Ministry of Higher Education
and Scientific Research
University of Anbar

College of Engineering
Mechanical Engineering Department
2nd Year – ME2303

THERMODYNAMICS

Instructor: ***Asst. Prof. Dr. SAAD M. JALIL***

➢ Textbooks:

1. *T.D. ESTOP – A. MCCNKEY* "Applied Thermodynamics".
2. *RAYNER JOEL* "Basic Engineering Thermodynamics".

➢ Other useful books:

1. *SONNTAG, BORGNAKKE and VAN WYLEN"* Fundamental of Thermodynamics".
2. *YUNUS A. CENGEL and MICHAEL A. BOLES"* Thermodynamics an Engineering Approach".
3. *MERLE C. POTTER and CRAIG W. SOMERTON* "Engineering thermodynamics".

➢ Course Contents:

Week	Subject	Week	Subject
1	***Concepts, Definitions, And Basic Principles***	17	***The Second Law of Thermodynamics***
2	Dimensions and Units	18	Heat Engine and Its Types
3	Thermodynamic Systems	19	Refrigerators & Heat Pumps
4	Properties and State of Substance	20	***Entropy***
5	Processes and Cycles	21	Entropy of Single Phase (Ideal Gas)
6	Forms of Energy & Reversibility	22	Entropy of Tow Phase (Vapor)
7	The Zeroth & First Laws of Thermodynamics	23	***Heat Engine Cycles***
8	The Steady & Non-Flow Energy Equations	24	Carnot & Otto Cycles
9	***Ideal Gas (Single Phase System) and Its Laws***	25	Brayton & Diesel Cycles
10	Reversible & Irreversible Processes	26	Dual Cycle and Mean Effective Pressure
11	Specific Heats	27	***Steam Cycles (Carnot & Rankine Cycles)***
12	***Steam and Tow Phase System (Vapor)***	28	Superheated & Reheated Rankine Cycles
13	Important Terms for Steam	29	***Refrigeration System***
14	Reversible & Irreversible Processes	30	Carnot Cycle
15	Measurement of Quality	31	Refrigeration Cycles
16	***First Semester Exam (Fall Semester)***	32	***Second Semester Exam (Spring Semester)***

THERMODYNAMICS

1

CHAPTER ONE

Introduction and Basic Concepts

.Thermodynamics:-

can be defined as the science of energy. The name thermodynamics Stems from the Greek words therme (Heat) and dynamics (Power).

Applied thermodynamics: is the science of relationship between heat, work, and the properties of the System. It is concerned with the means necessary to convert heat energy from available sources such as chemical fuels or nuclear piles into mechanical work.

.Working Substance:-

the working substances are, in general fluids which are capable of deformation in that they can readily be expanded and compressed. Common examples of working substance used in thermodynamic System air and Steam.

.Pure Substance:- Is a single substance or mixture of substance which has the same consistent composition throughout. such as water, Nitrogen, Helium and Carbon dioxide

In other words, it is a homogenous substance and its molecular structure dose not vary. For example, Steam or water or mixture of both can be considered as a pure substance. This is because it has the same molecular or chemical structure through its mass.

-• Dimensions and Units:

Any phisical quantity can be characterized by «dimensions». The arbitrary magnitudes assigned to the dimensions are called « Units ».

Some basic dimensions such as mass (m), Length (L), time (t), and temperature (T) are selected as [primary] or fundamental dimensions, While others such as velocity (V), energy (E) and volume (V) are expressed in terms of the primary dimensions and are called [secondary] dimensions, or derived dimensions.

Two sets of units are still in common use today:

1. The English System
2. System International (SI) Units

Dimension	Unit
Length	meter (m)
mass	Kilogram (kg)
Time	second (s)
Temperature	Kelvin (K)
Electric current	Ampere (A)
Amount of Light	Candela (C)
Amount of matter	mole (mol)

Quantity	SI Units	from English to SI Unit
Area	m^2	1 ft = 0.3048 m
Density	kg/m^3	1 in = 0.0254 m
Energy	J	1 Ibm = 0.4536 kg
Energy per unit mass	J/kg	1 Slug = 14.594 kg
Force	N	1 Ibf = 4.448 N
Heat flux	W/m^2	
Heat transfer rate	W	1 Btu = 1055.06 J 1 cal = 4.1868 J
		1 Btu/Ibm = 2326 J/kg
mass flow rate	kg/s	
		1 hp = 745.7 W
Power	W (J/s)	
pressure & Stress	N/m^2	1 Ibf/ft^2 = 47.88 N/m^2
Specific heat	J/kg·K	1 psi = 1 Ibf/in^2 = 6894.8 N/m^2
Surface tension	N/m	
Velocity	m/s	1 standard atmosphere = 1.0133 * 10^5 N/m^2
Viscosity (kin.)	m^2/s	
Volume	m^3	1 gal = 0.003785 m^3
Volume flow rate	m^3/s	
Specific Volume	m^3/kg	

-. Heat Engine:

is the name given to a system which by operating in a cyclic manner produces net work from a supply of heat.

-. Heat, work, and the System:

Heat is a form of energy which is transferred from one body to another body at a lower temperature by بفعل virtue of the temperature difference between the bodies.

Note that the heat and work are a transient quantities, not properties.

In mechanics, work is defined as the product of the force (F) and the distance moved (x) in the direction of the force ⇒ $W = F * x$

If a system exists in which a force at the boundary of the system is moved through a distance, then work is done by or on the System.

$$\boxed{\text{Work} = \text{Force} * \text{distance}} \quad \sim\sim *$$

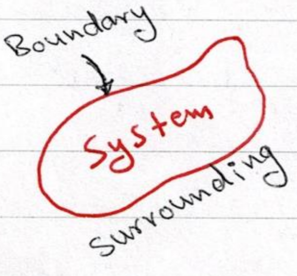
A system my be defined as a collection of matter within مفروض prescribed and identifiable boundaries.

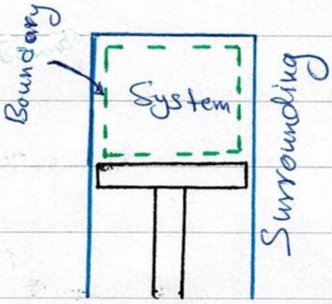
or

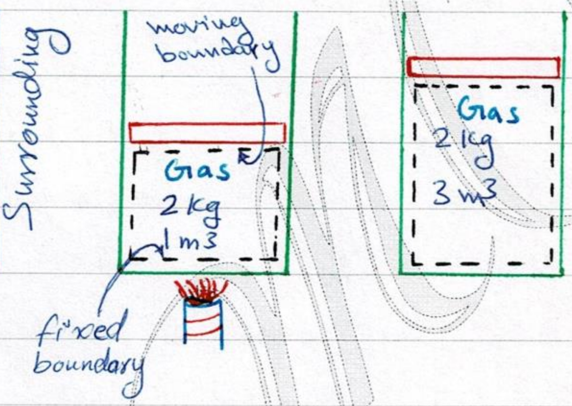
a quantity of matter or a region in space Chosen for Study.

The mass or region outside the System is Called the **Surrounding**.

The real or imaginary surface that Separates the System from its surrounding is called the **boundary**.





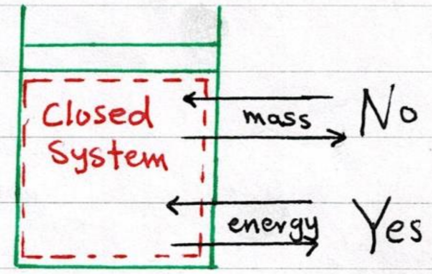


- Closed and Open System:

System may be considered to be closed or open depending on whether a fixed mass or a fixed volume in space is chosen for Study.

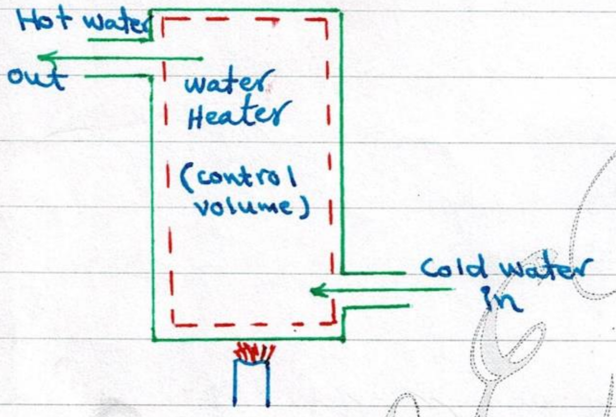
A closed System (also known as a **control mass**) consists of a fixed amount of mass, and no mass can cross its boundary. That is, no mass can enter or Leave a closed System.

But energy in the form of heat or work, can cross the boundary, and the volume of a closed System dose not have to be fixed.

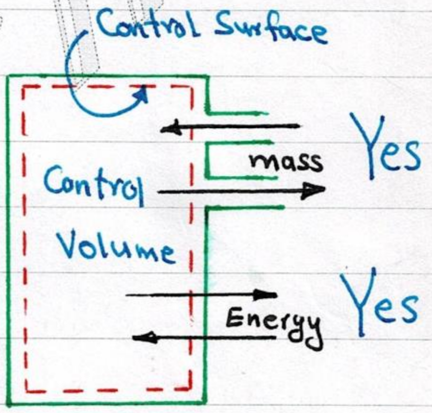


If, as aspecial case, even energy is not allowed to cross the boundary, that System is called an **isolated System**.

An Open System, or a control volume, as it is often called, is a properly selected region in space. It usually encloses a device that involves mass flow, such as a compressor, turbine, or nozzle. Both mass and energy can cross the boundary of a control volume which is called **a control surface**.



[An open system (a control volume) with one inlet and one exit]



[Both mass and energy can cross the boundaries of a control volume]

- Properties of a System :-

Any characteristic of a system is called a property. Some familiar examples are pressure P, temperature T, volume V, and mass m.

The list can be extended to include less familiar ones such as viscosity, thermal conductivity, modulus of elasticity, thermal expansion coefficient, electric resistivity, and even velocity and elevation.

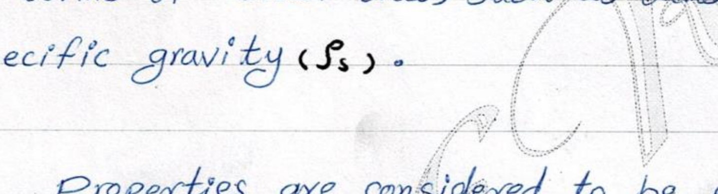
Not all properties are independent, some are defined in terms of other ones, such as density (ρ), Specific volume (v), Specific gravity (ρ_s).

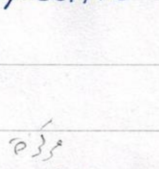
شاملة مركزة

Properties are considered to be either **intensive** or **extensive**.

Intensive properties are those that are independent of the size of a system, such as temperature, pressure, and density.

Extensive properties are those whose values depend on the size -or extent- of the System, such as mass, volume, and total energy (E).

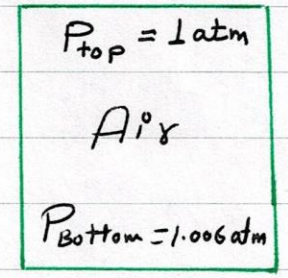


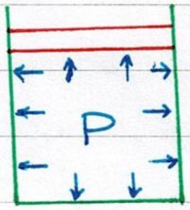


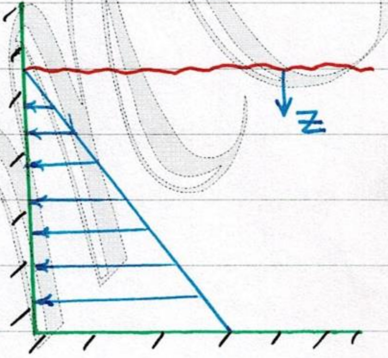
Intensive properties are independent of the size of System

-. Pressure :

is the force exerted by a fluid per unit area. We Speak of pressure only when we deal with a gas or a Liquid. The counterpart of pressure in solids is Stress.







In a container filled with a gas the variation of pressure with height is negligible

The pressure of a fluid at rest increases with depth (as a result of added weight)

Since pressure is defined as force per unit area, it has the unit of newtons per square meter (N/m^2), which is called a **pascal** (Pa).

$$\boxed{P = F/A} \quad *$$

$1\ N = 1\ kg \cdot m/s^2$

$1\ Pa = 1\ N/m^2$

$1\ MPa = 10^6\ Pa$

$1\ kPa = 10^3\ Pa$

Two other common pressure units are **bar** and **standard atmosphere**:

$$1 \text{ bar} = 10^5 \text{ pa} = 0.1 \text{ Mpa} = 100 \text{ kpa}$$

$$1 \text{ atm} = 101325 \text{ pa} = 101.325 \text{ kpa} = 1.01325 \text{ bars}$$

In the English System, the pressure unit is [pound-force per Square inch] Ibf/in² or psi

$$1 \text{ atm} = 14.696 \text{ psi} = 760 \text{ mm Hg}$$

the actual pressure at a given position is called **the absolute pressure**, and it is measured relative to absolute vacuum, i.e., absolute zero pressure.

the difference between the absolute pressure and the local atmospheric pressure is called the **gage pressure**.

Pressures below atmospheric pressure are called **Vacuum pressure**, and are measured by vacuum gage.

Absolute, gage, and vacuum pressure are all positive quantities and are related to each other by:

$\boxed{P_{gage} = P_{abs} - P_{atm}}$ (For pressure above P_{atm})

$\boxed{P_{vac.} = P_{atm} - P_{abs}}$ (" " below ")

Ex:- A vacuum gage connected to a chamber reads 5.8 psi at a location where the atmospheric pressure is 14.5 psi. Determine the absolute pressure in the chamber.

Sol:-

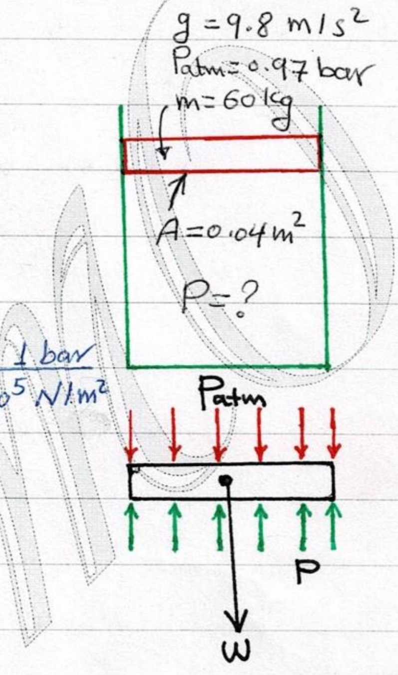
$$P_{abs} = P_{atm} - P_{vac}$$
$$= 14.5 - 5.8$$
$$= 8.7 \text{ Psi}$$

Ex:- The piston of a piston-cylinder device containing a gas has a mass of 60 kg and a cross-sectional area of 0.04 m^2, as shown below. The local atmospheric pressure is 0.97 bar and the gravitational acceleration is 9.8 m/s^2.

a- Determine the pressure inside the cylinder

b- If some heat is transferred to the gas and its volume doubles. do you expect the pressure inside the cylinder to change.

Sol: a. Equilibrium ⇒ $\Sigma F = 0$



$$P \cdot A = P_{atm} \cdot A + W \qquad , \quad W = mg$$

$$P = P_{atm} + \frac{mg}{A}$$

$$= 0.97\ bar + \frac{60\ kg * 9.8\ \frac{m}{s^2}}{0.04\ m^2} \cdot \frac{1\ N}{1\ kg \cdot \frac{m}{s^2}} * \frac{1\ bar}{10^5\ N/m^2}$$

$$= 1.117\ bars$$

- Temperature:

Although we are familiar with temperature as a measure of "hotness" or "coldness" it is not easy to give an exact definition for it.

حس، وظيفي،

Based on our physiological sensations, we express the level of temperature qualitatively with words like frezzing cold, cold, warm, hot, and red-hot.

The variation of an easily measurable property of a substance with temperature can be used to provide a temperature-measuring instrument. For example, the length of a column of mercury will vary with temperature due to the expansion and contraction of the mercury or another Liquid, gas, and Solid

- Temperature Scales:

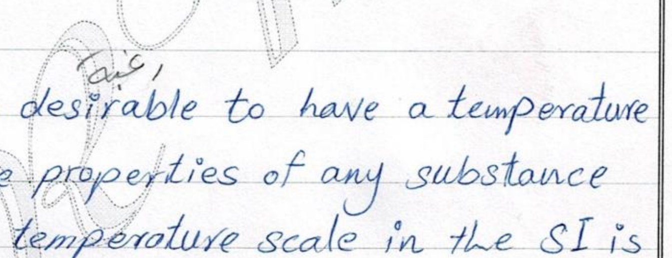
The temperature scales used in the SI and in the English System today are the **Celsius Scale** (formerly called the **Centigrade scale**) and the **Fahrenheit Scale**.

On the Celsius Scale, the ice and Steam point, are assigned the values of **0** and **100°C**, respectively, the corresponding values on the Fahrenheit scale are **32** and **212°F**

In thermodynamics, it is very desirable to have a temperature scale that is independent of the properties of any substance or substances. The thermodynamic temperature scale in the SI is the **Kelvin scale**. The temperature unit on this scale is the Kelvin, which is designated by **K** (not °K). The lowest temperature on the Kelvin scale is **0 K**.

The thermodynamic temperature scale in the English system is the **Rankine scale**, the temperature unit on this scale is the rankine, which is designated by **R**.

[P versus T plots at the expermental data obtained from a constant-volume gas thermometer using four different gases at different pressures]



$T(K) = T(°C) + 273.15$ *

$T(R) = T(°F) + 459.67$ *

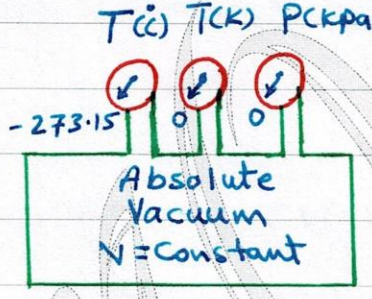
$T(R) = 1.8\, T(K)$ *

$T(°F) = 1.8\, T(°C) + 32$ *

$\Delta T(R) = 1.8\, \Delta T(K)$

$\Delta T(K) = \Delta T(°C)$ *

$\Delta T(R) = \Delta T(°F)$ *



A constant-volume gas thermometer would read -273.15 at absolute zero pressure

Ex: During a heating process, the temperature of a system rises by 10°C. Express this rise in temperature in K, °F, and R.

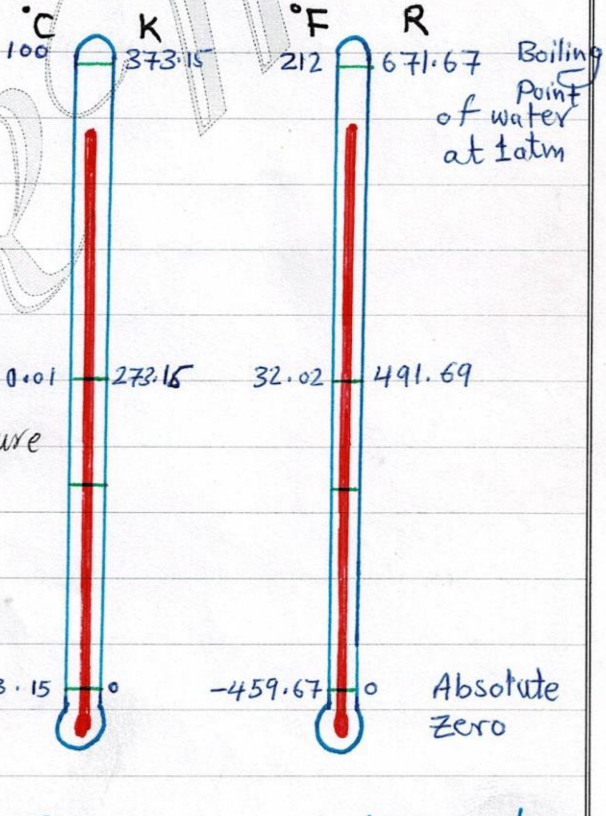
Sol:

$\Delta T(K) = \Delta T(°C) = 10°C$

$\Delta T(R) = 1.8\, \Delta T(K)$

$= 1.8 * 10 = 18\ R$

$\Delta T(°F) = \Delta T(R) = 18°F$



Comparision of temperature scales

قال رسول (صلى الله عليه وسلم) ؛ من دخل على غني او حاكم و تضعضع دينه لغناه او لحكمه ذهب ثلثا دينه "

Volume :

volume is a property, being that property which is associated with cubic measure.

The unit of volume is the cubic meter (m^3), Sometimes the liter L may be used.

1 Liter = 1 Cubic decimeter ($1\,dm^3 = [10^{-1}m]^3$)

If the volume of a substance increases then the substance is said to have been **Expanded**.

If the volume of a substance decreases then the substance is said to have been **Compressed**.

Specific volume is given the symbol (v)

$$\boxed{v = \frac{V}{m}} \quad m^3/kg$$

$v \equiv$ It is the reciprocal of density and is defined as the volume per unit mass.

Density defined as mass per unit volume.

$$\boxed{\rho = \frac{m}{V}} \quad kg/m^3$$

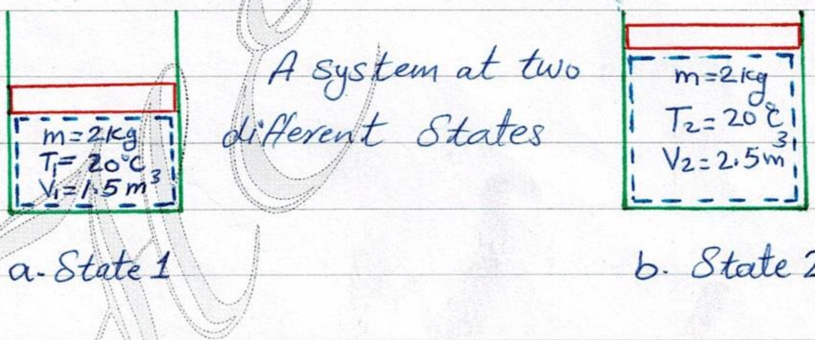
Specific gravity or relative density:-

is defined as the ratio of the density of a substance to the density of some standard substance at specified temperature, [(usually water at 4°C) for which $\rho_{H_2O} = 1000\ kg/m^3$]

$$\boxed{\rho_s = \frac{\rho}{\rho_{H_2O}}}$$

- State and Equilibrium:-

Consider a system that is not undergoing change. At this point, all properties can be measured or calculated throughout the entire System, which gives as a set of properties that completely describe the condition, or the state of the System.



A system at two different States

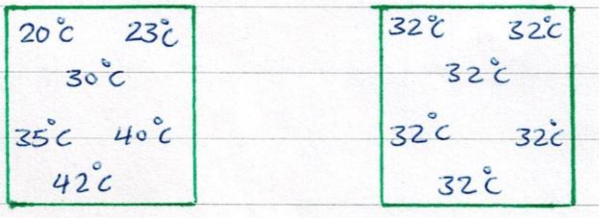
a. State 1

b. State 2

thermodynamics deals with equilibrium States. The word equilibrium يَعني implies a state of balance. In an equilibrium State, there are no unbalanced potentials (or driving forces) within the System.

Types of Equilibrium:

Thermal equilibrium: If the temperature is the same throughout the entire System, then the System is in thermal equilibrium.



a. Befor b. After

A closed System reaching thermal equilibrium

Mechanical Equilibrium: is related to pressure, and a System is in mechanical equilibrium if there is no change in pressure at any point of the System with time.

Phase Equilibrium: If a system involves two phases, it is phase equilibrium when the mass of each phase reaches an equilibrium level and Stays there.

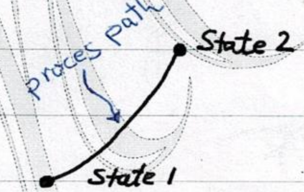
Chemical Equilibrium: A System is in chemical equilibrium if its chemical composition dose not change with time (no chemical reactions occur)

A System will not be in equilibrium unless all the relevant equilibrium criteria are satisfied.

Processes and Cycles:

Any change that a system undergoes from one equilibirum state to another is called a **Process**, and the series of states through which a system passes during a process is called the **Path** of the process.

Process diagrams that plotted by employing thermodynamic properties as coordinates are very useful in visualizing the processes.

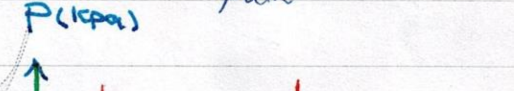


A process between states 1 and 2 and the process path

Some common properties that are used as coordinates are temperature T, Pressure P, and volume V (or Specific volume v).

The prefix **iso-** is often used to designate a process for which a particular property remains constant.

An **isothermal** process, for example, is a process during which the temperature T remains constant.



The P-V diagram of a compression process

An **isobaric** process is a process during which the pressure P remains constant.

An **isochoric** (or **isometric**) process is a process during which the specific volume v remains constant.

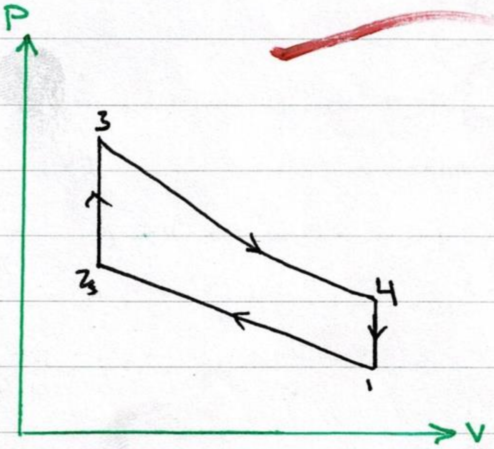
A system is said to have undergone a cycle if it returns to its initial state at the end of the process. That is, for a cycle the initial and final states are identical.

* Types of thermal Cycle :-

1- **Thermodynamic cycles:** In this cycle no change in the chemical structure and the properties of fluid, for example the Steam in power plant.

2. **Mechanical Cycles:** In this cycle the properties of fluid or substance will be change, for example the Internal-Combustion Engine (I.C.E).

a- A two-process cycle



b- A Four-process cycle

= Energy :-

Energy is defined as that capacity abody or substance possesses which can result in the performance of work. From the law of conservation of energy the energy cannot be created or destroyed.

= Forms of Energy :-

Energy can exist in numerous forms such as thermal, mechanical, kinetic, Potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **Total Energy "E"** of a System. The total energy of a System on unit mass basis denoted by **"e"** and is defined as:

$$\boxed{e = \frac{E}{m}} \qquad kj/kg$$

In thermodynamics analysis, it is often helpful to consider the various forms of energy that make up the total energy of a system in two groups:-

1. Microscopic
2. Macroscopic

the microscopic forms of energy are those related to the molecular structure of a System and the degree of the molecular activity, and they are independent of outside reference frams.

The sum of all the microscopic forms of energy is called the "Internal Energy" of a System and is denoted by "U"

$$U = m \cdot u \quad \text{KJ}$$

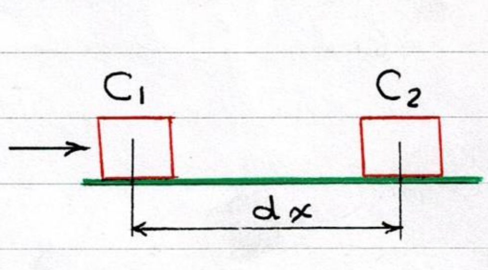
m ≡ mass Kg
u ≡ Specific internal energy KJ/Kg

The macroscopic energy of a System is related to motion and the influence of some external effect such as gravity, magnetism, electricity, and Surface tension.

the energy that a system possesses as a result of its motion relative to some reference fram is called "Kinetic Energy" KE

$$dE = F \cdot dx$$

$$\int dE = \int F \cdot dx$$



$$F = m \cdot a = m \cdot \frac{dc}{dt}$$

C = velocity
t = time

$$\int dE = \int m \cdot \frac{dc}{dt} \cdot dx$$

$$\int dE = m \int \frac{dx}{dt} \cdot dc \quad , \quad \frac{dx}{dt} = c$$

$$= m \int C \, dC$$

$$\int_{0}^{E} dE = m \int_{C_1}^{C_2} C \, dC$$

$$= m \left[\frac{C^2}{2} \right]_{C_1}^{C_2}$$

$$\boxed{K.E = \frac{1}{2} m (C_2^2 - C_1^2)} \quad , \quad C_1 = 0 \quad , \quad E \equiv K.E$$

$$\boxed{K.E = \frac{1}{2} m C_2^2} \quad kJ$$

or, on a unit mass basis (Specific Kinetic energy)

$$\boxed{k.e = \frac{C^2}{2}} \quad kJ/kg$$

- Single phase Point (Triple Point) of water:

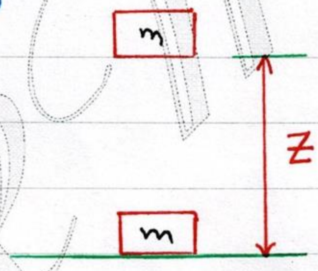
The state in which the solid, liquid and vapor exist together.

The energy that a System possesses as a result of its elevation in a gravitational field is called Potential Energy "PE" and is expressed as:

$$PE = W.Z$$
$$= mgZ \quad \text{Jole (N.m)}$$

or, on a unit mass basis, (Specific potential energy)

$$Pe = gZ \quad \text{kJ/kg}$$



g ≡ gravitational acceleration.
Z ≡ elevation.

Any volume of fluid entering or leaving a System displace an equal volume, the energy produced due to this flow is called Flow Energy "FE".

$$F.E = P.V$$

Heat Energy: It is one form of energy that produced only when Temperature difference between the System and Surrounding. There are three types of Heat transfer:

1. Conduction   2. Convection   3. Radiation

Heat energy is given the symbol "Q", to indicat a rate of heat transfer a dot is placed over the Symbol Q, thus

$$\dot{Q} = \text{heat transfer / unit time}$$

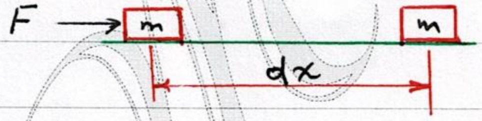
- Work Energy :-

It is a form of energy defined as the multiplication of the force that effected on the mass by the distance that the mass will be moved due to this effect.

$$dW = F \cdot dL \qquad , F = P \cdot A$$

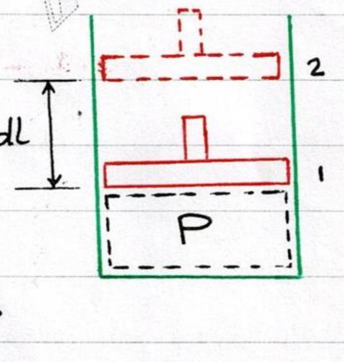
$$= P \cdot A \cdot dL \qquad , dV = A \cdot dL$$

$$= P \cdot dV$$



$$\int_1^2 dW = \int_{V_1}^{V_2} P \cdot dV$$

$$\boxed{W_{1-2} = \int_{V_1}^{V_2} P \cdot dV} \qquad kJ$$

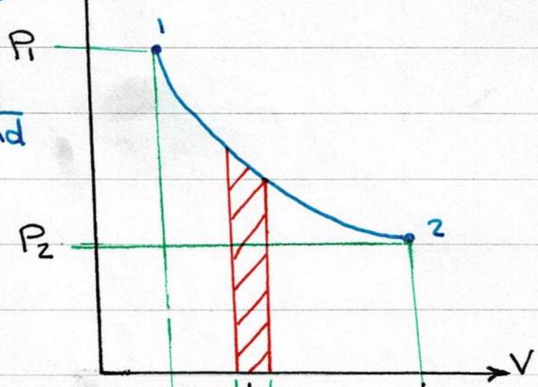


$$w_{1-2} = \int_{v_1}^{v_2} p \cdot dv \qquad kJ/kg$$

Power :- is the rate of doing work.

$$Power = \frac{\text{work done}}{\text{Time taken}} \quad , \frac{Joule}{Second}$$

$$P = \frac{W}{t} \qquad J/s \equiv Watt$$



$$Power = w \cdot \dot{m}$$

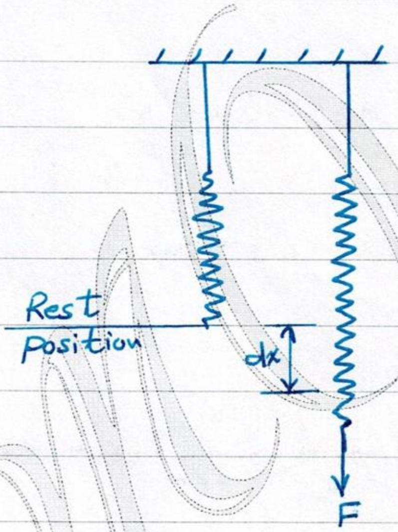
$$\equiv \frac{kJ}{kg} \cdot \frac{kg}{s} \equiv \frac{kJ}{s} = kW$$

w = Area under the curve

$$\dot{m} \equiv \text{flow rate} = \rho C A$$

ρ: density (kg/m^3) , C: Velocity (m/s) , A: Area (m^2)

- Spring Work :



$$dW = F \cdot dx \quad \text{----} \ ①$$

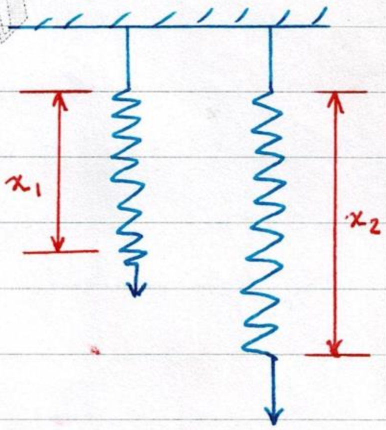
$$F = K \cdot x \quad \text{----} \ ②$$

$K \equiv$ Spring Constant (kN/m)

Sub eqn ② in ①

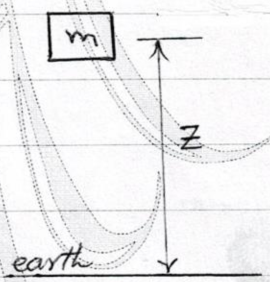
$$\int dW = \int_{x_1}^{x_2} K \cdot x \cdot dx$$

$$\boxed{W_{spring} = \frac{1}{2} K (x_2^2 - x_1^2)}$$



~~linear~~

Ex:- An insulated 2kg box falls from a ballon 3.5Km above the earth. what's the change in potential energy of the box after it has hit the earth Surface.



Sol:-

$$P.E = mgZ$$
$$= 2 * 9.81 * 3500 * 10^{-3}$$
$$= 68.67 \text{ kJ}$$

Ex:- A force, F, is proportional to (x^2) and has the value of 133N when $x = 2$, Determine the work done by it moves in object from $x=1$ to $x=4$ where (x) in meter.

Sol:-

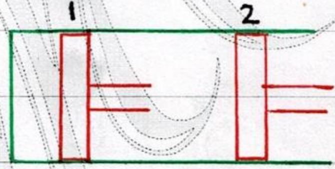
$$F \propto X^2$$
$$F = k \cdot x^2$$
$$133 = k(2)^2$$
$$\therefore k = \frac{133}{4} \quad N/m^2$$

$$\omega = \int_{X_1}^{X_2} F \cdot dx$$
$$= \int_1^4 k x^2 dx$$
$$= k \int_1^4 x^2 dx$$
$$= k \left[\frac{x^3}{3}\right]_1^4 = \frac{133}{4 * 3}\left[4^3 - 1^3\right]$$
$$= 69825 \quad N.m$$
$$= 69.825 \text{ kJ}$$

Ex:- Let the pressure in the cylinder in the figure given by the equation $P=C/V$ as a function of volume.

a. find the work done, if the initial pressure is 400 kpa. the initial volume $0.02 m^3$ and the final volume is $0.08 m^3$

b. Is the sign correct?

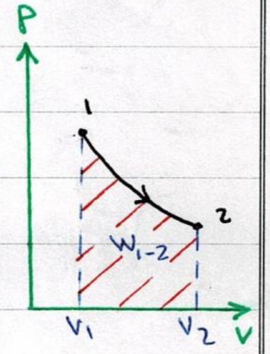


Sol:- a. $P=C/V \Rightarrow P_1V_1=P_2V_2$

$$w=\int_{V_1}^{V_2} P\cdot dV=\int_{V_1}^{V_2}\frac{C}{V}\,dV=C\int_{V_1}^{V_2}\frac{dV}{V}$$

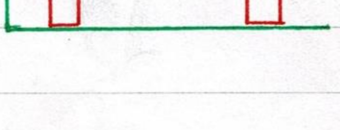
$$w=P_1V_1\int_{V_1}^{V_2}\frac{dV}{V}=P_1V_1\left[\ln V\right]_{V_1}^{V_2}=P_1V_1\ln\frac{V_2}{V_1}$$

$$w=400*0.02*\ln(0.08/0.02)=11.09\ kJ$$



b. the sign correct since it is positive and the work is done by the System.

Ex:- The pressure in the cylinder shown below varies in the following manner with volume $P=C/V^2$. if the* initial volume is $0.05 m^3$ and the final pressure is 200 kpa. find the work done by the System?



Sol:- $w=\int_{V_1}^{V_2} P\,dV$
$=\int_{V_1}^{V_2}\frac{C}{V^2}\,dV$

*initial pressure 500kpa,

$$W = C\left[\frac{1}{V_1} - \frac{1}{V_2}\right]$$

$$C = P_1 V_1^2 = P_2 V_2^2 \Rightarrow V_2 = V_1\left(\frac{P_1}{P_2}\right)^{1/2}$$

$$W = P_1V_1 - P_2V_2$$

$$= P_1V_1 - (P_2P_1)^{1/2} \cdot V_1$$

$$= 500 * 0.05 - (500 * 200)^{1/2} * 0.05$$

$$= 9.19\ \text{K N.m} = 9.19\ \text{KJ}$$ +ve work done by the System

Ex: A fluid in a cylinder is at a pressure of 700 K N/m². It is expanded at constant pressure from a volume of 0.28 m³ to a volume of 1.68 m³. Determine the work done?

Sol:

$$\text{Work done} = W = P(V_2 - V_1)$$

$$= 700 * 10^3 (1.68 - 0.28)$$

$$= 7 * 10^5 * 1.4$$

$$= 0.98\ \text{MJ}$$

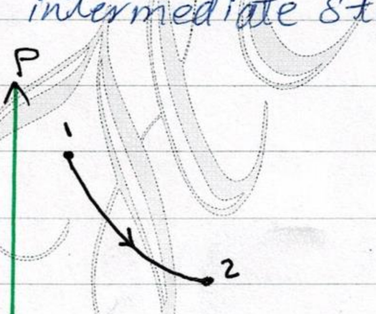
- Reversibility:

A more rigorous definition of reversibility is as follows: When a fluid undergoes a reversible process, both the fluid and its surroundings can always be restored to their original state. The criteria of reversibility are as follows:

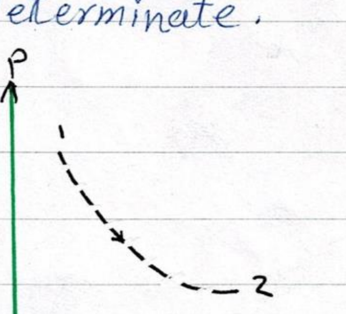
1. The process must be frictionless.
2. The difference in pressure between the fluid and its surroundings during the process must be infinitely small.
3. The difference in temperature between the fluid and its surroundings during the process must be infinitely small.

A reversible process between two states drawn as a line on any diagram of properties.

An irreversible process is usually represented by a dotted line joining the end states to indicate that the intermediate states are indeterminate.



reversible process



irreversible
Process

- Internal reversibility :-

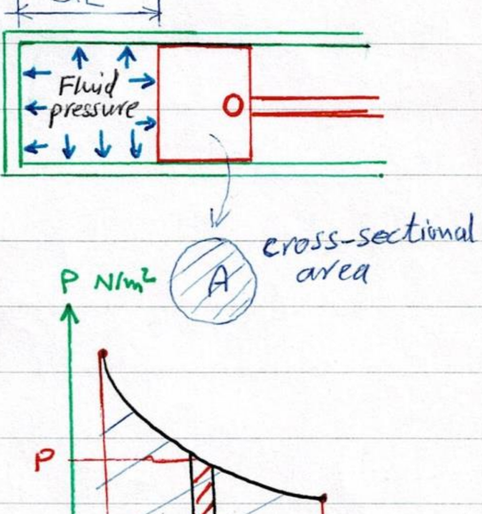
It is may be obtained, because no process in practice is truly reversible, but with conditions below:-

1. the surrounding can never be restored to their original state,
2. the fluid itself is at all times in an equilibrium state and the path of the process can be exactly ترجع retraced to the initial state.

- Reversible work :-

Consider an ideal frictionless fluid contained in a cylinder behind a piston, with the following assumptions:-

1. the pressure and temperature of the fluid are uniform
2. no friction between the piston and the cylinder walls.



work done by fluid = $(PA) * dL$
$= P\,dV$

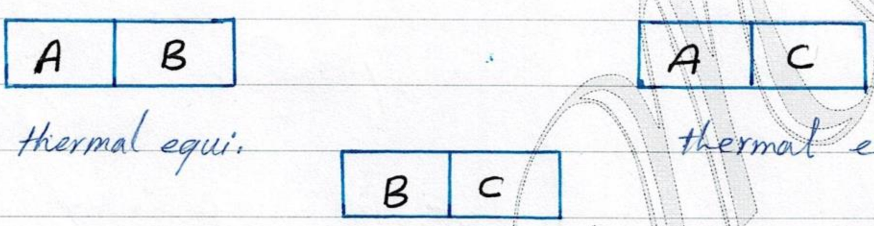
Per unit mass
Work done = $P\,dv$
(where v is the specific volume)

w.

work done = shaded area
$= \int_1^2 p\,dV$

- The zeroth Law (law number zero):

This law is concerned with thermal equilibrium. It states that "if two bodies are separately in thermal equilibrium with a third body then they must be in thermal equilibrium with each other".



If $T_A = T_B$ Also thermal equilibrium

$T_A = T_C$

$\therefore T_B = T_C$ (thermal equilibrium)

- The first Law of thermodynamics:

the concept of energy and the hypothesis that it can be neither created nor destroyed were developed by scientists in the early part of the nineteenth century, and became known as the Principle of the Conservation of Energy. The First Law of Thermodynamics is merely one statement of this general principle with particular reference to heat energy and mechanical energy (work).

The First Law of Thermodynamics can be stated as follows:

"When a System undergoes a thermodynamic cycle then the net heat supplied to the system from its surrounding is equal to the net work done by the system on its surroundings". In symbols,

$$\sum dQ = \sum dW \quad kW$$

$\dot{Q} = q \cdot \dot{m}$

$\dot{W} = w \cdot \dot{m}$

$$\sum dq = \sum dw \quad kJ/kg$$

where $\sum$ represents the sum for a complete cycle.

Ex: In a certain Steam plant the turbine develops 1000 kW, the heat supplied to the Steam in the boiler is 2800 kJ/kg, the heat rejected by the System to cooling water in the condenser is 2100 kJ/kg and the feed pump work required to pump the condensate back into the boiler is 5 kW. Calculate the Steam flow in $\frac{kg}{s}$.

Sol: $\sum dq = 2800 - 2100 = 700 \ kJ/kg$

$\sum dw = 1000 - 5 = 995 \ kW$

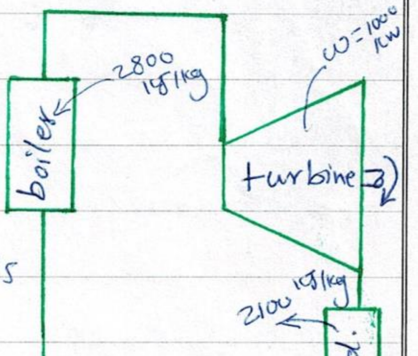
$Q = \dot{m} \, q$

from the first law of thermodynamics

$\sum Q = \sum W$

$\dot{m} \cdot 700 = 995$

$\therefore \dot{m} = 1.421 \ kg/s$ (Steam flow rate)



- The steady-flow energy equation :- (SFEE)

This equation is a mathematical statement of the principle of conservation of energy as applied to the flow of a fluid through a thermodynamic system.

The various forms of energy which the fluid can have are as follows:-

a. Potential Energy: $P.E = mgZ$ kJ

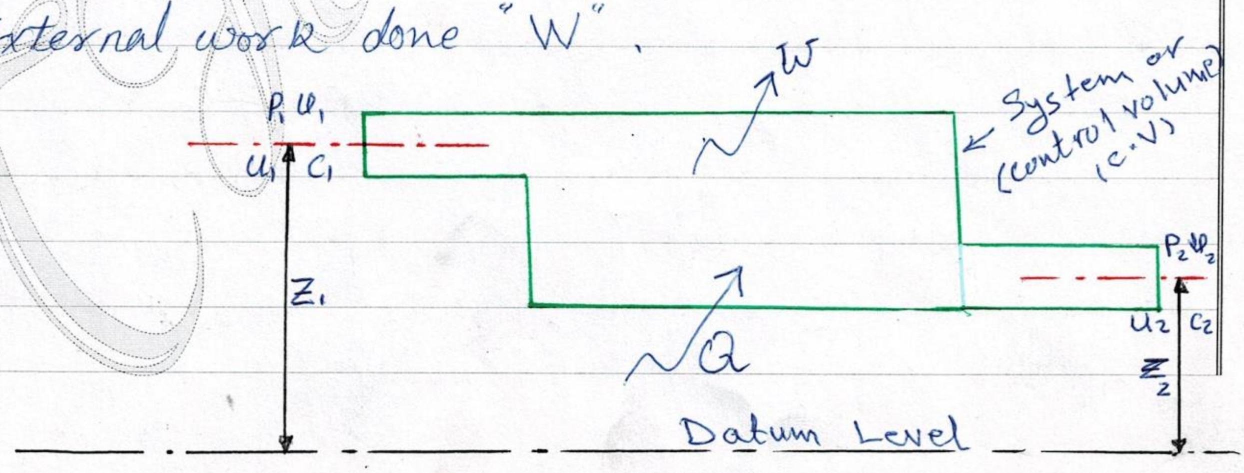
b. Kinetic Energy: $K.E. = \frac{1}{2} m C^2$ kJ

c. Internal Energy: $U = m.u$ kJ

d. Flow or displacement Energy: $F.E = P.V$ kJ

e. Heat received or rejected "Q".

f. External work done "W".



Applying the principle of conservation of energy to the System (or C.V.), then.

Total energy entering the system = Total energy leaving the System

$$E_{input} = E_{output}$$

$$P.E._1 + I.E._1 + F.E._1 + K.E._1 + Q = P.E_2 + I.E_2 + F.E_2 + K.E_2 + W$$

for 1 kg of fluid mass :-

$$gz_1 + u_1 + P_1 v_1 + \frac{1}{2}C_1^2 + q = gz_2 + u_2 + P_2 v_2 + \frac{1}{2}C_2^2 + w$$

or

$$gz_1 + (\overbrace{u_1 + P_1 v_1}^{h_1}) + \frac{1}{2}C_1^2 + q = gz_2 + (\overbrace{u_2 + P_2 v_2}^{h_2}) + \frac{1}{2}C_2^2 + w$$

$$\boxed{gz_1 + h_1 + \frac{1}{2}C_1^2 + q = gz_2 + h_2 + \frac{1}{2}C_2^2 + w}$$

" Steady flow Energy Equation " SFEE

, h ≡ Enthalpy

Where q & w per unit mass.

Mass flow rate :-

$$\dot{m} = \frac{CA}{v} = \rho C A \quad , \quad \dot{m}_1 = \dot{m}_2$$

*This equation is known as the continuity of mass equation. $\dot{m} = \frac{C_1 A_1}{v_1} = \frac{C_2 A_2}{v_2}$

– The non-flow energy equation : „NFEE„

In the case of a closed system, however, in which the fluid mass remains constant, no substance passing through the system boundary, the flow terms in stady flow E.E. will not apply. Thus the terms Pv and $C^2/2$ are neglected. The system is then said to be **non-flow**.

from the SFEE:

$$\cancelto{0}{gz_1} + u_1 + \cancelto{0}{P_1 v_1} + \cancelto{0}{\frac{1}{2}C_1^2} + q = \cancelto{0}{gz_2} + u_2 + \cancelto{0}{P_2 v_2} + \cancelto{0}{\frac{1}{2}C_2^2} + W$$

$$u_1 + q = u_2 + W$$

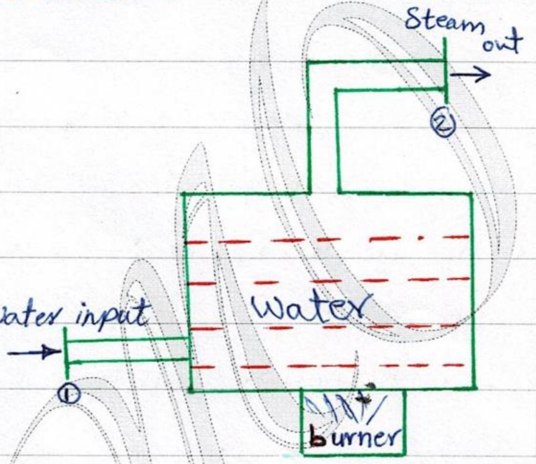
$$\boxed{q - W = u_2 - u_1}$$ «NFEE» per 1kg

When , $\Delta z , \Delta C^2 \simeq 0 \Rightarrow$

$$\boxed{q - W = h_2 - h_1}$$ «SFEE» per 1 kg

– Some Applications of the SFEE :

1. Steam Boilers :



$$gz_1 + h_1 + \frac{C_1^2}{2} + q = gz_2 + h_2 + \frac{C_2^2}{2} + w$$

in boiler :

1. $w = 0$
2. $C_2^2 - C_1^2/2$ very small
3. $\Delta Z \simeq 0$

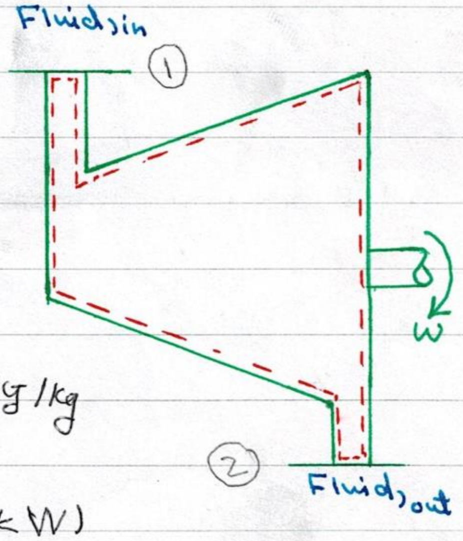
$\therefore q = h_2 - h_1$ kJ/kg

$\dot{Q} = \dot{m}_s (h_2 - h_1)$ kJ/s (kW)

$\dot{m}_s$ = Steam flow rate kg/s

$\dot{m}_s = \rho C A$

2. Turbine :



$$gz_1 + h_1 + \frac{C_1^2}{2} + q = gz_2 + h_2 + \frac{C_2^2}{2} + w$$

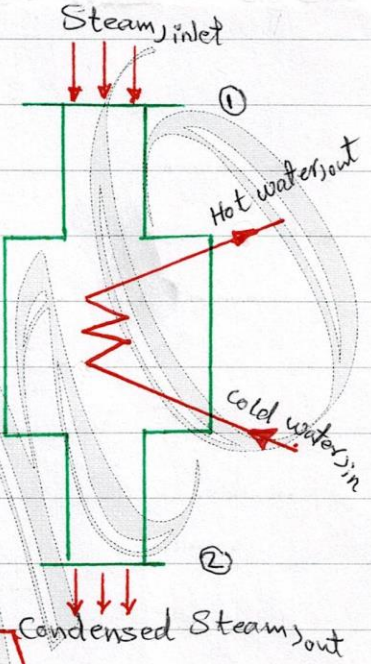
in turbine :

1. $Q = 0$
2. $C_2^2 - C_1^2/2 \simeq 0$
3. $\Delta Z \simeq 0$

$\therefore h_1 = h_2 + w \Rightarrow w = h_1 - h_2$ kJ/kg

$\dot{W} = \dot{m}_s (h_1 - h_2)$ kJ/s (kW)

- Heat Exchanger :-



in H.E. :-

1. $W=0$
2. $C_2^2-C_1^2/2 \simeq 0$ (neglect)
3. $\Delta Z \simeq 0$

from SFEE:

$\therefore\ q = h_2 - h_1$ (rejected heat)

$\dot{Q} = \dot{m}_s (h_2 - h_1)$

$$\boxed{\dot{Q} = \dot{m}_s (h_2 - h_1) = \dot{m}_w C_{pw} (T_{w_{out}} - T_{w_{in}})}$$

$\dot{m}_s \equiv$ Steam flow rate , $\dot{m}_w$ = Cooling water flow rate

$C_{pw} \equiv$ Specific Heat of water at constant pressure

$T_{w_{out}} \equiv$ outlet water Temperature.

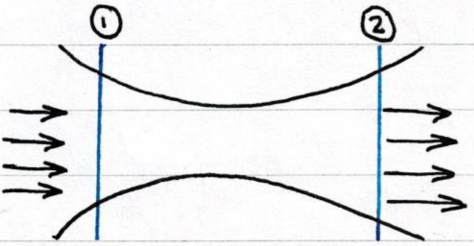
$T_{w_{in}} \equiv$ inlet " " .

- Nozzle :-

in Nozzle :- 1. $Q=0$ 2. $W=0$ 3. $\Delta Z = 0$

from SFEE :-

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



When $C_1 \simeq 0$

$$\frac{C_2^2}{2} = h_1 - h_2$$

$$\therefore\ \boxed{C_2 = \sqrt{2(h_1 - h_2)}}\ \text{m/s}$$

- Specific Heats:-

is defined as the energy required to raise the temperature of a unit mass of a substance by one degree.

$$\boxed{Q = m.C.\Delta T} \quad kJ$$

C= Specific heat capacity kJ/kg.K
m= mass of substance.
Q= heat transferred to produce temperature change.

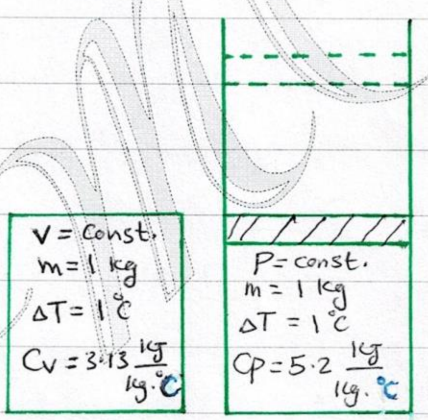
In general, the energy required to raise the temperature will depend on how the process is executed. In thermodynamics, we are interested in two kinds of specific heats:

1. Specific heat at constant volume "C_v".
2. " " " " Pressure "C_p".

physically, the specific heat at constant volume C_v can be viewed as "the energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.

The energy required to do the same as the pressure is maintained constant is the specific heat at constant Pressure C_p.

This is illustrated in fig. below. The specific heat at constant pressure Cp is always greater than Cv because at constant pressure the system is allowed to expand and the energy for this expansion work must also be supplied to the system



(Cv & Cp values of helium)

$\therefore \quad Q = m\,C\,\Delta T$

for unit mass

$$Q = q = C\,\Delta T$$

$$dq = C\,dT$$

$$\therefore \boxed{C = \frac{dq}{dT}}$$

1. at constant volume:-

from NFEE:

$$q - w = \Delta u \quad , \text{at } V = c \Rightarrow w = 0$$

$$q = \Delta u \Rightarrow dq = du$$

$$C_v = \frac{dq}{dT} = \frac{du}{dT} \Rightarrow du = C_v\,dT \Rightarrow \Delta u = C_v\,\Delta T$$

$\therefore$ at constant volume

$$\boxed{Q = \Delta U = m C_v \Delta T}$$

2. at Constant Pressure:-

$$W = P_2V_2 - P_1V_1$$

$$q = W + \Delta U$$

$$q = (P_2V_2 - P_1V_1) + (U_2 - U_1)$$

$$q = (P_2V_2 + U_2) - (P_1V_1 + U_1)$$

$$q = h_2 - h_1$$

$$q = \Delta h$$

$$dq = dh$$

$$C_p = \frac{dq}{dT} = \frac{dh}{dT}$$

$$dh = C_p \cdot dT$$

$$\Delta h = C_p \cdot \Delta T$$

$$\boxed{Q = \Delta H = mC_p \Delta T}$$

Notes: 1. Heat received by the System q is +ve
" rejected " " " q is -ve

2. Work done by the System W is +ve
" " on " " W " -ve

Ex: A certain fluid at 10 bar is contained in a Cylinder behind a piston, the initial volume being $0.05 m^3$. Calculate the work done by the fluid when it expands reversibly:

a. at constant pressure to a final volume of $0.2 m^3$.

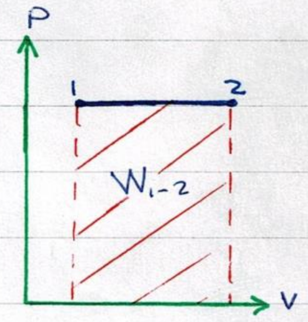
b. According to a linear law to a final volume of $0.2 m^3$ and a final pressure of 2 bar.

c. According to a law $pV=c$ to a final volume of $0.1 m^3$.

d. According to a law $pV^3=c$ to a final volume of $0.06 m^3$.

e. According to a law $p=(A/V^2)-(B/V)$ to a final volume of $0.1 m^3$ and final pressure of 1 bar, A & B are constant.

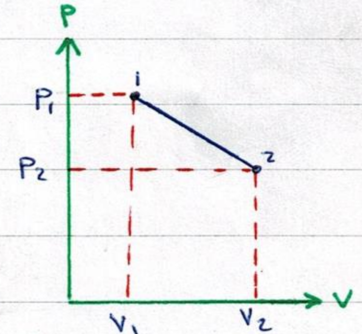
Sol:



a. $W=\int_1^2 p\,dV$, $p=c$

$= p_1\int_1^2 dV = p[V]_1^2 = p(V_2-V_1)$

$=10*10^2(0.2-0.05)=150$ kJ



b. linear law $= \frac{P-P_1}{V-V_1} = \frac{P_2-P_1}{V_2-V_1}$

$$\frac{P-10*10^2}{V-0.05} = \frac{2*10^2-10*10^2}{0.2-0.05}$$

$0.15P+800V-190=0$

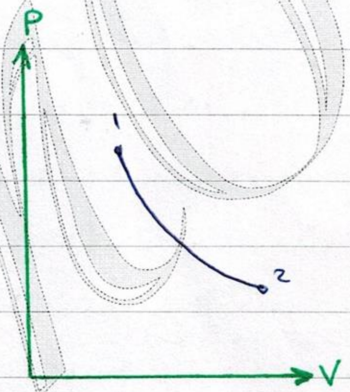
$$P=\frac{190-800V}{0.15}$$

$$w = \int p\,dV = \int_1^2 \frac{190 - 800V}{0.15}\,dV = \left[\frac{190V - 400V^2}{0.15}\right]_{0.05}^{0.2}$$

$\therefore w = 90$ kJ

c. $PV = C \Rightarrow 10*10^2*0.05 = C \quad \therefore C = 50$

$\therefore p = 50/V$



$$w = \int_1^2 p\,dV = \int_1^2 50\,\frac{dV}{V} = 50\ln V\Big]_1^2$$

$$= 50[\ln V_2 - \ln V_1]$$

$$= 50\{\ln(0.1) - \ln(0.05)\}$$

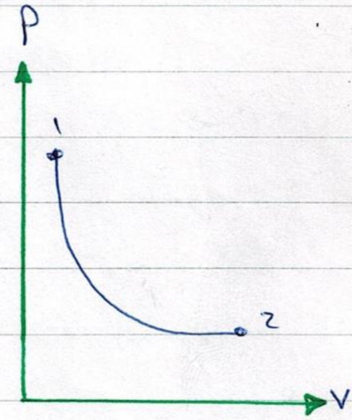
$$= 34.65 \text{ kJ}$$

d. $PV^3 = C$

$10*10^2(0.05)^3 = C \Rightarrow C = 0.125 \Rightarrow p = \frac{0.125}{V^3}$

$$w = \int_1^2 p\,dV = \int_1^2 0.125\,\frac{dV}{V^3} = \left[0.125*\frac{-1}{2V^2}\right]_1^2$$

$w = 7.638$ kJ



e. $p = \frac{A}{V^2} - \frac{B}{V} \Rightarrow 10*10^2 = \frac{A}{0.05^2} - \frac{B}{0.05} \quad , \quad 1*10^2 = \frac{A}{0.1^2} - \frac{B}{0.1}$

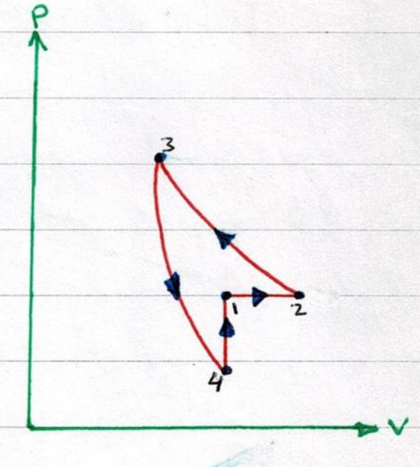
$\therefore A = 4 \qquad B = 30$

$\therefore p = \frac{4}{V^2} - \frac{30}{V}$

$$w = \int_1^2 p\,dV = \int_1^2 \left(\frac{4}{V^2} - \frac{30}{V}\right) dV = \left[-\frac{4}{V} - 30\ln V\right]_1^2$$

$\therefore w = 19.2$ kJ

Ex:- A fluid is heated reversibly at a constant pressure of 1.05 bar until it has a specific volume of 0.1 m^3/kg. It is then compressed reversibly according to a law pV=c to a pressure 4.2 bar, then allowed to expand reversibly according to a law $pV^{1.3}=c$ and finally heated at constant volume back to initial condition. The work done in the constant pressure process is 515 N.m and the mass of fluid present is 0.2 kg. Calculate the net work done on or by the fluid in the Cycle and sketch the cycle on the pv diagrame.



Sol:- $P_1 = 1.05$ bar $v_1 = ?$

$P_2 = P_1 = 1.05$ bar $v_2 = 0.1\ m^3/kg$

$P_3 = 4.2$ bar $v_3 = ?$

$P_4 = ?$ $v_4 = v_1$

- process $1 \to 2$, $W_{1-2} = 515$ N.m

$$w = \int_1^2 P.dv = P_1 \int_1^2 dv = p(v_2 - v_1)$$

$$W = m.w = m[p(v_2 - v_1)]$$

$$515 = 0.2 * 1.05 * 10^5 (0.1 - v_1)$$

$$v_1 = 0.075\ m^3/kg$$

- process $2 \to 3$ $pv = c \Rightarrow p_2 v_2 = c$

$$1.05 * 10^5 \times 0.1 = c \Rightarrow c = 10500$$

$$p = \frac{c}{v}$$

$w = \int_2^3 P\,dV = C \int_2^3 \frac{dV}{V} = 10500\left[\ln V_3 - \ln V_2\right]$

$\therefore P_2V_2 = P_3V_3 \Rightarrow V_3 = \frac{P_2}{P_3} \cdot V_2 = \frac{1.05}{4.2} * 0.1 = 0.025\ \frac{m^3}{kg}$

$\therefore w = 10500\left[\ln 0.025 - \ln 0.1\right] = -14556\ \frac{N.m}{kg}$

$W_{2-3} = m.w = 0.2 * -14556 = -2911.2\ N.m = -2911.2$ Joule

- Process 3-4 , $pV^{1.3} = C$

$V_4 = V_1 = 0.075\ m^3/kg$

$P_3 V_3^{1.3} = P_4 V_4^{1.3} = C$

$\therefore P = \frac{C}{V^{1.3}}$

$w = \int_3^4 P\,dV = \int_3^4 C \frac{dV}{V^{1.3}} = P_3 V_3^{1.3} \int_3^4 \frac{dV}{V^{1.3}}$

$w = P_3 V_3^{1.3}\left[-\frac{1}{0.3\,V^{0.3}}\right]_3^4 = 4.2*10^5 (0.025)^{1.3}\left[-\frac{1}{0.3(0.075)^{0.3}} + \frac{1}{0.3(0.025)^{0.3}}\right]$

$= 9827.4\ J/kg$

$W_{3-4} = m.w_{3-4} = 0.2 * 9827.4 = 1965.5\ J$

$w_{4-1} = \int_1^2 P\,dV$ since $V = C \Rightarrow dV = 0 \quad \therefore W = 0$

$W_{net} = W_{1-2} + W_{2-3} + W_{3-4} + W_{4-1}$

$= 515 + (-2911.2) + 1965.5 + 0$

$= -430.7$ Joule

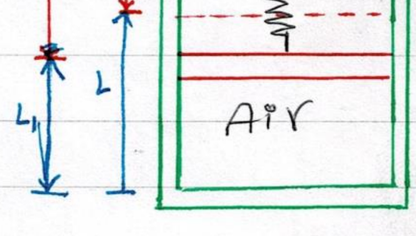
$= -0.4307$ kJ (work done on the system)

Ex:- consider the System shown in figure. the initial volume inside the cylinder is (0.1 m^3). At this stats the pressure inside is (100) kpa, which just balance the atmospher pressure plus the piston weight, the spring is touching but excerts no force on the piston at this state. The gas now heated until the volume is doubled. The final pressure of the gas is (300 kpa), and during the process the Spring force is proportional to the displacement of the piston from the initial position. Calculate the work done by the System, what persentage of work is done against the Spring.

Sol:-

$P_1 = 100$ kpa $\quad V_1 = 0.1$ m^3

$P_2 = 300$ kpa $\quad V_2 = 0.2$



force $\propto \Delta L$, $\Delta L = L_2 - L_1 = L - L_1$

$$F_s \propto (L - L_1) \Rightarrow \frac{F_s}{A} \propto \frac{L - L_1}{A} \cdot \frac{A}{A}$$

$$P_s \propto \frac{(L - L_1)A}{A^2} \Rightarrow P_s \propto \frac{(V - V_1)}{A^2}$$

$$P_s = \frac{c}{A^2}(V - V_1) = a(V - V_1) \quad , \text{ at } p = 300 \quad , V = 0.2$$

$$P_t = P_0 + P_s = 100 + a(V - V_1)$$

$$300 = 100 + a(0.2 - 0.1) \Rightarrow a = 2000$$

$\therefore\ P_t = 100 + 2000(V - 0.1) = 100 - 200 + 2000V = 2000V - 100$

$$W = \int_1^2 P\,dV = \int_1^2 (2000V - 100)\,dV$$

$$W_{1-2} = \left[\frac{2000V^2}{2} - 100V\right]_1^2$$

$$W_{1-2} = \left(\frac{2000(0.2)^2}{2} - 100(0.2)\right) - \left(\frac{2000\times(0.1)^2}{2} - 100\times0.1\right)$$

$$= 20\ \text{kJ}$$

If there is no Spring the piston will rise at constant pressure

$$W = \int_1^2 P\cdot dV = P\int dV$$

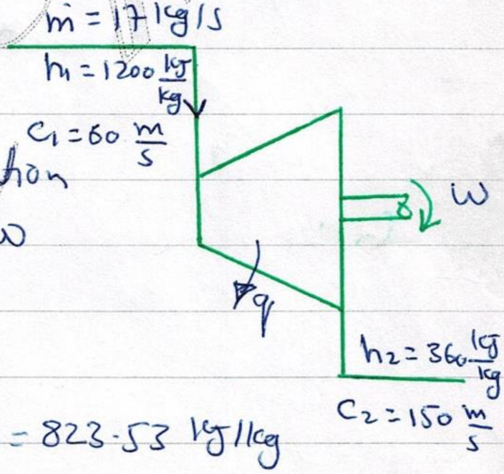
$$= P(V_2 - V_1)$$

$$= 100(0.2 - 0.1)$$

$$= 10\ \text{kJ}$$

$$\% = \frac{10}{20} = 50\%$$

Ex:- In a turbine of gas turbine unit, the gases flow through the turbine at 17 kg/s and the power developed by the turbine is 14000 kW. The enthalpies of the gases at inlet and outlet are 1200 kJ/kg and 360 kJ/kg respectively and the velocities of the gas at inlet and outlet are 60 m/s and 150 m/s respectively. Find the rate at which heat is rejected from the turbine. Find also the inlet pipe cross-sectional area when the inlet specific volume is 0.5 m^3/kg.



Sol:-

from Steady flow Energy Equation

$$gz_1 + h_1 + \frac{1}{2}C_1^2 + q = gz_2 + h_2 + \frac{1}{2}C_2^2 + w$$

$z_1 \simeq z_2$

power = 14000 kW

$$p = \dot{m} \cdot w \Rightarrow w = 14000/17 = 823.53 \text{ kJ/kg}$$

$$h_1 + \frac{1}{2}C_1^2 + q = h_2 + \frac{1}{2}C_2^2 + w$$

$$\therefore q = (h_2 - h_1) + \frac{1}{2}(C_2^2 - C_1^2)*10^{-3} + w$$

$$= (360 - 1200) + \frac{1}{2}(150^2 - 60^2)*10^{-3} + 823.53$$

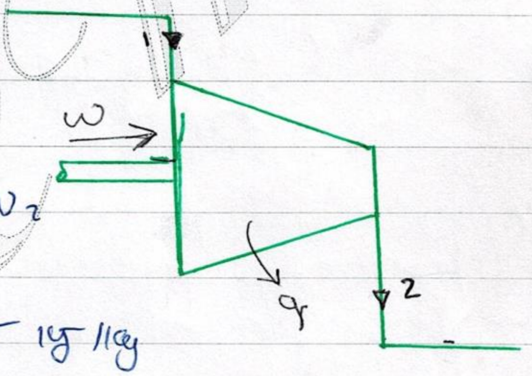
$$= -7.05 \text{ kJ/kg}$$

= 7.05 rejected heat

$$Q = \dot{m} \cdot q = 17*(-7.05) = -119.85 \text{ kW}$$

$$\dot{m} = \frac{C_1 A_1}{v_1} \Rightarrow A_1 = \frac{\dot{m} \cdot v_1}{C_1} = \frac{17 * 0.5}{60} = 0.142 \text{ m}^2$$

Ex:- Air flows at a rate of 0.4 kg/s through an air compresser entering at 6 m/s, 1 bar and 0.85 m^3/kg and leaving at 4.5 m/s, 6.9 bar and 0.16 m^3/kg. The internal energy of the air leaving is greater than that of entering air by 88 kJ/kg, cooling water in the jacket surrounding the cylinder absorbs heat from the air at the rate of 59 kJ/s. Find the power required to drive the compressor and the inlet and outlet pipe cross-sectional area.



Sol:- from Steady flow EE

$$gz_1 + P_1 v_1 + u_1 + \frac{1}{2} C_1^2 + q = gz_2 + P_2 v_2 + u_2 + \frac{1}{2} C_2^2 + w$$

$$Q = \dot{m} \cdot q \Rightarrow q = 59/0.4 = 147.5 \text{ kJ/kg}$$

$$P_1 v_1 + u_1 + \frac{1}{2} C_1^2 + q = P_2 v_2 + u_2 + \frac{1}{2} C_2^2 + w \qquad (u_2 - u_1 = 88 \text{ kJ/kg})$$

$$w = (P_1 v_1 - P_2 v_2) + (u_1 - u_2) + \frac{1}{2}(C_1^2 - C_2^2) \underline{*10^{-3}} + q \qquad (Z_1 \simeq Z_2)$$

$$w = (1*10^2 * 0.85 - 6.9*10^2 * 0.16) + (-88) + \frac{1}{2}(6^2 - 4.5^2)*10^{-3} + (-147.5)$$
$$= -260.9 \text{ kJ/kg}$$

$$W = \dot{m} \cdot w = 0.4 * (-260.9) = -104.35 \text{ kW}$$

$$A_1 = \frac{\dot{m} \cdot v_1}{C_1} = 0.057 \text{ m}^2$$

$$A_2 = \frac{\dot{m} \cdot v_2}{C_2} = 0.0148 \text{ m}^2$$

(Sheet No. 1)

Q1 :-

1 kg of fluid is compressed reversibly according to a $pV = 0.25$, where ,p, in bar and v in m^3/kg. The final volume is one fourth the initial volume. Calculate the work done on the fluid and sketch the process on p-v diagram.

Ans.[34660 N.m]

Q2 :-

$0.05\ m^3$ of gas at 6.9 bar expands reversibly in a Cylinder behind a piston according to a law $pV^{1.2} = C$ until the volume is $0.08\ m^3$. Calculate the work done by the gas and Sketch the process on p-v diagram.

Ans.[15300 N.m]

Q3 :-

One kilograme of fluid expand reversibly according to a linear Law from 4.2 bar to 1.4 bar. The initial and final volume are $0.004\ m^3$ and $0.02\ m^3$ respectively. The fluid is then cooled reversibly at constant pressure, and finally compressed reversibly according to a law $pV = c$ back to initial condition of 4.2 bar and $0.004\ m^3$. Calculate the work done for each process, the net work done and sketch the cycle on p-v diagram. Ans.[4480 J , -1120 J , -1845 J , 1515 J]

Q4 :- $0.09\, m^3$ of fluid at 0.7bar is compressed reversibly to a pressure of 3.5 bar according to a law of $pV^n = C$. The fluid is then heated reversibly at constant volume until the pressure is 4 bar, the specifice volume is $0.5\, m^3/kg$. A reversible expansion according to a law $pV^2 = c$ restores the fluid to its initial state. Calculate the mass of the fluid present, the value of (n) and the net work done on or by the system. Sketch the cycle on p-v diagram.

Ans. [0.0753 kg, 1.85, 676 N.m]

Q5 :-

Air at 200 kpa, 30 °C is contained in a cylinder/piston with initial volume of $0.1\, m^3$. The inside pressure balances ambient pressure of 100 kpa plus an external imposed force that proportinal to $V^{0.5}$. Now heat is transfer to the System to final pressure of 225 kpa. Find the work done for this process.

Ans. [8.65 kJ]

Q6 :- In an air compresser, the compression is takes place at constant internal energy, and 50 kJ of heat is rejected to the cooling water for every one kilograme of air. Find the work required for the compression.

Ans. [50 kJ/kg]

Q7: In a compression strok of gas engine the work done on the gas by the piston is 70 kJ/kg and heat rejected to the cooling water is 42 kJ/kg. Find the change of internal energy. Stating whether if is gain or Lost.

Ans. [28 $\frac{kJ}{kg}$]

Q8:

A mass of gas with an internal energy of 1500 kJ is contained in a cylinder which has perfect thermal insulated. The gas is allowed to expand behind a piston until it's internal energy is 1400 kJ. Calculate the work done by the gas. If the expansion follows a law $pv^2=c$ and the internal energy is changed. and initial pressure and volume are 28 bar and 0.06 m^3 respectively. Calculate the final pressure and volume.

Ans. [100 kJ, 4.59 bar, 0.148 m^3]

Q9: A Steam turbine recives a steam flow at 1.35 $\frac{kg}{s}$ and delivers 5000 kW. The heat loss from the casing is negligible. Find a. the change of enthalpy across this turbine when the velocities at entrance and exit and the difference in elevation at entrance and exit are negligible. b. the change of enthalpy across the turbine when the velocity at entrance and exit are 60 $\frac{m}{s}$ and 360 $\frac{m}{s}$, and the inlet pipe is 3m above the exhaust pipe.

Ans. [-3704 kJ/kg , -3766 kJ/kg]

Q10 :- A steady flow of steam enters a condenser with an enthalpy of 2300 kJ/kg and velocity of 350 m/s. The condensate leaves the condenser with an enthalpy of 160 kJ/kg and velocity of 70 m/s. Find the heat transfer to the cooling water per kg of steam.

Ans. [-2199 kJ/kg]

Q11 :- A turbine recives steam at 13.8 bar, 0.143 m^3/kg, internal energy 2590 kJ/kg, and 30 m/s. At leaving the condenser is 0.35 bar, 4.37 m^3/kg, internal energy 2360 $\frac{kJ}{kg}$ and 90 m/s. Heat is lost to surrounding at 0.25 kJ/s. If the rate of steam flow is 0.38 kg/s. What is the power developed by the turbine.

Ans. [102.8 kW]

Q12 :- A nozzle is a device for increasing the velocity of fluid. At inlet to a nozzle the enthalpy is 3026 kJ/kg and the velocity is 60 m/s. At exit from the nozzle the enthalpy is 2790 kJ/kg. The nozzle is horizontal and there is negligible heat loss from the turbine.

a. find the velocity at the nozzle exit. [688 m/s]

b. If the inlet area is 0.1 m^2 and the specific volume at the inlet is 0.19 m^3/kg. find the mass flow rate. [0.36 kg/s]

c. If $v = 0.5\ m^3/kg$ find the exit area of the nozzle. [0.0229 m^2]

Q13:- In a non-flow process there is a heat loss of 1055 kJ and an internal energy increase of 210 kJ. How much work is done and is the process is expansion or compression.

Ans. [-1265 kJ, Comp.]

Q14:- Air and fuel enter furnace used for home heating. The air has an enthalpy of 320 kJ/kg and the fuel an enthalpy of 43027 kJ/kg. The gases leaving the furnace has an enthalpy of 616 kJ/kg. There are 17 $\frac{kg_a}{kg_f}$, water circulate through the wall furnace receiving heat. The house required 17.02 kW of heat, what is the fuel consumption per day.

Ans. [41 kg/day]

THERMODYNAMICS

2

CHAPTER TWO

IDEAL GAS

((IDEAL GAS))

(Perfect gas)

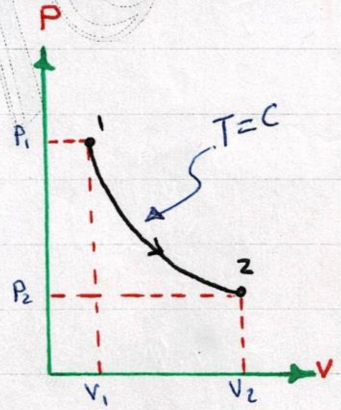
- Boyle's Law:-

It is defined as: when a change of state of any gas in which the mass and the temperature remain constant, the volume varies inversely as the pressure.

$$P \propto \frac{1}{V} \Rightarrow P = C \cdot \frac{1}{V}$$

$$\therefore \boxed{PV = C} \quad \text{Boyle's Law}$$

$$\therefore P_1 V_1 = P_2 V_2$$



Ex:-

A gas whose original pressure and volume were $300\,kN/m^2$ and $0.14\,m^3$ is expanded until its new pressure is $60\,kN/m^2$ while its temperature remains constant. What is its new volume?

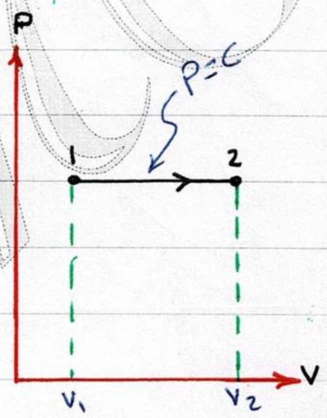
Sol:- $P_1 V_1 = P_2 V_2$ or $V_2 = V_1 \frac{P_1}{P_2}$

$$V_2 = 0.14 * \frac{300}{60}$$

$$= 0.7\,m^3$$

- Charles's Law :-

It is defined as: When the change of state of any gas in which the mass and pressure remain constant, the volume varies in proportion with the absolute temperature.



$$V \propto T \Rightarrow V = CT$$

$$\therefore \boxed{\frac{V}{T} = C} \sim\sim \text{Charles's Law}$$

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

Ex:- A quantity of gas whose original volume and temperature are 0.2 m^3 and 303°C, respectively, is cooled at constant pressure untile its volume becomes 0.1 m^3. What will be the final temperature of the gas?

SoL:-

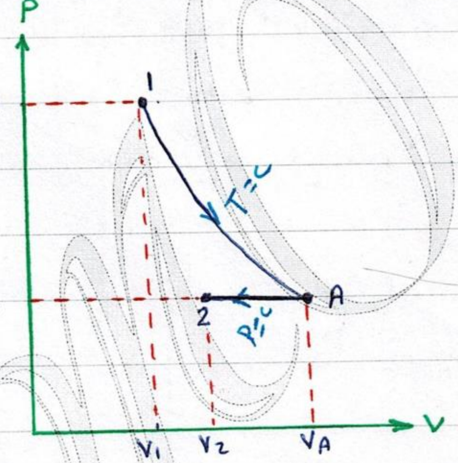
$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \Rightarrow T_2 = T_1 \cdot \frac{V_2}{V_1}$$

$$T_1 = 303 + 273 = 576\ K$$

$$T_2 = 576 * \frac{0.1}{0.2} = 288\ K$$

$$\therefore t_2 = 288 - 273 = 15^\circ C$$

(The characteristic equation of a perfect gas)



the process 1→A

$PV = C$ (Boyle) ($T = Const.$)

$P_1 V_1 = P_A V_A$, ∴ $T_1 = T_A$

$$V_A = \frac{P_1}{P_A} \cdot V_1 \quad ----- (1)$$

$V = CT$ (charles) ($P = const.$)

$$\frac{V_A}{T_A} = \frac{V_2}{T_2} = \frac{V}{T} = C$$

$$V_A = \frac{T_A}{T_2} \cdot V_2 \quad ----- (2)$$

from Boyle's Law ($T_A = T_1$) ⇒ sub in eq.(2)

$$V_A = \frac{T_1}{T_2} \cdot V_2 \quad ---- (3)$$

from eq's (1) & (3):

$$V_A = \frac{P_1}{P_A} \cdot V_1 = \frac{T_1}{T_2} \cdot V_2$$, from charles law $P_A = P_2$

$$\frac{P_1}{P_2} \cdot V_1 = \frac{T_1}{T_2} \cdot V_2 = C$$

$$\boxed{\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} = R}$$, R = gas constant

$P_1 V_1 = R T_1$ for 1 kg

$$\boxed{P_1 V_1 = m R T_1}$$ for m kg

$\therefore m = n . M$

Where : m = mass kg

n = number of moles mol

M = molecular weight

$P V = m R T$ (In general)

$P V = n M R T$

$M R = \frac{P V}{n T}$ (P & T are constant)

$M R = C . \frac{V}{n}$, ($\frac{V}{n} = C$) (Avogadro's theorm)

$$\therefore \boxed{M R = R_o}$$. R_o = Universal gas Constant

Avogadro's theorm : volume of one mole of any gas is same for all gases at any temperature and pressure.

	M
O_2	32
N_2	28
CO_2	44

$\therefore \quad R_0 = \dfrac{PV}{nT}$

$\therefore$ Volume of 1 mole at 0°c and $P = P_{atm} = 1.0132$ bar equal to 22.7 m^3.

$\therefore \quad R_0 = \dfrac{1.0132 * 10^5 * 22.7}{1 * (0+273)} = 8.314 \ \text{kJ/kg.k}$

Ex: for O_2 : $R = R_0 / M = 8.314 / 32 = 0.259$

Ex: A volume of 3.6 m^3 of O_2 milarally at 220°C and pressure 400 kpa, is compressed reversibly at constant temperature to a final volume of 0.06 m^3. Calculate the mass, the final pressure, the increase in internal energy and the work done.

Sol:

$PV = mRT$, for O_2, $R = R_0/M = 0.26$ kJ/kg.k

$m = 400 * 10^3 \times 3.6 / 0.26 * 10^3 \times (220 + 273) \equiv \dfrac{\cancel{N/m^2} * \cancel{m^3}}{J / kg.\cancel{K} * \cancel{K}}$

$= 11.23$ kg

$P_1V_1 = P_2V_2 \Rightarrow P_2 = (3.6/0.06) * 400 = 24$ Mpa

$Q = W + \Delta U$, $\Delta U = 0$ (since $T = C$)

$W = \int_1^2 P dv = C \int_1^2 \dfrac{dv}{V} = P_1V_1 \int \dfrac{dv}{V} = P_1V_1 \ln \dfrac{V_2}{V_1}$

$W = 400 * 10^3 * 3.6 * \ln \dfrac{0.06}{3.6} = Q = -5.896$ MJ

- Joule's Law :-

It is defined as :-

the internal energy of a gas is a function of temperature only and is independent of changes in pressure and volume.

∴ If $T=C \Rightarrow \Delta U=0$

- The specific heat Capacities of a gas :-

a. the constant volume heating of a gas:

let a mass of gas m be heated at constant volume such that its temperature rises from T_1 to T_2 and its pressure rises from P_1 to P_2. Then

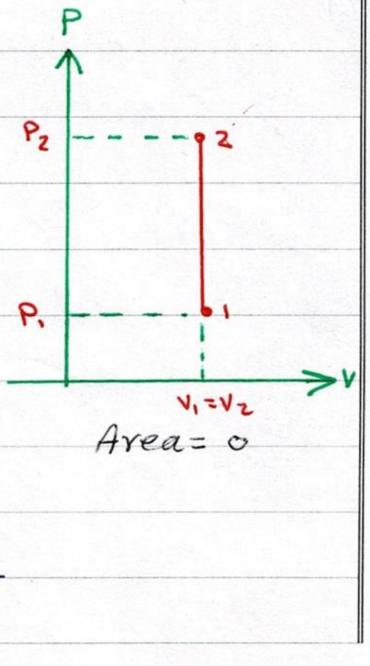
Heat received by the gas $= m\,C_v\,(T_2-T_1)$

from NFEE , $Q=\Delta U+W$

∴ $V=C \Rightarrow W=0$

$Q=\Delta U$,

or $mC_v(T_2-T_1)=U_2-U_1$



Area= 0

from the perfect gas equation (characteristic equation)

$$\frac{P_1\cancel{V_1}}{T_1}=\frac{P_2\cancel{V_2}}{T_2} \Rightarrow P_2=P_1\,\frac{T_2}{T_1}$$

Ex: 2 kg of gas, occupying 0.7 m^3, had an original temperature of 15°C. It was then heated at constant volume until its temperature became 135°C. How much heat was transferred to the gas and what was its final pressure?

Take, $C_v = 0.72$ kJ/kg K and $R = 0.29$ kJ/kg K

Sol: Heat transferred at $(V=C) = m C_v (T_2 - T_1)$

$$= 2 \times 0.72 \times (135 - 15)$$

$$= 2 \times 0.72 \times 120$$

$$= 172.8 \text{ kJ}$$

Now $P_1 V_1 = m R T_1$

$$\therefore \quad P_1 = \frac{m R T_1}{V_1} = \frac{2 \times 0.29 \times 288}{0.7} = \frac{167.04}{0.7} = 238.6 \text{ kPa}$$

Since the volume remains constant, then

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \quad \therefore \quad P_2 = P_1 \frac{T_2}{T_1}$$

$$= 238.6 * \frac{408}{288}$$

$$= 338.1 \text{ kN/m}^2$$

Or $P_2 V_2 = m R T_2$

$$P_2 = m R T_2 / V_2 = 2 * 0.29 * (135 + 273) / 0.7$$

$$= 338.1 \text{ kPa}$$

b. the constant pressure heating of a gas :

Let a mass of gas (m) be heated at constant pressure such that its temperature rises from T_1 to T_2 and its volume increases from V_1 to V_2. Then

Heat received by the gas = $m\,C_p\,(T_2 - T_1)$

$$Q = \Delta U + W$$

$$m\,C_p\,(T_2 - T_1) = (U_2 - U_1) + P(V_2 - V_1)$$

$$= (U_2 + PV_2) - (U_1 + PV_1)$$

$$= H_2 - H_1$$

or

$$U_2 - U_1 = m\,C_p\,(T_2 - T_1) - P(V_2 - V_1)$$

When $PV = mRT$ then

$$U_2 - U_1 = m\,C_p\,(T_2 - T_1) - mR\,(T_2 - T_1)$$

$$= m(T_2 - T_1)(C_p - R)$$

from the characteristic equation of a perfect gas :

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2} \quad , P_1 = P_2$$

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

Note : $H = m\,C_p\,T$, $h = C_p\,T$, $\Delta h = C_p\,\Delta T$

$U = m\,C_v\,T$, $u = C_v\,T$, $\Delta u = C_v\,\Delta T$

Ex:- A gas whose pressure, volume and temperature are 275 kN/m², 0.09 m³ and 185 °C, respectively, has its state changed at constant pressure until its temperature becomes 15 °C. How much heat is transferred from the gas and how much work is done on the gas during the process?

Take: $R = 0.29\ kJ/kg.K$, $C_p = 1.005\ kJ/kg.K$.

Sol:- $P_1V_1 = mRT_1$

∴ $m = P_1V_1/RT_1 = 275\times10^3 \times 0.09 / 0.29\times10^3 \times 458$

$= 0.186$ kg

Heat transferred $= mC_p(T_2 - T_1)$

$= 0.186 \times 1.005 \times (288 - 458)$

$= -31.78$ kJ (the heat has been extracted from the gas)

∴ P = constant (given)

∴ $\frac{V_1}{T_1} = \frac{V_2}{T_2} \Rightarrow V_2 = V_1 * \frac{T_2}{T_1} = 0.09 \times \frac{288}{458}$

$= 0.0566\ m^3$

Work done $= p(V_2 - V_1)$

$= 275 \times (0.0566 - 0.09)$

$= -9.19$ kJ

. Relation Between Specific Heat (Cp&Cv):-

from the non-flow energy equation NFEE

$$Q = W + \Delta U \quad , \Delta U = m C_v (T_2 - T_1)$$

$$W = \int_1^2 P \cdot dV = P_2 V_2 - P_1 V_1$$

Ideal Gas Law $pV = mRT$

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

$$\therefore Q = mR(T_2 - T_1) + m C_v (T_2 - T_1)$$
$$= m(R + C_v)(T_2 - T_1)$$

$$\therefore Q = \Delta H = m C_p (T_2 - T_1)$$

$$\therefore m C_p (T_2 - T_1) = m(R + C_v)(T_2 - T_1)$$

$$\therefore C_p = R + C_v \Rightarrow \boxed{C_p - C_v = R}$$

$\boxed{\gamma = \frac{C_p}{C_v}}$, γ = the ratio of the specific heat.

$$\frac{C_p}{C_v} - \frac{C_v}{C_v} = \frac{R}{C_v}$$

$$\gamma - 1 = R / C_v \Rightarrow \boxed{C_v = \frac{R}{\gamma - 1}}$$

$$C_p = \gamma * C_v \Rightarrow \boxed{C_p = \frac{\gamma R}{\gamma - 1}}$$

Ex:- A perfect gas have specific heat as $C_p = 0.846 \frac{kJ}{kg.K}$ $C_v = 0.657$ kJ/kg.K . find the gas constant and molecular weight of gas.

Sol:- $R = C_p - C_v = 0.846 - 0.657 = 0.189$ kJ/kg.K

$= 189$ J/kg.K

$M = R_o/R = 8314/189 = 44$

Ex:- A perfect gas has molecular weight of 26 and avalue of $\gamma = 1.26$, Calculate the heat rejected per 1kg when:-

a. the gas is contained in arigid vessel at 3bar and 315°C and cooled until the pressure fails to 1.5 bar.

b. the gas enters pipe at 280°C and flow steady in the end of the pipe where T = 250°C . Neglect any change in velocity of the gas.

Sol:- a. $Q = W + \Delta U$, arigid vessel $\Rightarrow V = C \Rightarrow dv = 0$

$w = \int p.dv = 0$

$\therefore Q = \Delta U = m C_v (T_2 - T_1)$, for $v = c$ only

$M = 26$, $\gamma = 1.26$

$R = R_o/M = 8.314/26 = 0.3198$ kJ/kg.K

$C_v = \frac{R}{\gamma - 1} = \frac{0.3198}{1.26 - 1} = 1.229$ kJ/kg.K

$Q = m C_v (T_2 - T_1) = 1 * 1.229 * (T_2 - T_1)$

since $V = C \Rightarrow V_1 = V_2$

from the characteristic equation

$$\frac{P_1 \cancel{V_1}}{T_1} = \frac{P_2 \cancel{V_2}}{T_2} \Rightarrow \frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$\therefore T_2 = \frac{P_2}{P_1} \cdot T_1 = \frac{1.5}{3}(315 + 273) = 294\ K$

$Q = 1 * 1.229 * (294 - 588)$

$= -361$ kJ (rejected)

$= 361$ kJ rejected

b. Steady flow Energy Equation SFEE

$$gZ_1 + P_1 V_1 + u_1 + \frac{1}{2} C_1^2 + q = gZ_2 + P_2 V_2 + u_2 + \frac{1}{2} C_2^2 + w$$

$\Delta Z \simeq 0$, $\Delta C \simeq 0$, $w \simeq 0$

$\therefore h_1 + q = h_2 \Rightarrow q = h_2 - h_1$

$Q = m(h_2 - h_1) = m C_p (T_2 - T_1)$

$C_p = \gamma \cdot C_v = 1.26 * 1.229 = 1.548$ kJ/kg.K

$\therefore Q = 1 * 1.548 * (250 - 280)$

$= -46.44$ kJ (rejected)

$= 46.44$ kJ rejected

Ex:- Five kilogram of oxygen are heated from 250 to 400K at constant pressure. Calculate the change of enthalpy, change in internal energy, heat transferred and work done. $\gamma = 1.4$

Sol:-

a non-flow energy equation

$$Q = W + \Delta U$$

$$w = \int p\,dv = p(V_2 - V_1) \quad , \quad p = c \text{ (given)}$$

$$Q = (P_2V_2 - P_1V_1) + (U_2 - U_1)$$

$$Q = (P_2V_2 + U_2) - (P_1V_1 + U_1)$$

$$= H_2 - H_1 = mC_p(T_2 - T_1) \quad \text{for } p=c \text{ only}$$

for O_2:

$$M = 32 \quad , \quad \gamma = 1.4$$

$$R = R_0/M = 8.314/32 = 0.2598 \text{ kJ/kg.K}$$

$$C_p = \frac{\gamma R}{\gamma - 1} = \frac{1.4 \times 0.2598}{1.4 - 1} = 0.9093 \text{ kJ/kg.K}$$

$$\Delta H = 5 * 0.9093 * (400 - 250) = 692 \text{ kJ}$$

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

$$C_v = C_p - R = 0.9093 - 0.2598 = 0.6495 \ \frac{\text{kJ}}{\text{kg.K}}$$

$$\Delta U = 5 * 0.6495 * (400 - 250) =$$

$$Q = W + \Delta U \quad , \quad \text{at } p = c \Rightarrow Q = \Delta H$$

$$\therefore W = Q - \Delta U$$

$$= 682 - 487 = 195 \text{ kJ}$$ (work done by the System)

Ex: An Oxygen cylinder has a capacity of 300L, and contains O_2 at 3.1 Mpa and 18°C. The valve is open and some gas is used. If the pressure and temperature of the oxygen fall to 1.7 Mpa and 15°C respectively. Find the mass of oxygen used. If بعد after the valve is closed the Oxygen remain in the Cylinder is تدريجيا gradualy تحقق attains its initial temperature of 18°C. Find the amount of heat transfer through the Cylinder wall. Oxygen density at 0°C and 0.1013 Mpa is 1.429 $\frac{kg}{m^3}$ and $\gamma = 1.4$.

Sol: $P_1V_1 = mRT_1 \Rightarrow m_1 = \frac{P_1V_1}{RT_1}$

$$R(O_2) = 8.314/32 = 0.26 \text{ kJ/kg·K}$$

$$\text{initial mass} = m_1 = \frac{3.1*10^3 * 300*10^{-3}}{0.26*(18+273)} = 12.29 \text{ kg}$$

$$\text{final mass} = m_2 = \frac{1.7*10^3 \times 300*10^{-3}}{0.26*(15+273)} = 6.8 \text{ kg}$$

$$\text{mass used} = m_1 - m_2 = 12.29 - 6.8 = 5.49 \text{ kg}$$

$$Q = W + \Delta U \quad , V = c \Rightarrow W = 0$$

$$Q = mC_v(T_2 - T_1)$$

$$C_v = R/\gamma-1 = 0.26/1.4-1 = 0.65 \text{ kJ/kg·K}$$

$$Q = 6.8 * 0.65 * (18-15) = 13.26 \text{ kJ}$$

(Heat gain)

(Sheet No. 2)

Q1:- The molecular weight of Carbon dioxide CO_2 is 44. In an experment the value of γ was found to be 1.3. Assuming that CO_2 is a perfect gas. Calculate the gas constant R and the Specific heats at constant P&V. Ans.[0.189 , 0.63 and 0.819 kJ/kg.K]

Q2:- Calculate the internal energy and enthalpy of 1kg of air occupying 0.05 m^3 at 20bar. If the internal energy is increased by 120 kJ/kg as the air compressed to 50 bar. Calculate the new volume occupied by 1 kg of air. Ans.[250.1, 350.1 kJ/kg , 0.0296 m^3]

$R_{air} = 0.287$

Q3:- When a certine perfect gas is heated at constant pressure from 15°C to 95°C, the heat required is 1130 kJ/kg. While when the same gas is heated at constant volume between the same temperature limits above, the heat required is 808 kJ/kg. Calculate Cp, Cv, γ, R and M of the gas.

Ans.[14.2 , 10.1 kJ/kg.K , 1.405 , 4.1 kJ/kg.K , 2.028]

Q4:- In an air compressor the pressure at inlet and outlet are 1bar & 5bar respectively. The temperature of the air at inlet is 15°C and the volume at beging of compression is three times that at the end of compression. Calculate the temperature of air at outlet and the increase in internal energy.

Ans. [207 °C, 138 kJ/kg]

Q5: The exhaust gas leaving an oil engine is passed through a heat exchanger which consist of tubes surr-onding by water. The gas enters at 327 °C and leaves at 193 °C. The water enters the exchanger at 17 °C and leaves at 56 °C. If the mass flow rate of water is 2.54 kg/min. Determine the mass flow rate of gas. Take: $C_{p_g} = 1.04$ kJ/kg.K , $C_{p_w} = 4.186 \frac{kJ}{kg.K}$

Ans. [2.98 kg/min]

Q6: A working fluid enters a steady-flow system with velocity 30 m/s and leaves with velocity 140 m/s. The mass flow rate is 9 kg/s. The properties of the fluid are at entry, 13.8 bar, 0.122 m^3/kg, internal energy 422 kJ/kg, and exit properties are 1.035 bar, 0.805 m^3/kg, internal energy 208 $\frac{kJ}{kg}$. The heat transfer from the system is 4.22 kJ/kg. Determine the work transfer in kW from the system.

Ans. [2565 kW]

Reversible and Irreversible Processes for The Ideal Gas

1. Reversible non-flow Processes:

a. Constant volume Process (Isometeric)

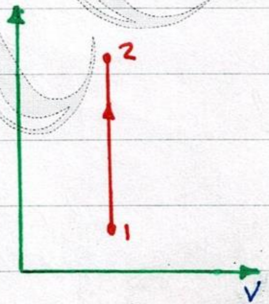
from the non-flow E.E.

$$Q = W + \Delta U$$

$$W = \int P\,dV \quad , \quad V = C \Rightarrow dV = 0$$

$$\therefore W = 0 \Rightarrow Q = \Delta U$$

$$\boxed{Q = m C_v (T_2 - T_1)}$$



b. Constant pressure Process (Isobaric)

from the NFEE

$$Q = W + \Delta U$$

$$W = P_2 V_2 - P_1 V_1$$

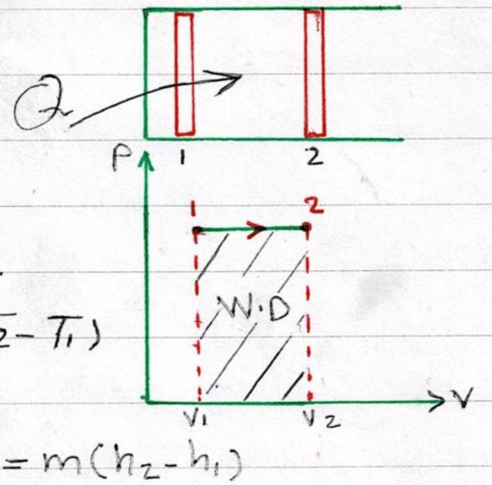
$$= mR(T_2 - T_1)$$

$$\Delta U = m C_v (T_2 - T_1)$$

$$Q = mR(T_2 - T_1) + m C_v (T_2 - T_1)$$

$$= m(R + C_v)(T_2 - T_1)$$

$$= m C_p (T_2 - T_1) = \Delta H = m(h_2 - h_1)$$



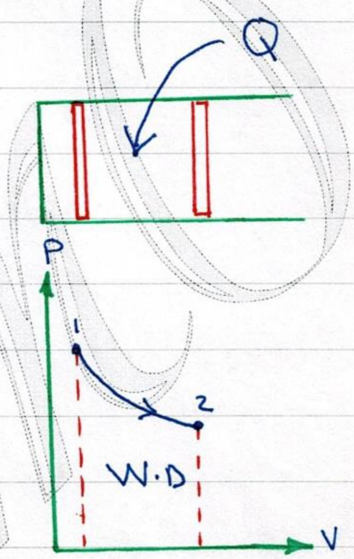
$$\boxed{Q = m C_p (T_2 - T_1)}$$

c. Constant temperature process (Isothermal)

from NFEE :

$$Q = W + \Delta U$$

$$W = \int_1^2 P\,dV$$



we have $\frac{P_1 V_1}{T_1} = C$, since $T = C$

$$\therefore P_1 V_1 = C \Rightarrow P = \frac{C}{V}$$

$$W = \int_1^2 \frac{C}{V}\,dV = C \ln \frac{V_2}{V_1}$$

$$W = PV \ln \frac{V_2}{V_1} = mRT_1 \ln \frac{V_2}{V_1}$$

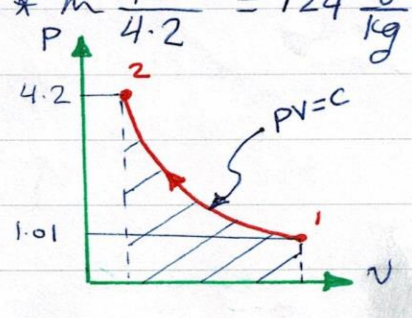
$$U_2 - U_1 = mC_v(T_2 - T_1) \quad , T_2 = T_1 \Rightarrow \Delta U = 0$$

$$\boxed{\therefore Q = PV \ln \frac{V_2}{V_1} = PV \ln \frac{P_1}{P_2} = mRT \ln \frac{P_1}{P_2}}$$

Ex: 1 kg of nitrogen (Molecular weight 28) is compressed reversibly and isothermally from 1.01 bar, 20°C to 4.2 bar. Calculate the work done and the heat flow during the process. Assume nitrogen to be a perfect gas.

Sol: $R = R_o/M = 8.314/28 = 0.297$ kJ/kg K

$$W = RT \ln \frac{P_1}{P_2} = 0.297 * 293 * \ln \frac{1.01}{4.2} = 124 \frac{kJ}{kg} \text{ (comp.)}$$



$Q = W = -124$ kJ/kg

Heat rejected $= +124$ kJ/kg

d. Adiabatic Process :-

In this process the System must be in thermal insulated, to prevent the heat transfer between the System and Surrounding.

To find the Relation between P & V :

from the non-flow E.E

$$Q = W + \Delta U$$

adiabatic process $\Rightarrow Q = 0$

$$\left.\begin{array}{l} dQ = dU + dW \Rightarrow dq = du + dw \\ dU = m C_v \, dT \Rightarrow du = C_v \, dT \\ dW = p \, dV \Rightarrow dw = p \, dv \end{array}\right\} \text{per unit mass}$$

$$\therefore \; dq = C_v \, dT + p \, dv$$

$$pv = RT \Rightarrow p = RT / v$$

$$\therefore \; dq = C_v \, dT + RT \frac{dv}{v} = 0$$

$$0 = C_v \, dT + RT \frac{dv}{v}$$

$$0 = C_v \frac{dT}{T} + R \frac{dv}{v}$$

$$0 = \frac{dT}{T} + \frac{R}{C_v} \cdot \frac{dv}{v} \quad , \quad \frac{R}{C_v} = \gamma - 1$$

$$0 = \frac{dT}{T} + (\gamma-1)\frac{dv}{v}$$

$$\int 0 = \int_{T_1}^{T_2}\frac{dT}{T} + (\gamma-1)\int_{v_1}^{v_2}\frac{dv}{v}$$

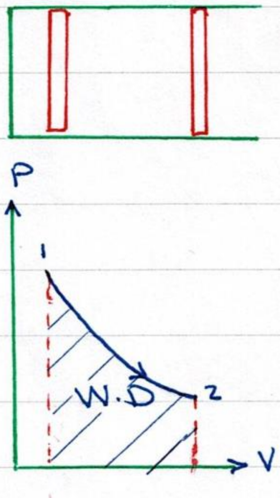
$$\ln T + (\gamma-1)\ln V = C \quad , \quad T = \frac{Pv}{R}$$

$$\ln\left(\frac{Pv}{R}\right) + (\gamma-1)\ln v = C$$

$$\ln\frac{Pv\cdot v^{\gamma-1}}{R} = C$$

$$\frac{Pv^{\gamma}}{R} = e^{C} \Rightarrow Pv^{\gamma} = Re^{C} = C$$

$$\therefore \boxed{PV^{\gamma} = C}$$ adiabatic process



the non-flow energy

$$Q = W + \Delta U \quad , Q = 0 \ \text{(adiabatic)}$$

$$W = -\Delta U$$

$$= mC_v(T_1 - T_2) = m\left(\frac{R}{\gamma-1}\right)(T_1 - T_2)$$

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

$$\boxed{W = \frac{P_1V_1 - P_2V_2}{\gamma-1}}$$ ~~ Adiabatic work

The Relation Between P,V and T in Adiabatic Process:-

$$\frac{P_1 v_1}{T_1} = \frac{P_2 v_2}{T_2} = C$$

$$\frac{P_1}{P_2} = \frac{v_2}{v_1} \cdot \frac{T_1}{T_2} \quad \text{---} \; ①$$

$$P_1 v_1^{\gamma} = P_2 v_2^{\gamma}$$

$$\frac{P_1}{P_2} = \left(\frac{v_2}{v_1}\right)^{\gamma} \quad \text{---} \; ②$$

Sub. eq ① in eq ②

$$\left(\frac{v_2}{v_1}\right)^{\gamma} = \left(\frac{v_2}{v_1}\right) \cdot \left(\frac{T_1}{T_2}\right)$$

$$\therefore \frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} \quad \text{---} \; ③$$

Sub eq ② in eq ③ , where $\frac{v_2}{v_1} = \left(\frac{P_1}{P_2}\right)^{1/\gamma}$

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

$$\therefore \boxed{\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{v_2}{v_1}\right)^{\gamma-1}}$$

the relation between P, v and T for adiabatic process

Ex: Air at 1.02 bar, 22°C, initially occupying a cylinder volume of 0.015 m^3, is compressed reversibly and adiabatically by a piston to a pressure of 6.8 bar. Calculate the final temperature, the final volume, and the work done on the mass of air in the cylinder.

Sol: $\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$ or $T_2 = T_1 * \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$

$$T_2 = 295 * \left(\frac{6.8}{1.02}\right)^{\frac{1.4-1}{1.4}} = 295 * 6.67^{0.286}$$
$$= 507.5 \text{ K}$$

(Where $T_1 = 22 + 273 = 295$, $\gamma = 1.4$)

Final temperature $= 507.5 - 273 = 234.5$ °C

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^{\gamma} \quad \text{or} \quad \frac{V_1}{V_2} = \left(\frac{P_2}{P_1}\right)^{1/\gamma}$$

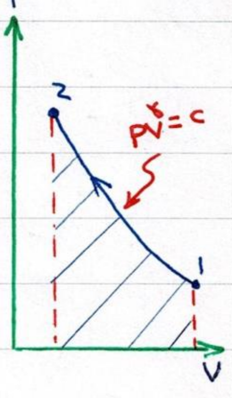
$$\therefore \frac{0.015}{V_2} = \left(\frac{6.8}{1.02}\right)^{1/1.4} \Rightarrow V_2 = 0.00388 \, m^3$$

$W = U_1 - U_2$ (adiabatic process)

$= C_v (T_1 - T_2)$ (per kg of gas)

$= 0.718 (295 - 507.5) = -152.8$ kJ/kg

$\therefore$ Work input per kg $= 152.8$ kJ/kg



$$m = \frac{P_1 V_1}{R T_1} = \frac{1.02 * 10^5 * 0.015}{0.287 * 10^3 * 295} = 0.0181 \text{ kg}$$

Total work done $= 0.0181 * 152.8 = 2.76$ kJ

e. Polytropic Processes:

This general case of expansion or compression of a substance according to the law $PV^n = C$, It is called a polytropic expansion or compression or a polytrope.

It is should be noted that the value of the constant "C" will change with each change of condition. So also will the value of "n" which is called the "index" of the expansion or compression or the polytropic exponent.

$$PV^n = C$$

The non-flow energy equation

$$Q = W + \Delta U$$

$$W = \int P\,dV = C \cdot \int \frac{dV}{V^n} = PV^n \int (V^{-n})\,dV$$

$$W = PV^n \left[\frac{V^{-n+1}}{-n+1} \right]_1^2 = \frac{P_2 V_2^n \cdot V_2^{-n+1} - P_1 V_1^n \cdot V_1^{-n+1}}{-n+1}$$

$$W = \frac{P_2 V_2 - P_1 V_1}{-n+1}$$

$$W = \frac{P_1 V_1 - P_2 V_2}{n-1}$$

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

$$\Delta U = m C_v (T_2 - T_1) = - m C_v (T_1 - T_2)$$

$$\Delta U = -m(R/\gamma-1)(T_1 - T_2)$$

$$\therefore \quad Q = \frac{mR(T_1 - T_2)}{n-1} - m\frac{R}{\gamma-1}(T_1 - T_2)$$

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

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

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

$$= (mR(T_1 - T_2)/n-1)(\gamma-n/\gamma-1)$$

$$\boxed{\therefore \quad Q = \left(\frac{\gamma-n}{\gamma-1}\right) \cdot W}$$

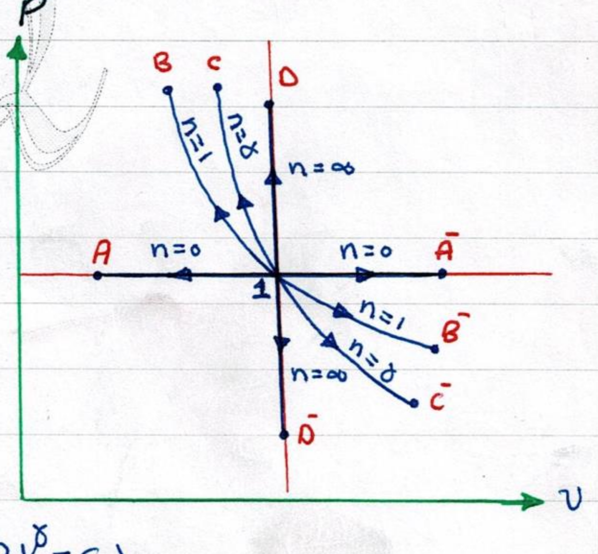
In a polytropic process the value of (n) depends on the a mount of heat added or rejected and on the work done during the process

$$PV^n = C$$

When:

1. $n=0 \rightarrow PV^0=C \rightarrow P=C$ (isobaric)
2. $n=1 \rightarrow PV^1=C \rightarrow PV=C$ (isothermal $T=C$)
3. $n=\gamma \rightarrow PV^\gamma=C \rightarrow Q=0$ (adiabatic)
4. $n=\infty \rightarrow PV^\infty=C \rightarrow P^{\frac{1}{\infty}}.V=C \rightarrow V=C$ (isometeric or isochoric)

- Processes:



$1 \rightarrow A$ Cooling at $P=C$
$1 \rightarrow A'$ Heating at $P=C$

$1 \rightarrow B'$ Expansion at $T=C$
$1 \rightarrow B$ Compression at $T=C$

$1 \rightarrow C$ Adiabatic compression $(PV^\gamma=C)$
$1 \rightarrow \bar{C}$,, Expansion

$1 \rightarrow D$ Heating at $V=C$
$1 \rightarrow \bar{D}$ Cooling ,, ,,

- Work and the hyperbolic process :-

The hyperbolic process is a particular case of the polytropic process, ($PV^n=C$), being the case When ($n=1$). Thus, the law for the hyperbolic process is.

$$\boxed{PV=C}$$

For ahyperbolic change from state 1 to state 2.

$$P_1V_1=P_2V_2$$

An expression for the work done during a polytropic process has already been determined.

$$\text{Work done}=\frac{P_1V_1-P_2V_2}{n-1}$$

for hyperbolic process, $P_1V_1=P_2V_2$ & $n=1$

$$\therefore \text{Work done}=\frac{P_1V_1-P_2V_2}{n-1}=\frac{0}{0}$$

∴ to compute the work done. It is necessary to determine the area under curve.

$$\text{work done} = \int_{V_1}^{V_2} P\,dV$$

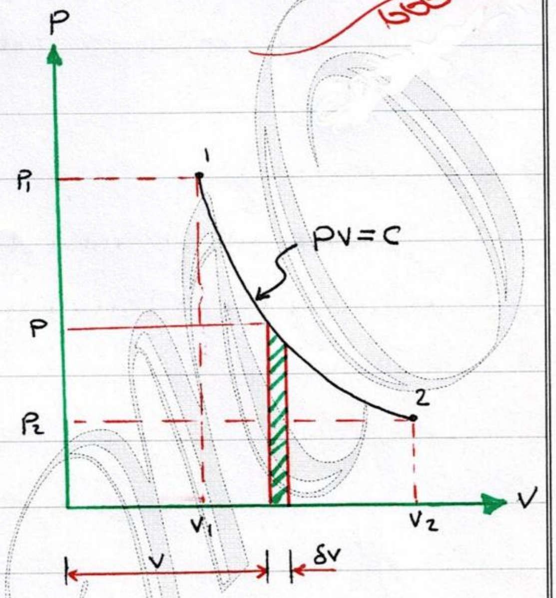
$$PV = C \Rightarrow P = C/V$$

$$W = C\int_{V_1}^{V_2} \frac{dV}{V} = C\left[\ln V\right]_{V_1}^{V_2}$$

$$W = C\left[\ln V_2 - \ln V_1\right]$$

$$= C\ln\frac{V_2}{V_1} = PV\ln\frac{V_2}{V_1}$$

$$\therefore \quad \boxed{W = PV\ln\frac{V_2}{V_1}}$$



Ex:-

A gas is compressed hyperbolically from a pressure and valume of 100 kN/m² and 0.056 m³, respectively, to a volume of 0.007 m³. Determine the final pressure and the work done on the gas.

Sol:- since the gas is compressed hyperbolically, then

$$P_1V_1 = P_2V_2 \quad \text{or} \quad P_2 = 100 * \frac{0.056}{0.007} = 800 \text{ kPa}$$

$$\text{work done} = P_1V_1\ln\frac{V_2}{V_1} = 100*10^3 \times 0.056 \times \ln\frac{0.007}{0.056}$$

$$= -11.65 \text{ kJ}$$

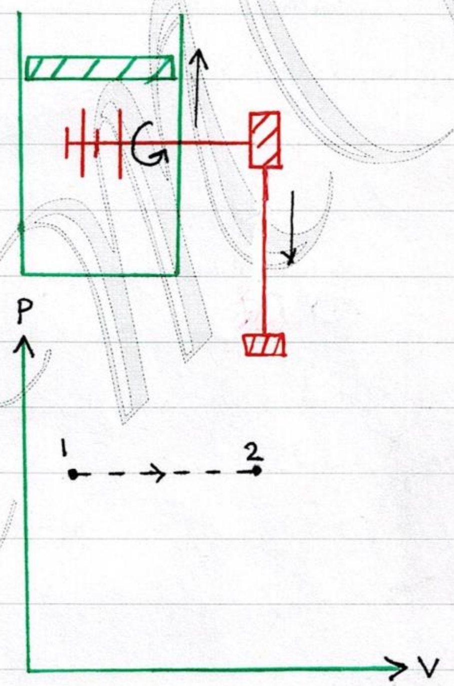
work done on the gas = 11.65 kJ

2. Irreversible Processes (Closed System)

a. Paddle work (P=c)

W_p = Paddle work
from NFEE

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



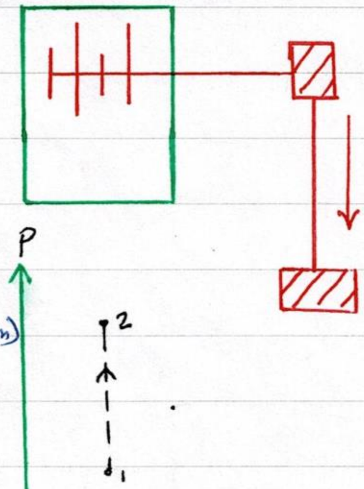
Q may be equal to zero if the process is very fast or insulated.

$$\Delta U = mC_v(T_2 - T_1)$$
$$W = P(V_2 - V_1) = mR(T_2 - T_1)$$

$W_p = -ve$ since it is done on the System.

b. Paddle work (V=C)

$$Q = W + \Delta U + W_p$$
$W = 0 \ (V=C)$, $Q = 0$
$$\Delta U = mC_v(T_2 - T_1)$$
$W_p = -ve$ (done on the System)



3. Reversible Processes (Open System)

a. Constant Pressure Process : (such as condenser)

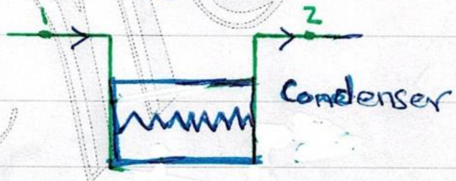
$$gZ_1 + P_1v_1 + u_1 + \frac{1}{2}C_1^2 + q = gZ_2 + P_2V_2 + u_2 + \frac{1}{2}C_2^2 + w$$

$$P_1 = P_2$$

$$w - q = (P_1v_1 - P_2V_2) + (u_1 - u_2) + \frac{1}{2}(C_1^2 - C_2^2)*10^{-3} + g(Z_1 - Z_2)*10^{-3}$$

or

$$\dot{w} - \dot{Q} = \dot{m}[w - q]$$



P = Constant

b. Constant temperature process :

$T = C$, $P_1V_1 = P_2V_2$, $u_1 = u_2$

$$\therefore W = q + \left[g(Z_1 - Z_2) + \frac{1}{2}(C_1^2 - C_2^2)\right]*10^{-3}$$

or $$w = \int_1^2 P\,dv = pv \ln\frac{V_2}{V_1} = mRT \ln\frac{V_2}{V_1}$$

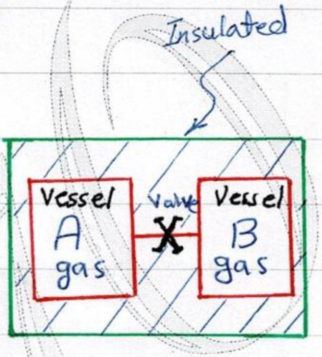
c. Polytropic Process :

from Steady flow Energy Equation SFEE.

$$W - q = (P_1V_1 - P_2V_2) + (u_1 - u_2) + \frac{1}{2}(C_1^2 - C_2^2)*10^{-3} + g(Z_1 - Z_2)*10^{-3}$$

4. Irreversible Processes (Open System)

a. Unresisted, or free, expansion :



$$Q = W + \Delta U$$

$Q = 0$ (adiabatic) , $W = 0$

$\therefore \Delta U = 0 \Rightarrow U_2 = U_1$ (Per 1 kg)

$$C_v T_2 = C_v T_1$$

$\therefore T_1 = T_2$ (Irreversible)

Ex: Air at 20 bar is initially contained in vessel "A" as shown in the fig. above, the volume of which can be assumed to be $1 m^3$. The valve X is opened and the air expands to fill vessels A and B. Assuming that the vessels are of equal volume, Calculate the final pressure of the air.

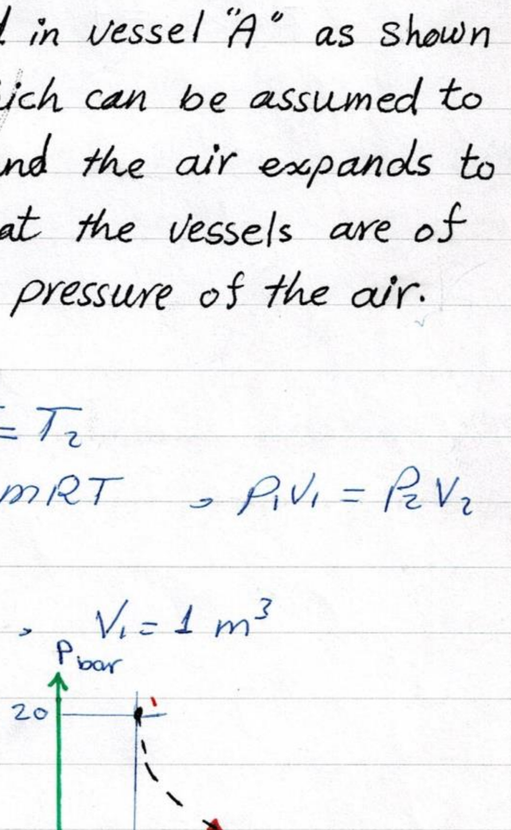
Sol:

$\therefore$ Free expansion $\Rightarrow T_1 = T_2$

for a perfect gas $pV = mRT$, $P_1 V_1 = P_2 V_2$

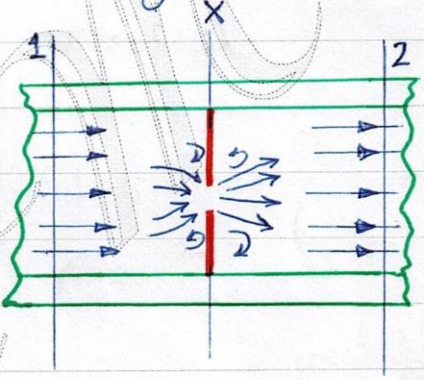
$V_2 = V_A + V_B = 1 + 1 = 2 m^3$, $V_1 = 1 m^3$

$$P_2 = P_1 \cdot \frac{V_1}{V_2} = 20 * \frac{1}{2} = 10 \text{ bar}$$



b. Throttling Process :

A flow of fluid is said to be throttled when there is som restriction to the flow, When the velocities before and after the restriction are either equal or negligibly small, and when there is a negligible heat loss to the surroundings.



from SFEE :

$$gz_1 + P_1 v_1 + u_1 + \frac{1}{2} C_1^2 + q = gz_2 + P_2 v_2 + u_2 + \frac{1}{2} C_2^2 + w$$

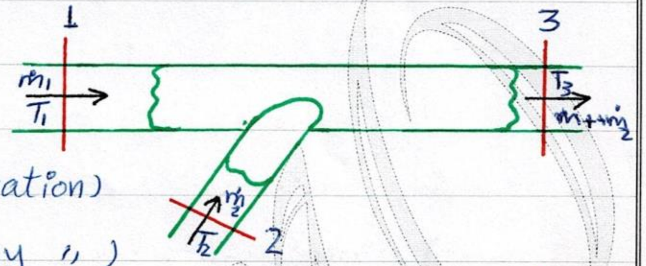
$$z_1 = z_2 \quad , w = 0 \quad , Q = 0 \quad , C_1 \simeq C_2$$

$$\therefore \quad P_1 v_1 + u_1 = P_2 v_2 + u_2$$

$$h_1 = h_2 \Rightarrow C_p T_1 = C_p T_2$$

$$\therefore T_1 = T_2 \quad \text{(Irreversible)}$$

c. Adiabatic mixing :



$m_1 + m_2 = m_3$ (mass conservation)

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

$$\dot{m}_1 C_p T_1 + \dot{m}_2 C_p T_2 = \dot{m}_3 C_p T_3$$

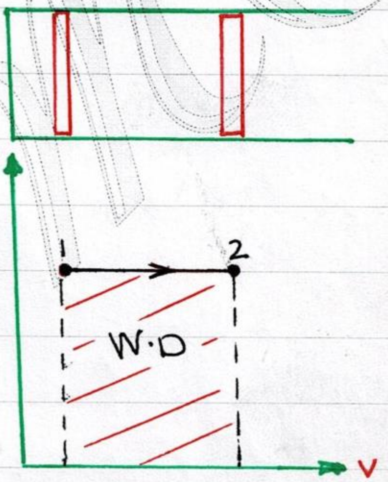
for the same gases mixing $C_p =$ Constant

$$\dot{m}_1 T_1 + \dot{m}_2 T_2 = \dot{m}_3 T_3$$

$$\boxed{\dot{m}_1 T_1 + \dot{m}_2 T_2 = (\dot{m}_1 + \dot{m}_2) T_3}$$

Ex: 0.05 kg of air is heated at constant pressure of 2bar until the volume occupied is $0.0658\,m^3$. Calculate the heat supplied and work done, When the initial temperature is 130°C. Take $C_p = 1.005$ kJ/kg.K, $R = 0.287$ kJ/kg.K

Sol: the non-flow energy equation



$Q = W + \Delta U$

$W = \int_1^2 P \cdot dV = P(V_2 - V_1) =$

$= mR(T_2 - T_1)$

$\Delta U = (U_2 - U_1) = mC_v(T_2 - T_1)$

$\therefore Q = mC_p(T_2 - T_1)$

$P_2V_2 = mRT_2 \Rightarrow T_2 = P_2V_2/mR$

$T_2 = 2*10^2*0.0658/0.05*0.287$

$= 912\,K$

$T_1 = 130 + 273 = 403\,K$

$Q = 0.05*1.005*(912-403)$

$= 25.6\,kJ$

$W = mR(T_2 - T_1) = 0.05*0.287*(912-403)$

$= 7.3\,kJ$

or $W = P(V_2 - V_1)$, $V_1 = mRT_1/P_1 = 0.0289\,m^3$

$\therefore W = 2*10^2(0.0658 - 0.0289) = 7.38\,kJ$

$\Delta U = mC_v(T_2 - T_1) = 0.05*(1.005 - 0.287)(912 - 403)$

$= 18.27\,kJ$

$Q = W + \Delta U = 7.38 + 18.27 = 25.65\,kJ$

Ex: A constant pressure adiabatic System contain 0.13 kg of air at 1.3 bar. The System recives paddle work. The temperature of air rises from 29 to 185°C. Find the total work. mechanical work, change in internal energy and enthalpy. Take $R = 0.287$, $\gamma = 1.4$.

Sol: $Q = W + \Delta U + W_p$, $Q = 0$ (adiabatic)

$W = mR(T_2 - T_1) = 0.13 * 0.287 * (185 - 29) = 5.82\ kJ$

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

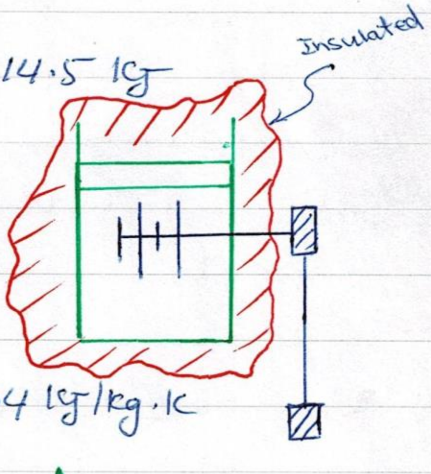
$C_v = \frac{R}{\gamma - 1} = \frac{0.287}{1.4 - 1} = 0.7175$

$\Delta U = 0.13 * 0.7175 * (185 - 29) = 14.5\ kJ$

$Q = W + \Delta U + W_p$

$0 = 5.82 + 14.5 + W_p$

$W_p = -20.32\ kJ$

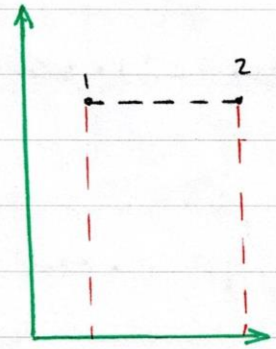


$C_p = \gamma R / \gamma - 1 = \frac{1.4 * 0.287}{1.4 - 1} = 1.004\ kJ/kg.K$

$\Delta H = mC_p(T_2 - T_1)$

$= 0.13 * 1.004 * (185 - 29)$

$= 20.3\ kJ$

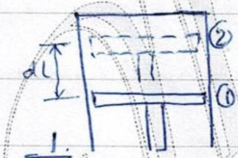


Ex: Air at 1.02 bar and 22°C initialy occuping a cylinder of $0.015\ m^3$, is compressed reversibly and adiabaticaly by a piston to a pressure of 6.8 bar. Calculate the final volume, the final temperature and the work done on the mass of air in the Cylinder.

Sol:

$Q = 0$ (adiabatic)

$\therefore\ W = -\Delta U$



$P_1 V_1^{\gamma} = P_2 V_2^{\gamma}$

$$V_2 = \left(\frac{P_1}{P_2}\right)^{\frac{1}{\gamma}} \cdot V_1 = \left(\frac{1.02}{6.8}\right)^{\frac{1}{1.4}} * 0.015$$

$$= 3.86 * 10^{-3}\ m^3$$

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

$$T_2 = \left(\frac{6.8}{1.02}\right)^{\frac{0.4}{1.4}} * (22+273)$$

$$= 507.25\ K$$

$\Delta U = m C_v (T_2 - T_1)$

$m = P_1 V_1 / RT = 1.02 * 10^2 * 0.015 / 0.287 * 295 = 0.018\ kg$

$\Delta U = 0.01807 * 0.717\ (507.25 - 295) = 2.749\ kJ$

$W = -\Delta U = -2.749\ kJ$

(Sheet No. 3)

Q1: Oxygen (molecular weight 32) expands reversibly in a Cylinder behind a piston at constant pressure of 3bar. The initial volume is $0.01\ m^3$ and finaly is $0.03\ m^3$, the initial temperature is $17^\circ C$. Calculate the work done by the Oxygen and the Heat flow to or from the Cylinder walls during the expansion. Take $C_p = 0.917\ kJ/kg.K$.

Ans. [6 kJ , 21.26 kJ]

Q2: $0.05\ m^3$ of a perfect gas at 6.3 bar undergoes a reversible isothermal process to a pressure of 1.05 bar. Calculate the heat flow to or from the gas.

Ans. [56.4 kJ]

Q3: 1kg of air at 1bar, $15^\circ C$ is compressed reversibly adiabatically to a pressure of 4bar. Calculate the final temperature and the work done on the air.

Ans. [$155^\circ C$, 100.5 kJ/kg]

Q4: 1kg of air at 1.02bar, $20^\circ C$ is compressed reversibly according to a Law $PV^{1.3}$ = constant, to apressure of 5.5bar Calculate the work done <u>on</u> the air and the heat flow during the compression.

Ans. [$133.5\ \frac{kJ}{kg}$, $-33.38\ \frac{kJ}{kg}$]

Q5: Nitrogen (molecular weight 28) expands reversibly in a perfectly thermally insulated Cylinder from 3.5 bar, 200°C to a volume of 0.09 m³. If the initial volume occupied was 0.03 m³, Calculate the work done during the expansion. Assume nitrogen to be aperfect gas and take $C_v = 0.741$ kJ/kg.K   Ans. [9.31 kJ]

Q6: 0.05 kg of Carbon dioxide ($M = 44$), occupying a volume of 0.03 m³ at 1.025 bar, is compressed reversibly until the pressure is 6.15 bar. Calculate the final temperature, the work done on the CO_2, and the heat flow to or from the Cylinder walls.

a. When the process is according to a law $PV^{1.4} = C$.

b. " " " " isothermal.

c. " " " takes place in a perfectly thermally insulated Cylinder. $\gamma = 1.3$

Ans. [270°C, 5.138 kJ, 1.713 kJ, 52.6°C, 5.51 kJ, -5.511 kJ, 219°C, 5.25 kJ, 0 kJ]

Q7: 225 kg/h of air at 40°C enter amixing chamber where it mixes with 540 kg/h of air at 15°C. Calculate the temperature of the air leaving the chamber, assuming steady flow conditions. Assume that the heat loss is negligible.

Ans.[22.4°C]

Q8: Aquantity of gas occupying 0.14 m³ at a pressure of 1.4 MN/m² and temperature of 300°C is expanded adiabatically to 280 kN/m². Cv = 0.74 kJ/kg.K , Cp = 1.04 kJ/kg.K , determine:

a. the mass of gas
b. the temperature of the gas after expansion.
c. the work done during the expansion.

Ans.[a. 1.14 kg b. 87°C c. 180 kJ]

Process	P,V,T	Work(W)	Heat(Q)	Internal Energy (Δu)
Isometric **V=C**	$P_1/P_2=T_1/T_2$	0	$mC_v(T_2-T_1)$	$mC_v(T_2-T_1)$
Isobaric **P=C**	$V_1/V_2=T_1/T_2$	$P(V_2-V_1)$	$mC_p(T_2-T_1)$	$mC_v(T_2-T_1)$
Isothermal **T=C**	$P_1V_1=P_2V_2$	$PV.Ln(V_2/V_1)$	$PV.Ln(V_2/V_1)$	0
Adiabatic **$Pv^{\gamma}=C$**	$(T_1/T_2)=(V_2/V_1)^{(\gamma-1)}$ $=(P_1/P_2)^{(\gamma-1)/\gamma}$	$(P_1V_1-P_2V_2)/\gamma-1$ <u>OR</u> $mR(T_1-T_2))/\gamma-1$	0	$mC_v(T_2-T_1)$
Polytropic **$Pv^{n}=C$**	$(T_1/T_2)=(V_2/V_1)^{(n-1)}$ $=(P_1/P_2)^{(n-1)/n}$	$(P_1V_1-P_2V_2)/n-1$ <u>OR</u> $mR(T_1-T_2))/n-1$	$mC_v(\gamma-n/1-n)$ (T_2-T_1)	$mC_v(T_2-T_1)$

THERMODYNAMICS

3

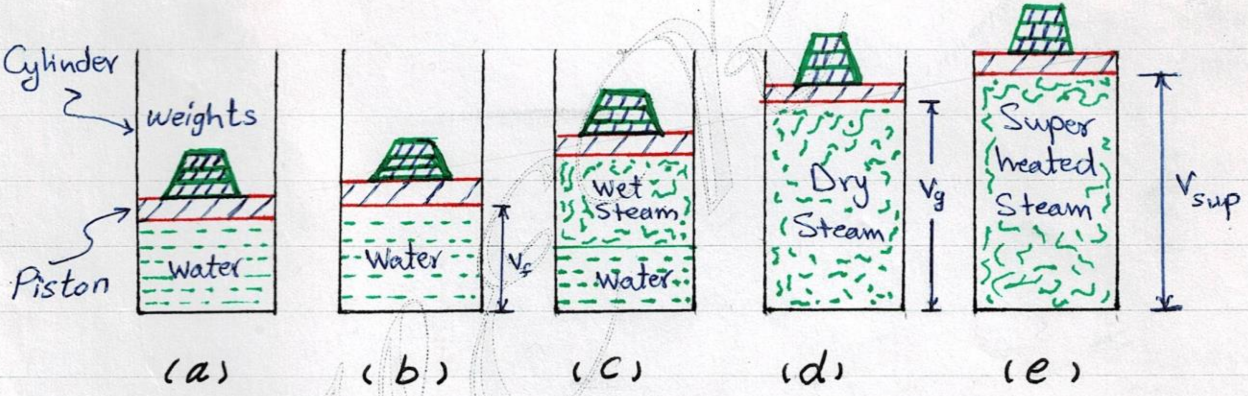
CHAPTER THREE

Steam and Two-Phase System

(Steam and Two-Phase System)

Steam :- is a vapour of water, and is invisible when pure and dry. It is used as the working substance in the operation of steam engines and Steam turbines. Steam does not obey laws of perfect gases, until it is perfectly dry.

Formation of Steam at Constant Pressure from water :-



(a) (b) (c) (d) (e)

Consider 1 kg of water at 0°C contained in the piston-cylinder arrangement as shown in the figure (a).

The piston and weights maintain a constant pressure in the Cylinder. If we heat the water contained in the cylinder, it will be converted into Steam as below:

1. The volume of water will increase slightly with the increase in temperature as shown in fig (b). It will cause the piston to move slightly upwards and hence work is obtained. This increase in volume of water (or work) is generally neglected for all types of calculation.

2. On further heating, temperature reaches boiling point. The boiling point of water, at normal atmospheric pressure of 1.013 bar is 100°C, but it increases with the increase in pressure. When the boiling point is reached, the temperature remains constant and the water evaporates, thus pushing the piston up against the constant pressure. Consequently, the Specific volume of Steam increase as shown in fig (c). At this stage, the steam will have some particles of water in suspension, and is termed as «Wet Steam». This process will continue till the whole water is converted into wet Steam.

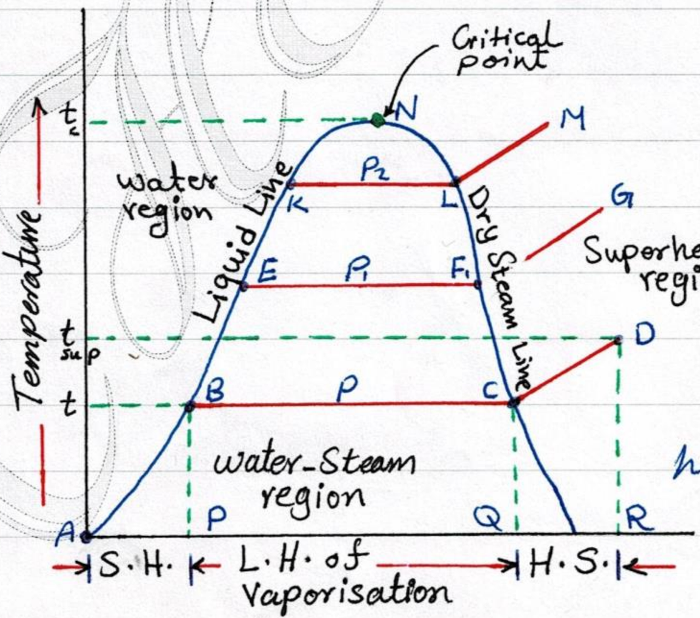
3. On further heating, the particles in suspension will be converted into Steam. The entire Steam, in such a state, is termed as dry Steam or Saturated Steam as shown in fig(d). Practically

the dry Steam behaves like a perfect gas.

4. On further heating, the temperature of the Steam Starts rising. The steam, in such a state is termed as Superheated Steam as shown in fig. (e).

Temperature vs. Total Heat Graph during Steam Formation:

The process of Steam formation may be represented on a graph, whose abscissa represents the total heat and the vertical ordinate represents the temperature. The point (A) represents the initial condition of water at 0°C and pressure p (in bar) as shown in figure below. Line ABCD shows the relation between temperature and heat at a specific pressure of p (in bar).



Temperature-total heat graph during Steam formation

During the formation of the superheated steam, from water at freezing point, the heat is absorbed in the following three stages:

1. The heating of water up to boiling temperature or saturation temperature (t) is shown by AB. The heat absorbed by the water is AP, known as **Sensible heat (S.H.)** or **Liquid heat or total heat of water.**

2. The change of state from Liquid to Steam is shown by BC. The heat absorbed during this stage is PQ, known as **Latent heat (L.H.) of vaporisation.**

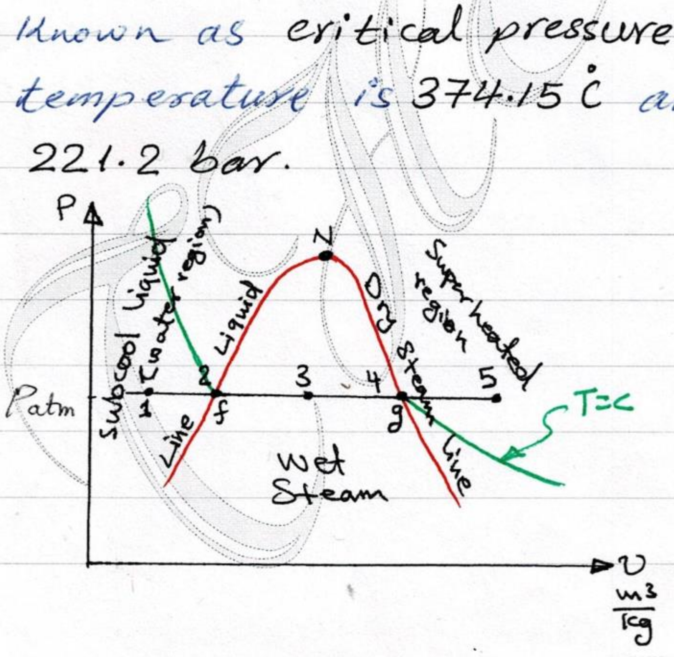
3. The Superheating process is shown by CD. The heat absorbed during this stage is QR, known as **heat of Superheat (H.S.)**. Line AR represents the **total heat** of the **Superheated Steam**.

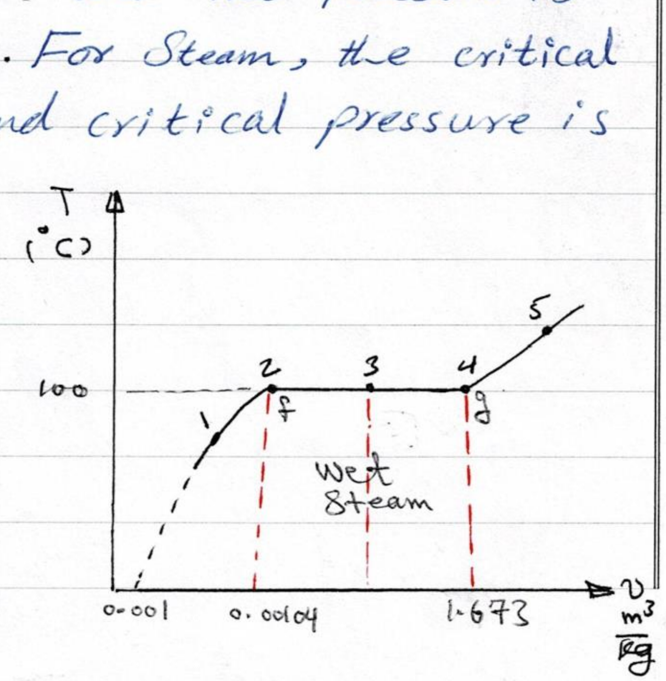
If the pressure is increased (Say P_1 bar), the boiling temperature also increas. The point (E) represents the boiling temperature or saturation temperature at pressure (P_1) and (F) is the point of dry saturated steam. Line (FG) Shows the constant pressure process, in which the steam is superheated.

The line passing through the points A, B, E, K is known as « Saturated liquid line » which forms boundary line between water and steam. Similarly, a line passing through dry steam points L, F, C is known as « dry Saturated Steam line » which forms boundary line between wet and superheated steam.

It may also be noted from the figure, that when the pressure and saturation temperature increases, the latent heat of vaporisation decreases. It becomes zero at point « N » where liquid and dry steam lines meet.

This point « N » is known as the critical point and at this point, the liquid and vapour phases merge. The temperature corresponding to critical point « N » is known as critical temperature and the pressure is known as critical pressure. For steam, the critical temperature is 374.15 °C and critical pressure is 221.2 bar.





Important Terms for Steam :

1. **Wet Steam :** When the steam contains moisture or particles of water in suspension, it is said to be **wet steam**. It means that the evaporation of water is not complete, and the whole of the latent heat has not been absorbed.

2. **Dry Saturated Steam :** When the wet steam is further heated, and it does not contain any suspended particles of water, it is known as **dry saturated steam**. The dry saturated steam has absorbed its full latent heat and behaves practically, in the same way as a perfect gas.

3. **Superheated Steam :** When the dry steam is further heated at a constant pressure, thus raising its temperature, it is said to be **superheated steam**. Since the pressure is constant, therefore the volume of superheated steam increases.

4. **Dryness fraction or quality of wet Steam :**
It is the ratio of the mass of actual dry steam to the mass of same quantity of wet steam, and generally denoted by 'x'.

Mathematically, $x = \frac{m_g}{m_g + m_f} = \frac{m_g}{m}$

m_g = Mass of actual dry steam.
m_f = Mass of water in suspension, and
m = Mass of wet Steam.

5. **Sensible heat of water:-** It is the amount of heat absorbed by 1 kg of water, when heated at a constant pressure, from the freezing point (0°) to the temperature of formation of steam. The sensible heat is also known as liquid heat.

The specific heat of water at constant pressure is usually taken as 4.2 kJ/kg.K.

$$Q_{sensible} = \text{mass} * \text{Specific heat} * \text{Rise in temp.}$$
$$= m\,C_p\,(T_2 - T_1)$$
$$= m\,(h_2 - h_1)$$
$$= H_2 - H_1$$

$h_2, h_1 \equiv$ Enthalpy of fluid (water), denoted by h_f

6. **Latent heat of vaporisation:-** It is the amount of heat absorbed to evaporate 1 kg of water, at its boiling point or saturation temperature without change of temperature. It is denoted by h_{fg} and its value depends upon the pressure.

The heat of vaporisation of water or latent heat of Steam is 2257 kJ/kg at atmospheric pressure.

It has been experimentally found that the value of h_{fg} decreases as the pressure increases and it is **zero** at critical pressure.

If the Steam is wet with a dryness fraction x, then the heat absorbed by it during evaporation is $x\, h_{fg}$.

7. Enthalpy or total heat of Steam:

It is amount of heat absorbed by water from freezing point to saturation temperature plus the heat absorbed during evaporation.

∴ Enthalpy or total heat of Steam
= Sensible heat + Latent heat

It is denoted by h_g and its value for the dry Saturated Steam may be read directly from the Steam tables. The expressions for the enthalpy of wet Steam, dry Steam and superheated Steam are as follows:

i. Wet Steam: the enthalpy of wet Steam is given by:

$$\boxed{h = h_f + x\, h_{fg}}$$

$h_f = u_f + P v_f$

ii. Dry Steam: We know that in case of dry Steam, $x=1$

$$\therefore \quad h = h_f + 1 * h_{fg}$$
$$= h_f + (h_g - h_f)$$
$$\boxed{h = h_g}$$

iii. Superheated Steam: If we further add heat to the dry Steam, its temperature increases while pressure remaining constant. This increase in temperature shows the superheat stage of the Steam. Thus, the total heat required for the Steam to be Superheated is:

$$h_{sup} = \text{Total heat for dry Steam} + \text{Heat for Superheated Steam}$$

$$= h_f + h_{fg} + C_p(t_{sup} - t) = h_g + C_p(t_{sup} - t)$$

Where:

C_p = Specific heat at constant pressure for Superheated Steam.

t_{sup} = Temperature of the Superheated Steam.

t = Saturation temperature at the given constant pressure.

Notes: 1. The difference $(t_{sup} - t)$ is known as degree of Superheated

2. The value of C_p for Steam lies between 1.67 kJ/kg.K to 2.5 kJ/kg.K.

8. **Specific volume of Steam:** It is the volume occupied by the Steam per unit mass at a given temperature and pressure, and is expressed in m^3/kg. It is the reciprocal of density of Steam in kg/m^3.

The value of specific volume decreases with the increase in pressure.

The expressions for the volumes occupied by Steam are as follows:

i. **Wet steam:** Consider 1kg of wet Steam of dryness fraction x. When know that this Steam will have x kg of dry Steam and $(1-x)$ kg of water. Let v_f be the volume of 1kg of water, then

Volume of one kg of wet Steam $= x\,v_g + (1-x)\,v_f$

Since v_f is very small as compared to v_g, therefore the expression $(1-x)\,v_f$ may be neglected

$\therefore$ Volume of one kg of wet steam $= x \cdot v_g \quad m^3$

or Specific volume of wet Steam, $\Rightarrow \quad v = x \cdot v_g \quad m^3/kg$

ii. **Dry Steam:** We know that in case of dry steam, the mass of water in suspension is zero and dryness fraction is unity. Therefore Specific volume of dry Steam $= v_g \ m^3/kg$

iii. **Superheated Steam:** We have already discussed that when the dry saturated Steam is further heated under a constant pressure, there is an increase in volume with the rise in temperature. The superheated Steam behaves more or Less Like a perfect gas. Therefore, according to Charles' law.

$$\frac{v_{sup}}{T_{sup}} = \frac{v_g}{T} \quad \text{or} \quad \boxed{v_{sup} = \frac{v_g * T_{sup}}{T}}$$

Where:

v_{sup} = Specific volume of Superheated Steam.

v_g = Specific volume of dry Steam at the pressure of Steam formation.

$T_{sup.}$ = Absolute temperature of Superheated Steam

T = " Saturation temperature at the pressure of Steam formation.

Ex:- Calculate the enthalpy of 1 kg of Steam at a pressure of 8 bar and dryness fraction of 0.8. How much heat would be required to raise 2 kg of this Steam from water at 20°C?

Sol:- from Steam tables, at $P = 8\,bar$

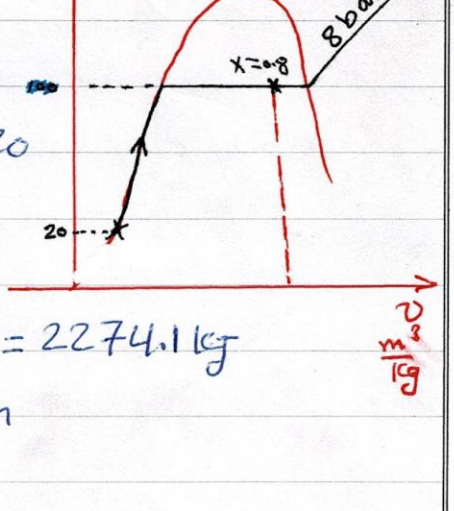
$$h_f = 720.9\ kJ/kg \quad , \quad h_{fg} = 2046.5\ kJ/kg$$

$$\therefore\ h = h_f + x\,h_{fg}$$

$$= 720.9 + 0.8 * 2046.5 = 2358.1\ kJ$$

Heat required to raise 2 kg of this Steam from water at 20°C.

We have calculated above the enthalpy or total heat required to raise 1 kg of Steam from water at 0°C. Since the water, in this case, is already at 20°C, therefore



Heat already in water $= m\,C_p\,T$

$$= 1 * 4.2 * 20$$

$$= 84\ kJ$$

Heat required per 1 kg of Steam

$$= 2358.1 - 84 = 2274.1\ kJ$$

and Heat required for 2 kg of Steam

$$= 2 * 2274.1$$

$$= 4548.2\ kJ$$

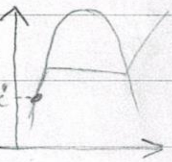
Ex:- Determine the quantity of heat required to produce 1kg of Steam at a pressure of 6 bar at a temperature of 25°C, under the following conditions:

1. When the steam is wet having a dryness fraction 0.9
2. When the steam is dry saturated.
3. When it is superheated at a constant pressure at 250°C assuming the mean specific heat of superheated steam to be 2.3 kJ/kg.K.

Sol:- From Steam tables, at $p = 6$ bar

$h_f = 670.4$ kJ/kg.K , $h_{fg} = 2085$ kJ/kg.K

$t = 158.8°C$



1. When the Steam is wet:

$h = h_f + x h_{fg} = 670.4 + 0.9 * 2085$

$= 2546.9$ kJ (for 1 kg)

Since the water is at a temperature of 25°C, therefore enthalpy or Heat already in water $= m\,C_p\,T$

$= 1 * 4.2 * 25 = 105$ kJ

∴ Heat actually required $= 2546.9 - 105$

$= 2441.9$ kJ

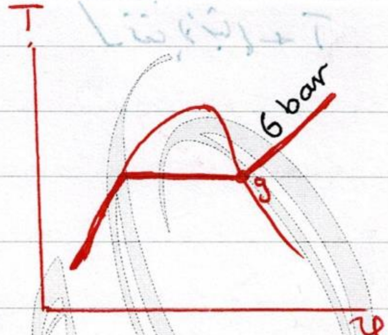
2. When the Steam is dry saturated: $h = h_g$, $x = 1$

enthalpy or total heat of 1kg of dry saturated Steam, $h = h_f + 1 * h_{fg}$

$\Rightarrow h_g = 670.4 + 2085 = 2755.4$ kJ

Heat actually required $= 2755.4 - 105$

$= 2650.4$ kJ



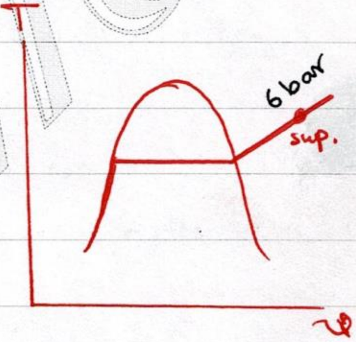
3. When the Steam is superheated.

enthalpy or total heat of 1kg of Superheated Steam,

$$h_{sup} = h_g + C_p(t_{sup} - t)$$

$$= 2755.4 + 2.3(250 - 158.8)$$

$$= 2965.16 \text{ kJ}$$



Heat actually required $= 2965.16 - 105$

$= 2860.16$ kJ

Ex: Determine the condition of Steam in the following cases:

1. At apressure of 10 bar and temperature 200°C.
2. " " " " " " volume $0.175 \text{ m}^3/\text{kg}$.

Sol:

1. from Steam tables, at $P = 10$ bar

$v_g = 0.194 \text{ m}^3/\text{kg}$, $h_f = 762.6$ kJ/kg

$t_{sat} = 179.9°C \equiv t$(saturation)

$\therefore$ $t > t_{sat} \Rightarrow$ the Steam is Superheated

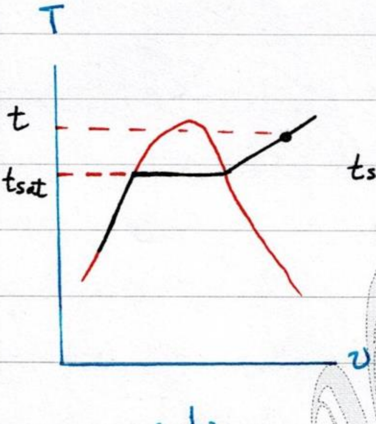
$\therefore$ the degree of Superheated $= t - t_{sat}$

$= 200 - 179.9 = 20.1°C$

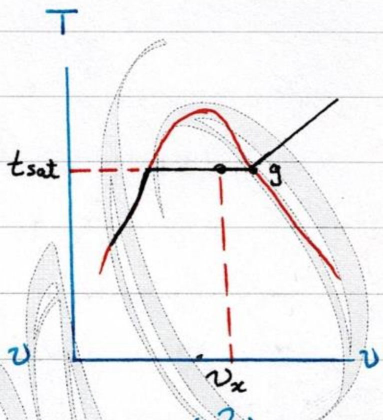
2. $\because v < v_g$

$\therefore$ the Steam is wet

$$x = \frac{v}{v_g} = \frac{0.175}{0.194} = 0.902$$



(1)



(2)

Ex: Steam enters on engine at a pressure of 12 bar with a 67°C of Superheated. It is exhausted at a pressure of 0.15 bar and 0.95 dry. Find the drop in enthalpy of the Steam. Take $Cp_{,sup} = 2$ kJ/kg.K

Sol: from Steam tables, at 12 bar

$h_f = 798$ kJ/kg. , $h_{fg} = 1986$ kJ/kg.

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

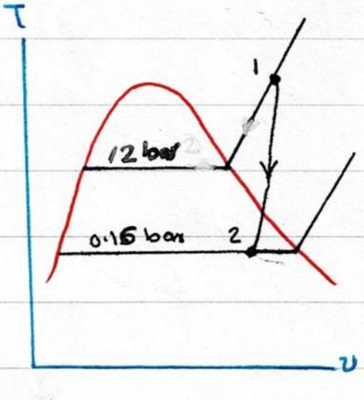
$= 798 + 1986 + 2 * 67 = 2918$ kJ/kg

from Steam tables at 0.15 bar

$h_f = 232$ kJ/kg , $h_{fg} = 2369$ kJ/kg

$h = h_f + x\,h_{fg} = 232 + 0.95 * 2369$

$= 2482.55$ kJ/kg



Drop in enthalpy of the steam

$= h_{sup} - h = 2918 - 2482.55$

$= 435.45$ kJ/kg

* Interpolation :-

Ex:- When $P = 133$ bar Compute (t_{sat}, h_f, h_g, v_g) u_f

Sol:- from Steam tables.

P [bar]	t_{sat} [°C]	v_g [m³/kg]	u_f [kJ/kg]	h_f [kJ/kg]	h_g [kJ/kg]
130	330.8	0.01278	1511	1531	2662
133	t_s ?	v_g ?	u_f ?	h_f ?	h_g ?
135	333.8	0.01211	1530	1551	2650

$$\frac{133-130}{135-130} = \frac{t_s - 330.8}{333.8-330.8} = \frac{v_g - 0.01278}{0.01211-0.01278} = \frac{u_f - 1511}{1530-1511}$$

$$= \frac{h_f - 1531}{1551-1531} = \frac{h_g - 2662}{2650-2662}$$

$$\therefore\ t_s = 330.8 + \frac{133-130}{135-130}(333.8-330.8) = 332.6\ °C$$

$$v_g = 0.01278 + \frac{3}{5}(0.01211 - 0.01278) = 0.017398\ \frac{m^3}{kg}$$

$$u_f = 1511 + \frac{3}{5}(1530 - 1511) = 1522.4\ kJ/kg$$

$$h_f = \quad + \frac{-}{-}(\quad - \quad) = 1543\ kJ/kg$$

$$h_g = \quad + \frac{-}{-}(\quad - \quad) = 2654.8\ \frac{kJ}{kg}$$

$$h_{fg} = \quad + \frac{-}{-}(\quad - \quad) = 1111.8\ \frac{kJ}{kg}$$

Ex: If $P = 12$ bar & $t = 255°C$, find (h) ?

Sol: at $P = 12$ bar from Steam tables
$t_{sat} = 188°C$ $\therefore t > t_{sat} \Rightarrow$
the Steam is Superheated

from Superheated Steam table:

	250°C	(255°C)	300°C
10 bar	2944	h_1	3052
(12)	h_1 ?	h_{sup}	h_2 ?
15 bar	2925	h_2	3039

$$h_1 = 2944 + \frac{12-10}{15-10}(2925-2944) = 2936.4 \text{ kJ/kg}$$

$$h_2 = 3052 + \frac{12-10}{15-10}(3039-3052) = 3046.8 \text{ kJ/kg}$$

$$h_{sup} = h_1 + \frac{255-250}{300-250}(h_2 - h_1)$$

$$= 2936.4 + \frac{255-250}{300-250}(3046.8-2936.4)$$

$$= 2947.44 \text{ kJ/kg}$$

It is called double Interpolation.

H.W: find for the same case (u, v)

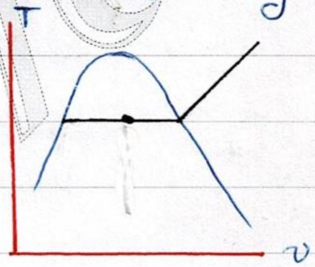
Ex:- Find the missing properties of water and given the phase of it: a. $T = 120°C$, $v = 0.5\ m^3/kg$, u, P, x?

b. $T = 100°C$, $P = 10\ Mpa$, u, x, v?

Sol:- a. Saturation Condition of H_2O at 120°C from Steam tables , $v_g = 0.8908$

$v_f = 0.00108\ m^3/kg$

Since $v < v_g \Rightarrow$ wet Steam



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

$0.5 = 0.00108 + x(0.8908 - 0.00108)$

$\therefore x = 0.56$, $P = 198.5\ kpa = 1.985\ bar$

$u = u_f + x(u_g - u_f)$, By Interpolation

$= 503.48 + 0.56(2529.24 - 503.48)$

$u = 1639.7\ kJ/kg$

b. $T = 100°C$ $P = 10\ Mpa$

from Steam tables at $P = 10\ Mpa$

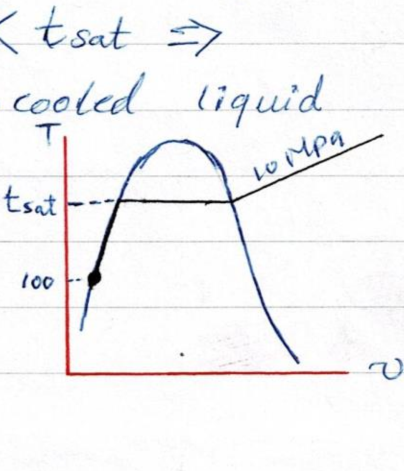
$t_{sat.} = 311.06$ $\therefore t < t_{sat} \Rightarrow$

Subcooled liquid

$\therefore x = 0$

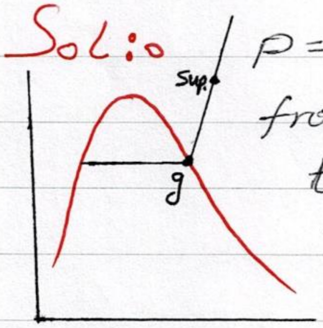
$u = u_f = 418.91\ kJ/kg$

$v = v_f = 0.00104\ m^3/kg$



Ex: Determine the volume of 1 kg of superheated Steam at a pressure of 20 bar and a temperature of 300 °C. (using Charles's law)

Sol: $P = 20\,bar$, $T_{sup} = 300°C = 300 + 273 = 573\,K$



from Steam tables, at $P = 20\,bar$

$t_{sat} = 212.4\,°C$, $v_g = 0.09957\ m^3/kg$

$T_{sat} = 212.4 + 273 = 485.4\,K$

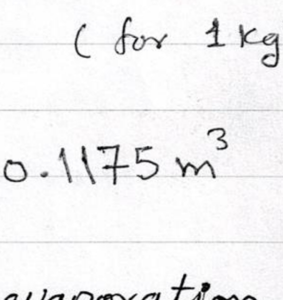
from Charles's law $\dfrac{v_g}{T_{sat}} = \dfrac{v_{sup}}{T_{sup}}$ (for 1 kg)

$\therefore v_{sup} = \dfrac{v_g}{T} * T_{sup} = \dfrac{0.09957}{485.4} * 573 = 0.1175\ m^3$

Ex: Find the external work done during evaporation per kg of Steam at a pressure of 15 bar when the Steam is (a) 90% dry (or 10% wet)
(b) dry Saturated.

Sol: at $P = 15\ bar$

from Steam tables, $v_g = 0.1317\ m^3/kg$



a. $\because P = C \Rightarrow W = P\,(V_2 - V_1)$

$= P\,(V_g - V_f)$

$\because$ (v_f) very small, as compared with v_g therefore neglecting the value of v_f

∴ $W = P * v_g$, when the steam is not completely dry, and has dryness fraction of x., the the work:

$$W = P * x v_g$$
$$= 15 * 10^2 * 0.9 * 0.1317$$
$$= 177.8 \text{ kJ/kg}$$

b. Work done when the steam is dry saturation

$$W = P * v_g$$
$$= 15 * 10^2 * 0.1317 = 197.5 \text{ kJ/kg}$$

Ex: A vessel having volume of 0.4 m^3 contains 2 kg of a liquid water and water vapour mixture in equilibrium of 600 kpa. Calculate the volume and mass of liquid, the volume and mass of vapour.

Sol:

$$v = V/m = 0.4/2 = 0.2 \text{ m}^3/\text{kg}$$

at 600 kpa, from steam tables.

$v_g = 0.3157 \text{ m}^3/\text{kg}$ since $v < v_g$

∴ wet steam

$$v = v_f + x v_{fg}$$

$0.2 = 0.001014 + x * 0.3146 \Rightarrow x = 0.6322$

$v_L = v_f$
$m_L = m_f$

$$x = \frac{m_{vapour}}{m_{total}} \Rightarrow m_v = x \cdot m_t$$
$$= 0.6322 * 2$$
$$= 1.2644 \text{ kg}$$

$V = V_{Liq} + V_{vap}$

$mv = m_{Liq} \cdot v_f + m_v v_g$

$$m_f = m_t - m_v$$
$$= 2 - 1.2644$$

$V_{Liq} = m_{Liq} * v_f$
$V_{vap} = m_v * v_g$

$$= 0.7356 \text{ kg} = m_{Liquid} \text{ or } m_L$$

$$v_v = \frac{V_v}{m_v} \Rightarrow$$

$v_g = v_v$

$$V_v = m_v * v_v = 1.2644 * 0.3157$$
$$= 0.3992 \text{ m}^3$$

$$V_L = V_t - V_v = 0.4 - 0.3992 = 8.2 * 10^{-4} \text{ m}^3$$

Ex:- A 200 l volume tank contain R-12 at 25°C has 10% liquid and 90% vapour by volume. Find the dryness fraction of R-12.

Sol: at 25°C, from R-12 tables.

$$v_L = 0.000763 \frac{m^3}{kg} \quad , v_g = 0.02685 \frac{m^3}{kg}$$

$$V = \frac{200}{1000} = 0.2 \text{ m}^3$$

$$V_L = 0.1 * V = 0.1 * 0.2 = 0.02 \text{ m}^3$$
$$V_g = 0.9 * V = 0.9 * 0.2 = 0.18 \text{ m}^3$$

$$v_L = \frac{V_L}{m_L} \Rightarrow m_L = \frac{V_L}{v_L} = \frac{0.02}{0.000763} = 26.2 \text{ kg}$$

$$m_g = \frac{V_g}{v_g} = \frac{0.18}{0.02685} = 6.7 \text{ kg}$$

$m_t = m_L + m_g = 26.2 + 6.7 = 32.9$ kg

$$x = \frac{m_g}{m_t} = \frac{6.7}{32.9} = 0.203$$

Ex: A vessel contains 0.1 kg Saturated Liquid and Vapour water at 100 kpa, quality of 0.25. Find the total volume of vessel and the persentage of Liquid and vapour by volume.

Sol: from Steam tables, at 100 kpa

$v_f = 0.001043 \frac{m^3}{kg}$ $\quad v_g = 1.694 \frac{m^3}{kg}$

$v = v_f + x\, v_{fg}$

$= 0.001043 + 0.25(1.694 - 0.001043)$

$= 0.4242\ m^3/kg$

$v = V/m \Rightarrow V = v \cdot m = 0.4242 * 0.1$

$= 0.04242\ m^3$

$V_L = v_L * m_L$, $V_g = v_g * m_g$

$m_g = x \cdot m_t = 0.25 * 0.1 = 0.025$ kg

$m_L = m_t - m_g = 0.1 - 0.025 = 0.075$ kg

∴ $V_L = 0.001043 * 0.075 = 7.8225 * 10^{-5}$ m³

$V_g = 1.644 * 0.025 = 0.0423$ m³

$V_t = V_L + V_g = 7.8225 * 10^{-5} + 0.0423 = 0.0423782$

$\% \; V_L = \frac{V_L}{V_t} * 100 = \frac{7.8225 * 10^{-5}}{0.042378} * 100 = 0.1845 \%$

$\% \; V_g = \frac{V_g}{V_t} * 100 = \frac{0.0423}{0.0423782} * 100 = 99.815 \%$

Ex: Find the dryness fraction, the Specific volume and internal energy of Steam at 7 bar and enthalpy (2600 kJ/kg).

Sol: at 7 bar, from Steam tables,

$h_g = 2764$ kJ/kg $\quad h_f = 697$ kJ/kg

Since $h_f < h_{steam} < h_g$

$697 < 2600 < 2764 \Rightarrow$ wet Steam

∴ $h_x = 2600 = h_f + x h_{fg}$

$= 697 + x(2764 - 697) \Rightarrow x = 0.921$

$v_x = x v_g$, $v_g = 0.2728$ m³/kg

$v_x = 0.921 * 0.2728$

$= 0.2515$ m³/kg

$u_x = u_f + x(u_g - u_f)$,

$= 696 + 0.921(2573 - 696)$

$= 2420$ kJ/kg

(Sheet No. 4)

Q1:- Find the missing properties among (P, T, v, u, h) together with x if applicable and give the phase of Substance:

a.	H_2O	$T = 120\,°C$	$v = 0.5\ m^3/kg$
b.	H_2O	$P = 100$ kpa	$v = 0.18\ m^3/kg$
c.	H_2O	$T = 340\,°C$	$h = 3150$ kJ/kg
d.	N_2	$P = 750$ kpa	$v = 0.2\ m^3/kg$
e.	R_{12}	$P = 600$ kpa	$h = 230$ kJ/kg
f.	$R22$	$T = 10\,°C$	$u = 200$ kJ/kg
g.	$R134a$	$T = 40\,°C$	$u = 407$ kJ/kg
h.	NH_3	$T = 20\,°C$	$v = 0.1\ m^3/kg$

Q2:- A water Storage tank contains Liquid and vapour in equilibruim at 110°C. The distance from bottom of the tank to the Liquid level is 8 m. What is the absolute pressure at the bottom of the tank. [218 kpa]

Q3:- Saturated water vapour at 60°C has it's pressure decrease to increase the volume by 10% keeping the temperature constant. To what pressure should be expands. [18.9 kpa]

Q4:- 5kg of Steam at pressure of 4.9 bar is produced from water at 20°c. Determine the amount of heat supplied if the Steam is 0.9 dry.

[12263 kJ]

Q5:-

1 kg of water at 47.8°c is heated under constant pressure of 13.7 bar until it is converted into Steam with 111 of Superheated. Determine the quantity of heat Supplied during Superheating and the total heat.

[268 kJ , 2852 kJ]

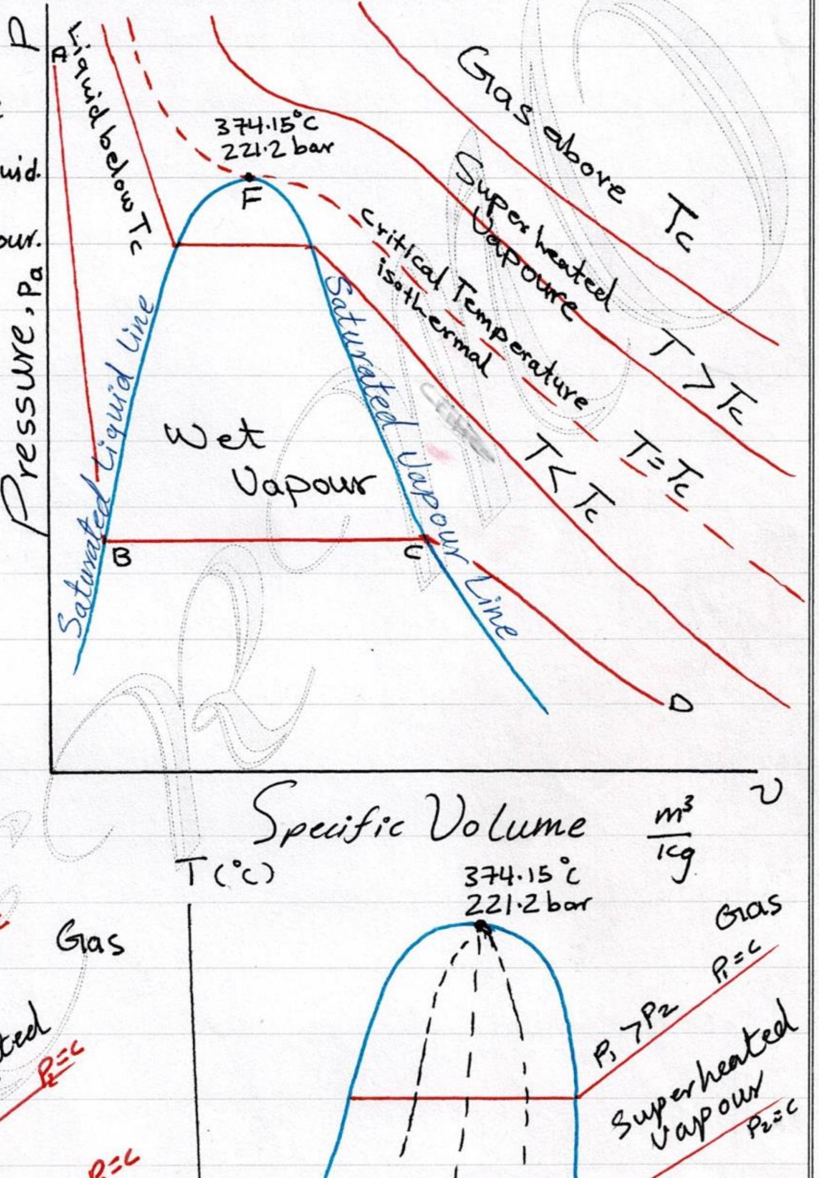
Q6:- A tank of $2 m^3$ volume contains saturated ammonia at a temperature of 40°c, the tank contains 50% liquid and 50% vapour by volume. Find the Specific volume, enthalpy and internal energy of the mixture.

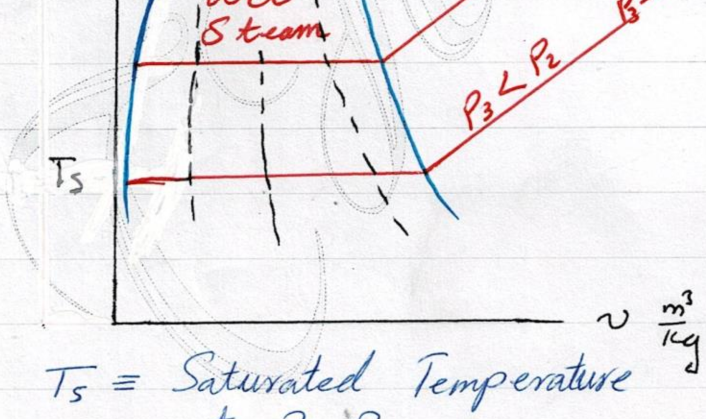
$[3.369 * 10^{-3} \frac{m^3}{kg}$, 232908 kJ , 229816 kJ]

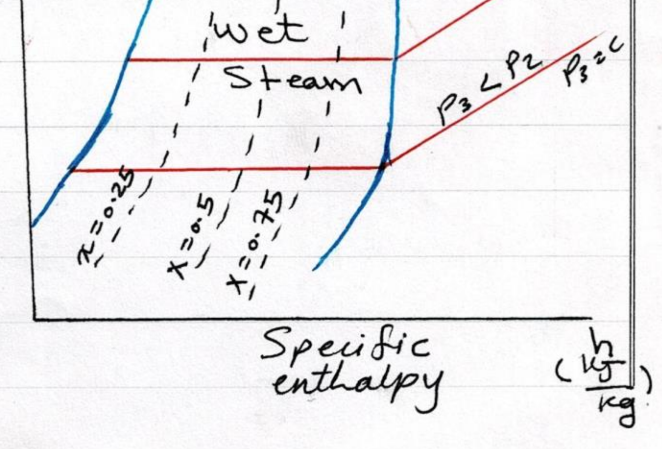
The Pressure-Volume Diagram:-

ABCD ≡ Isothermal Line
point B ≡ Saturated liquid.
" C ≡ " Vapour.
" F ≡ Critical point

Note:
Area under curve (or line) represent the magnitud of work.







T_s ≡ Saturated Temperature at $P = P_3$

* Reversible and Irreversible Processes :

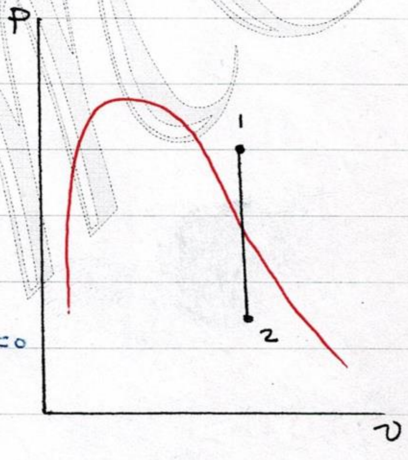
1. Closed System (Reversible)

a. Constant volume process (Isometric process)

From non-flow Energy Equation :

$$Q = W + \Delta U$$

per unit mass



$$q = w + \Delta u \quad , \quad v = c \Rightarrow W = 0$$

$$\therefore q = u_2 - u_1 \quad , \quad h = u + Pv$$

$$\therefore \boxed{q = (h_2 - h_1) - v(P_2 - P_1)}$$ heat added or rejected

Ex : A vessel having a volume of $5 m^3$ contains $0.05 m^3$ of Saturated Liquid water and $4.95 m^3$ of Saturated water vapour at 0.1 Mpa. Heat is transfered until the vessel is fitted with saturated vapour. Determine the heat transfer for this Process.

Sol : condition (1) wet Steam

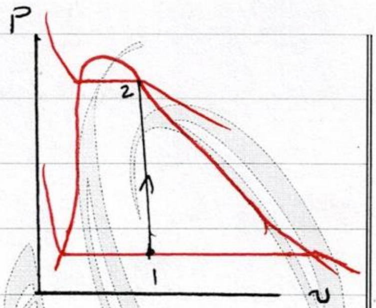
at 0.1 Mpa $\quad v_f = 1.0432 * 10^{-3} \ m^3/kg$

$v_g = 1.694 \ m^3/kg$

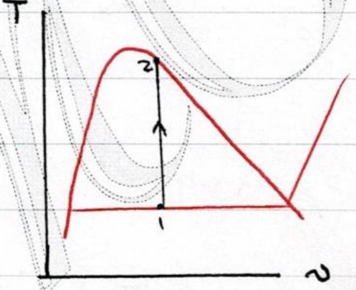
$m_l = V_l / v_f = 0.05 / 1.043 \times 10^{-3} = 47.93$ kg

$m_g = V_g / v_g = 4.95 / 1.694 = 2.92$ kg

$m_t = m_l + m_g = 47.93 + 2.92 = 50.85$ kg



$x = m_g / m_t = 2.92 / 50.85 = 0.0574$



$Q = W + \Delta U \quad , \quad V = c \quad \therefore W = 0$

$= U_2 - U_1 = m(u_2 - u_1)$

$u_1 = u_f + x\, u_{fg} = 417.36 + 0.0574 * 2088.7 = 521.8 \ \frac{kJ}{kg}$

$v_1 = \frac{V}{m} = \frac{5}{50.85} = 0.09833 \ m^3/kg \quad , \quad v_1 = v_2 = 0.09833 = v_g$

from Steam tables:

By Interpolation, $u_2 = 2600.465 \ \frac{kJ}{kg}$

v_g	u_g
0.09963	2600.26
(0.09833)	u_2
0.08875	2601.98

$\therefore Q = 50.85(2600.465 - 521.8)$

$= 105700.1$ kJ

When (C_v) is given:

$$\boxed{Q = m C_v (T_2 - T_1)}$$

for Sensible Heat

(for gas)

Ex:- A closed vessel of $0.6\ m^3$ capacity contains dry Saturated Steam at $360\ kN/m^2$. The vessel is cooled until the pressure is reduced to $200\ kN/m^2$. Calculate:

a. the mass of Steam in the vessel,

b. the final dryness of the Steam,

c. the amount of heat transferred during the cooling process.

Sol:-

a. At $360\ kN/m^2$, $v_g = 0.510\ m^3/kg$

$\therefore$ mass of Steam in vessel $= \frac{0.6}{0.51} = 1.18\ kg$

b. $V = c$, $v_2 = v_g = 0.510\ m^3/kg$, $v_f \simeq 0$

$v_2 = x\, v_g$, at $P = 200\ kN/m^2$ $v_g = 0.885\ m^3/kg$

$0.510 = x * 0.885 \Rightarrow x = 0.510/0.885 = 0.576$

c. $Q = m(u_2 - u_1)$, $V = c \Rightarrow W = 0$

$u_1 = u_g$ at $p = 360\ kN/m^2$

from Steam tables, $u_g = 2549.87$ (By Interpolation)

$u_2 = u_f + x\, u_{fg}$

from Steam tables, $u_f = 504.47\ kJ/kg$, $u_{fg} = 2025.02\ \frac{kJ}{kg}$

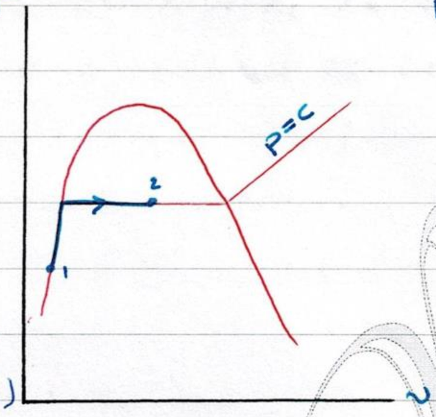
$u_2 = 504.47 + 0.576 * 2025.02$

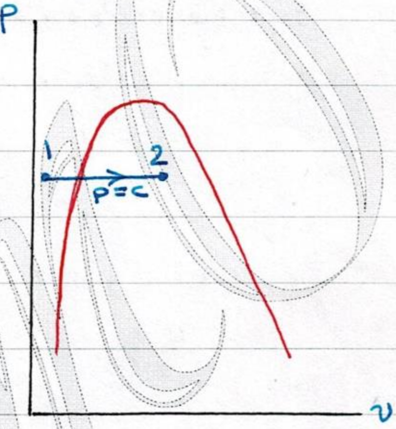
$= 1670.88\ kJ/kg$

$\therefore Q = 1.18 * (1670.88 - 2549.87)$

$= -1037.2\ kJ$

b. Constant Pressure Process (Isobaric Process)





from NFEE

$Q = W + \Delta U$

$W = \int p\,dV$

$= P(V_2 - V_1)$

$Q = (P_2V_2 - P_1V_1) + (U_2 - U_1)$

$= H_2 - H_1 \Rightarrow$

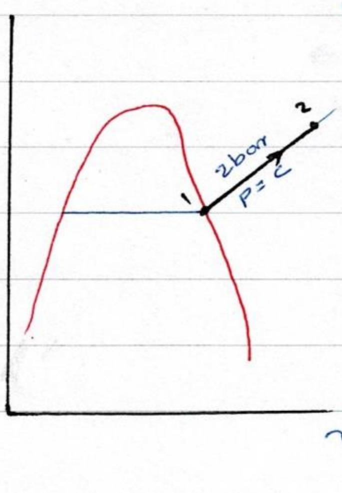
$$\boxed{Q = m(h_2 - h_1)}$$

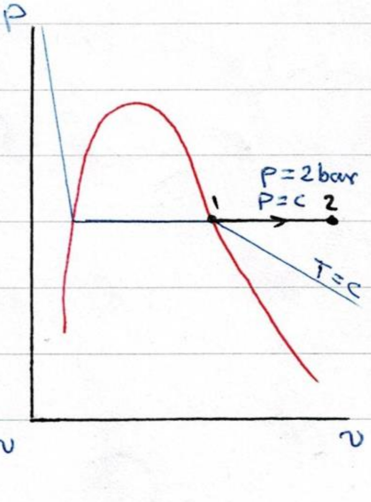
When C_p is given (for Sensible Heat) (for gas)

$Q = m C_p (T_2 - T_1)$

Ex: 0.05 kg of a dry Saturated Steam is heated at a constant pressure of 2 bar until the volume occupied is 0.0658 m³. Calculate the heat supplied and the work done.

Sol:





$h_1 = h_g$ at 2 bar

$= 2707$ kJ/kg

$v_2 = \frac{V}{m} = \frac{0.0658}{0.05} = 1.316 \frac{m^3}{kg}$

the Steam is Superheated, from Steam tables at 2bar & 1.316 $\frac{m^3}{kg}$ ⇒ $h_2 = 3072$ kJ/kg

$Q = H_2 - H_1 = m(h_2 - h_1) = 0.05(3072 - 2707)$

∴ Heat Supplied = 18.25 kJ/kg

$W = p(v_2 - v_1)$, $v_1 = v_g$ at 2bar $= 0.8856$ m³/kg

$v_2 = 1.316$ m³/kg

$w = 2*10^5(1.316 - 0.8856)$

$W = m \cdot w = 0.05 * 2*10^5 * 0.4304$

$= 4304 J = 4.304 kJ$

Ex: Steam at 4 MN/m² and dryness fraction 0.95 receives heat at constant pressure until its temperature becomes 350°C. Determine the heat recived by the steam per unit mass.

Sol: At $P = 4 Mpa$ and $x = 0.95$ dry , $h_1 = h_f + x h_{fg}$

$h_1 = 1087.4 + 0.95 * 1712.9 = 2714.7$ kJ/kg

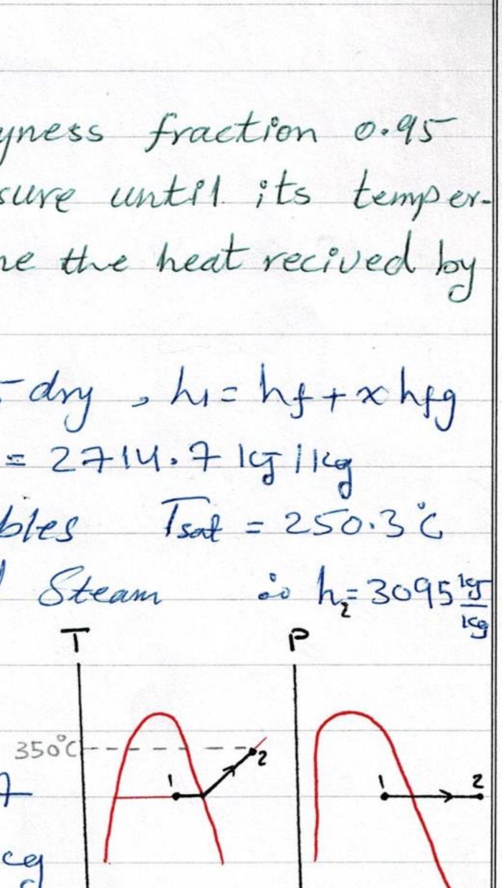
At $P = 4 Mpa$, from Steam tables $T_{sat} = 250.3°C$

∴ $T > T_{sat}$ ⇒ Superheated Steam ∴ $h_2 = 3095 \frac{kJ}{kg}$

Heat received $= h_2 - h_1$

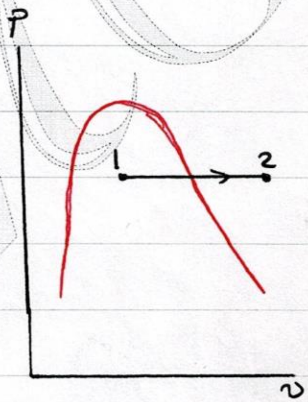
$= 3095 - 2714.7$

$= 380.3$ kJ/kg



Ex:- A cylinder fitted with a piston has a volume of $0.1\ m^3$ and contains 0.5 kg of Steam at 0.4 Mpa. Heat is transfer to the steam until the temperature is 300°c. While the pressure remains constant. Determine the heat transfer and work done.

Sol:-



$$Q = W + \Delta U = m(h_2 - h_1)$$

$$v_1 = V/m = 0.1/0.5 = 0.2\ m^3/kg$$

at 0.4 Mpa $v_g = 0.4625\ m^3/kg$

since $v < v_g$ ∴ wet Steam

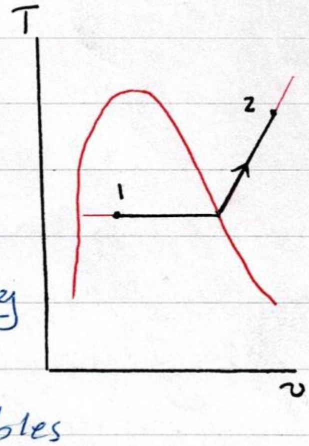
$$v = v_f + x\, v_{fg}$$

$$0.2 = 1.0836 * 10^{-3} + x(0.4625 - 1.0836 * 10^{-3})$$

$$x = 0.431$$

$$\therefore u_1 = u_f + x\, u_{fg} = 604.31 + 0.431 * 1949.3$$
$$= 1444.6\ kJ/kg$$

$$h_1 = 604.74 + 0.431 * 2133.8 = 1524.6\ kJ/kg$$



point (2) $P = 0.4\ Mpa$, from Steam tables

$t_s = 143.63$°c, since $T_2 > T_{sat} \Rightarrow$ Superheated

from Superheated Steam tables, $u_2 = 2804.8\ kJ/kg$

$h_2 = 3066.8\ kJ/kg$

$$Q = 0.5(3066.8 - 1524.6) = 771.1\ kJ$$

$$W = Q - \Delta U = 771.1 - 0.5(2804.8 - 1444.6)$$
$$= 91\ kJ$$

c. Constant Temperature process (Isothermal Process)

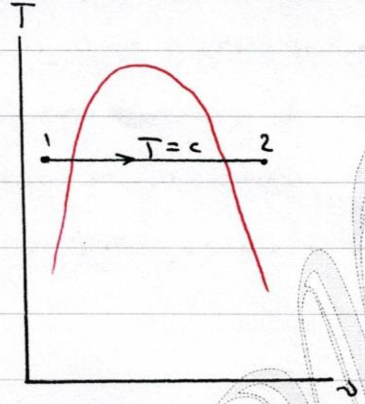
$Q = W + \Delta U$

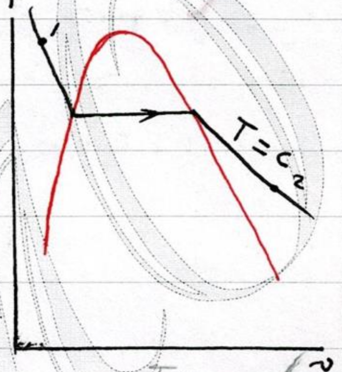
$W \neq PV \ln \frac{U_2}{U_1}$

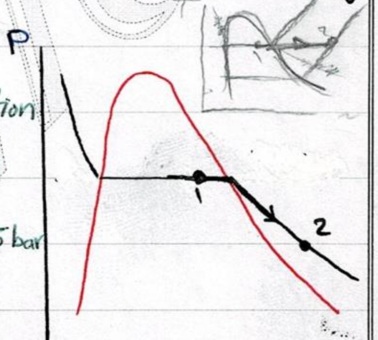
$\Delta U = U_2 - U_1$

$Q = H_2 - H_1$

$W = Q - \Delta U$







Ex: Steam at 7 bar and dryness fraction 0.9 expands in a Cylinder behined a piston isothermally and reversibly to a pressure of 1.5 bar Calculate the change of internal energy and the change of enthalpy per kg of Steam. The heat supplied during the process is found to be 400 $\frac{kJ}{kg}$ Calculate the work done per kg of Steam.

SoL: $u_1 = u_f + x u_{fg}$ (at 7 bar), $T_{sat} = 165°C$

$= 2385.3$ kJ/kg

from Steam tables (Superheated) at 1.5 bar & 165°C

$u_2 = 2602.8$ kJ/kg , $h_2 = 2803$ kJ/kg

$\therefore \Delta u = u_2 - u_1 = 2602.8 - 2385.3 = 217.5$ kJ/kg

$h_1 = h_f + x h_{fg} = 697 + 0.9 * 2067 = 2557.3$ kJ/kg

$\therefore \Delta h = h_2 - h_1 = 2803 - 2557.3 = 245.7$ kJ/kg

$Q = \Delta U + W \Rightarrow \therefore W = q - \Delta u$

$= 400 - 217.5 = 182.5$ kJ/kg

d. The hyperbolic Process $PV=C$

$$P_1V_1 = P_2V_2$$

Work done $= W = PV \ln \frac{v_2}{v_1}$ for any mass

$$W = Pv \ln \frac{v_2}{v_1} \quad \text{for unit mass}$$

the NFEE.

$$\begin{aligned} q &= \Delta u + W \\ &= (u_2-u_1) + Pv \ln \frac{v_2}{v_1} \\ &= (h_2-P_2v_2)-(h_1-P_1v_1) + Pv \ln \frac{v_2}{v_1} \qquad , P_1v_1=P_2v_2 \\ &= (h_2-h_1) + Pv \ln \frac{v_2}{v_1} \end{aligned}$$

$$\therefore Q = (H_2-H_1) + PV \ln \frac{v_2}{v_1}$$

Ex:- A quantity of dry saturated steam occupies 0.2634 m³ at 1.5 MN/m². Determine the final condition of the Steam if it is compressed until the volume is halved:

a. if the compression is carried out in an isothermal manner:

b. " " " follows the law $PV=C$.

Sol:-

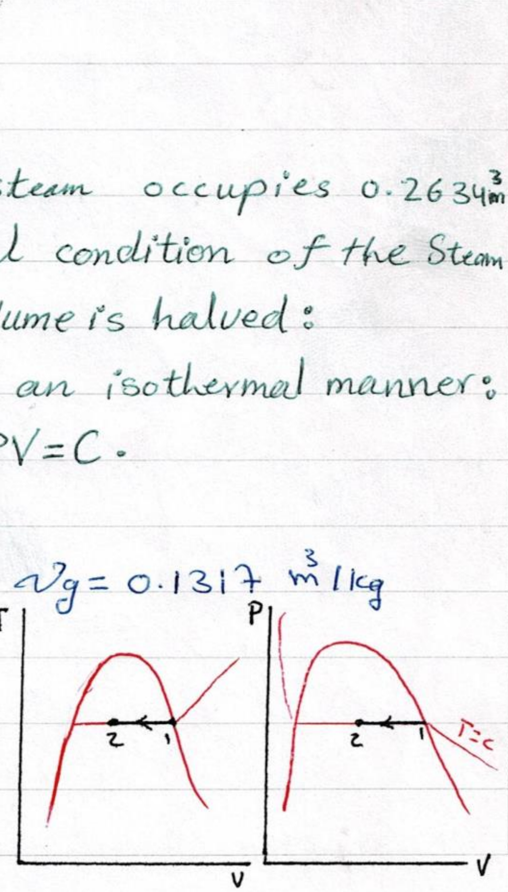
a. from Steam tables at 1.5 Mpa, $v_g = 0.1317\ m^3/kg$

$$m = \frac{V}{v} = \frac{0.2634}{0.1317} = 2\,kg$$

When the volume is halved.

$$v_2 = \frac{v_g}{2} = \frac{0.1317}{2} = 0.0659\ m^3/kg$$

$$x = \frac{0.0659}{0.1317} = 0.5$$



In this case the steam is operating in the evaporation region, since the temperature remains constant.

$h_2 = h_f + x\, h_{fg}$, from Steam tables at $P = 1.5$ Mpa
$h_f = 844.7$ kJ/kg , $h_{fg} = 1945.2$ kJ/kg

$h_2 = 844.7 + 0.5 * 1945.2 = 1817.3$ kJ/kg
$H_2 = m \cdot h_2 = 2 * 1817.3 = 3634.6$ kJ

Heat loss $= 0.5\, h_{fg} = 0.5 * 1945.2 = 972.6$ kJ/kg
for 2 kg , Heat loss $= 2 * 972.6 = 1945.2$ kJ

b. If the compression is according to the law $PV = C$,
then $P_1 V_1 = P_2 V_2$

$$\therefore P_2 = P_1 \cdot \frac{V_1}{V_2} = 1.5 * 2 = 3 \text{ Mpa}$$

Specific volume after compression, $v_2 = \frac{v_1}{2} = \frac{v_g}{2} = 0.0659$ m³/kg
from Steam tables,
at $P_2 = 3$ Mpa, $v_g = 0.0666$ m³/kg , $h_f = 1008.4$ kJ/kg
$v_2 < v_g \Rightarrow$ Wet Steam $h_{fg} = 1793.9$ kJ/kg

$$x = \frac{v_2}{v_g} = \frac{0.0659}{0.0666} = 0.989$$

$h_2 = h_f + x\, h_{fg} = 1008.4 + 0.989 * 1793.9 = 2782.6$ kJ/kg
$H_2 = m * h_2 = 2 * 2782.6 = 5565.2$ kJ

Ex:- 1 kg of water at 30 bar, 300°C, expand reversibly to 0.75 bar. Calculate the heat flow and the work done when the process is hyperbolic.

Sol:-

at $P = 30\,bar$, $T_s = 233.9°C$, $T_1 = 300°C$

since $T_1 > T_{sat} \Rightarrow$ Superheated Steam

from Steam tables at 30 bar & 300°C

$v_1 = 0.08119\ m^3/kg$, $u_1 = 2750.1\ kJ/kg$

$$P_1 v_1 = P_2 v_2 \Rightarrow v_2 = \frac{P_1}{P_2} \cdot v_1 = \frac{30}{0.75} * 0.08119$$
$$= 3.243\ m^3/kg$$

at $P = 0.75\,bar$, $v_g = 2.21711\ m^3/kg$

$\therefore v_2 > v_g \Rightarrow$ Superheated Steam

$\therefore$ at 0.75 bar & 3.243 from Superheated Steam tables

$h_2 = 2986.3\ kJ/kg$, $u_2 = 2742.9\ kJ/kg$

$$w = P_1 v_1 \ln \frac{v_2}{v_1} = 30*10^2 * 0.08114 \ln \frac{3.2456}{0.08119}$$
$$= 897.9\ kJ/kg$$

$$W = m \cdot w = 1 * 897.9 = 897.9\ kJ$$

$$\Delta U = m(u_2 - u_1) = 1 * (2742.9 - 2750.1)$$
$$= -7.21\ kJ$$

$$Q = W + \Delta U = 897.9 - 7.21$$
$$= 890.68\ kJ$$

e. The polytropic process $PV^n = C$

Here the steam is assumed to be expanded or compressed according to the law $PV^n = C$.

$$Q = W + \Delta U \quad , \quad W = \frac{P_1V_1 - P_2V_2}{n-1}$$

$$q = w + \Delta u$$

$$\Delta u = u_2 - u_1 = (h_2 - P_2v_2) - (h_1 - P_1v_1)$$

$$= (h_2 - h_1) - (P_2v_2 - P_1v_1)$$

$$q = \frac{P_1v_1 - P_2v_2}{n-1} + (h_2 - h_1) - (P_2v_2 - P_1v_1)$$

$$= (h_2 - h_1) + \frac{P_1v_1 - P_2v_2}{n-1} + (P_1v_1 - P_2v_2)$$

$$= (h_2 - h_1) + (P_1v_1 - P_2v_2)(1 + n - 1/n - 1)$$

$$= (h_2 - h_1) + n \cdot \frac{P_1v_1 - P_2v_2}{n-1}$$

$$\therefore \boxed{q = (h_2 - h_1) + n \cdot w}$$

$$Q = (H_2 - H_1) + n \cdot W$$

Ex: A quantity of Steam at a pressure of 2.1 Mpa and 0.9 dry occupies avolume of 0.2562 m^3. It is expanded according to the law $PV^{1.25} = C$, to a pressure of 0.7 Mpa. Determine:

a. the mass of Steam present,

b. the external work done,

c. the change of internal energy,

d. the heat exchange between the Steam and surroundings.

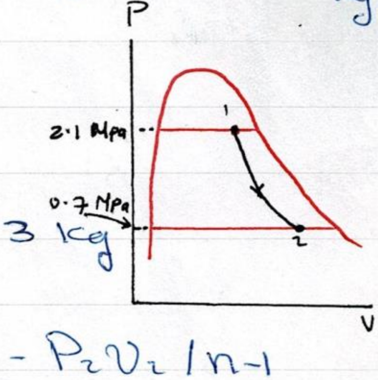
Sol:

a. $v_1 = v_f + x_1 v_{fg}$, from Steam tables at 2.1 Mpa

$v_f = 1.181 * 10^{-3}$, $v_g = 0.0949 \ \frac{m^3}{kg}$

$\therefore v_1 = 1.181 * 10^{-3} + 0.9 (0.0949 - 1.181 * 10^{-3})$

$= 0.0856 \ m^3/kg$



$v = V/m \Rightarrow m = \frac{V}{v} = \frac{0.2562}{0.0856} = 3 \ kg$

b. $Q = W + \Delta U$, $w = P_1 v_1 - P_2 v_2 / n-1$

$P_2 v_2^{1.25} = P_1 v_1^{1.25} \Rightarrow v_2 = (P_1/P_2)^{1/1.25} * v_1$

$= (2.1/0.7)^{1/1.25} * 0.0856$

$= 0.206 \ m^3/kg$

$w = \frac{2.1 * 10^3 * 0.0856 - 0.7 * 10^3 * 0.206}{1.25 - 1} = 143.36 \ kJ/kg$

$W = m \cdot w = 3 * 143.36 = 430 \ kJ$

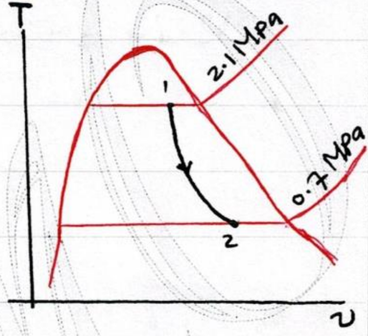
c. at $P = 0.7\ \text{Mpa}$, $v_g = 0.273\ m^3/kg$, $v_2 = 0.206$

$v_g > v_2 \Rightarrow$ wet Steam

$v_2 = v_f + x\, v_{fg}$

$0.206 = 1.108 * 10^{-3} + x_2(0.273 - 1.108 * 10^{-3})$

$x_2 = 0.753$



$\therefore\ u_1 = u_f + x_1 u_{fg} = 917.5 + 0.9(2598.2 - 917.51)$
$= 2430\ kJ/kg$

$u_2 = u_f + x_2 u_{fg} = 696.3 + 0.753(2571.1 - 696.3)$
$= 2108\ kJ/kg$

$\Delta U = m(u_2 - u_1) = 3 * (2108 - 2430) = -966\ kJ$

d. $Q = W + \Delta U = 430 - 966 = -536\ kJ$ (loss to the Surrounding)

Ex: In a steam engine the steam at the beginning of the expansion process is at 7 bar, dryness fraction 0.95, and the expansion follows the law $pv^{1.1} = c$, down to a pressure of 0.34 bar. Calculate the work done per kg of steam during the expansion, and the heat flow per kg of steam to or from the cylinder walls during the expansion.

Sol:- At 7 bar , $v_g = 0.2728 \ m^3/kg$, $v_f \simeq 0$

$\therefore v_1 = x_1 v_g = 0.95 * 0.2728 = 0.259 \ m^3/kg$

$$P_1/P_2 = \left(\frac{v_2}{v_1}\right)^n \Rightarrow v_2 = v_1 \left(\frac{P_1}{P_2}\right)^{1/n} = 0.259 \left(\frac{7}{0.34}\right)^{\frac{1}{1.1}}$$

$\therefore v_2 = 4.05 \ m^3/kg$

$$W = \frac{P_1 v_1 - P_2 v_2}{n-1} = \frac{7*10^2*0.259 - 0.34*10^2*4.05}{1.1-1}$$

$\therefore W = 436 \ kJ/kg$

At 0.34 bar , $v_g = 4.649 \ m^3/kg$,

$v_2 < v_g \Rightarrow$ Wet Steam

$$x_2 = \frac{v_2}{v_g} = \frac{4.05}{4.649} = 0.873$$

$u_1 = u_f + x_1 u_{fg} = 696 + 0.95(2573 - 696) = 2476.8 \ kJ/kg$

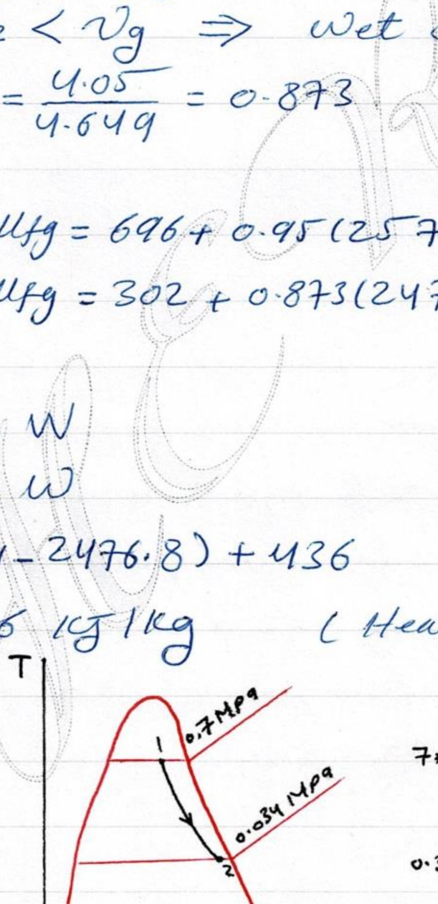
$u_2 = u_f + x_2 u_{fg} = 302 + 0.873(2472 - 302) = 2196.4 \ kJ/kg$

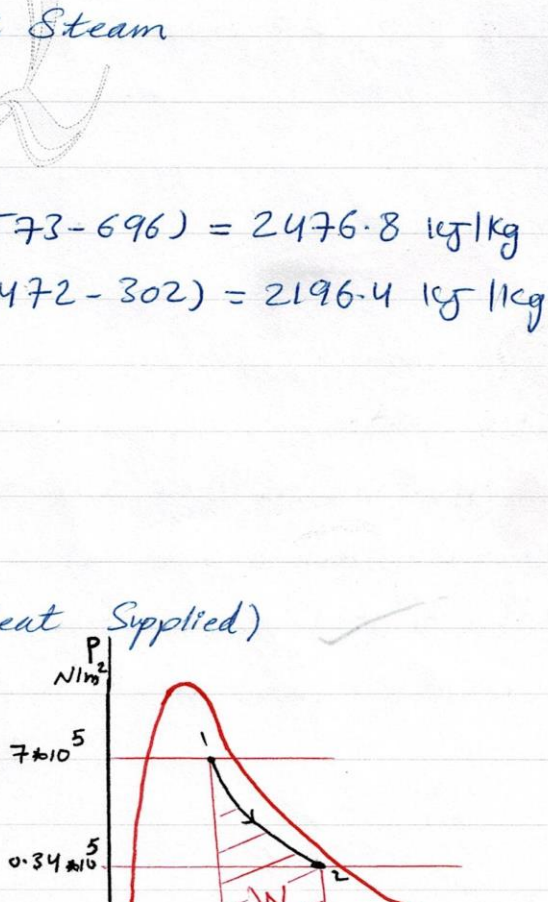
$Q = \Delta U + W$

$q = \Delta u + w$

$= (2196.4 - 2476.8) + 436$

$= 155.6 \ kJ/kg$ (Heat Supplied)





f. Adiabatic Process:

An adiabatic process is one in which no heat is transferred to or from the fluid during the process.

from NFEE,

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

$$W = -\Delta U$$

$$W = U_1 - U_2$$

Per 1 kg, $w = u_1 - u_2$

Ex: 1 kg of Steam at 100 bar and 375 °C expands reversibly in a perfectly insulated cylinder behind a piston until the pressure is 38 bar and the Steam is then dry saturated. Calculate the work done by the System.

Sol:

$Q = W + \Delta U$, $Q = 0$ (perfectly insulated)

$\therefore w = u_1 - u_2$

at 100 bar , $t_s = 311$ °C , since $t > t_s \Rightarrow$ Superheated

$\therefore u_1 = 2621.78$ kJ/kg , $u_2 = u_g = 2608$ kJ/kg

$$W = m \cdot w$$

$$= m(u_2 - u_1)$$

$$= 1 * (2621 - 2608)$$

$$= 13 \text{ kJ/kg}$$

Ex:o Determine the volume occupied by 2kg of Steam at 0.85 Mpa and dryness fraction of 0.95. If this Steam is expanded reversibly and adiabatically to 0.17 Mpa, the law of expansion is ($PV^{1.13}=C$). Determine the final dryness fraction and the change in internal energy during expansion.

Sol:o $v_1 = v_f + x_1(v_g - v_f)$, at 0.85 Mpa & $x_1 = 0.95$

$= 1.118*10^{-3} + 0.95(0.227) = 0.2167\ m^3/kg$

$v_1 = \frac{V}{m} \Rightarrow V_1 = v * m = 0.2167 * 2 = 0.4335\ m^3$

$P_1 v_1^{1.13} = P_2 v_2^{1.13} \Rightarrow v_2 = (0.85/0.17)^{1/1.13} * 0.2167$

$= 0.9\ m^3/kg$

$Q = W + \Delta U$ ∴ $Q = 0$

$W = m(u_1 - u_2)$ or $u_2 - u_1 = -(P_1 v_1 - P_2 v_2)/n-1$

$u_1 = u_f + x u_{fg} = 731.1 + 0.95(2577.1 - 731.1) = 2484.8\ \frac{kJ}{kg}$

at $P_2 = 0.17$ Mpa , $v_g = 1.0312\ m^3/kg$, $v_2 = 0.9\ m^3/kg$

∴ $v_2 < v_g \Rightarrow$ wet Steam

$v_2 = v_f + x_2 v_{fg}$

$0.9 = 1.056*10^{-3} + x_2 * (1.0312 - 1.056*10^{-3}) \Rightarrow x_2 = 0.8717$

$u_2 = u_f + x_2 u_{fg} = 483.02 + 0.8717 * 2040.9$

$= 2262.1\ kJ/kg$

$W = 2 * (2484 - 2262.1)$

$= 445.26\ kJ$

2. Irreversible Process:-

1. Adiabatic mixing:

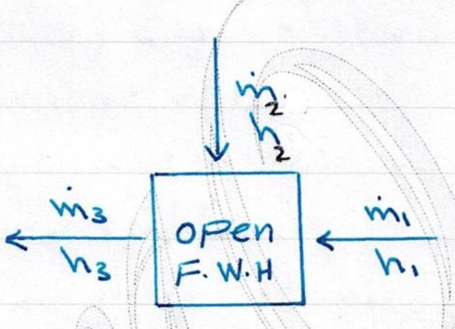
from flow Equation

$$H_1 + H_2 = H_3$$

$$\dot m_1 h_1 + \dot m_2 h_2 = \dot m_3 h_3$$

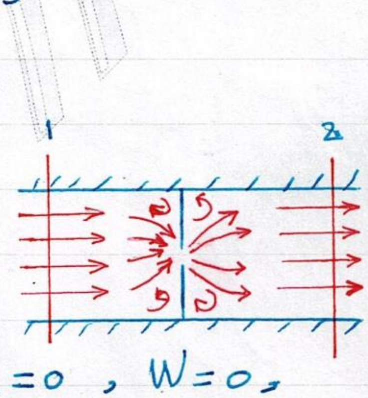
$$\dot m_1 h_1 + \dot m_2 h_2 = (\dot m_1 + \dot m_2) h_3$$

$$\dot m_1 \cdot C_{p_1} \cdot T_1 + \dot m_2 \cdot C_{p_2} \cdot T_2 = (\dot m_1 + \dot m_2) \cdot C_{p_3} \cdot T_3$$



open feedwater heater

2. Throttling:



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

Q=0 , W=0 ,

$$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2}$$, $C_1^2 - C_2^2/2 \simeq 0$

$$h_1 = h_2 \Rightarrow C_{p_1} T_1 = C_{p_2} T_2$$

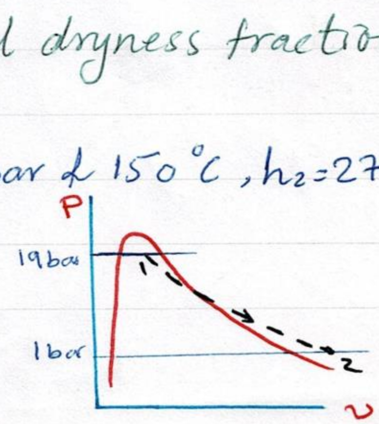
Ex:- Steam at 19 bar is throttled to 1 bar and the temperature after throttling is found to be 150°C. Calculate the initial dryness fraction of the Steam.

Sol:- from Steam tables, at 1 bar & 150°C, $h_2 = 2777$

$h_2 = h_1 = h_f + x h_{fg} \Rightarrow$

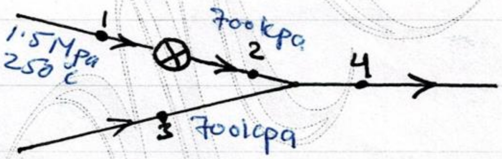
$2777 = 897 + x_1 * 1901$

$\therefore x = 0.989$



Ex:- Steam at 1.5 Mpa and 250°C flowing at 1.5 kg/s is throttled to 700 kpa and then mixed with a Steam at 700 kpa also 0.97 dryness fraction with a flow rate of 3.6 kg/s. find the condition of resulting Steam.

Sol:-



at 1.5 Mpa from Steam tables, $t_s = 198.32°C$

Since $t_1 > t_s$ ∴ Superheated Steam at point 1

from Superheated Steam tables, $h_1 = 2925 \ kJ/kg = h_2$

$$\dot{m}_2 h_2 + \dot{m}_3 h_3 = \dot{m}_4 h_4$$

$h_3 = h_{f3} + x_3 h_{fg3}$, at $P = 700 \ kpa$, $h_f = 697 \ kJ/kg$

$h_{fg} = 2067 \ kJ/kg$

$$h_3 = 697 + 0.97 * 2067 = 2702 \ kJ/kg$$

$$h_4 = \frac{\dot{m}_2 h_2 + \dot{m}_3 h_3}{\dot{m}_2 + \dot{m}_3} = \frac{1.5 * 2925 + 3.6 * 2702}{1.5 + 3.6} = 2767.6 \ kJ/kg$$

at 700 kpa , $h_g = 2763.5 \ kJ/kg$, $T_s = 164.97°C$

Since $h_4 > h_g$ ⟹ Superheated Steam

from Superheated Steam tables, $T_4 = 166.64°C$

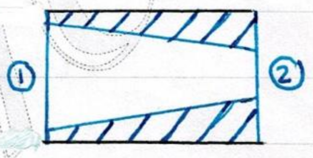
∴ Degree of Superheated $= (t - t_s)$

$= 166.64 - 164.92$

$= 1.67°C$

Ex:-

Steam at 0.6 Mpa, 200°C enters an insulated nozzle with a velocity of 50 m/s. It leaves at 0.15 Mpa and velocity of 600 m/s. Determine the final temperature of Steam if it is superheated and quality if it is wet.



Sol:- from SFEE

$$gz_1 + \frac{1}{2}C_1^2 + h_1 + q = gz_2 + \frac{1}{2}C_2^2 + h_2 + w$$

$z_1 \simeq z_2$, $q = 0$ (insulated) , $w = 0$ (for nozzle)

$$\therefore h_2 = h_1 + \frac{1}{2}(C_1^2 - C_2^2) * 10^{-3}$$

at 0.6 Mpa , $t_s = 158.8°C$, since $T_1 > T_s$ $\therefore$ Superheated

from Superheated Steam tables at 0.6 Mpa & 200°C

$h_1 = 2850.1$ kJ/kg

$h_2 = 2850.1 + \frac{1}{2}(50^2 - 600^2) * 10^{-3} = 2671.4$ kJ/kg

at 0.15 Mpa $h_g = 2693.6$ kJ/kg (from Steam tables)

Since $h_2 < h_g$ $\Rightarrow$ wet Steam

$h_2 = h_{f_2} + x_2 h_{fg}$, at $P = 0.15$ Mp from Steam table

$h_f = 467.1$ kJ/kg , $h_{fg} = 2226.5 \ \frac{kJ}{kg}$

$\therefore 2671.4 = 467.1 + x_2 * 2226.5$

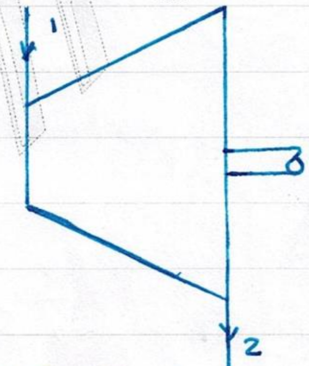
$x_2 = 0.99$

Ex: The mass flow rate of steam turbine is 1.5 kg/s and the heat transfer from the turbine is 8.5 kW. The following data are known for steam entering and leaving turbine. Find the power output of turbine.

	P (Mpa)	t (°C)	x	C (m/s)	Z (m)
input	2	350	—	50	6
output	0.1	—	100%	200	3

Sol: $gz_1 + h_1 + \frac{1}{2}C_1^2 + q = gz_2 + h_2 + \frac{1}{2}C_2^2 + w$

$w = g(z_1 - z_2)*10^{-3} + (h_1 - h_2) + \frac{1}{2}(C_1^2 - C_2^2)*10^{-3} + \frac{Q}{\dot{m}}$



from Superheated Steam tables at

2 Mpa & 350°C , $h_1 = 3137$ kJ/kg

at $P = 0.1$ Mpa & dry , $h_2 = h_g = 2675.5$ kJ/kg

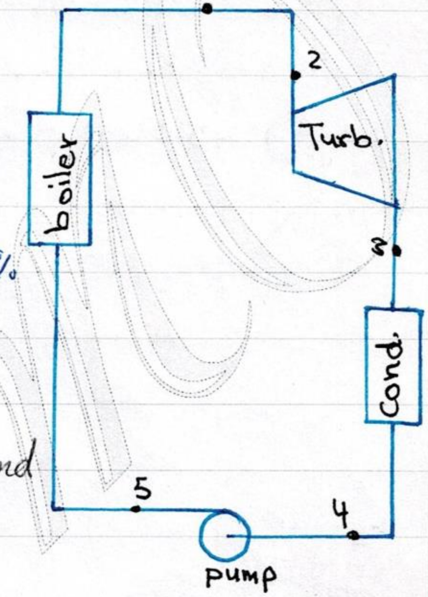
$w = 9.8(6-3)*10^{-3} + (3137 - 2675.5) + \frac{1}{2}(50^2 - 200^2)*10^{-3} + \left(\frac{-8.5}{1.5}\right)$

$= 437.11$ kJ/kg

Power $= \dot{W} = \dot{m} \cdot w = 1.5 * 437.11$

$= 656$ kW

Ex: Consider the simple power plant, as shown, the following data are:



	P	t(°C)	x
Leaving boiler	2 Mpa	300	—
entering turbine	1.9 Mpa	290	—
leaving turbine	15 kpa	—	90%
leaving condenser	14 kpa	45	—

pump work = 4 kJ/kg, Find:

a. heat transfer between boiler and turbine

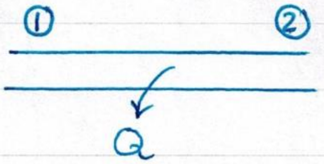
b. turbine work

c. heat transfer in condenser

d. heat transfer in boiler

Sol: a. pipe 1→2

$$gz_1 + \frac{1}{2}C_1^2 + h_1 + q = gz_2 + \frac{1}{2}C_2^2 + h_2 + w$$



$z_1 \simeq z_2$, $C_1 = C_2$, $w = 0$

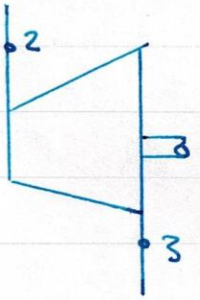
$\therefore \; q = h_2 - h_1$

from Superheated Steam, at 2 Mpa & 300°C , $h_1 = 3023.5 \frac{kJ}{kg}$

" " " , at 1.9 Mpa & 290°C , $h_2 = 3002.5 \frac{kJ}{kg}$

$\therefore \; q = 3002.5 - 3023.5 = -21$ kJ/kg

b. Turbine 2→3



$$gz_2 + \frac{1}{2}C_2^2 + h_2 + q = gz_3 + \frac{1}{2}C_3^2 + h_3 + w$$

$z_2 \simeq z_3$, $C_2 = C_3$, $q = 0$

$w = h_2 - h_3$

$h_3 = h_f + x\, h_{fg}$, at 15 kpa , $h_f = 226$ kJ/kg
$h_{fg} = 2373.1$ kJ/kg

$h_3 = 226 + 0.9 * 2373.1 = 2361.8$ kJ/kg

∴ $W_t = 3002.5 - 2361.8 = 640.7$ kJ/kg

c. Condenser 3→4

$$gz_3 + \frac{1}{2}C_3^2 + h_3 + q = gz_4 + \frac{1}{2}C_4^2 + h_4 + w$$

$z_3 \simeq z_4$, $C_3 = C_4$, $w = 0$

∴ $q = h_4 - h_3$

at $P = 14$ kpa $t_s = 52.5°C$, $t_4 = 45°C$

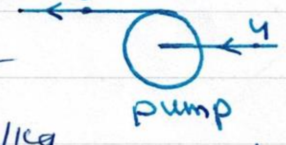
∴ $t_4 < t_s$ ⇒ Subcooled liquid

from Steam table at $t_s = 45°C$, $h_4 = 188.5$ kJ/kg

$q = 188.5 - 2361.8 = -2173.3$ kJ/kg

d. Pump 4→5

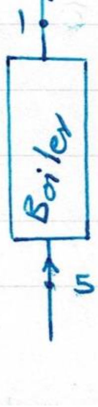
$$\cancel{gz_4} + \frac{1}{2}\cancel{C_4^2} + h_4 + \cancel{q} = \cancel{gz_5} + \frac{1}{2}\cancel{C_5^2} + h_5 + w$$



$w = h_4 - h_5 \Rightarrow -4 = 188.5 - h_5$

∴ $h_5 = 192.5$ kJ/kg

e. Boiler 5→1

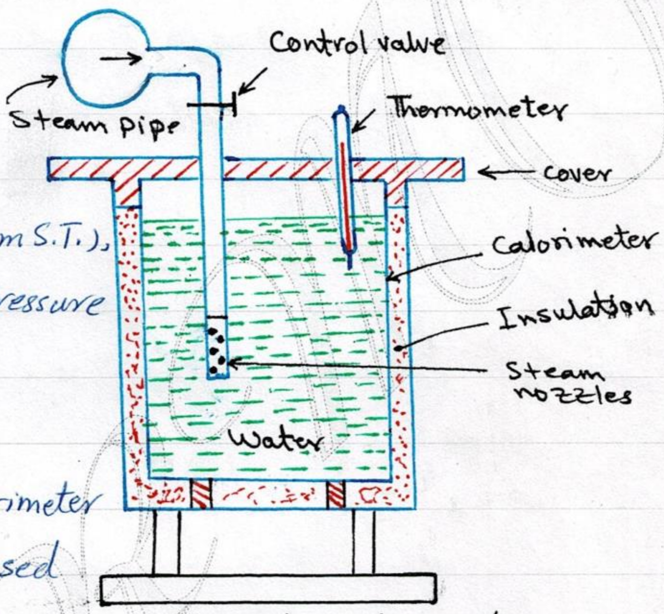


$$\cancel{gz_5} + \frac{1}{2}\cancel{C_5^2} + h_5 + q = \cancel{gz_1} + \frac{1}{2}\cancel{C_1^2} + h_1 + \cancel{w}$$

∴ $q = h_1 - h_5 = 3023 - 192.5$
$= 2831$ kJ/kg

- Measurement of Dryness Fraction - „ of Steam „

1. Barrel Calorimeter



Barrel Calorimeter

p = pressure of the Steam,

t = temperature of Steam formation at pressure P (from S.T.),

h_{fg} = latent heat of steam at pressure P (from Steam tables)

m_c = Mass of the calorimeter

C_c = Specific heat of the calorimeter

m_s = Mass of the Steam Condensed

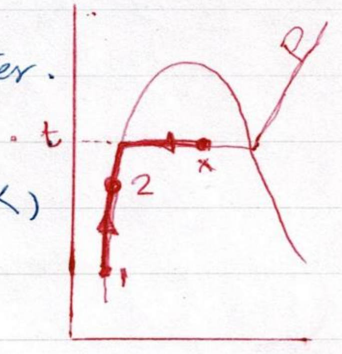
m_w = Mass of cold water in the Calorimeter

t_1 = Initial temperature of water and calorimeter.

t_2 = Final " " " " "

C_w = Specific heat of water (4.2 kJ/kg.K)

x = Dryness fraction of steam sample.



According to the law of conservation, the heat lost by Steam is equal to the heat gained by water and calorimeter.

$$\text{Heat lost} = m_s[x\,h_{fg} + C_w(t-t_2)]$$

$$\text{Heat gained} = (m_w C_w + m_c C_c)(t_2-t_1)$$

$$\therefore \quad m_s[x\,h_{fg} + C_w(t-t_2)] = (m_w C_w + m_c C_c)(t_2-t_1)$$

from this equation, the dryness fraction (x) may be determined.

Ex:- In a laboratory experiment on wet Steam by a barrel calorimeter, the following observations were recorded:

Mass of copper calorimeter = 1 kg = m_c
Mass of calorimeter + water = 3.8 kg = $m_c + m_w$
Mass of calorimeter + water + Steam = 4 kg = $m_c + m_w + m_s$
Initial temperature of water = 10 °C
Final temperature of water = 50 °C
Steam pressure = 5.5 bar

If the Specific heat of Copper is 0.406 kJ/kg.K. Determine the dryness fraction of Steam.

Sol:- $m_w = 3.8 - m_c = 3.8 - 1 = 2.8\ kg$

$m_s = 4 - (m_c + m_w) = 4 - (3.8) = 0.2\ kg$

from Steam tables at $P = 5.5$ bar , $t_s = 155.°C$

$h_{fg} = 2095.5\ \frac{kJ}{kg}$

Heat lost by Steam $= m_s[x h_{fg} + C_w(t - t_2)$

$= 0.2\,[x * 2095.5 + 4.2(155.5 - 50)]$

$= 419.1x + 88.6\ kJ$ --- ①

Heat gained by water and calorimeter

$= (m_w C_w + m_c C_c)(t_2 - t_1)$

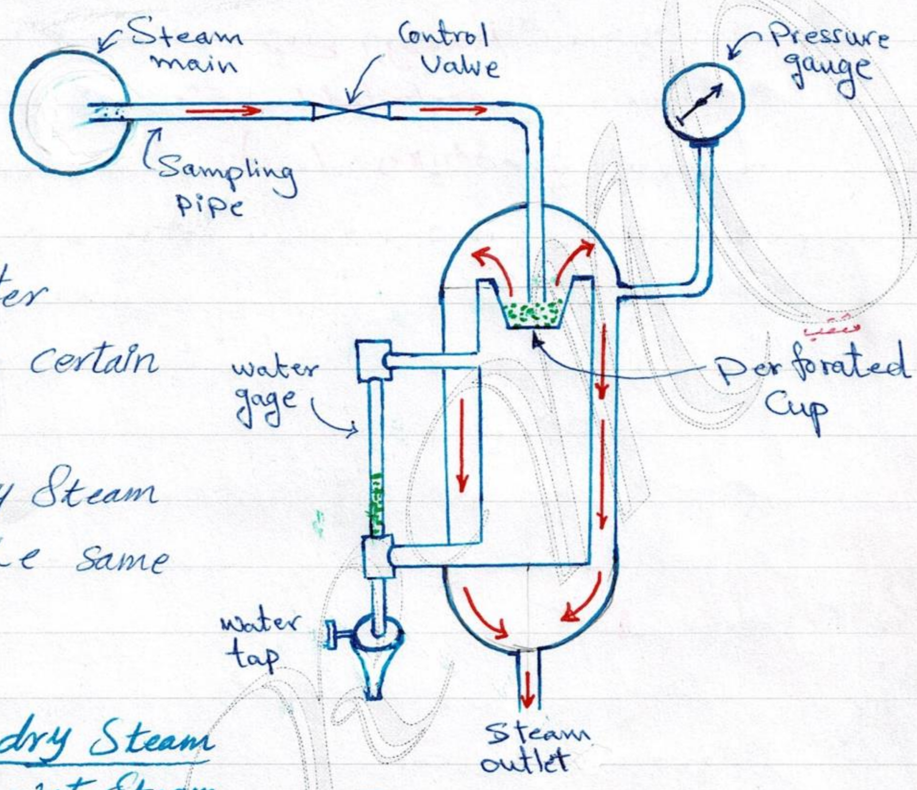
$= (2.8 \times 4.2 + 1 \times 0.406)(50 - 10) = 486.6\ kJ$ --- ②

Equating eqs ① and ②

$419.1x + 88.6 = 486.6$

$\therefore x = 0.95$

2. Separating Calorimeter :-



Separating calorimeter

m = Mass of water collected in a certain time

M = Mass of dry Steam passing in the same time

$$x = \frac{\text{Mass of dry Steam}}{\text{Mass of wet Steam}}$$

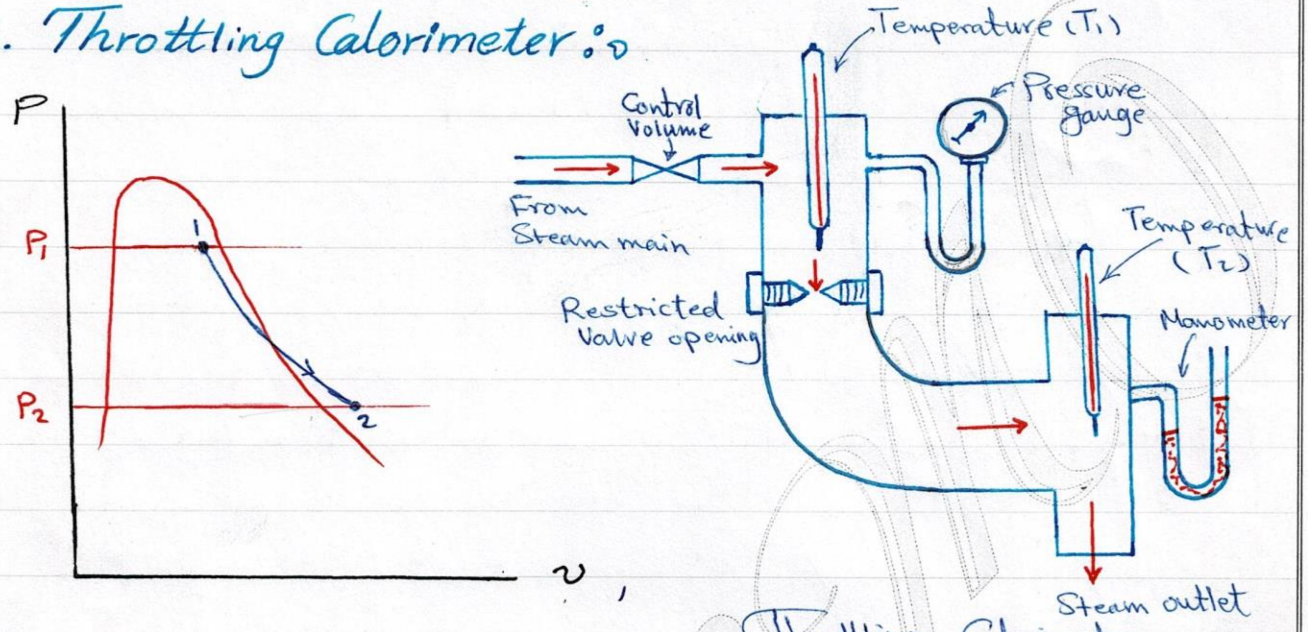
$$\boxed{x = \frac{M}{M+m}}$$

Ex:- In a laboratory experiment, a sample of wet Steam is allowed to pass through a separating calorimeter. At some instant, the water collected in the chamber was 0.1 kg whereas the condensed steam was found to be 1.25 kg. Determine the dryness fraction of Steam entering the calorimeter.

Sol:- $m = 0.1\,kg$, $M = 1.25\,kg$

$$x = \frac{M}{M+m} = \frac{1.25}{1.25+0.1} = 0.926$$

3. Throttling Calorimeter:-



Throttling Calorimeter

the Steam in point (2) after throttling in superheated state and at a lower pressure than (P_1)

Total heat befor throttling = Total heat after throttling

or $$h_1 = h_2$$

$$\underbrace{h_{f_1} + x\,h_{fg_1}}_{\text{at } P_1} = \underbrace{h_{g_2} + C_p(t_{sup} - t_2)}_{\text{at } P_2}$$

ع ل بمجهول

Ex:- In a throttling calorimeter, the steam is admitted at a pressure of 10 bar. If it is discharged at atmospheric pressure and 110°C after throttling, determine the dryness fraction of steam. Assume specific heat of steam as 2.2 kJ/kg.K.

Sol:- $P_1 = 10$ bar, $P_2 = 1.013$ bar, $t_{sup.} = 110°C$, $C_p = 2.2$ kJ/kg.K

from Steam tables at 10 bar, $h_{f_1} = 762.6$ kJ/kg

$h_{fg_1} = 2013.6$ kJ/kg

from Steam tables at 1.013 bar, $t_2 = 100°C$, $h_{g_2} = 2676$ kJ/kg

$$h_{f_1} + x\, h_{fg_1} = h_{g_2} + C_p(t_{sup} - t_2)$$

$$762.6 + x * 2013.6 = 2676 + 2.2(110 - 100)$$

$$x = 0.961$$

4. Combined Separating and Throttling Calorimeter:-

A very Successful method of measuring the dryness fraction of Steam is by a combined separating and throttling calorimeter.

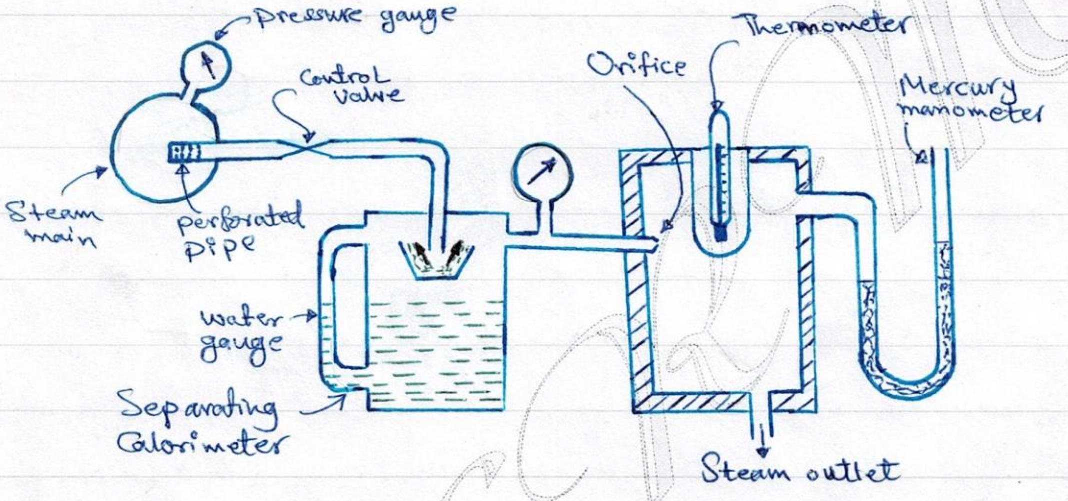
In this calorimeter, the wet Steam is first collected in a perforated collecting pipe and then passed through a separating calorimeter. A part of water is removed by Separating calorimeter owing to quick change of direction of flow. The resulting semi-dry steam is throttled into a throttling calorimeter. This method ensures that the Steam will be Superheated after throttling. This instrument is well insulated to prevent any loss of heat.

x_1 = Dryness fraction of Steam considering separating calorimeter.

x_2 = Dryness fraction of steam entering the throttling " .

Now the actual dryness fraction of Steam in the Steam main.

$$x = x_1 * x_2$$



" Combined Separating and throttling calorimeter "

Note: It is not possible to obtain results with this instrument if the final condition of Steam is wet. The final condition of Steam must be just dry or superheated

Ex:- In a laboratory experiment, the following observations were recorded to find the dryness fraction of Steam by combined separating and throttling calorimeter:

Total quantity of Steam passed = 36 kg = $m_s + m_w$
Water drained from Separating = 1.8 kg = m_w
Steam pressure befor throttling = 12 bar = P_1
Temperature of Steam after throttling = 110°C = t_{sup}
Pressure after throttling = 1.013 bar = P_2
Specific heat of Steam = 2.1 kJ/kg.K
Determine the dryness fraction of Steam befor inlet to the calorimeter

Sol:- $m_s \neq l$

we know that mass of dry Steam

$m_s = (m_s + m_w) - m_w = 36 - 1.8 = 34.2\,kg$

$x_1 = m_s / m_s + m_w = 34.2/36 = 0.95$

from Steam tables, corresponding to $P_1 = 12\,bar$

$h_{f_1} = 798.4\,kJ/kg$, $h_{fg} = 1984.3\,kJ/kg$

at $P_2 = 1.013\,bar$

$h_{g_2} = 2676\,kJ/kg$, $t_2 = 100°C$

$h_{f_1} + x_2 h_{fg_1} = h_{g_2} + Cp(t_{sup} - t_2)$

$798.4 + x_2 * 1984.3 = 2676 + 2.1(110 - 100)$

$x_2 = 0.957 \Rightarrow x = x_1 * x_2 = 0.95 * 0.957$
$= 0.909$

(Sheet No. 5)

Q1: Steam at a pressure of 28 kpa is passed into a condenser and it leaves as condensate at a temperature of 59°c. Cooling water circulates through the condenser at the rate of 45 kg/min. It enters at 15°c and leaves at 30°c. If the Steam flow rate is 1.25 kg/min, determine the dryness fraction of steam as it enters the condenser.

Q2: 1 kg of Saturated steam at 10 bar undergoes a non-flow constant volume process until the pressure becomes 3.5 bar. Determine:

a. the final condition of Steam.
b. the change in internal energy.
c. the change in Specific enthalpy
d. the heat energy transfered.

Ans. [0.37, -1273 kJ/kg, -1500 kJ/kg, -1273 kJ]

Q3: A sample of Steam at 1.4 Mpa is taken from a boiler and passed through a throttling calorimeter where after throttling to 0.11 Mpa, its temperature is observed to be 110°c. Determine the dryness fraction of the Steam leaving the boiler.

Ans. [0.95]

Q4: 0.5 kg of water at 7 bar and 15°c is contained in a cylinder 0.3 m diameter by friction-Less piston. Heat energy is supplied until the temperature of cylinder contents becomes 204°c, the pressure of the contents remains at 7 bar.

Determine:
a. the heat energy supplied
b. the distance moved by the piston,
c. the work energy,
d. the change in internal energy.

Ans. [1395.8 kJ/kg, 2.14 m, 105 kJ, 1290.8 kJ]

Q5: 0.075 m^3 of dry saturated steam at 8 bar and contained in a cylinder by friction-Less piston if the Steam undergose hyperbolic equation to a pressure of 4 bar. Determine the work energy, the change in internal energy and the heat energy transfered.

Ans. [41.5 kJ, 0.624 kJ, 40.5 kJ]

Q6: A quantity of dry saturated Steam occupies 0.2634 m^3 at 1.5 Mpa. Determine the final condition of the Steam if it is compressed until the volume is halved.

a. if the compression is carried out in an isothermal manner, then find the heat rejected.
b. if the compression follows the Law pv = c.

Ans. [a. 0.5, 972.6 kJ/kg, b. 0.989]