
$$\eta_{car}=1-\frac{T_2}{T_1}$$

Heat engines that are working between two heat reservoirs are less efficientthan theCarnotheatenginethatisoperatingbetween thesame reservoirs.

Carnot/sTheoremProof

Consideraheat enginethatdrawsheat Q_1fromaheatreservoirat T_1 delivers work and dumps heat Q_2 into a heat atT_2

The heat engine operates in cycles (each of which includes two isothermal and two adiabatic processes), meaning it takes in heat Q_1, performsworkW,dumpsheat$Q_2$and thenretunstoitsoriginalunaltered state



T1 Temperature of Source
T2 Temperature of Sink
Q1 Heat flow from Source of Heat Engine
Q2 Heat Rejected from Heat Engine to Sink

Energy Balance $Q_1-Q_2=W$

Efficiency, $\eta = \frac{\text{Work Output}}{\text{Energy Supplied}}$

$$\eta = \frac{W}{Q_1} = \frac{Q_1-Q_2}{Q_1} = 1-\frac{Q_2}{Q_1}$$

Considertheuniverse'snetchangeinentropyΔS

At a steadytemperatureT_1 ,theheatreservoiremitsQ_1 , Asaresult,the change in its entropy is

$$\Delta S_1 = \frac{Q_1}{T_1}$$

At a steadytemperatureT_2 , theheat reservoiremitsQ_2 ,Asa result,the change in its entropy is

$$\Delta S_2 = \frac{Q_2}{T_2}$$

Asaresult,theuniverse'snetentropychangeis

$$\Delta S=\Delta S_1+\Delta S_2$$

$$\Delta S = \frac{Q_2}{T_2} - \frac{Q_1}{T_1}$$

Usingthesecondlawofthermodynamics,$\Delta S \geq 0$,itfollowsthat

$$\frac{Q_2}{T_2} - \frac{Q_1}{T_1} \geq 0$$

$$\frac{Q_2}{T_2} \geq \frac{Q_1}{T_1}$$

$$\frac{Q_2}{Q_1} \geq \frac{T_2}{T_1}$$

$$1-\frac{Q_2}{Q_1} \leq 1-\frac{T_2}{T_1}$$

Becausetheleftsidereflectstheefficiencyofthesuppliedheatengine ηtherightsideindicates the efficiencyofacarnotengine

$\eta \leq \eta_{carnot} \rightarrow \eta_{max}=\eta_{carnot}$

Henceproved

Example1:*Aninventorclaimsthathisenginehasthefollowing specifications :*
Temperaturelimits .....750°Cand25°C
Powerdeveloped 75kW
Fuelburnedperhour .....3.9 kg
Heatingvalueofthefuel 74500kJ/kg
Statewhetherhisclaimisvalidornot.
Tofind

i) η_{carnot} ii) $\eta_{thermal} = \frac{\text{Heat supplied}}{\text{Work done}}$

Solution.

Temperatureofsource, $T_1 = 750 + 273 = 1023K$

Temperature of sink, $T_2 = 25 + 273 = 298\ K$

$\eta_{carnot} = 1 - \frac{T_2}{T_1} = 1 - \frac{298}{1023} =$ **0.7086or70.86%**

Theactualthermalefficiencyclaimed,

$\eta_{thermal} = \frac{\text{Heatsupplied}}{\text{Workdone}} = \frac{75 \times 1000 \times 60 \times 60}{39 \times 74500 \times 1000}$.=**0.9292or92.92%.**

Since

$\eta_{thermal} > \eta_{carnot}$,

thereforeclaimoftheinventoris**notvalid(orpossible**). (Ans.)

Example 2:*What is thehighest possible theoretical efficiency of a heat engineoperatingwithahotreservoiroffurnacegasesat2100°Cwhen the cooling water available is at 15°C ?*

Tofind:theoreticalefficiency $\eta_{theoretical}$

Solution.

Temperatureoffurnacegases, $T_1 = 2100 + 273 = 2373$ K Temperature of cooling water, $T_2 = 15 + 273 = 288$ K

Now, $\eta_{max} (= \eta_{carnot}) = 1 - \frac{T_2}{T_1}$

$= 1 - \frac{288}{2373} =$ **0.878or 87.8%.(Ans.)**

Example3: *A Carnot cycle operates between source and sink temperaturesof250°Cand –15°C.Ifthe systemreceives90kJfromthe source, find :*

(i) Efficiencyofthesystem; $\eta_{carnot} = 1 - \frac{T_2}{T_1}$

(ii) Thenetworktransfer; $[\eta_{carnot} = \frac{W}{Q_1}]$

(iii) Heatrejectedto sink. $W = Q_1 - Q_2$

Solution. Temperatureof source, $T_1 = 250 + 273 = 523K$

Temperature of sink, $T_2 = -15 + 273 = 258\ K$

Heatreceivedbythesystem, $Q_1 = 90kJ$

(i) $\eta_{carnot} = 1 - \frac{T_2}{T_1} = 1 - \frac{288}{2373} = 0.506 = 50.6\%$.(Ans.)

ii) **Thenetworktransfer,**

$W = \eta_{carnot} \times Q_1 \qquad [\eta_{carnot} = \frac{W}{Q_1}]$

$= 0.506 \times 90 = 45.54kJ.$ (Ans.)

(iii)**Heatrejectedtothesink**, Q_2

$= Q_1 - W\ [\ W = Q_1 - Q_2]$

$= 90 - 45.54 = 44.46kJ.$ (Ans.)

Example4: *A fish freezing plant requires 40 tons of refrigeration. The freezingtemperatureis–35°Cwhiletheambienttemperatureis30°C.If the performance of the plant is 20% of the theoretical reversed Carnot cycle working within the same temperature limits, calculate the power required.*

Given:1tonofrefrigeration=210kJ/min.

Solution.

Coolingrequired =40tons=40 ×210 =8400kJ/min

Ambient temperature, $T_1 = 30 + 273 = 303\ K$

Freezing temperature, $T_2 = -35 + 273 = 238\ K$

Performanceofplant=20%ofthetheoreticalreversedCarnotcycle

(C.O.P.)refrigerator$= \frac{T_2}{T_1 - T_2} = \frac{238}{303 - 238} = 3.66$

∴ActualC.O.P=0.20×3.66=0.732

$$(C.O.P.)_{actual}=\frac{\text{Coolingreqd.}}{\text{Workneeded}} \quad 0.732=\frac{8400}{W} \quad \text{or} W=\frac{8400}{0732} \quad \text{kJ/min}$$

=191.25kJ/s=191.25 Kw

Hence,powerrequired=191.25kW.(Ans.)

Example5.** *A reversible heat engine operates between two reservoirs at temperatures 700°C and 50°C. The engine drives a reversible refrigerator which operates between reservoirs at temperatures of 50°C and – 25°C. The heat transfer to the engine is 2500 kJ and the net work outputofthecombinedengine refrigeratorplantis400kJ. (i)Determine the* ***heattransfer *to the refrigerant and the* ***net heat transfer*** *to the reservoirat50°C ;(ii)Reconsider(i)given thattheefficiencyoftheheat engine and the C.O.P. of the refrigerator are each 45 per cent of their maximum possible values.*

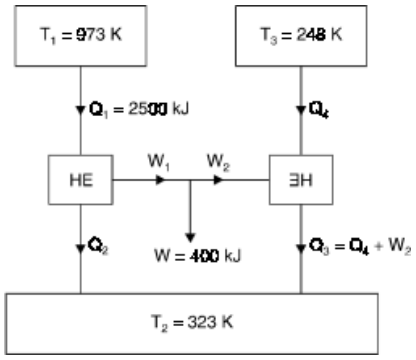
Given:

Temperature,T_1=700 +273=973K

Temperature, T_2 = 50 + 273 = 323 K

Temperature, T_3 =–25+273 =248K

Theheattransfertotheheatengine,Q_1=2500kJ



Solution.

Thenetworkoutputofthecombinedenginerefrigeratorplant,

$$W= W_1 – W_2=400\text{kJ}.$$

(i) Maximumefficiency

$\eta_{max}=1-\frac{T_2}{T_1}=1-\frac{323}{973}==0.668$

EfficiencyCarnotengine

$\eta_{carnot}=\frac{W}{Q_1}=0.668$

$\therefore \mathbf{W_1}=0.668\times2500=\mathbf{1670kJ}$

CoefficientOfPerformance(C.O.P)

$(C.O.P.)max=\frac{T3}{T_2-T_3}=\frac{248}{323-248}==3.306$

Also,**C.O.P.**$=\frac{Q4}{W}=\mathbf{3.306}$

Since, $W=400kJ=W_1-W_2$

$W_2=W_1-W=1670-400=1270kJ$

$\frac{Q_4}{W}=\mathbf{3.306}$; $Q_4=\mathbf{3.306}\times W$

$\therefore Q_4=3.306\times1270=4198.6$ kJ

$Q_3=Q_4+W_2=4198.6+1270=5468.6kJ$ $Q_2=$

$Q_1 - W_1 = 2500 - 1670 = 830$ kJ.

Heatrejectiontothe50°Creservoir

$=Q_2+Q_3=830+5468.6=$**6298.6 kJ.(Ans.)**

(ii) Efficiencyofactualheatenginecycle,η=0.45

η =*45percentoftheirmaximumpossiblevalues*. $\eta=$

$0.45\times\eta_{max}$

$\eta=0.45\times0.668=0.3$

$\eta_{carnot}=\frac{W}{Q_1}$

$\therefore W_1 = \eta \times Q_1 = 0.3 \times 2500 = 750 kJ$ $W_2 =$

$W_1 - W$

$\therefore W_2 = 750 - 400 = 350$ kJ

C.O.P.oftheactualrefrigeratorcycle,

$C.O.P. = \frac{Q_4}{W} = 0.45 \times 3.306 = 1.48$

$\therefore Q_4 = 350 \times 1.48 = 518 kJ$.(Ans.) $Q_3 =$

$518 + 350 = 868$ kJ

$Q_2 = 2500 - 750 = 1750 kJ$

Heatrejectedto50°Creservoir

$= Q_2 + Q_3 = 1750 + 868 = 2618 kJ$. (Ans.)

Example6. *A heat pump is to be used to heat a house in winter and then reversed to cool the house in summer. The* ***interior temperature*** *is to be maintainedat****20°C.Heattransfer****throughthewallsand roofisestimated tobe* ***0.525kJ/s****perdegreetemperature differencebetween theinsideand outside. (a) If the outside temperature in winter is 5°C, what is the minimum power required to drive the heat pump? (b) If the power output is the same as in part (a), what is the maximum outer temperature for which the inside can be maintained at 20°C?*

Given:

Sourcetemperature=20°C:=293K

outside temperature = 5°C:= 278 K Heat

transfer=0.525 kJ/s

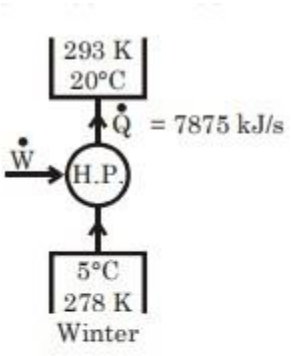
Tofind

i) whatistheminimumpowerrequired

ii) maximumoutertemperatureforwhichtheinsidecanbe maintained at 20°C?

Solution.

Calculateminimumpowerrequired



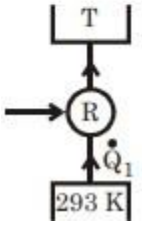
a) EstimatedHeatrateQ=q(T_1-T_2)

=0.525× (20 –5)kJ/s=7.875 kJ/s

COP=$\frac{293}{293-278}$ =19.53

$W_{min}=\frac{Q}{COP_{max}}=\frac{7.875}{19.53}$ =0.403kW

minimum power required= 403 W



(b)***Calculatemaximumoutertemperature***

GivenW=403 W

Heatrate(Q)=0.525 (T–293)kW

=525(T–293)W

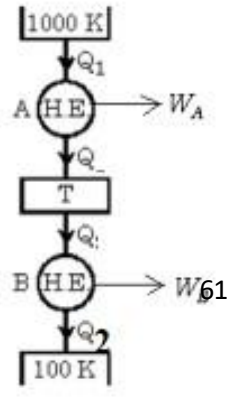
∴COP=$\frac{525(T-293)}{403}=\frac{293}{(T-293)}$

(T–293)=$\frac{403\times293}{525}$ =15

T=308K=35ºC

∴MaximumoutsideTemperature=35ºC

Example 7 . Two Carnot engines **A** and **B** are connected in **series** between two thermal reservoirs maintained at 1000 K and 100 K respectively. Engine **A receives 1680 kJ of heat** from the high-temperature reservoir and rejects heat to the Carnot engine B. EngineBtakesinheatrejectedbyengineAand rejectsheattothe low-temperature reservoir. If engines A and B have equal thermal efficiencies, determine (a) The heat rejected byengineB(b)Thetemperatureatwhich heat is rejected by engine, A (c) The work done



during the process by engines, A and B respectively. If engines A andBdeliverequalwork,determine(d)Theamountofheattakenin by engine B (e) The efficiencies of engines A and B

Given:

Temperature =1000K

Temperature = 100 K

Highreservoirofheat=1680kJ

Tofind:

Case:1AandBhaveequalthermalefficiencies,

Calculate

i) heatrejectedbyengineB

ii) workdone

Case:2AandBhavedeliverequalwork,

AmountofheattakeninbyB η_A

andη_B

Solution:

Basedonefficiencies$\eta_A=\eta_B$

$$\eta_A = \frac{WA}{Q_1} = \frac{Q1-Q}{Q_1} = 1-\frac{Q}{Q_1} = 1-\frac{T}{T_1} = 1-\frac{T}{1000}$$

$$\eta_B = \frac{WB}{Q} = \frac{Q-Q1}{Q} = 1-\frac{Q1}{Q} = 1-\frac{T1}{T} = 1-\frac{100}{T}$$

$$1-\frac{T}{1000} = 1-\frac{100}{T}$$

$$T=\sqrt{1000\times100}$$

T=316.3K

$$\frac{Q}{T}=\frac{Q_1}{T_1};Q=\frac{Q_1}{T_1}\times T;=\frac{1680\times316.3}{1000}$$

Q=531.26kJ

$$\frac{Q}{T}=\frac{Q2}{T_2};Q_2=\frac{QT}{T};=\frac{531.26\times100}{316.3}=168\text{kJ}$$

$$Q_2 = 168\text{kJ}$$

$W_A = Q_1 - Q_2 = (1880 - 531.26)\text{kJ}$

$= 1148.74\text{kJ}$

$W_B = (531.26 - 168)\text{kJ} = 363.26\text{Kj}$

Iftheequal work

$T = \frac{100+1000}{2} = 550\text{K}$

$\frac{Q}{T} = \frac{Q_1}{T_1}$

$\therefore Q = \frac{Q1}{T_1} \times T1000 = \frac{1680 \times 550}{1000} = 924\text{kJ}$

EfficienciesofenginesAandB

$\eta_A = 1 - \frac{5}{T_1} = 1 - \frac{550}{1000} = 0.45$

$\eta_B = 1 - \frac{T1}{} = 1 - \frac{100}{550} = 0.8182$

*****Example8.** A heat pump working on the **Carnot cycle takes in heat from a reservoir at 5°C** and delivers heat to a **reservoir at 60°C.** The heat pump is driven by a reversible heat engine which takes in heat from a **reservoir at 840°C** and rejects heat to a **reservoirat60°C.** Thereversibleheat enginealsodrivesamachine that**absorbs30 kW.** Iftheheatpumpextracts**17 kJ/s** fromthe5°C reservoir, determine (a) The rate of heat supply from the 840°C source (b) The rate of heat rejection to the 60°C sink.

Given:

reservoir=840+*273=1113K*[T_1]

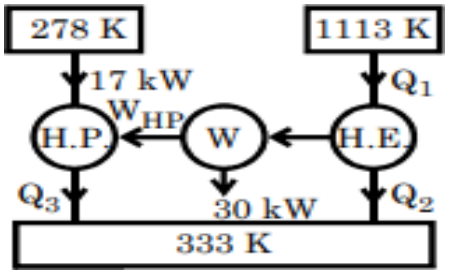
Cycle takes in heat at 5°C = 273+5 = 278 K[T_4]

Deliversreservoirat60°C.=273+60=333K[$T_2 = T_3$]

Heatpumpextracts=17kJ/s =Q4

work down= 30 kW

Tofind: Solution:



Solution:**Therateofheatsupplyfromthe840°C**

COPofH.P.=$\frac{T2}{T_2-T_1}\frac{333}{333-278}$= 6.05454

COPofH.P.=$\frac{Q3}{Q_3-17}$=6.05454

Q_3=20.36kW

WorkinputtotheheatpumpW2=Q_3-Q_4=20.36−17=3.36kW

∴Work outputoftheHeatengineW$_{H.E.}$=30+3.36=**33.36 kW**

Maximumefficiencyofheatengine[η]=1−$\frac{333}{1113}$=**0.7**

ηMaxi=$\frac{W_1}{Q_1}$$Q_1$=$\frac{W_1}{\eta_{Maxi}}$ = $\frac{333}{0.7008}$ =47.6kW

$W_1=Q_1-Q_2$

Heatrejectiontosink.

$Q_2=Q_1-W_1$=47.6−33.36=14.24kW

Netheattransferredtoreservoirat60^0

Q_2+Q_3=14.24+20.36=34.6kW

Example 9 .Aheat engineoperating between two reservoirsat 1000 K and 300 K is used to drive a heat pump which extracts heat from the reservoirat300Kata ratetwicethatatwhich the enginerejectsheatto*

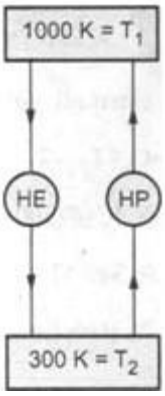
it. If the efficiency of the engine is 40 % of the maximum possible and the cop of the heat pump is 50 % of the maximum possible, what is the heat temperatureofthe reservoirtowhichtheheatpumprejectsheat? Whatis the rate of heat rejection from the heat pump if the rate of heat supply to the engine is 50 kW ?

Sol.:Givendata:

T_1=1000 K,T_2=300K

actualη_{engine}=40%η_{car}

COP_{max}= 50 %Cop



Q_1=supplytotheengineis50kW

TofindCarnotefficiency

$\eta_{\text{carnot}} = 1 - \frac{T_2}{T_1} = 1 - \frac{300}{1000}$

η_{carnot}=0.7

actualη_{engine}=40%η_{car}

=0,4×0.7=28%

Rateofheatrejectionfromtheheatengine

$actual\eta_{\text{engine}} = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1}$

$0.28 = \frac{50 - Q2}{50}$

Q_2=36×kW

Reservoirheatreject=twicetheenginerejects

$Q_3 = 2Q_2$

Q_3=2×36=72kW

NetWork down

$(W)_{H.E}$=Heatsupplied($Q_{1)}$)−Heatrejected(Q_2)

=50−36= 14kW

Calculateheattemperatureofthereservoirheatpumprejects

$cop_{HP} = \frac{Q_3}{Q_1 - Q_2} = \frac{86}{86-72} = 6.14$

$Actual cop_{HP} = 0.5 cop_{carnot}$

$6.14 = 0.5 \times \frac{T_3}{T_3 - T_2}$

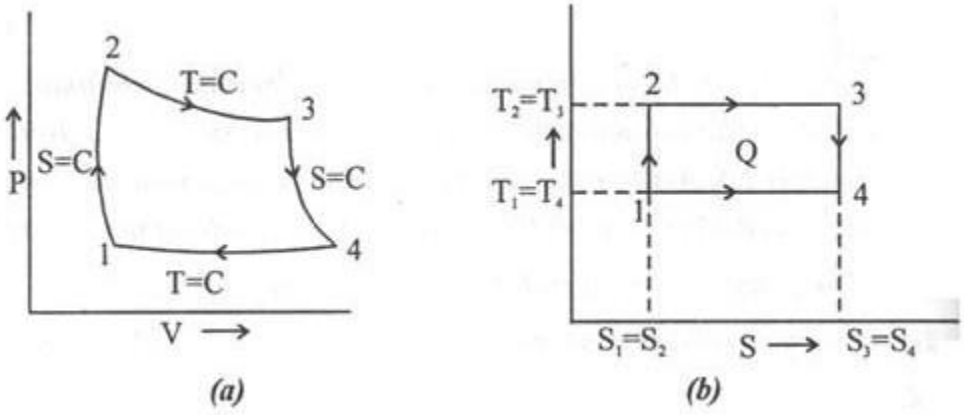
$$6.14 = 0.5 \times \frac{T_3}{T_3 - 300}$$

T_4=326.67K

*****Example10.*In a carnot cycle the maximum pressure & temperature are limited to 18 bar & 410°C. The volume ratio of isentropic compression is 6 & isothermal expansion is 1.5. Assume the volume of air at the beginning of isothermal expansion as 0.18 m^3. Show the cycle onp-V& T-s diagrams & determine***

Thepressure&temperatureatmainpoints

Thermal efficiency of the cycle



Givendata:

Maximumpressure, P_2=18bar=18×100

$= 1800 kN/m^2 or kPa$

Maximum Temperature, $T_2 = 410°C$

$= 410 + 273$

$= 683K = T_3$

Volume at the beginning of isothermal expansion $V_2 = 0.18\ m^3$

Volume ratio for isothermal compression $= \frac{V_1}{V_2} = 6$

Volume ratio for isothermal expansion $= \frac{V5}{V_2} = 1.5$

To find:

Pressure and temperature at main point - P_1, P_3 & P_4 *and* $T_p T_3$ *Thermal efficiency '*$n_{|her}$*'*

Solution: From p -V- T relation for an isentropic process,

Calculate the *temperature at main point* T_1, T_2, T_3, T_4.

PROCESS 1-2 *isothermal compression*

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma - 1}$$

$$T_1 = \frac{T_2}{\left(\frac{V_1}{V_2}\right)^{\gamma - 1}} = \frac{638}{6^{1.4-1}} = 333.55$$

From T-S diagram $T_1 = T_4; T_2 = T_3;$

Calculate *Pressure at main point*

$$\left(\frac{V_1}{V_2}\right)^{\gamma} = \frac{P_2}{P_1}; P_1 = \frac{P_2}{\left(\frac{V_1}{V_2}\right)^{\gamma}} = \frac{1800}{6^{1.4}} = 146 kPa$$

Process 2-3 for an isothermal Process

$p_3V_3=p_2V_2$

$P_3=P_2(\frac{V_2}{V_3})=1800\times\frac{1}{1.5}=1200\text{kPa}$

***Process3-4*ReverseAdiabaticProcess**

$p_3V_3^{\gamma}=p_4V_4^{\gamma}$

$\boldsymbol{p_4=p_3(\frac{V_3}{V_4})^{\gamma}=1200\times\frac{1}{6}^{1.4}}$

p_4=97.7kPa

Calculatethe*Thermalefficiency'$n_{|her}$'*$1-\frac{T_1}{T_4}$

$$=1-\frac{333.5}{683}=51.79\%$$

Example 11**:SourceA'can supply energyatarateof11,000kJ/min at 320°C. Another source 'B' can supply energy at a rate of 11,000 kJ/min at 68°C. Which source 'A' or 'B' would you choose to supply energy to an ideal reversible engine that is to produce large amount of power, if the temperature of the***

surroundingsis40°C

Givendata:

Temperatureofthesurroundings(or)sink,T_t=40°C

Source A:

= 313K

Heatsupplied,Q_{S1} =11,000 kJ/min=183.33kJ/s Source temperature, T_{H1} = 320° C= 593 K

Source B:

Heatsupplied,Q_{S2} =11,000 kJ/min=183.33kJ/s Source

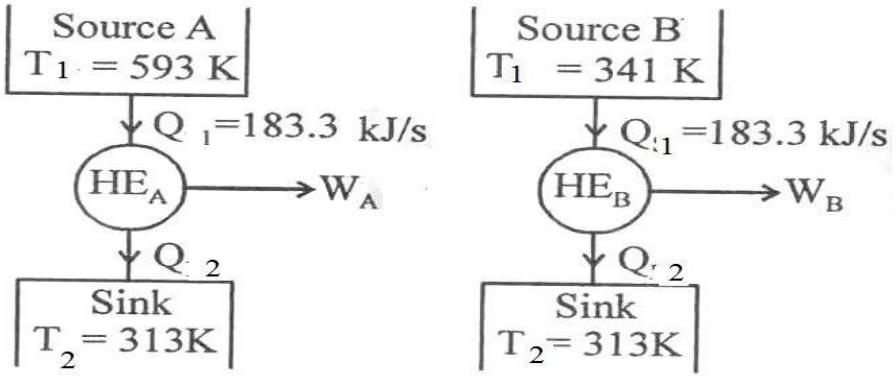
temperature, T_{H2} = 68°C =341 K

Tofind:

Sourcewhichproduceshighestpower' W'

CaseA :

Forareversibleengine



$\frac{Q_2}{T_2}=\frac{Q_1}{T_1}.=\frac{Q_2}{Q_1}=\frac{T_2}{T_1}$;$\frac{Q_2}{183.33}=\frac{313}{593}$

$Q_2=96.77kJ/s$

ByenergybalanceW$_A$=Q$_1$−Q$_2$=183.33−96.77=86.56kJ/s

CaseB:

Forareversibleengine

$\frac{Q_2}{T_2}=\frac{Q_1}{T_1}.=\frac{Q_2}{Q_1}=\frac{T_2}{T_1}$;$\frac{Q_2}{183.33}=\frac{313}{341}$

$Q_2=168.28kJ/s$

ByenergybalanceW$_B$=Q$_1$−Q$_2$=183.33−168.28=15.05kJ/s

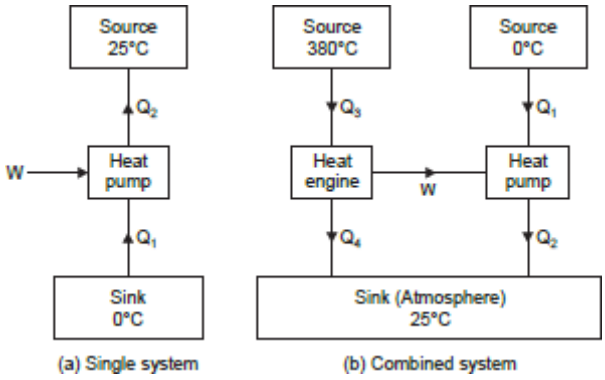
Here,*W$_A$*>.*W$_B$*So,sourceAispreferred

Example12:*A reversible heat pump is used to maintain a temperature of 0°C inarefrigeratorwhenit rejectsthe heattothesurroundingsat25°C. If the heat removal rate fromthe refrigerator is 1440 kJ/min, determine the C.O.P. of the machine and work input required*.(*ii*) *If the required input to run the pump is developed by a reversible engine which receivesheatat380°Cand rejectsheattoatmosphere,thendeterminethe overall C.O.P. of the system.*

Solution.

(i) Temperature, T_1=25+273=298K

Temperature, T_2 = 0 + 273 = 273 K



Heatremovalratefromtherefrigerator,

Q_1=1440kJ/min=24kJ/s

Now,co-efficientofperformance,forreversibleheatpump,

$$\text{C.O.P.}=\frac{T1}{T_1-T_2}=\frac{298}{(298-273)}=\mathbf{11.92.(Ans.)}$$

$$\therefore(\text{C.O.P.})ref.=\frac{T2}{T_1-T_2}=\frac{273}{(298-273)}=10.92$$

Now,10.92= $\frac{Q1}{W}=\frac{24}{W}$

$\therefore W$ =2.2kW

i.e.,**Workinputrequired=2.2kW. (Ans.)**

$Q_2=Q_1+W$=24+2.2=26.2 kJ/s

(ii) ReferFig.(*b*).

TheoverallC.O.P.isgivenby,

$$\text{C.O.P.}=\frac{\text{Heatremovedfromtherefrigerator}}{\text{Heatsuppliedfromthesource}}$$

$$\frac{Q_1}{Q_3}$$

Forthereversibleengine,wecanwrite

$$\frac{Q_3}{T_3}=\frac{Q_4}{T_4}$$

$$\frac{Q_4+W}{T_3}=\frac{Q_4}{T_4}$$

$$\frac{Q_4+22}{653}=\frac{Q_4}{298}$$

$298(Q_4+2.2)=653Q_4$

$Q_4(653-298)=298\times 2.2$

$Q_4=\frac{298\times 2.2}{(653-298)}=1.847$kJ/s

$\therefore Q_3 = Q_4+ W$=1.847+2.2=4.047kJ/s

Substitutingthisvalueineqn.(*i*),weget

C.O.P.= $\frac{24}{4.047}$**=5.93.(Ans.)**

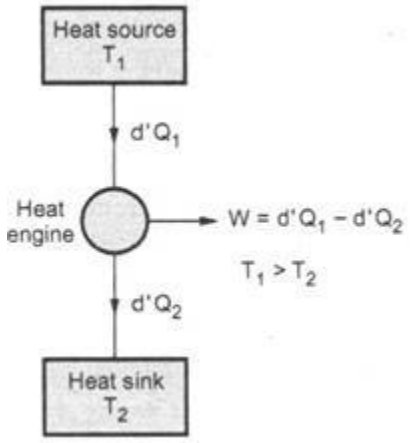
Ifthepurposeofthesystemistosupplytheheattothesinkat25°C,then

OverallC.O.P.=$\frac{Q2+Q4}{Q_3}$=$\frac{26.2+1.87}{4.047}$**=6.93.(Ans.)**

***InequalityinClausiustheorem

Astheefficiencyofa reversiblecarnotcycle is,

$$\eta=1-\frac{d'Q_2}{d'Q_1}=1-\frac{T_2}{T_1}$$



efficiency of reversibleengine (R)is greaterthentheirreversibleenginewhen they operate at same temperatures.

$$\left(1-\frac{d'Q_2}{d'Q_1}\right)_R \geq \left(1-\frac{d'Q_2}{d'Q_1}\right)_I$$

$$1-\frac{T_2}{T_1} \geq \left(1-\frac{d'Q_2}{d'Q_1}\right)_I$$

$$\frac{T_2}{T_1} \leq \frac{d'Q_2}{d'Q_1}$$

$$\frac{d'Q_1}{T_1} \leq \frac{d'Q_2}{T_2}$$

$$\frac{d'Q_1}{T_1}-\frac{d'Q_2}{T_2} \leq 0$$

$$\frac{d'Q_1}{T_1}-\left(-\frac{d'Q_2}{T_2}\right) \leq 0$$

$$\frac{d'Q_1}{T_1}+\frac{d'Q_2}{T_2} \leq 0$$

$\oint \frac{d'Q}{T} \leq 0$ **thisequationiscallasInequalityinClausiustheorem**

Forreversiblecycle $\oint_R \frac{d'Q}{T}=0$

Forirreversiblecycle $\oint_R \frac{d'Q}{T}<0$

$\oint \frac{d'Q}{T} > 0$(notpossible)

***** EntropyChangeforandReversible Adiabaticand Reversible isothermal process**

Reversibleadiabaticprocess

• For a reversible adiabatic process heat transfer between thesystem and surroundingis zero.

$ds = \left(\frac{d'Q}{T}\right)_{\text{Rev adiabatic}} = 0$

S=constant

Reversibleisothermalprocess

• For a reversible isothermal process, the temperature T of the system is constant. Hence, the entropy change for an isothermal process is given by,

$(ds) = \left(\oint \frac{d'Q}{T}\right)_R = \frac{1}{T}\int d'Q_R$

$ds = \frac{Q}{T}$

• It means, the entropy change in an isothermal process is the ratio of heat transfer to the temperature of the system during the process.

***Principleofincreaseentropy

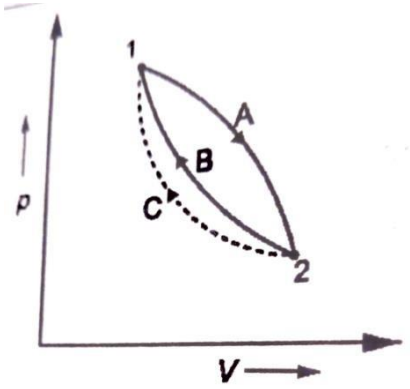
The principle of increase of entropy states that the entropy of the Universe also increases. Itneverdecreases butremainsconstantonlyinareversible process.

Theentropychangeofasystemisgiven bytheequation:

$$\Delta S = \frac{dQ}{T}$$

Where, dQisthechangeofheatofthesystemand Tis the temperature of the system.

Changeinentropyisexaminedforanirreversibleprocess



Forthereversiblecycle1-A-2-B-1,

$$\int_{1A}^{2A}\frac{dQ}{T}+\int_{2B}^{1B}\frac{dQ}{T}=0 \quad \ldots\ldots\ldots\ldots\ldots\ldots 1$$

Fortheirreversiblecycle1-A-2-C-1,

$$\int_{1A}^{2A}\frac{dQ}{T}+\int_{2C}^{1C}\frac{dQ}{T}=0 \quad \ldots\ldots\ldots\ldots\ldots\ldots 2$$

Subtracting theequation1from2

$$\int_{2C}^{1C}\frac{dQ}{T}-\int_{2B}^{1B}\frac{dQ}{T}\leq 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots 3$$

Onreversingthelimitandrearranging,

$$\int_{2B}^{1B}\frac{dQ}{T}\geq\int_{2C}^{1C}\frac{dQ}{T}$$

Since,process2-B-is1isreversible,$dS=\frac{dQ}{T}$

Substitutingthisvalueinequation3

$$\int_{1}^{2}ds\geq\int_{1C}^{2C}\frac{dQ}{T} \text{ ordS}\geq\frac{dQ}{T}$$

Foranisolatedsystem:

$\Delta S>0$,forirreversible processes

$\Delta S=$, for reversible processes

$\Delta S<0$,thisisanimpossiblecase

****Example10.***300 kJ/s of heat is supplied at a constant fixed temperatureof290°Ctoaheatengine. Theheat rejection takesplaceat 8.5°C.Thefollowingresultswereobtained:*

(i) 215kJ/sarerejected.

(ii) 150kJ/sarerejected
(iii) 75kJ/sare rejected.

Classifywhichoftheresultreportareversiblecycleorirreversiblecycle or impossible results.

Solution.

Heatsuppliedat290°C=300kJ/s Heat

rejected at 8.5°C :

(i) 215kJ/s,
(ii) 150kJ/s,
(iii) 75 kJ/s.

ApplyingClausiusinequalitytothecycleorprocess, we

have :

(i) cycle$\sum \frac{\delta Q}{T} = \frac{300}{290+273} - \frac{215}{85+273}$

=0.5328–0.7637=–0.2309< 0.

∴ Cycleisirreversible.(Ans.)

(ii) $\sum \frac{\delta Q}{T} = \frac{300}{290+273} - \frac{150}{85+273}$

=0.5328–0.5328=0

∴ Cycleisreversible.(Ans.)

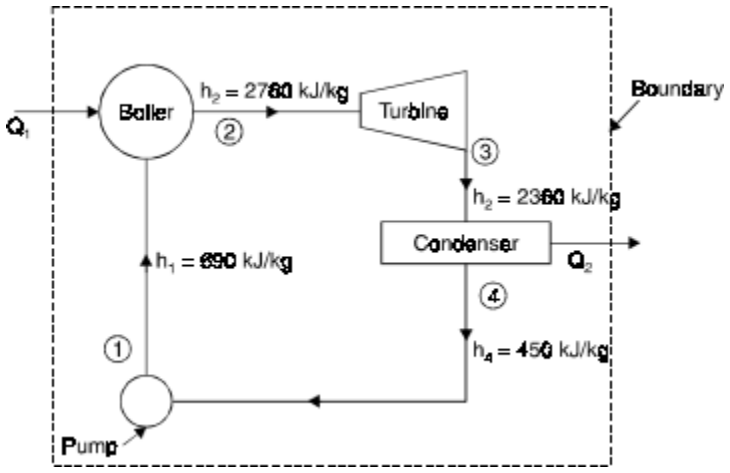
(iii) $\sum \frac{\delta Q}{T} = . \frac{300}{290+273} - \frac{75}{85+273}$

=0.5328–0.2664=0.2664>0.

Thiscycleisimpossiblebysecond lawofthermodynamics,i.e., Clausius inequality. (Ans.)

Example11. In a power plant cycle, the temperature range is 164°C to 51°C,theuppertemperaturebeingmaintainedintheboilerwhereheat is received and the lower temperature being maintained in the

condenserwhereheat isrejected.Allotherprocessesinthesteadyflow cycle are adiabatic. The specific enthalpies at various points are given in Fig. Verify the Clausius Inequality



Solution.Temperaturemaintainedinboiler, T_1= 164 +273=437 K

Temperature maintained in condenser, T2 = 51 + 273 = 324 K

Heattransferredintheboilerperkgoffluid, Q_1 =

$h_2 – h_1$ = 2760 – 690 = 2070 kJ/kg

Heattransferredoutatthecondenserperkgoffluid,

$Q_2=h_4–h_3$=450–2360=–1910kJ/kg

Sincethereisnotransferofheatatanyotherpoint,wehaveperkg

$\sum_{cycle}\frac{\delta Q}{T}=\frac{Q_1}{T_1}+\frac{Q_2}{T_2}=\frac{2070}{437}+\left(\frac{-1910}{324}\right)$

=4.737–5.895=–1.158kJ/kgK< 0.

TheClausiusInequalityisproved. Thesteadyflowcycleisobviously irreversible.

Ifthecycleisreversiblebetween thesametemperaturelimitsand the heat supplied at higher temperature is same, the heat rejected can be calculated as follows :

$\eta_{reversible} = 1 - \frac{T2}{T_1} = 1 - \frac{324}{437} = 0.2586 \text{ or } 25.86\%$

∴Heatrejectedperkgisgivenby

$Q_2 = (1 - 0.2586) \times Q_1 = (1 - 0.2586) \times 2070 = 1534.7 \text{kJ/kg}$δQTcycle

∑

$\sum_{cycle} \frac{\delta Q}{T} = \frac{2070}{437} - \frac{15347}{324} = = 4.73 - 4.73 = 0$

$\sum_{cycle} \frac{\delta Q}{T} = \frac{Q_{added}}{T_{source}} + \frac{Q_{rejected}}{T_{sink}}$

ThusClausiusEqualitysignforareversibleengineisverified

Availableenergy(A.E.),

Sourcesofenergycanbedividedintotwogroups,

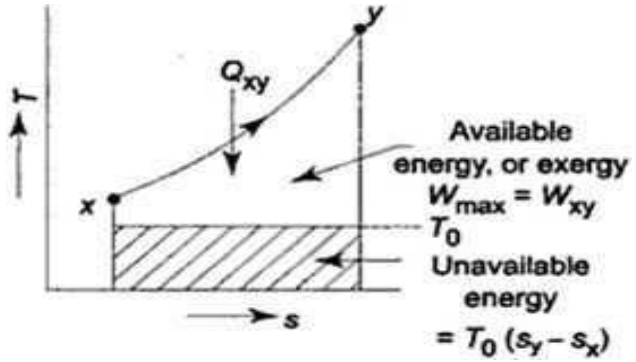
- highgradeenergy
- lowgradeenergy

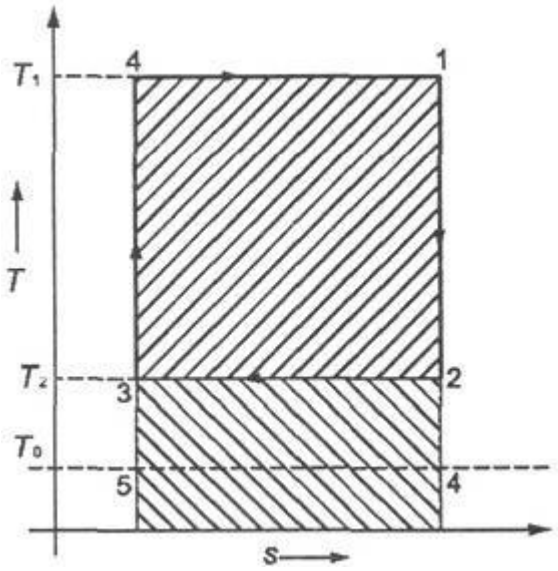
Availableenergy

Themaximumwork outputobtainablefromacertainheatinputina cyclic heat engine is called the *available energy* (A.E.),

Unavailableenergy

Theminimumenergythathastoberejected tothesinkbythesecond law is called the ***unavailable energy***





Accordingtothesecondlawofthermodynamics,the reaof1-2-3-4iscalled*usefulenergy*.But,theareaof2-3-5-6referstheenergylossestothesurroundingsduetofriction(uncontrollableloss).

Availableenergy:

$$A.E=Q-T\Delta S_0[(1-\frac{T_0}{T_1})Q;\Delta S=\frac{Q}{T_1}]$$

Q=HeattransferkJT_1=Sourcetemperature

T_2or T_0surroundingtemperatureEntropyprincipleΔS

Un*availableenergy:*

$$U.A.E=Q-A.E \quad [Q-[(Q-T_0\Delta S)]$$

$$=T_0\Delta S$$

Typeofprocess	***Availableenergy:***	**Un*available energy:***
Constantvolume process	$A.E=Q-T_0\Delta S$where $\Delta S=mC_v\ln\frac{T_2}{T_1}$ $Q=mC_v(T_2-T_1)$	$Q-A.E=T_0\Delta S$ $U.A.E=T_0\Delta S$
Constant pressure or isobaricprocess	$A.E=Q-T_0\Delta S$ $Q=mC_p(T_2-T_1)$	$U.A.E=T_0\Delta S$

	$\Delta S = mC_p \ln \frac{T_2}{T_1}$	
Constant temperature or isothermal process	A.E $= Q - T_0 \Delta S$ $Q = pV \ln(\frac{p_2}{p_1})$ $\Delta S = \frac{Q}{T_1}$ or $\frac{Q}{T_2}$	U.A.E $= T_0 \Delta S$
Polytrophic Process	$Q = (\gamma - n)\frac{p1V1 - p2V2}{n-1}$ $= (\gamma - n)\frac{mR(T_1 - T_2)}{n-1}$ $\Delta S = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$ $\Delta S = C_V \ln \frac{T_2}{T_1} - R \ln \frac{V_2}{V_1}$ A.E or $W_{max} = Q - T_0 \Delta S$	**Irreversibility** $I = W_{max} - W$ $= T_0 \Delta S$

OpenSystemInTermsOfAvailabilityAndSecondLawEfficiency

	Availabilitychange	**Irreversibility**
Turbine:	A.E $= W_{max} = \boldsymbol{m}(h_1 - h_2 - T_0(S_1 - S_2))$ $\boldsymbol{Secondlawefficiency} = \eta_{(II)}$ $\eta_{(II)} = \frac{W_{max}}{A_{act}}$	$I = W_{max} - W_{act}$ $= T_0 \Delta S$
Compressor /pump	Maximumworkinput,[A.E] $W_{max} = \boldsymbol{m}(h_2 - h_1 - T_0(S_2 - S_1)$ ***Secondlawefficiency*** $\eta_{(II)} = \frac{W_{max}}{A_{act}}$	**Irreversibility** $I = W_{max} - W$ $= T_0 \Delta S$
Heat Exchanger	Availabilityofcoldfluid, $\boldsymbol{B_c = m_2 C_2 (T_4 - T_3) - T_o}(S_4 - \boldsymbol{S_3})$ Availability,ofHotfluid,	Irreversibility, $\boldsymbol{I = B_h - B_c}$

	$B_h = m_1 C_2 (T_1 - T_2) - T_o(S_1 - S_2)$ ***Secondlawefficiency***= $\eta_{(II)}$=	
Throttling process	$W_{max} = (h_1 - h_2 - T_0(S_1 - S_2))$ $W_{max} = (h_1 - T_0 S_1) - (h_2 - T_0 S_2))$ $= \psi_1 - \psi_2$	

EFFECTIVENESS

Effectiveness*isdefinedastheratioof actualusefulworktothe maximum useful work.*

$$\text{Effectiveness}, \in = \frac{\text{Increaseofavailabilityofsurroudinds}}{\text{Lossofavailabilityofthesystem}}$$

Firstlawefficiency

Fristlawof efficiencyisdefinedastheratiobetween network output and heat supplied to the system

$$\eta_{\text{Frist(I)}} = \frac{networkoutput}{\text{heatsuppliedtothesystem}}$$

Secondlawefficiency isdefinedastheratiobetween thechangeinthe available energy the system and change in the available energy of the source

$\eta_{(II)} = \frac{\text{Change intheavailableenergyofthesystem}}{\text{Changeintheavailableenergy ofthesource}} = \frac{A_{out}}{A_{in}}$

OpenSystemInTermsOfAvailabilityAndSecondLawEfficiency

Turbine:

Reversible work (or) maximum work or availabilitychange

availabilitychangeA.E=W_{max}=**m**$(h_1 - h_2 - T_0(S_1 - S_2))$

IrreversibilityI=$W_{max} - W_{act}$

$= T_0 \Delta S$

Secondlawefficiency= $\eta_{(II)} = \frac{W_{max}}{A_{act}}$

Compressor/pum

Maximumworkinput,[A.E]

W_{max}=**m**$(h_2 - h_1 - T_0(S_2 - S_1))$

Irreversibility

I=$W_{max} - W$

$= T_0 \Delta S$

Secondlawefficiency

= $\eta_{(II)} = \frac{W_{max}}{A_{act}}$

HeatExchanger

Availabilityofcoldfluid,

$B_c = m_2 C_2 (T_4 - T_3) - T_o(S_4 - S_3)$

Availability,ofHotfluid,

$B_h = m_1 C_2 (T_1 - T_2) - T_o(S_1 - S_2)$

Irreversibility,

$I = B_h - B_c$

Secondlawefficiency= $\eta_{(II)}$= −

Throttlingprocess

W_{max}=$(h_1-h_2-T_0(S_1-S_2))$

W_{max}=$(h_1-T_0S_1)-(h_2-T_0S_2))=\psi_1-\psi_2$

EFFECTIVENESS

Effectiveness*isdefinedastheratioof actualusefulworktothe maximum useful work.*

Effectiveness,$\in=\frac{\text{Increaseofavailabilityofsurroudinds}}{\text{Lossofavailabilityofthesystem}}$

Example 1:.*15kgofwaterisheatedinaninsulatedtankbyachurning process from300 K to 340 K. If the surrounding temperature is 300 K, find the loss in availability for the process.*

Solution.

Mass of water, *m* = 15 kg

Temperature, T_1 = 340 K

Surroundingtemperature, T_0 =300K

Specificheatofwater, c_p=4.187kJ/kgK

Lossinavailability:

Workaddedduringchurning

=Increaseinenthalpyofthewater

$=mc_v(T_2–T_0)$

=15×4.187×(340–300)=2512.2kJ

energy in the water = 2512.2 kJ

availabilityoutofthisenergyisgivenby

$m(h_1-h_2-T_0(S_1-S_2))$

where$\Delta s=c_p\log_e\ln\frac{T_1}{T_0}$

$\therefore\Delta s=4.187\log_e\frac{340}{300}$

=0.524kJ/kgK

∴Availableenergy

= $m[c_v(T_1–T_0)–T0\Delta s]$

=15[4.187(340–300)–300×0.524]=158.7kJ

∴Lossinavailability
=2508–158.7=**2349.3kJ. (Ans.)**

Example 2:*Onekgofairiscompressedpolytropically from1bar pressure and temperatureof 300 K to a pressure of 6.8 bar and temperature of 370 K. Determine the irreversibility if thesink temperatureis293K.AssumeR =0.287kJ/kg K, c_p =1.004kJ/kg K and c_v = 0.716 kJ/kg K.*

Given:

p_1*=1bar:temperature*$T_1=300K$

p_2*=6.8bar:temperature*$T_2=370K$

$T_0=293$ *KR = 0.287 kJ/kg K ,c_p =1.004kJ/kgK c_v = 0.716 kJ/kg K.:*

*Tofind:****irreversibility*****Irreversibility**I=$W_{max}-W_{act}$
=$W_{max}=(h_1-h_2-T_0(S_1-S_2))$

Solution:

Irreversibility$I=W_{max}-W_{act}$

$-W_{max}$=Changeininternalenergy–T_0×Changein entropy

$-Wmax=(h_1-h_2-T_0(S_1-S_2))$

$-W_{max}=c_v(T_2-T_1)-T_0[c_p\ln(T_2/T_1)-R\ln(p_2/p_1)]$

$=0.716(370-300)-293\times[1.005\ln\frac{370}{300}-0.287\ln\frac{6.8}{1}]$

$W_{max}=-149.53$kJ/kg=$Wrev$

(negativesignindicatesthatworkisdoneonair)

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

Theindexofcompression‘n’isgiven by

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

$\frac{n-1}{n} = \frac{\ln\frac{370}{300}}{\ln\frac{6.8}{1}}$

n=1.123

$W_{act} = \frac{mR(T_1-T_2)}{n-1} = \frac{1\times0.287(370-300)}{1.123-1}$

=–163.33kJ/kg

$I = Wrev – Wact$ =–149.53–(–163.33)

Irreversibility=**13.8kJ/kg.(Ans.)**

Example 3:*8 kg of air at 650 K and 5.5 bar pressure is enclosed in a closed system.Iftheatmospheretemperatureandpressureare300Kand 1 bar respectively, determine :*
(i) *Theavailabilityifthesystemgoesthroughtheidealworkproducing process.*
(ii) *The availability and effectiveness if the air is cooled at constant pressuretoatmospherictemperaturewithoutbringingittocompletedead state.Takec_v=0.718 kJ/kgK;c_p=1.005kJ/kg K.*
Solution. Mass of air, m = 8 kg
Temperature, T_1 = 650 K
Pressure, p_1 = 5.5 bar
Atmosphericpressure, p_0 =1bar
Atmospherictemperature, T_0=300K
Forair:c_v=0.718kJ/kgK;c_p=1.005kJ/kgK.

ChangeinavailabilityA.E=$W_{max} = m(h_1 - h_2 - T_0(S_1 - S_2))$ ($h_1 - h_2$)= $c_v(T_1 - T_0)$
$(S_1 - S_2) = \Delta S = C_V \ln\frac{T_2}{T_1} - R\ln\frac{V_1}{V_0}$

Usingtheidealgasequation,$\frac{p1v1}{T_1} = \frac{p_0v_0}{T_0} =$

$\frac{v_0}{v_1} = \frac{p_1}{p_0} = \frac{T_0}{T_1} = \frac{5.5}{1} \times \frac{300}{650} = \mathbf{2.54}$

$\therefore \Delta s = 0.718 \log_e\left(\frac{650}{300}\right) + 0.287 \log_e\left(\frac{1}{2.54}\right) +$

$= 0.555 + (-0.267) = 0.288$ kJ/kgK

Δs=0.288kJ/kgK

Changeinavailableenergy

$= m(h_1 - h_2 - T_0(S_1 - S_2))$

$= 8[0.718(650 - 300) - 300 \times 0.288] = 1319.2$ kJ

Lossofavailabilityperunitmassduringtheprocess

$= p_0(v_0 - v_1)$perunitmass

Totallossofavailability$= p_0(V_0 - V_1)$

But$V_1 = \frac{mRT_1}{p_1} = \frac{8 \times 287 \times 650}{5.5 \times 10^5}$

$= 2.713 \text{m}^3$

$V_0 = 2.54 \times 2.713 = 6.891 \text{ m}^3$

$\therefore$**Lossofavailability**$= \frac{1 \times 10^5}{10^3}(6.891 - 2.713) =$**417.8kJ.(Ans.)**

Lossofavailability=417.8kJ.(Ans.)

ii)Heattransferredduringcooling(constantpressure)process

$= m.c_p(T_1 - T_0)$

$= 8 \times 1.005\ (650 - 300) = 2814$kJ

Changeinentropyduringcooling

$\Delta s = mc_p \log_e \ln \frac{T_1}{T_0} = 8 \times 1.005 \times \log_e\left(\frac{650}{300}\right)$

$= 6.216$kJ/K

Unavailableenergy$= T_0 \Delta S$

$= 300 \times 6.216 = 1864.8$ kJ

Availableenergy $= 2814 - 1864.8 =$**949.2kJ.(Ans.)**

Effectiveness, $\in = \frac{Available\ energy}{ChangeinAvailableenergy}$

$= \frac{942.2}{1319.2} =$**0.719.(Ans.)**

Example4: *Whatisthe maximumusefulworkwhichcanbeobtained when 100 kJ*
are abstracted from a heat reservoir at 675 K in an environment at 288 K? What is the loss of useful work if (a) A temperature drop of 50°C is introducedbetweentheheat sourceandtheheatengine,on theonehand, and the heat engine and the heat sink, on the other
(b) The source temperature drops by 50°C and the sink temperature risesby50°Cduring theheattransferprocessaccordingtothelinear law $\frac{dQ}{dT} = \pm$ *Cconstant?*

Q=100kJ *heatreservoir* $T_2 = 675K$ *environment* $T_0 = 288K$

Solution:

Entropychangeforthisprocess

$\Delta S = \frac{Q}{T} = \frac{-100kJ}{675}$ =0.14815 kJ/K

(a) Nowmaximumworkobtainable

$W_{max} = Q\left(1 - \frac{T_0+50}{T_2-50}\right)$

$W_{max} = 100\left(1 - \frac{338}{625}\right)$

=45.92kJ

∴Lossofavailablework=57.333–45.92

=11.413Kj

b) Given : $\frac{dQ}{dT} = \pm$ *Cconstant*

LetdQ=±mcpdT

∴When sourcetemperatureis(675 –T)andsincetemperature(288+T)at that time if dQheat is flow then maximum.

Availableworkfromthat dQisdW.

$dW = dQ\left(1 - \frac{288+T}{675-T}\right)$

$= \left(1 - \frac{288+T}{675-T}\right) mc_p dT$

$\therefore W_{max} = mc_p \int_0^{50} \left(1 - \frac{288+T}{675-T}\right) dT$

$= mc_p \int_0^{50} \left(1 + 1 - \frac{288+T}{675-T}\right) dT$

$$=mc_p\{2(50-0)+963ln(^{675-50}_{675-0})\}$$

=25.887Pmc$_p$kJ

mc$_p$×50=100kJ

=51.773kJ

∴mc$_p$=2kJ/K

∴Lossofavailability=(57.333–51.773)kJ

=5.5603kJ

******Example5:***Two kg of air at 500 kPa, 80°C expands adiabatically ina closed system until its volume is doubled and its temperature becomes equal to that of the surroundings which is at 100 kPa, 5°C. For this process, determine (a) the maximum work, (b) the change in availability, and (c) the irreversibility. For air, take c_v = 0.718kJ/kg K, u = c_vT where c_v is constant, and pV = mRT where p is pressure in kPa, V volume in m^3, m mass in kg, R a constant equal to 0.287 kJ/kg K, and T temperature in K.*

Solution:

Pressurep_1= 500kPa

Initialtemperature,T_1=80+273=353K

Final temperature,T_2=5 +273= 278 K

Surroundings Pressure100 kPa,

Surroundingstemperature 5°C,

Tofind:(a)themaximumwork $\boldsymbol{W_{max}=m}(h_2-h_1)-T_0(S_2-S_1))$

(b) thechangeinavailability,$\phi_1-\phi_2$

(c) theirreversibility.I=$W_{\boldsymbol{max}}-W_{act}$

Calculatethemaximumwork $\boldsymbol{W_{max}}$

$=\boldsymbol{m}(h_2-h_1)+T_0(S_2-S_1))$

m=2

$(h_2-h_1)=c_v(T_2-T_1)$

$=$

$S_2-S_1=\Delta S=mC_V\ln\frac{T_2}{T_1}+mR\ln\frac{V_2}{V_1}$

$\Delta S=m(C_V\ln\frac{T_2}{T_1}+R\ln\frac{V_2}{V_1})$

$=(0.718\ln\frac{278}{353}+0.287\ln\frac{2}{1})=[(-0.172+0.199)]$

$=7.51$

$\boldsymbol{S_2-S_1=\Delta S=0.054}$

$\boldsymbol{W_{max}=m}(h_2-h_1)+T_0(S_2-S_1))$

$\boldsymbol{=2}\ [c_v(T_1-T_2)]+T_0(S_2-S_1)$

=2(53.85+7.51)

=122.72kJ

***Calculate*thechangeinavailability**

$=\phi_1-\phi_2=\boldsymbol{m}(h_2-h_1)-T_0(S_2-S_1))+p_0(V_0-V_1)$

$=122.72[-100\times\frac{2\times0.287\times353}{500}]$

$=82.2$**kJ**

Calculatetheirreversibility. $\boldsymbol{I=W_{max}-W_{act}}$

$\boldsymbol{W_{act}=T_0\Delta S=278\times0.054=15.2Kj}$

Example6 : *A gas is flowing through a pipe at the rate of 2 kg/s. Because of inadequate insulation the gas temperature decreases from 800 to790°C between two sections in the pipe. Neglecting pressure losses, calculate the irreversibility rate (or rate of energy degradation) due tothis heat loss. Take* T_a *= 300 K and a constant* c_p *= 1.1 kJ/kg K.*

For the same temperature drop of 10°C when the gas cools from 80°C to70°Cduetoheatloss,what istherateofenergydegradation?Takethe same values of T_o *and* c_p*. What is the inference you can draw from this*

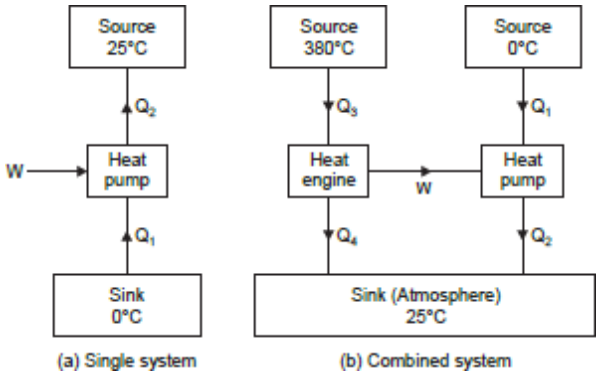
example?

Example: *A reversible heat pump is used to maintain a temperature of 0°C ina refrigeratorwhen it rejectstheheat tothe surroundingsat25°C. If the heat removal rate from the refrigerator is 1440 kJ/min, determine the C.O.P. of the machine and work input required*.(*ii*) *If the required input to run the pump is developed by a reversible engine which receives heat at 380°C and rejects heat to atmosphere, then determine the overall C.O.P.ofthe system*.

Solution.

(i) Temperature, T_1=25+273=298K

Temperature, T_2 = 0 + 273 = 273 K



Heatremovalratefromtherefrigerator,

$$Q_1=1440\text{kJ/min}=24\text{ kJ/s}$$

Now,co-efficientofperformance,forreversibleheatpump,

$$\text{C.O.P.}=\frac{T1}{T_1-T_2}=\frac{298}{(298-273)}=\mathbf{11.92.(Ans.)}$$

$$\therefore(\text{C.O.P.})ref.=\frac{T2}{T_1-T_2}=\frac{273}{(298-273)}=10.92$$

Now, $$10.92=\frac{Q1}{W}=\frac{24}{W}$$

$\therefore$ $$W=2.2\text{kW}$$

i.e.,**Workinputrequired=2.2kW. (Ans.)**

$$Q_2=Q_1+W=24+2.2=26.2\text{ kJ/s}$$

(ii) ReferFig.(*b*).

TheoverallC.O.P.isgivenby,

$$\text{C.O.P.}=\frac{\text{Heatremovedfromtherefrigerator}}{\text{Heatsuppliedfromthesource}}$$

$$\frac{Q_1}{Q_3}$$

Forthereversibleengine,wecanwrite

$\frac{Q_3}{T_3} = \frac{Q_4}{T_4}$

$\frac{Q_4+W}{T_3} = \frac{Q_4}{T_4}$

$\frac{Q_4+22}{653} = \frac{Q_4}{298}$

$$298(Q_4+2.2)=653Q_4$$

$Q_4(653–298)=298\times 2.2$

$Q_4=\frac{298\times 2.2}{(653-298)}=1.847\text{kJ/s}$

$\therefore Q_3 = Q_4 + W = 1.847+2.2=4.047\text{kJ/s}$

Substitutingthisvalueineqn.(*i*),weget

C.O.P. = $\frac{24}{4.047}$ =**5.93. (Ans.)**

Ifthepurposeofthesystemistosupplytheheattothesinkat25°C,then

OverallC.O.P.=$\frac{Q2+Q4}{Q_3}=\frac{26.2+1.87}{4.047}$**=6.93.(Ans.)**

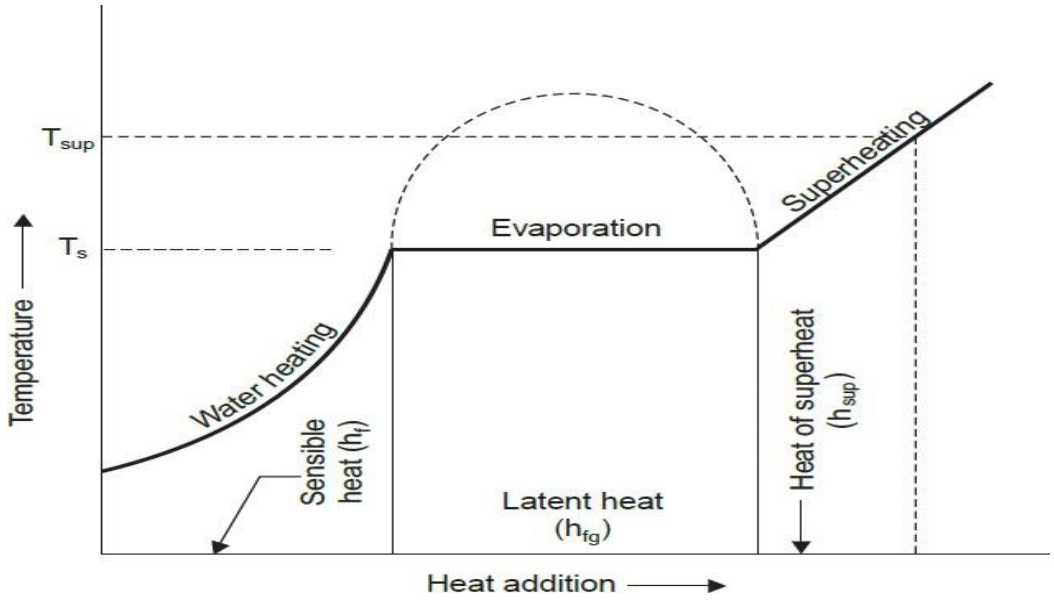
Unit-4

IntroductiontoPureSubstance

- Therearethreephaseofsubstancesolid,liquidandgasses.
- Steamisagaseousform ofliquid.
- Thevapourizationofliquidiscalledvapour.
- The process changing liquid to gaseous phase is called vapourization.

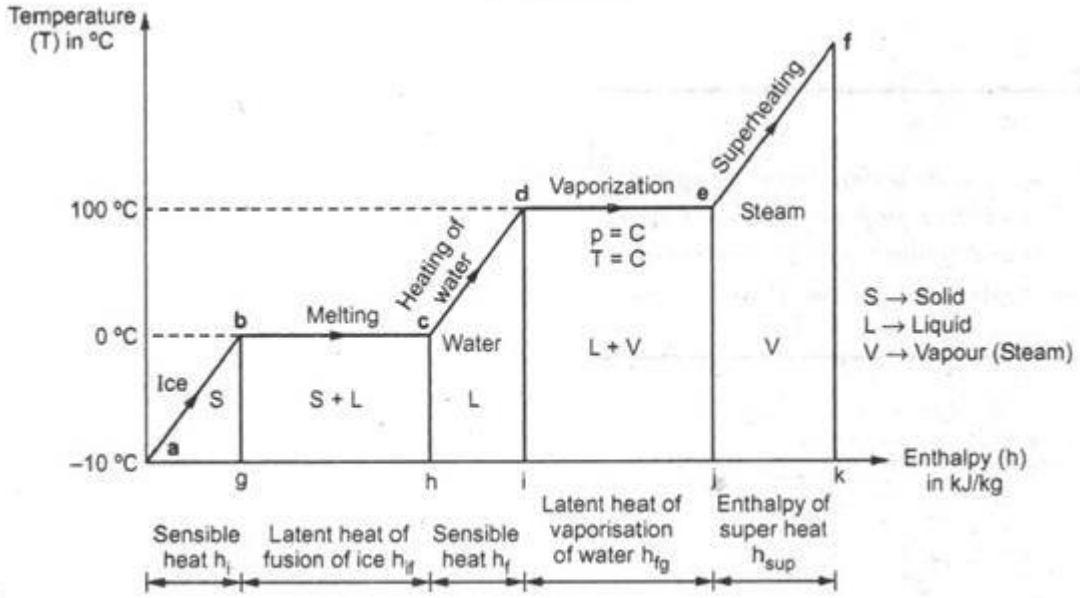
PhaseChangeatConstantpressure

- Steamproducedfromthewateract asworkingfluid forthethermal power plant.
- Formation of steam from ice at constant pressure is shown in Fig. on a temperature enthalpy (T - h) diagram.

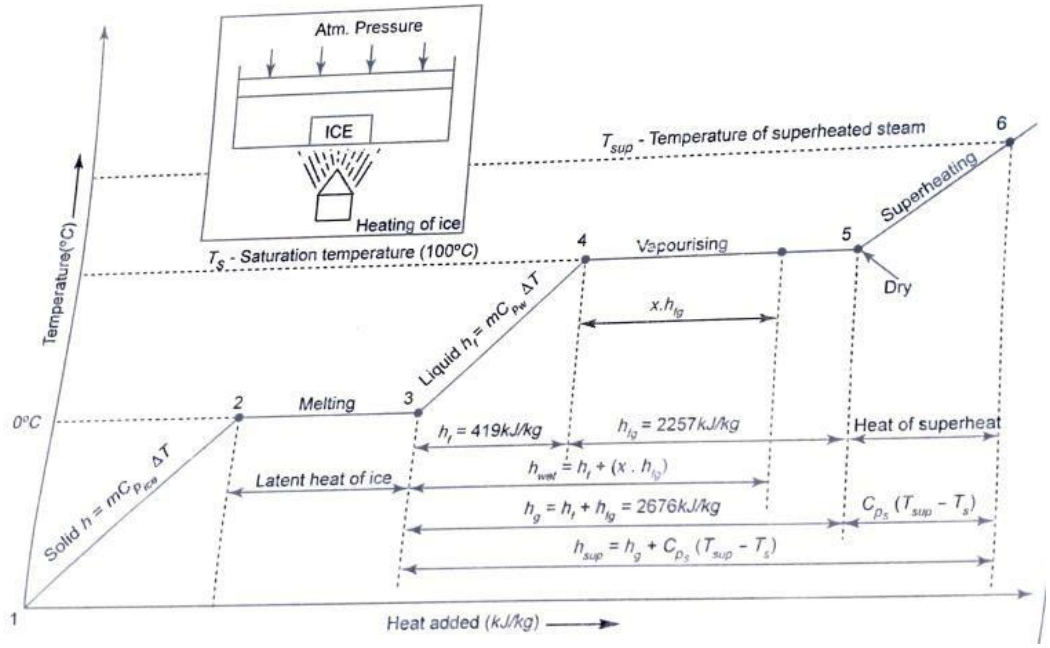


Processab :Asheatissupplied,temperatureoficeincreasesfrom - 15°C till it reaches 0°C. This is the sensible heating of ice

- Process be: On further addition ofheat,melting oficetakes placeat constant temperature till the complete ice melts. The amount of heat added is latent heat of fusion or enthalpy of fusion.
- Process cd : Further heat addition after point C causes the increase inemperature of water upto 100 °C. Water at point D is saturated liquid and this process of heating is sensible heating of water.
- Process de : Thisprocess shows thecomplete conversion of water to steam and amount of heat added is known as latent heat of vaporisation or enthalpy of vaporisation (h_{fg}). This heat is added at constant temperature.



. Graphical representation of formation of steam.

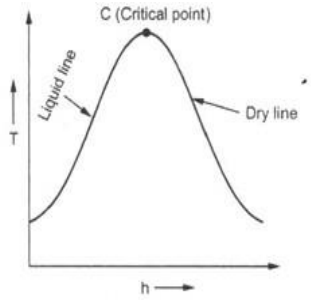


Processef: Thisprocessrepresentsthesuperheatingofsteam.Theheatis being added to improve thequality of steam. The temperature of steam is raised above the 100 °C

CriticalPointandTriplePointonPhaseDiagram

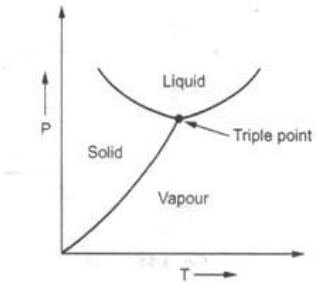
CriticalPoint:

• Itisapointatwhichthelatentheatbecomeszero(hf_g=0).
• Thefollowingdiagramshowscriticalpoint.
• Incriticalpointtheliquidisdirectlyconvertedintodry steam



TriplePoint:

• Itisapointatwhichthesolid,liquidandgaseousphasesaremeet.



L***Enthalpyofsteam(h):***

Itisthe amountof heat added to the waterfromfreezing point to till the water becomes wet or dry or superheated steam.

Forwetsteam, $h_{wet}=h_f+xh_{fg}$

Fordrysteam,$h_{dry}=h_g=h_f+h_{fg}$

Forsuperheatedsteam,$h_{sup}=h_g+C_p(T_{sup}-T_{sat})$

where,

h=Enthalpyofsteamin ***kJ/kg***

v=Specificvolumeofsaturatedsteam

h_g=EnthalpyofdrysaturatedsteaminkJ/kg

h_f=Enthalpyofwater(4.187kJ/kgK)

h_{fg}=EnthalpyofevaporationinkJ/kg

v_{sup}=Specificvolumeofsuperheatedsteam T_s = Temperature of saturated steam

T_{sup}=Temperatureofsuperheatedsteam

(T_{sup}–T_{Sat}) iscalledas ***'degreeofsuperheat'.***

h_{sup} = Enthalpy of superheated steam C_p=Specificheatofsuperheatedsteam

= 2kJ/kgK

(ii) Densityofsteam(p):

It is defined as the ratio of mass to the unit volume of steam at given pressuretemperature. Itsvalueforwet,dry,andsuperheated steamisthe reciprocal of specific volume of the steam.

(iii) Specificvolumeofsteam(v):

It isdefined asthevolumeoccupiedbytheunitmassofsteamatthe given pressure and temperature.

ItisdenotedbyVandisgiven by

$$V = \frac{1}{\rho}$$

where,

v=Specificvolume ρ=Density

Forwetsteam, $v_{wet} = xv_g = (1 - x)v_f + xv_g$ For dry steam, $= v_g$

Forsuperheatedsteam, $v_{sup} = \frac{v_g T_{sup}}{T_{sat}}$

where

v= Specificvolumein m^3/kg

(iv) Workdoneduringexpansion(W):

energyrequired forabsorption oflateheatforincreasingvolumeof the steam.

Forwetsteam, $W_{wet}=100pxv_g$

Fordrysteam, $W_{dry}=100pv_gk$

Forsuperheatedsteam, $W_{sup}=100pv_{sup}$

where,

W*=**WorkdoneinkJ*

p*=**Pressureatwhichevaporationtakesplacein ***bar. (v)Internal energy of steam (U):

Internalenergyofsteamisdefined astheactualheat energystored in the steam above the freezing point of water at the given conditions. It is the difference between. enthalpy of steam and the external work done.

$$h=u+W_e=u+pv$$

$$W_e=pv=\text{Evaporationwork}$$

Forwetsteam, $u_{wet}=[h_f+xh_{fg}]$—[100pxv$_g$] For

dry steam, $U_{dry}=[h_f+h_{fg}]$ —[100p v$_g$]

Forsuperheatedsteam, $u_{sup}=h_{sup}$—[100pv$_{sup}$]

where

u=Enthalpyofsteamin***kJ/kg***

(iv)Entropyofsteam(s):

Itisthepropertyofthesteamwhichincreaseswithincreaseintemperature and decreases with decrease in temperature.

Forwetsteam,$s_{wet}=s_f+xs_{fg}$

Fordrysteam$S_{dry}=s_f+s_{fg}$

Forsuperheatedsteam,$s_{sup}=s_g+C_{ps}log(\frac{T_{sup}}{T_s})$

where

s=EntropyofsteaminkJ/kgK

Theabovementionedpropertiesatdifferentpressuresaretabulatedinthe form of tables as

p=Absolutepressure(barorkPa);

s_f=Entropyofsaturatedliquid(kJ/kgK);

s_{fg}=Entropyofvapourisation(kJ/kgK);

s_g=Entropyofsaturatedvapour(steam)(kJ/kgK);

v_f=Specificvolumeofsaturatedliquid(m^3/kg);

v_g=Specificvolumeofsaturatedvapour(steam)(m^3/kg).

Change of enthalpy during evaporation,

$h_{fg}=h_g–h_f$.....

Changeofentropyduringevaporation

$s_{fg}=s_g–s_f$.....

Changeofvolumeduring evaporation.

$v_{fg}=v_g–v_f$.....

Internalenergyofsteam

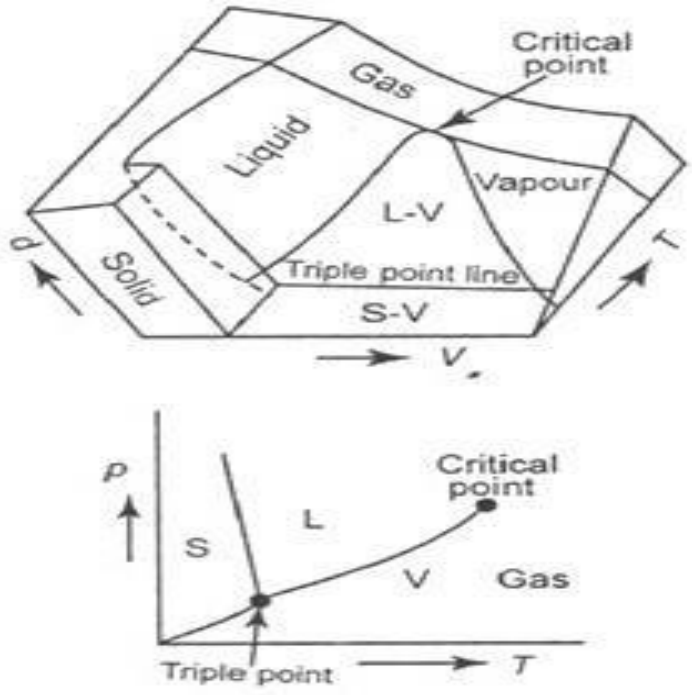
$u=h–pv$

Externalworkofevaporation

$=p(v_g–v_f)$

p-v-TSURFACE

- The three important thermodynamic properties such as pressure (p), specific volume (v) and temperature (T) are plotted in three dimensional coordinates. This is called as ***p-v-T*** surface.
- That is represented on both the T-V and P-T diagram can be shown on one diagram if the three coordinates P, V and T are plotted along the rectangular axes.
- TheobtainedsurfaceiscalledasthePVTsurfaceasshowninfigure
- When the surface is projected on the PT plane, the solid-vapour region projects into the sublimation curve, the liquid-vapour region projects into the fusion curve and the triple point line projects into the triple point.
- ThecriticalpointisdenotedbytheletterCjandthetriplepointbyT



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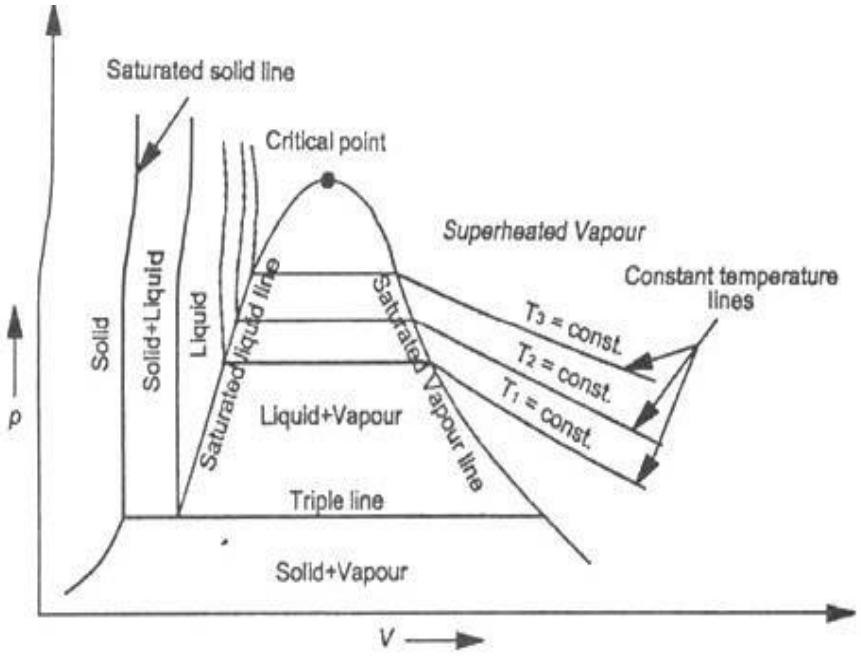
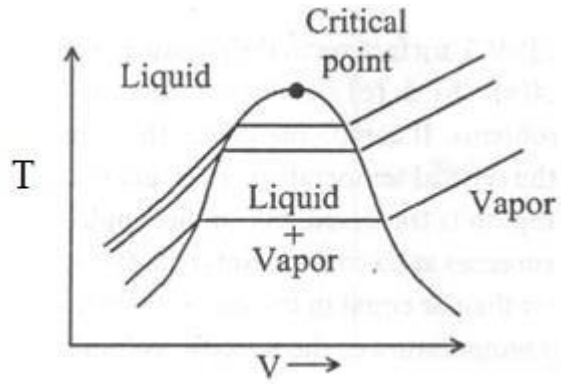
*p-V*DIAGRAM

p-V diagram is the plot between specific volume and pressure. Specific volume is taken along X-axis and pressure is taken along X-axis. The state changes of a pure substance when it is slowlyheated at different constant pressures as shown in FigureMost of the substances contract duringa solidification or freezing process. Some substances such as water expand as they freeze. ***p-V*** diagram type of substances are given in the Figure



The liquid, two phase liquid-vapour and vapour regions of the P-V-T surface rejected on the Temperature- volurne plane results in a T-V diagram, as shown in Figure The T-V diagram is also convenient for solving problems. For pressure less than the critical pressure, the pressure remains constant with temperature in the two phase flow region. In the single phase liquid and vapour regions, the pressure decreases as the specific volume increases forpressures greater than or equalto the critical pressure.



Example1 :*Calculate the dryness fraction (quality) of steam which has 1.5 kg of waterin suspension with 50 kg of steam*.

Solution. Mass of dry steam, m_g= 50 kg

Massofwaterinsuspension, m_f=1.5kg

∴**Drynessfraction,** $x=\frac{m_g}{m_f+m_g}$

Drynessfraction, $\frac{\text{Massofdrysteam}}{\text{Massofdrysteam+massofwaterinsuspension}}$

$\frac{50}{50+1.5}$=**0.971.(Ans.)**

Example2 :*Tenkgofwaterat45°Cisheatedataconstantpressureof10 bar until itbecomes superheated vapour at 300°C. Find the change in volume,enthalpy, internal energy and entropy.*

Given:

Massm=10kgat45°C

Pressure p= 10 bar.

Superheated vapour at 300°C.

FromSteamtable:p=10 bar.

To find;

i) changeinvolume,

ii) enthalpy,

iii)internalenergy

iv)entropy.

Atstate (1)	Atstate (2)
p_1=10bar=1000 kPa	$p_2=p_1$=10bar
T_1=45ºC=318K	T_2=300ºC

v_1=0.001010m^3/kgv_2=0.258m^3/kg

h_1=188.4kJ/kgu_2=2793.2kJ/kg

u_1 = $h_1-p_1v_1$=187.39kJ/kgh_2 =3051.2kJ/kg s_1=

0.693 kJ/kg – K s_2= 7.123 kJ/kg – K

∴Changein volume=m(v_2-v_1)=2.57m^3

Enthalpy change = $m(h_2 - h_1) = 28.628$ MJ

InternalEnergychange $= m(u_2 - u_1) = 26.0581$MJ

Entropychange$= m(s_2 - s_1) = 64.3$kJ/K

Example3:*A rigidvesselofvolume0.86m^3 contains1kgof steamata pressure of 2 bar. Evaluate the* ***specific volume,temperature,dryness fraction, internal energy, enthalpy, and entropy of steam.***

Given:*volumev=0.86m^3 Mass*
m= 1kg

Pressurep=2bar.
FromSteamtable:p=2bar.

t_s	v_f	V_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
120.2	0.001061	0.885	504.7	2201.6	2706.3	1.530	5.597	7.127

Calculatethespecificvolume

Specificvolume$=\frac{\text{Volume}}{\text{mass}}=\frac{0.86}{1}=0.86\text{m}^3/\text{kg}$

Calculatethedrynessfraction

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

$\therefore$***drynessfraction*** $x=\frac{v-v_f}{v_g-v_f}=\frac{0.86-0.001061}{0.885-0.001061}=0.97172$

CalculatetheInternalenergy (u)

$=h-pv=2644-200\times0.86=2472$kJ/kg

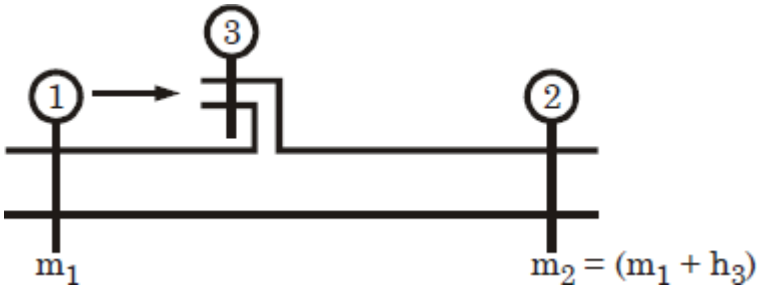
Calculatetheenthalpy,

$h = h_f+xh_{fg}=504.7+0.97172\times2201.6=2644$kJ/kg

Calculatetheentropyofsteam.

$s=s_{fg}+xs_f=1.5301 +0.97172\times5.5967=6.9685$kJ/kg –K

Example4 :*Water at 40°C is continuously sprayed into a pipeline carrying 5 tonnesofsteam at 5 bar, 300°C per hour. At a section downstreamwherethepressureis3bar,thequalityistobe95%.Find the rate of water spray inkg/h.*



P_1=5bar=500kPa	P_2=3bar
T_2=300°C	T_2=133.5°C
h $_1$=3064.2 kJ/kg	h_2=561.4 +0.95×2163.2 =2616.44kJ/kg

T_3=40ºC

h_3=167.6kJ/kg

∴Foradiabaticsteadyflow

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

$\dot{m}_1 (h_1 - h_2) = \dot{m}_3 (h_2 - h_3)$

$\dot{m}_3 = \dot{m}_1 \frac{(h_1 - h_2)}{(h_2 - h_3)}$

$= 5000 \times \left\{ \frac{3064.2 - 2616.44}{2616.44 - 167.6} \right\}$ kg/hr

=914.23kg/hr.

Example 5:*Avesselhavinga volumeof0.6 m^3 contains3.0kgofliquid waterand watervapourmixtureinequilibriumatapressureof0.5 MPa. Calculate :*

(i) *Massandvolumeofliquid* ;

(ii) *Massandvolumeofvapour*.

Solution.

Volumeofthevessel,V=0.6m^3

Massofliquid waterandwatervapour, m=3.0kg Pressure, p = 0.5 MPa = 5 bar

specific volume, $v = \frac{V}{m} = \frac{0.6}{3.0} = 0.2 m^3/kg$

At5bar: Fromsteamtables,

t_s	v_f	V_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
151.8	0.001093	0.3746	640.1	2107.4	2747.5	1.860	4.959	6.819

Calculatethedryfraction

$v_{fg} = v_g - v_f = 0.375 - 0.00109 = 0.3739 m^3/kg$ We

know that,

$v = v_g - (1 - x)v_{fg}$, where x = qualityofthevapour.

$0.2 = 0.375 - (1 - x) \times 0.3739$

$\therefore (1 - x) = \frac{(0.375 - 0.2)}{0.3739} = 0.468$

$x = 0.532$

(i) **Massandvolumeofliquid, $m_{liq.} = ?$ $V_{liq.} = ?$**

$m_{liq.} = m(1 - x) = 3.0 \times 0.468 =$ **1.404 kg. (Ans.)**

$V_{liq.} = m_{liq}.v_f = 1.404 \times 0.00109 =$ **$0.0015 m^3$.(Ans.)**

(ii) **Massandvolumeofvapour, $m_{vap.} = ?$ $V_{vap.} = ?$**

$m_{vap.} = m.x = 3.0 \times 0.532 =$ **1.596 kg. (Ans.)**

$V_{vap.} = m_{vap}.v_g = 1.596 \times 0.375 =$ **$0.5985 m^3$.(Ans.)**

Example6 :*1000 kg of steam at a pressure of 16 bar and 0.9 dry is generatedbyaboilerperhour. Thesteampassesthroughasuperheated via boiler stop valve where its temperature israised to 380°C. If the temperature of feed water is 30°C, determine* :
(i) *Thetotalheatsuppliedtofeedwaterperhourtoproducewetsteam.*
(ii) *Thetotalheatabsorbedperhourin the superheater*.
Takespecificheatforsuperheated steamas2.2 kJ/kgK.
Solution.
Massofsteamgenerated, m=1000kg/h
Pressure of steam, p = 16 bar
Dryness fraction, x = 0.9
Temperatureofsuperheatedsteam,

T_{sup}=380+273=653K
Temperatureoffeedwater= 30°C
Specificheatofsuperheatedsteam,c_{ps}=2.2kJ/kgK.

At16bar. Fromsteamtables,
t_s=201.4°C(*Ts*=201.4+273=474.4K);
h_f=858.6kJ/kg;h_{fg}=1933.2 kJ/kg
(i) *Heatsuppliedtofeedwaterperhour*toproducewetsteamisgivenby
:
$H=m[(h_f+xh_{fg})–1\times4.18\times(30–0)]$
=1000[(858.6+0.9×1933.2)–4.18× 30]
=1000(858.6+1739.88–125.4)
=**2473.08×103kJ. (Ans.)**
(ii) *Heatabsorbedbysuperheaterper hour*
$=m[(1–x)hfg+cps(Tsup–Ts)]$
=1000[(1–0.9)×1933.2+2.2(653–474.4)]
=1000(193.32+392.92)
=**586.24×103kJ. (Ans.)**

Example7 :*A vessel havingacapacityof0.05m3containsamixture of saturated water and saturated steam at a temperature of 245°C. The mass of the liquid present is 10 kg. Find the following:
(i) *Thepressure,*(*ii*)*Themass,*
(iii) *Thespecificvolume,*(*iv*)*Thespecificenthalpy,*
(*v*)*Thespecificentropy,and* (*vi*)*Thespecificinternalenergy*.
Solution.
Fromsteamtables,correspondingto245°C:

p_{sat}	v_f	V_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
36.5 bar	0.001239	0.0546	1061.4	1740.2		2.7474		3.3585

i)**Thepressure=36.5 bar**

(ii) **Themass,m:**
Volumeofliquid,
$V_f=m_fv_f$*[mass*×Specificvolumeofsaturated*]*

$=10\times0.001239=0.01239 m^3$

Totalvolumeofthevessel

V=volumeofliquid+volumeofsteam

$=V_1+V_2$

$0.05=0.01239+V_g$

Volumeofvapour, Vg

=0.05–0.01239=0.03761 m3

∴Massof vapour, $m_g=\frac{VS}{V_S}=\frac{003761}{00546}$

=0.688kg

∴Thetotalmassofmixture,

m$=m_f+m_g$=10+0.688 =**10.688kg.(Ans.)**

(iii) **Calculatethespecificvolume,v :**

Qualityofthemixture**x**$=\frac{m_g}{m_g+m_f}=\frac{0.688}{0.688+10}$ =0.064

.

∴**v**$=vf+xvfg$

=0.001239+0.064×(0.0546–0.001239)(_ $vfg=vg-vf$)

=**0.004654m^3/kg.(Ans.)**

(iv) **Thespecificenthalpy,h:**

h $=h_f+xh_{fg}$

=1061.4+0.064×1740.2=**1172.77kJ/kg.(Ans.)**

(v) **Thespecificentropy,s:**

s= $s_f+ xs_{fg}$

=2.7474+0.064×3.3585=**2.9623kJ/kgK. (Ans.)**

(vi) **Thespecificinternalenergy,u:**

u $=h–pv$

$=1172.77-\frac{36.5\times0.004654}{1000}$==**1155.78kJ/kg.(Ans.)**

☞**Example3.9.***Apressurecookercontains1.5kgof****saturatedsteam****at5 bar. Find thequantity of heat which must be rejected so as to reduce the qualityto60%dry.Determinethepressureand temperatureof thesteam at the new state*.

Solution.

Massofsteaminthecooker=1.5kg Pressure of steam, p = 5 bar

Initialdrynessfractionofsteam,x_1=1(*saturatedsteam*)

Finaldrynessfractionofsteam,x_2=0.6 (*dry*)

Heattoberejected:

Pressureandtemperatureof thesteamatthenew state: At 5 bar. From steam tables,

t_s=151.8°C;h_f=640.1kJ/kg;

h_{fg}=2107.4kJ/kg; v_g=0.375m3/kg volume of pressure cooker

$$=m\times v_g$$

$=1.5\times0.375=0.5625m^3$

Internalenergyofsteamperkgatinitialpoint1,

$u_1=h_1-p_1v_1$

$= (h_f+h_{fg})-p_1v_{g1}(\_v_1=v_{g1})$

$=(640.1+2107.4)-5\times10^5\times0.375\times10^{-3}$

$=2747.5-187.5=2560$kJ/kg

Also,$V_1=V_2$(V_2=volumeatfinalcondition)

i.e.,$0.5625=1.5[(1-x_2)vf_2+x_2vg_2]$

$=1.5x_2vg2(_vf2$isnegligible)

$= 1.5\times0.6\times vg_2$

$\therefore vg_2=\frac{0.5625}{1.5\times0.6}=0.625m_3$/kg.

Fromsteamtablescorrespondingto0.625m_3/kg,

p_2=**2.9bar**,t_s=**132.4°C**,h_f=556.5kJ/kg,h_{fg}=2166.6kJ/kg Internal energy of steam per kg, at final point 2,

$u_2=h_2-p_2v_2$

$=(h_{f2}+x_2h_{fg2})-p_2xv_{g2}$

$()\_v\ xvg2=2$

$=(556.5+0.6\times2166.6)-2.9\times105\times0.6\times0.625\times10-3$

$=1856.46-108.75=1747.71$kJ/kg.

Heattransferredatconstantvolumeperkg

$=u2-u1=1747.71-2560=-812.29$kJ/kg

Thus,**totalheattransferred**

$=-812.29\times1.5=-$**1218.43kJ.(Ans.)**

Negativesignindicatesthatheathasbeen**rejected.**

UNIT-5

Maxwell’sequation

Maxwell'srelationsare**asetofequationsinthermodynamics which are derivable from the symmetry of second derivatives and from the definitions of the thermodynamic potentials**.

Thermodynamicrelationwasdevelop bysinglephasehaveonly2 independent variable and four thermodynamic properties.

1) Internalenergy(U)
2) Enthalpy(H=U+pv)
3) Helmholtzfreeenergy(F=U−TS)
4) Gibbsfreeenergy(G=H−TS)

Accordingtofirstlaw

dQ=du+pdv ….. (1)

secondlaw,ds=$\frac{dQ}{T}$

d Q =T ds

SubstitutevalueofdQinequ:1

Tds=du+p dv

du= Tds−pdv.....(2)

ForEnthalpyH=U+pv

Differentialchangeininternalenergyequation

dh= du + vdp +pdv .....(3)

Substituteduvalueofin3 dh=

T ds − p dv+ vdp +pdv

dh=Tds+vdp.....(4)

Helmholtzfreeenergyfunction,F=U−TS

df = du – Tds – sdT ... (5)

Substitutedu value ofin 5

df=Tds−pdv–Tds–sdT...

= – pdv – sdT …..(6)

Gibb’s free energy function,

DifferentG=H−TS,

dg= dh–Tds–sdT .....(7)

Substitutedhvalueofin7

dg=–Tds +vdp+Tds–sdT

=vdp–sdT.....(8)

du =Tds− pdv

dh= T ds + vdp

df =–pdv–sdT

dg= vdp – sdT

thermodynamicpropertiesmustsatisfythetheorem-I

theorem-IISgiven by

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

du=Tds−pdv become

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V$$

dh= Tds+vdpbecome

$$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P$$

df =–pdv–sdTbecome

$$\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T$$

dg=vdp–sdT become

$$\left(\frac{\partial V}{\partial T_P}\right) = \left(\frac{\partial S}{\partial P_V}\right)$$

Theseareknownas **Maxwell'sequation**

ENTROPYRELATIONS

TdSequation

Entropy(s)maybeexpressedasafunctionofanyothertwoproperties, e.g.temperature(**T)**andpressure(p)

$$S=f(T,p)$$

$$ds= \left(\frac{\partial s}{\partial T_p}\right) dT+\left(\frac{\partial s}{\partial p_T}\right) dp$$

WhereC_p=T $\left(\frac{\partial s}{\partial T_p}\right)$: $\left(\frac{\partial s}{\partial T_p}\right) = \frac{C_p}{T}$

FromMaxwellrelation, $\left(\frac{\partial s}{\partial p_T}\right) = -\left(\frac{\partial v}{\partial T_p}\right)$

SubstitutingtheaboveexpressionindsEquation

$$ds=\frac{C_p}{T} dT-\left(\frac{\partial v}{\partial T_p}\right) dp$$

MultiplyingbyTonboth sideoftheequation

$$Tds=C_p\, dT-T \left(\frac{\partial v}{\partial T_p}\right) dp$$

Thisisknown asthefirstformofEntropyequation orfirstTds equation.

Entropy(s)maybeexpressedasafunctionofanyothertwoproperties, e.g.temperature**T**andspecificvolume**v**,

$$S=f(T,v)$$

$$ds= \left(\frac{\partial s}{\partial T_v}\right) dT+\left(\frac{\partial s}{\partial v_T}\right) dv$$

WhereC_v=T $\left(\frac{\partial s}{\partial T_v}\right)$: $\left(\frac{\partial s}{\partial T_v}\right) = \frac{C_v}{T}$

From Maxwell relation, $\left(\frac{\partial P}{\partial T_V}\right) = \left(\frac{\partial S}{\partial V_T}\right)$

Substituting the above expression in ds Equation

$$ds = \frac{Cv}{T} dt + \left(\frac{\partial P}{\partial T_V}\right) dv$$

Multiplying by T

$$Tds = C_v \, dT + T \left(\frac{\partial P}{\partial T_V}\right) dv$$

This is known as the second form of Entropy equation or second Tds equation.

Joule-Thomson Coefficient (p).

The *slope* of the constant enthalpy curve on a T - p diagram at any state point is callee **Joule - Thomson Coefficient** (p). It is defined as the ratio of change of temperature : change in pressure at any state under constant enthalpy condition .

$$\mu_j = \left(\frac{dT}{dp_h}\right)$$

EXPRESSION FOR JOULE-THOMSON CO-EFFICIENT

Value of μ_{JT} is mathematically represented as

$$\mu_{JT} = \left(\frac{\partial T}{\partial p_h}\right)$$

We known that

dh=Tds+vdp((H=U+pv)) Substituting for

TdS

Thesecond TdSEqu.is

$$TdS=mc_pdT-T\left(\frac{\partial V}{\partial T}\right)_P dp$$

Equationbecomesdh=$mc_pdT-(T(\frac{\partial V}{\partial T})_P-V)dp+vdp$

$$=mc_pdT-(T(\frac{\partial v}{\partial T})_P-v)dp$$

Forunitmass,theaboveequationbecomes

$$=c_pdT-(T(\frac{\partial v}{\partial T})_P-v)dp$$

$$=c_p(dT)_h-(T(\frac{\partial v}{\partial T})_P-v)(dp)_h \quad \therefore \text{ifh=Cthendh=0}$$

$$\left(\frac{dT}{dp}\right)_h=\frac{1}{c_p}(T(\frac{\partial v}{\partial T})_P-v)$$

$$\mu_j=\frac{1}{c_p}(T(\frac{\partial v}{\partial T})_P-v)$$

$$\mu_j=\frac{1}{c_p}(T(\beta v)_P-v) \qquad (\beta=\frac{1}{v}(\frac{\partial v}{\partial T})_P)$$

$$\mu_j=\frac{v}{c_p}(T(\beta)_P-1)$$

CLAUSIUS–CLAPEYRONEQUATION

clausius–clapeyronequationprovidesarelationshipbetweenvarious properties during a phase change process.

FirstTdSequationisgivenby

$$TdS=mc_vdT+T\left(\frac{\partial p}{\partial T}\right)_v dv$$

Foranyphasechangeprocess, thetemperature&pressureremains constant

Thereforedt=0

$$TdS=T\left(\frac{\partial p}{\partial T}_v\right) \quad dv \text{(or)} ds=T\left(\frac{\partial p}{\partial T}_v\right) \quad dv$$

Integratingbetweeninitialstate‘1’&finalstate‘2’

$$\int_1^2 ds = \int_1^2 \left(\frac{\partial p}{\partial T}_v\right) \quad dv$$

$$s_2 - s_1 = \left(\frac{dp}{dT}_v\right) \int_1^2 dv$$

$$s_2 - s_1 = \left(\frac{dp}{dT}_v\right) (v_2 - v_1)$$

$$\frac{dp}{dT} = \frac{s_2 - s_1}{v_2 - v_1}$$

Fromsecondlawofthermodynamics,

dh=Tds+vdp At

stated earlier , as P= const, dp =0

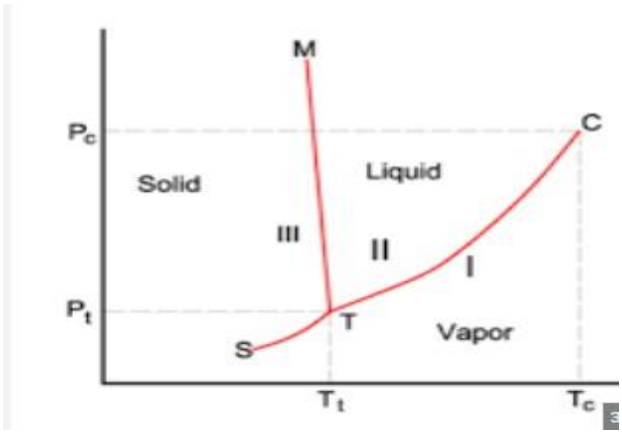
dh= Tds

Integratingbetweeninitialstate‘1’& ‘2’

$$\int_1^2 dh = \int_1^2 Tds$$

$$h_2 - h_1 = T(s_2 - s_1)$$

$$(s_2 - s_1) = \frac{(h_2 - h_1)}{T}$$



$$\frac{dp}{dT} = \frac{(h_2 - h_1)}{T(s_2 - s_1)}$$

Theaboveequationisknownasclausius–clapeyronequation

Clausius–Clapeyronfor

open&closedsystem,$ds=ds_{sys}+ds_{surr}$

Isolatedsystem$ds\geq_0$

Phase change process. Processthatoccursthatasubstance changesitsstatefromoneofthreesates,liquid&vapourtoanother