



Module 3



First law of thermodynamics



First Law of Thermodynamics

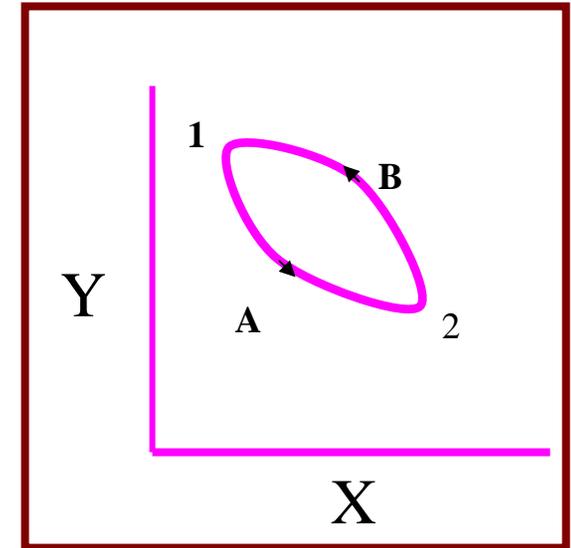
Statement:

- When a closed system executes a complete cycle the sum of heat interactions is equal to the sum of work interactions.

Mathematically

- $\Sigma Q = \Sigma W$

The summations being over the entire cycle





First Law (Contd...)



Alternate statement:

When a closed system undergoes a cycle the cyclic integral of heat is equal to the cyclic integral of work.

Mathematically $\oint \delta Q = \oint \delta W$

In other words for a two process cycle

$$Q_{A1-2} + Q_{B2-1} = W_{A1-2} + W_{B2-1}$$



First Law (Contd...)



$$Q_{A1-2} = \int_1^2 \delta Q$$

Along path A

$$\int_1^2 (\delta Q - \delta W) + \int_2^1 (\delta Q - \delta W) = 0$$

Along path A Along path B

Which can be written as

$$\int_1^2 (\delta Q - \delta W) - \int_1^2 (\delta Q - \delta W) = 0$$

Along path A Along path B

$$\int_1^2 (\delta Q - \delta W) = \int_1^2 (\delta Q - \delta W)$$

Along path A Along path B



First Law (contd...)



- Since A and B are arbitrarily chosen, the conclusion is, as far as a process is concerned (A or B) the difference $\delta Q - \delta W$ remains a constant as long as the initial and the final states are the same. The difference depends only on the end points of the process. Note that Q and W themselves depend on the path followed. But their difference does not.



First Law (contd...)



- This implies that the difference between the heat and work interactions during a process is a property of the system.
- This property is called the energy of the system. It is designated as E and is equal to some of all the energies at a given state.



First Law(contd...)



We enunciate the FIRST LAW for a process as

$$\delta Q - \delta W = dE$$

E consists of



$$E = U + KE + PE$$

U - internal energy

KE - the kinetic energy

PE - the potential energy

For the whole process A



$$Q - W = E_2 - E_1$$

Similarly for the process B



$$Q - W = E_1 - E_2$$



First Law(contd...)



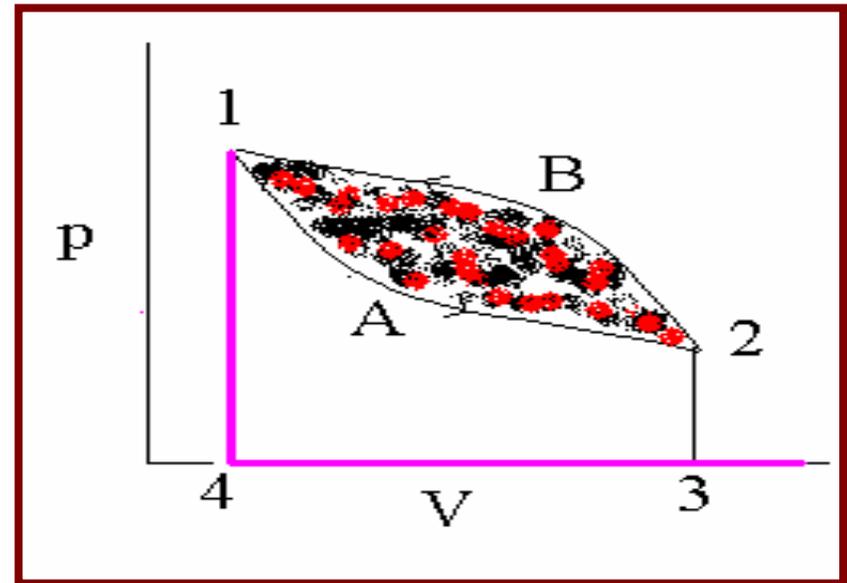
- An isolated system which does not interact with the surroundings $Q=0$ and $W=0$. Therefore, E remains constant for such a system.
- Let us reconsider the cycle 1-2 along path A and 2-1 along path B as shown in fig.
- Work done during the path A = Area under 1-A-2-3-4
- Work done during the path B = Area under 1-B-2-3-4
- Since these two areas are not equal, the net work interaction is that shown by the shaded area.



First Law (Contd...)



- The net area is 1A2B1.
- Therefore some work is derived by the cycle.
- First law compels that this is possible only when there is also heat interaction between the system and the surroundings.
- In other words, if you have to get work out, you must give heat in.





First Law (contd...)



- Thus, the first law can be construed to be a statement of conservation of energy - in a broad sense.
- In the example shown the area under curve A < that under B
- The cycle shown has negative work output or it will receive work from the surroundings. Obviously, the net heat interaction is also negative. This implies that this cycle will heat the environment. (as per the sign convention).



First Law(contd...)



- For a process we can have $Q=0$ or $W=0$
- We can extract work without supplying heat(during a process) but sacrificing the energy of the system.
- We can add heat to the system without doing work(in process) which will go to increasing the energy of the system.
- Energy of a system is an extensive property



Engineering Implications



- When we need to derive some work, we must expend thermal/internal energy.
- Whenever we expend heat energy, we expect to derive work interaction (or else the heat supplied is wasted or goes to to change the energy of the system).
- If you spend money, either you must have earned it or you must take it out of your bank balance!!
- !!There is nothing called a free lunch!!



Engineering implications (contd...)



- The first law introduces a new property of the system called the energy of the system.
- It is different from the heat energy as viewed from physics point of view.
- We have “energy in transition between the system and the surroundings” which is not a property and “energy of the system” which is a property.



Engineering Applications (contd...)



- It appears that heat (Q) is not a property of the system but the energy (E) is.
- ❖ How do we distinguish what is a property of the system and what is not?
- The change in the value of a “property” during a process **depends only on the end states** and **not on the path** taken by a process.
- In a cycle the net in change in “every property” is zero.



Engineering implications (contd...)



➤ If the magnitude of an entity related to the system changes during a process and if this depends only on the end states then the entity is a property of the system. (Statement 3 is corollary of statement 1)

HEAT and WORK are not properties because they depend on the path and end states.

HEAT and WORK are not properties because their net change in a cycle is not zero.



Analogy



- Balance in your bank account is a property. The deposits and withdrawals are not.
- A given balance can be obtained by a series of deposits and withdrawals or a single large credit or debit!



Analogy (contd...)



Balance is deposits *minus* withdrawals

❖ If there are no deposits and if you have enough balance, you can withdraw. But the balance will diminish

❖ If you don't withdraw but keep depositing your balance will go up.

Energy is heat *minus* work

If the system has enough energy you can extract work without adding heat. but the energy diminish

If you keep adding heat but don't extract any work, the system energy will go up.



Analogy(Contd)



- Between 2 successive 1 Januarys you had made several deposits and several withdrawals but had the same balance, then you have performed a cycle. - *it means that they have been equalled by prudent budgeting!!*
- ❖ Energy - balance; Deposits - heat interactions; Withdrawals - work interactions.
- ❖ Mathematically properties are called point functions or state functions
- ❖ Heat and work are called path functions.



Analogy (contd...)



To sum up:

I law for a cycle:

$$\oint \delta Q = \oint \delta W$$

I law for a process is

$$Q - W = \Delta E$$

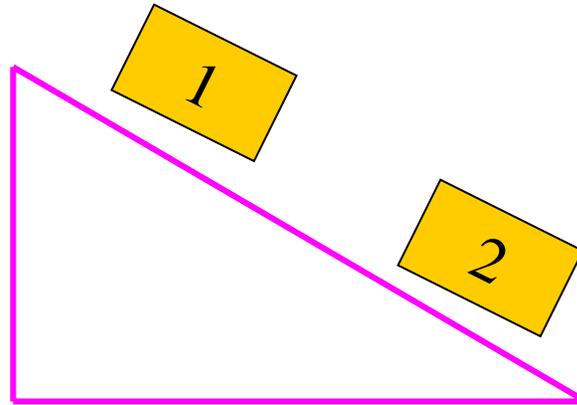
For an isolated system

$$Q=0 \text{ and } W=0.$$

Therefore $\Delta E=0$



Analogy (contd...)



Conducting plane; Insulating rough block in vacuum

| System | Q | W | ΔE |
|-------------|---|---|------------|
| Block | 0 | + | - |
| Plane | 0 | - | + |
| Block+plane | 0 | 0 | 0 |



Analogy (Contd...)

- The first law introduces the concept of energy in the thermodynamic sense.
- Does this property give a better description of the system than pressure, temperature, volume, density?

The answer is yes, in the broad sense.

- It is U that is often used rather than E . (Why? - KE and PE can change from system to system).
- They have the units of kJ



First law (Contd...)



- Extensive properties are converted to specific extensive properties (which will be intensive properties) ., i.E., U and E with the units kJ/kg .
- A system containing a pure substance in the standard gravitational field and not in motion by itself, if electrical, magnetic fields are absent (most of these are satisfied in a majority of situations) ‘ u ’ will be ‘ e ’.



First law (Contd...)



- The I law now becomes $Q - W = \Delta U$
- Per unit mass of the contents of the system
- If only displacement work is present
- Per unit mass basis
- Which can be rewritten as

$$\delta Q - \delta W = \delta U$$

$$(Q - W)/m = \Delta u$$

$$\delta Q - p dV = dU$$

$$\delta q - p dv = du$$

$$\delta q = du + p dv$$



Flow Process



Steady flow energy equation:

- Virtually all the practical systems involve flow of mass across the boundary separating the system and the surroundings. Whether it be a steam turbine or a gas turbine or a compressor or an automobile engine there exists flow of gases/gas mixtures into and out of the system.
- So we must know how the first Law of thermodynamics can be applied to an open system.



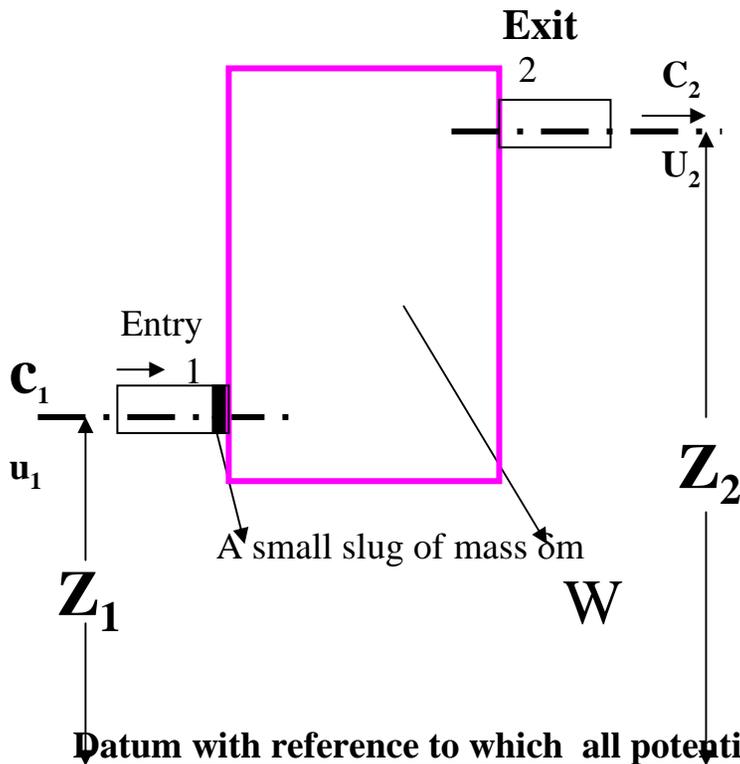
SFEE (contd...)



- The fluid entering the system will have its own internal, kinetic and potential energies.
- Let u_1 be the specific internal energy of the fluid entering
- C_1 be the velocity of the fluid while entering
- Z_1 be the potential energy of the fluid while entering
- Similarly let u_2 , C_2 and Z_2 be respective entities while leaving.



SFEE(Contd...)



Total energy of the slug at entry

$$= \text{Int. E} + \text{Kin. E} + \text{Pot. E}$$

$$= \delta m u_1 + \delta m C_1^2 / 2 + \delta m g Z_1$$

$$= \delta m (u_1 + C_1^2 / 2 + g Z_1)$$

Focus attention on slug at entry-1



SFEE(Contd...)



- Initially the system consists of just the large rectangle. Let its energy (including IE+KE+PE) be E'
- The slug is bringing in total energy of $\delta m (u_1 + C_1^2/2 + gz_1)$
- The energy of the system when the slug has just entered will be $E' + \delta m (u_1 + c_1^2/2 + gz_1)$.



SFEE(Contd...)



➤ To push this slug in the surroundings must do some work.

If p_1 is the pressure at 1,

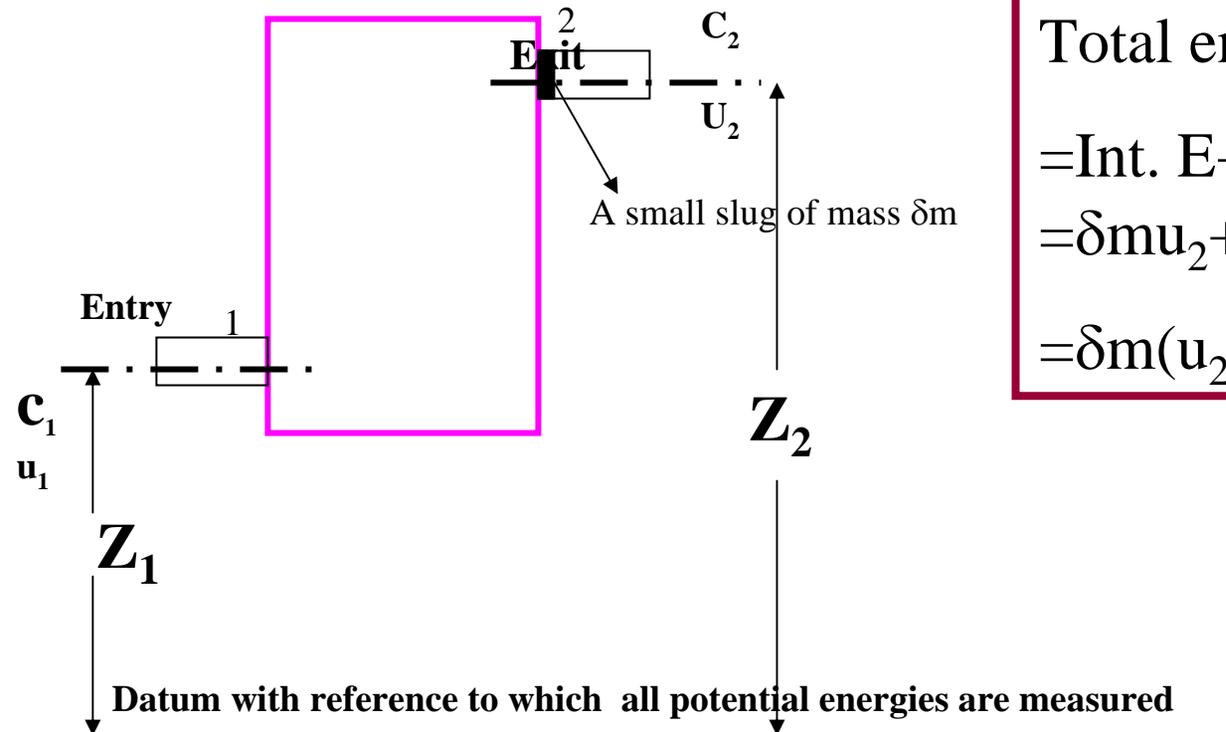
v_1 is the specific volume at 1,

This work must be $-p_1 dm v_1$

(-ve sign coming in because it is work done on the system)



SFEE (contd...)



$$\begin{aligned} & \text{Total energy of the slug at exit} \\ & = \text{Int. E} + \text{Kin. E} + \text{Pot. E} \\ & = \delta m u_2 + \delta m C_2^2 / 2 + \delta m g Z_2 \\ & = \delta m (u_2 + C_2^2 / 2 + g Z_2) \end{aligned}$$

Focus Attention on Slug at Exit-2



SFEE (contd...)

- The energy of the system should have been

$$= E' + \delta m (u_2 + C_2^2/2 + gZ_2)$$

- So that even after the slug has left, the original E' will exist.
- We assume that δm is the same. This is because what goes in must come out.



SFEE (contd...)



- To push the slug out, now the system must do some work.

If p_2 is the pressure at 2,

v_2 is the specific volume at 2,

This work must be $+ p_2 \delta m v_2$

(positive sign coming in because it is work done by the system)



SFEE (contd...)



- The net work interaction for the system is
- $W + p_2 \delta m v_2 - p_1 \delta m v_1 = W + \delta m (p_2 v_2 - p_1 v_1)$
- Heat interaction Q remains unaffected.
- Now let us write the First law of thermodynamics for the steady flow process.



SFEE (contd...)

Now let us write the First law of thermodynamics for the steady flow process.

| | |
|--|--|
| Heat interaction | = Q |
| Work interaction | = W + $\delta m(p_2 v_2 - p_1 v_1)$ |
| Internal energy at 2 (E_2) | = [$E' + \delta m (u_2 + C_2^2/2 + gZ_2)$] |
| Internal energy at 1 (E_1) | = [$E' + \delta m (u_1 + C_1^2/2 + gZ_1)$] |
| Change in internal energy ($E_2 - E_1$) | = [$E' + \delta m (u_2 + C_2^2/2 + gZ_2)$] - [$E' + \delta m (u_1 + C_1^2/2 + gZ_1)$] = $\delta m[(u_2 + C_2^2/2 + gZ_2) -$ $(u_1 + C_1^2/2 + gZ_1)]$ |



SFEE (contd...)



- $Q - [W + dm(p_2 v_2 - p_1 v_1)] = dm [(u_2 + C_2^2/2 + gZ_2) - (u_1 + C_1^2/2 + gZ_1)]$
- $Q - W = dm[(u_2 + C_2^2/2 + gZ_2 + p_2 v_2) - (u_1 + C_1^2/2 + gZ_1 + p_1 v_1)]$
- Recognise that $h = u + pv$ from which $u_2 + p_2 v_2 = h_2$ and similarly

$$u_1 + p_1 v_1 = h_1$$

- $Q - W = dm[(h_2 + C_2^2/2 + gZ_2) - (h_1 + C_1^2/2 + gZ_1)]$

Per unit mass basis

- $q - w = [(h_2 + C_2^2/2 + gZ_2) - (h_1 + C_1^2/2 + gZ_1)]$ or
 $= [(h_2 - h_1) + (C_2^2/2 - C_1^2/2) + g(Z_2 - Z_1)]$

- SFEE



SFEE (contd...)



➤ The system can have any number of entries and exits through which flows occur and we can sum them all as follows.

➤ If 1,3,5 ... are entry points and 2,4,6... are exit points.

$$Q-W = [m_2(h_2 + C_2^2/2 + gZ_2) + m_4(h_4 + C_4^2/2 + gZ_4) + m_6(h_6 + C_6^2/2 + gZ_6) + \dots]$$

$$- [m_1(h_1 + C_1^2/2 + gZ_1) + m_3(h_3 + C_3^2/2 + gZ_3) + m_5(h_5 + C_5^2/2 + gZ_5) + \dots]$$

It is required that $m_1 + m_3 + m_5 + \dots = m_2 + m_4 + m_6 + \dots$

which is the conservation of mass (what goes in must come out)



Some Notes On SFEE



- If the kinetic energies at entry and exit are small compared to the enthalpies and there is no difference in the levels of entry and exit
- $q-w=(h_2 - h_1)=\Delta h$: per unit mass basis or $Q-W= m\Delta h$ (1)
- For a flow process - open system- it is the difference in the enthalpies whereas for a non-flow processes - closed system - it is the difference in the internal energies.



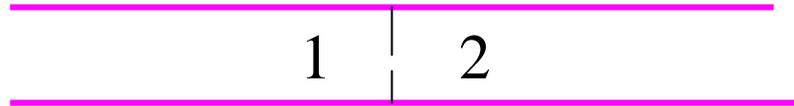
SFEE (contd...)

- $p\,v$ is called the “flow work”. This is not thermodynamic work and can't rise any weight, but necessary to establish the flow.
- For an adiabatic process $q = 0$
 - $-w = \Delta h$ (2)
- ie., any work interaction is only due to changes in enthalpy.
- Note that for a closed system it would have been $-w = \Delta u$



SFEE (Contd...)

Consider a throttling process (also referred to as wire drawing process)



There is no work done (rising a weight) $W=0$

If there is no heat transfer $Q=0$

Conservation of mass requires that $C_1=C_2$

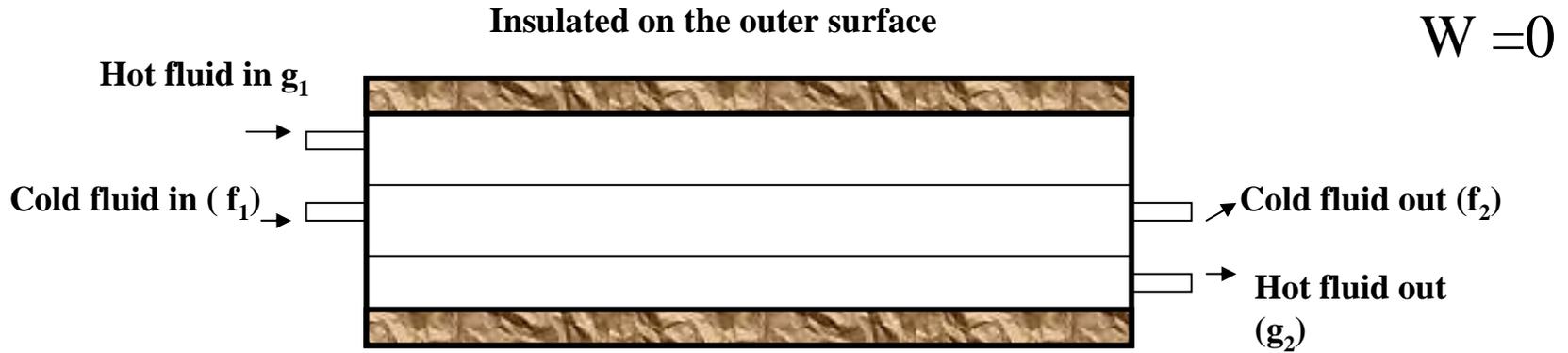
Since 1 and 2 are at the same level $Z_1=Z_2$

From SFEE it follows that $h_1=h_2$

Conclusion: Throttling is a constant enthalpy process
(isenthalpic process)



Heat Exchanger

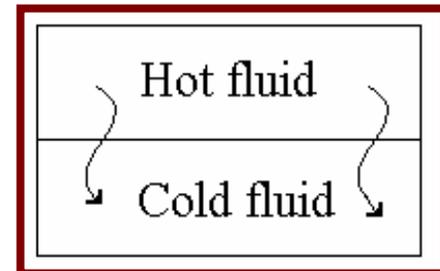


Hot fluid

$$Q_g = m_g (h_{g2} - h_{g1})$$

Cold fluid

$$Q_f = m_f (h_{f2} - h_{f1})$$





Heat Exchanger (contd...)



- ❖ **If velocities at inlet and outlet are the same**
- All the heat lost by hot fluid is received by the cold fluid.
But, for the hot fluid is -ve (leaving the system)
- Therefore $-Q_g = Q_f$
or $m_g (h_{g1} - h_{g2}) = m_f (h_{f2} - h_{f1})$
- You can derive this applying SFEE to the combined system as well (note that for the combined hot and cold system $Q=0; W=0$)
- $0 - 0 = m_f h_{f2} - m_f h_{f1} + m_g h_{g2} - m_g h_{g1}$



Adiabatic Nozzle



Normally used in turbine based power production.

It is a system where the kinetic energy is not negligible compared to enthalpy.

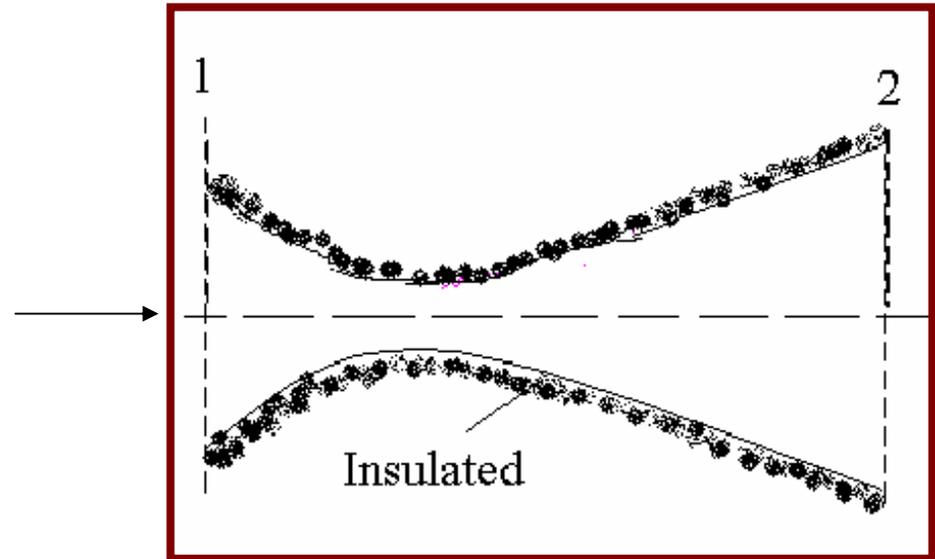
$$Q=0$$

$$W=0$$

SFEE becomes

$$0-0=h_2-h_1+(c_2^2/2-c_1^2/2)$$

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





Adiabatic Nozzle (Contd...)



➤ If h_1 is sufficiently high we can convert it into kinetic energy by passing it through a nozzle. This is what is done to steam at high pressure and temperature emerging out of a boiler or the products of combustion in a combustion chamber (which will be at a high temperature and pressure) of a gas turbine plant. Usually, C_1 will be small - but no assumptions can be made.



Analysis of Air Conditioning Process



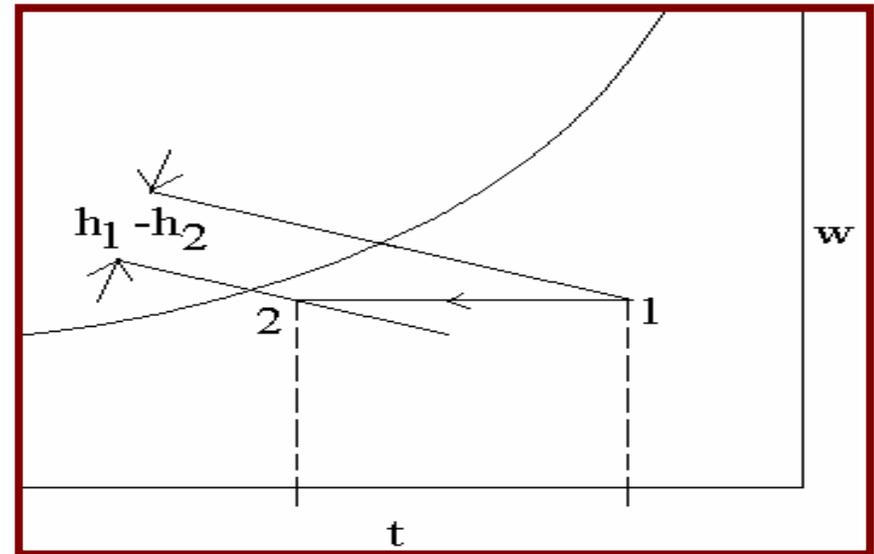
1. Heating of Moist Air

Application of SFEE

(system excluding the heating element)

$$q - 0 = m_a(h_2 - h_1)$$

Air will leave at a higher enthalpy than at inlet.





Air Conditioning Process (Contd...)



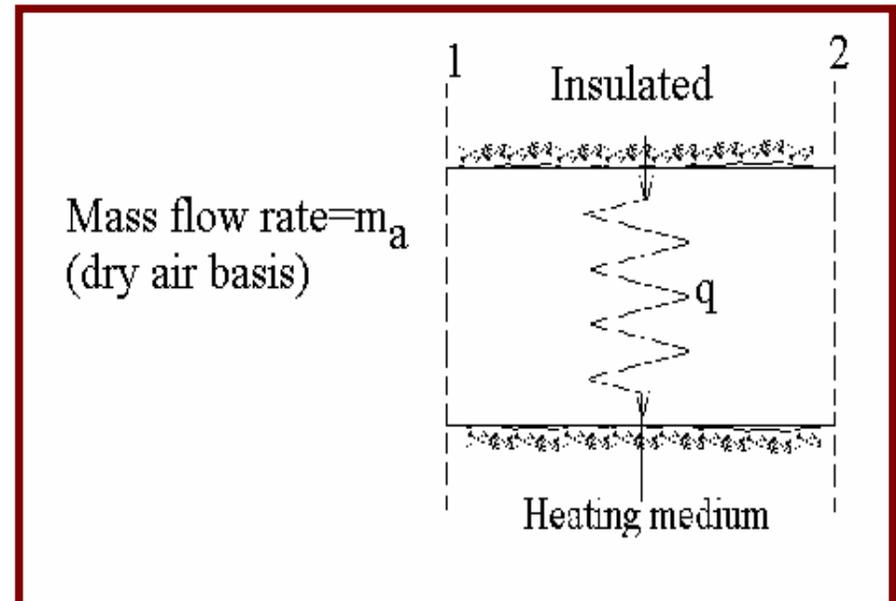
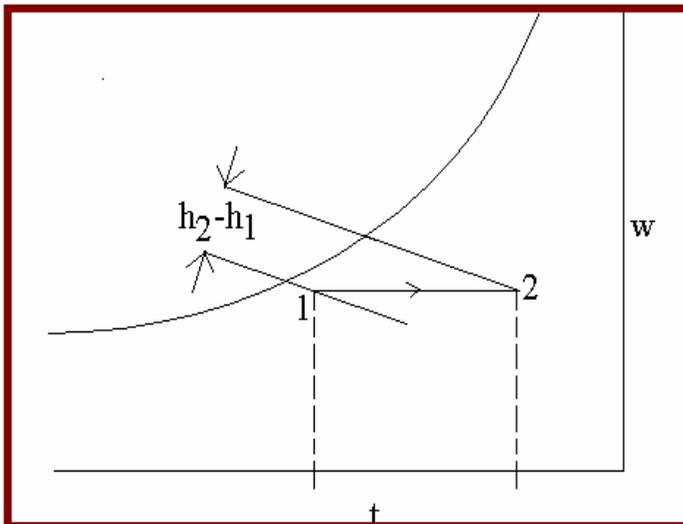
2. Cooling of moist air:

Two possibilities:

a) Sensible cooling (the final state is not below the dew point)

$$-q = m_a(h_2 - h_1) \quad \text{or} \quad q = m_a(h_1 - h_2)$$

Air will leave at a lower enthalpy than at inlet.





Moist Air (contd...)



b. Moisture separates out

- SFEE yields

$$-q - 0 = m_a(h_2 - h_1) + m_w h_w$$

- Moisture conservation

Humidity ratio of entering air at 1 = W_1

Moisture content = $m_a W_1$

Humidity ratio of leaving air at 2 = W_2

Moisture content = $m_a W_2$

Moisture removed = m_w

- What enters must go out !



Moisture Air (Contd...)

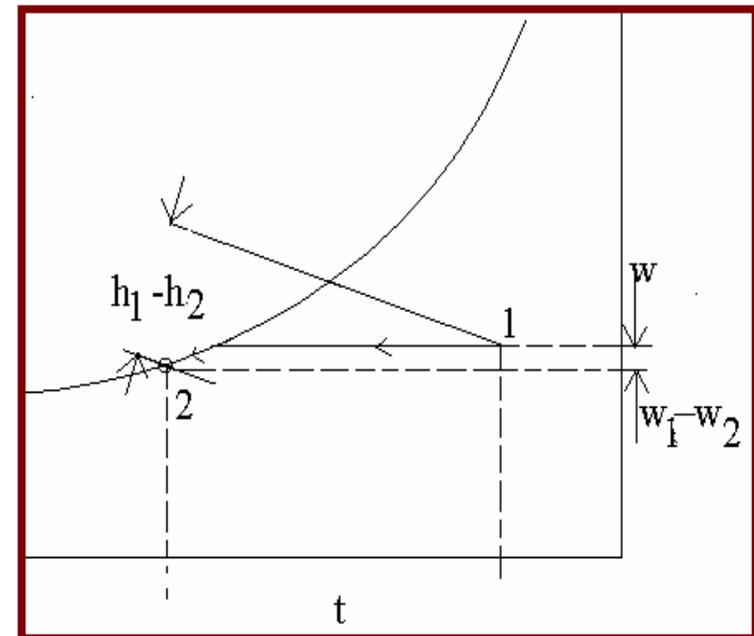
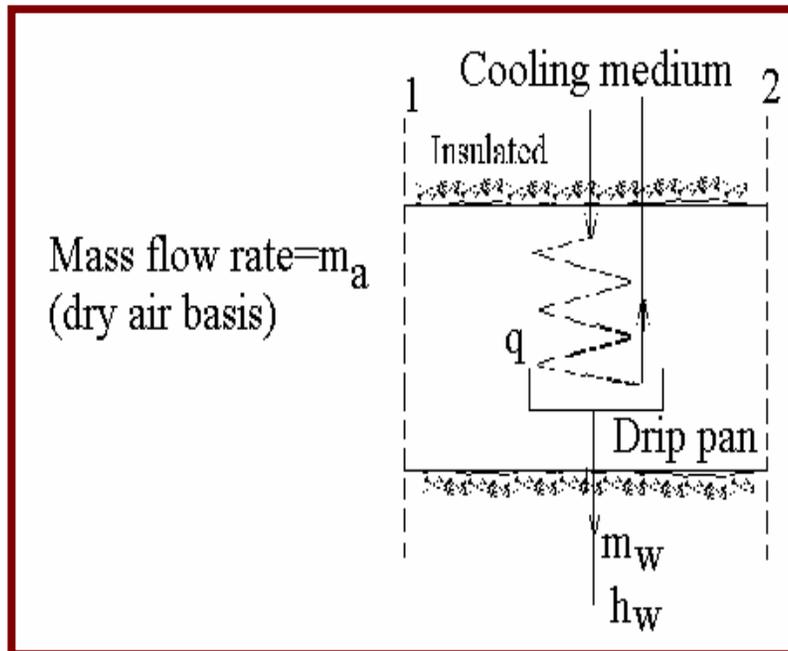


$$m_a W_1 = m_a W_2 + m_w$$

$$m_w = m_a (W_1 - W_2)$$

Substituting into SFEE

$$q = m_a [(h_1 - h_2) - (W_1 - W_2) h_w]$$



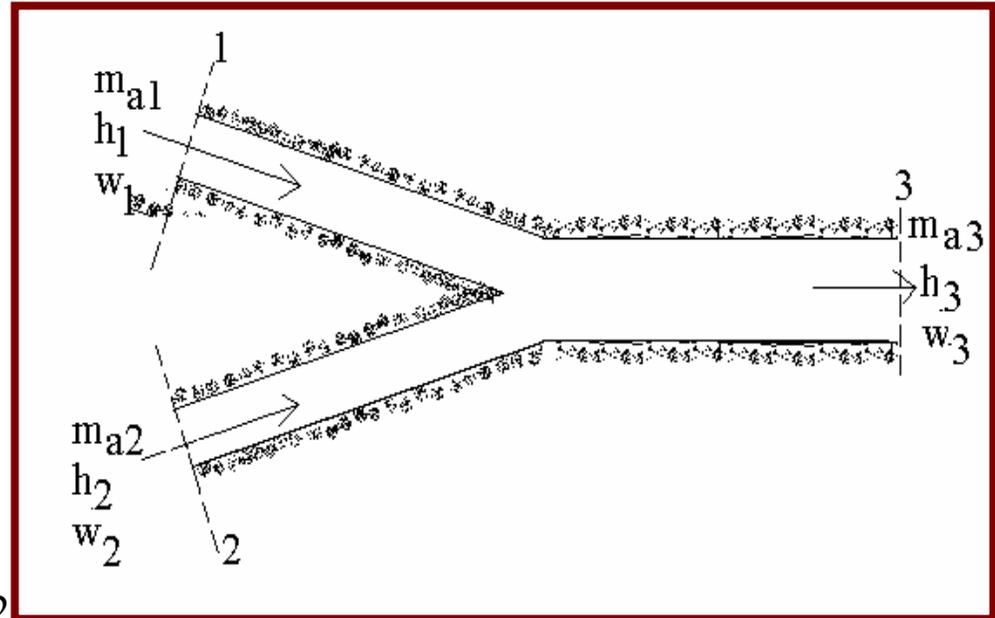


3. Adiabatic Mixture of Two Streams of Air at Separate States



SFEE

- $0-0=m_{a3}h_3-m_{a1}h_1-m_{a2}h_2$
- Dry air conservation
- $m_{a3} = m_{a1} + m_{a2}$
- Moisture conservation
- $m_{a3} w_3 = m_{a1} w_1 + m_{a2} w_2$
- Eliminate m_{a3}
- $(m_{a1}+m_{a2})h_3=m_{a1}h_1+ m_{a2}h_2$
- $m_{a1} (h_3- h_1) =m_{a2} (h_2- h_3)$



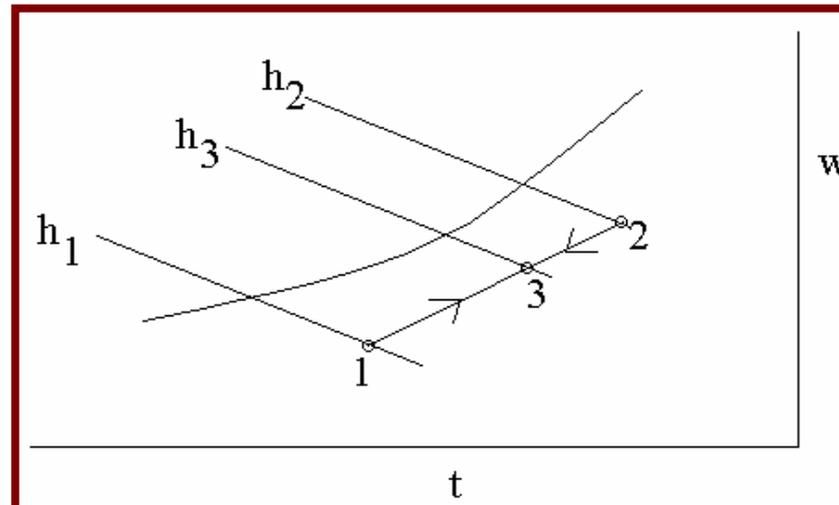


Adiabatic mixture (contd...)



$$\frac{(w_3 - w_1)}{(w_2 - w_3)} = \frac{m_{a2}}{m_{a1}}$$

$$\frac{(t_3 - t_1)}{(t_2 - t_3)} = \frac{m_{a2}}{m_{a1}}$$





Adiabatic mixture (contd...)



Moral: 1. The outlet state lies along the straight line joining the states of entry streams

Moral: 2. The mixture state point divides the line into two segments in the ratio of dry air flow rates of the incoming streams



4. Spraying of Water Into a Stream of Air



SFEE

$$\blacktriangleright 0-0 = m_a h_2 - m_a h_1 - m_w h_w$$

❖ Moisture conservation

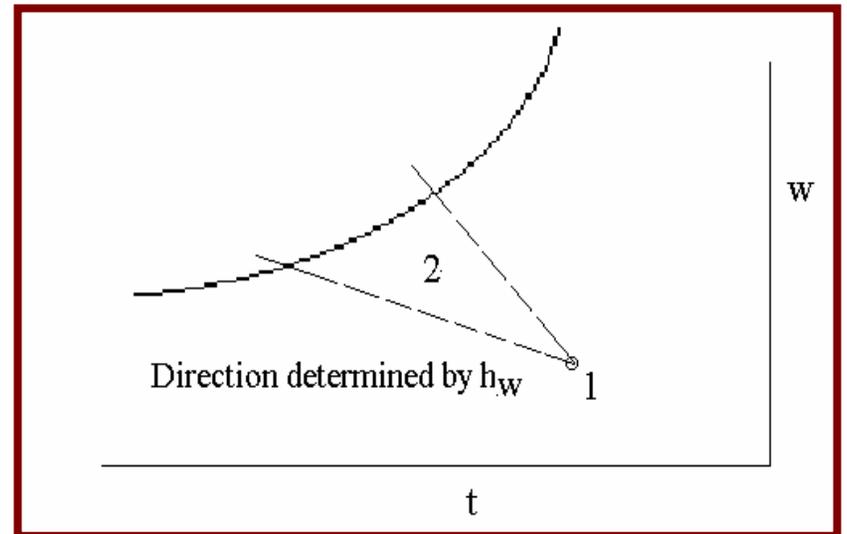
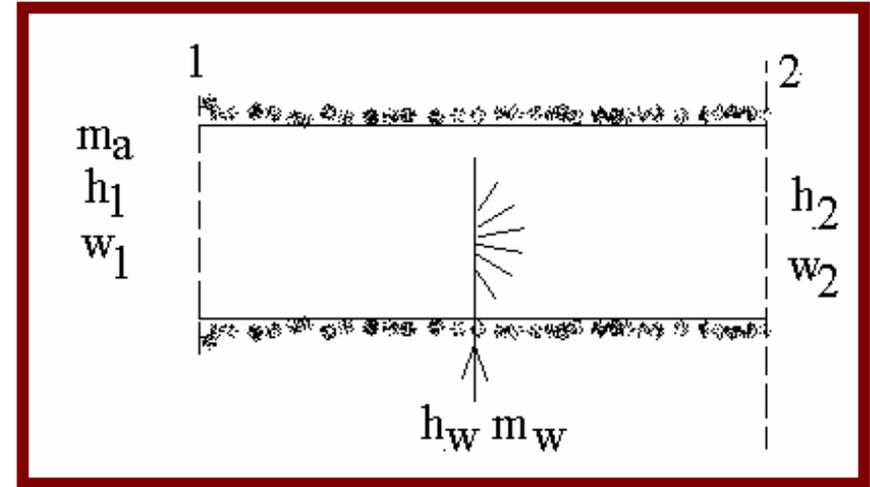
$$\blacktriangleright m_a w_2 = m_a w_1 + m_w$$

$$\blacktriangleright \text{or } m_w = m_a (w_2 - w_1)$$

➤ Substitute in SFEE

$$\blacktriangleright m_a (h_2 - h_1) = m_a (w_2 - w_1) h_w$$

$$\blacktriangleright \text{or } h_w = (h_2 - h_1) / (w_2 - w_1)$$





Spraying of Water (contd...)



Moral: The final state of air leaving lies along a straight line through the initial state Whose direction is fixed by the enthalpy of water injected



5. Injecting steam into a stream of air



- The mathematical treatment exactly the same as though water is injected
- The value of h_w will be the enthalpy of steam
- There is problem in cases 4 and 5!
- We don't know where exactly the point 2 lies
- All that we know is the direction in which 2 lies with reference to 1.



Injecting Steam (contd...)

- On a Cartesian co-ordinate system that information would have been adequate.
- !!But, in the psychrometric chart h and w lines are not right angles!!
- **HOW TO CONSTRUCT THE LINE 1-2 FOR CASES 4 AND 5 ??**



Injecting Stream(contd...)



From the centre of the circle draw a line connecting the value of which is equal to $\frac{\Delta h}{\Delta w}$. (Note that h_w units are kJ/g of water or steam). Draw a line parallel to it through 1.

