Applied Thermodynamics

Prof. Niranjan Sahoo
Department of Mechanical Engineering
Indian Institute of Technology, Guwahati

Module - 01
Review of Basic Thermodynamics
Lecture - 02
Heat and Work Transfer – First Law of Thermodynamics

Dear learners, greetings from IIT Guwahati. We are in the course Applied Thermodynamics.

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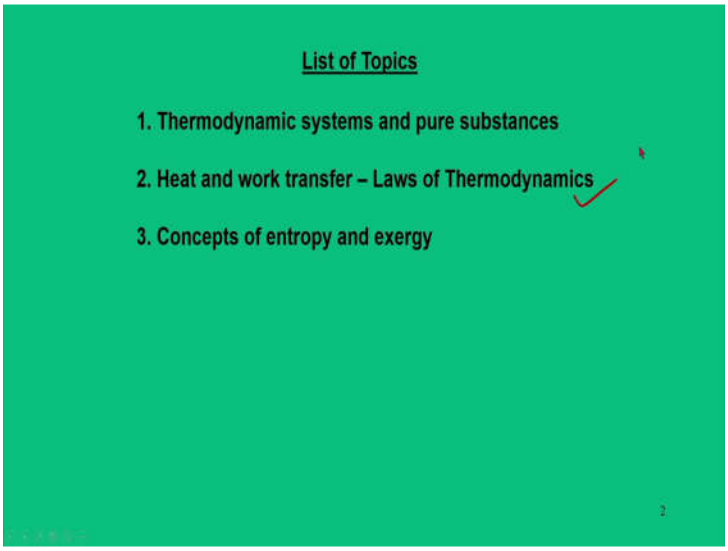

List of Topics

1. Thermodynamic systems and pure substances
2. Heat and work transfer – Laws of Thermodynamics ✓
3. Concepts of entropy and exergy

And in the 1st module that is Review of Thermodynamics or Basic Concepts, we are now in the lecture number 2 that is Heat and mass transfer and Laws of Thermodynamics.

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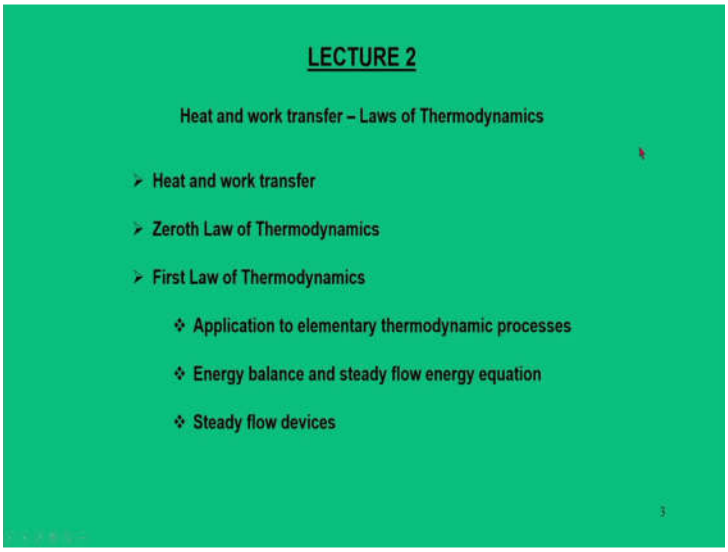

LECTURE 2

Heat and work transfer – Laws of Thermodynamics

- Heat and work transfer
- Zeroth Law of Thermodynamics
- First Law of Thermodynamics
    - Application to elementary thermodynamic processes
    - Energy balance and steady flow energy equation
    - Steady flow devices

So, in this lecture, we will touch upon some of the important concepts such as heat and work transfer. So, here, we will basically give the definitions of heat and work with a viewpoint of thermodynamics. Then, we will discuss about zeroth law of thermodynamics.

It will be followed by first law of thermodynamics. In fact, first law of thermodynamics has a very significant impact for most of the applications. So, in this regard, we will discuss about some elementary thermodynamic processes that will be little used in our applications which will be subsequently covered in the subsequent module.

Then, we will touch upon energy balance and steady flow energy equations and the application of this steady flow energy equation, we will try to see that what are the steady flow devices that can use these equations to solve some elementary problems.

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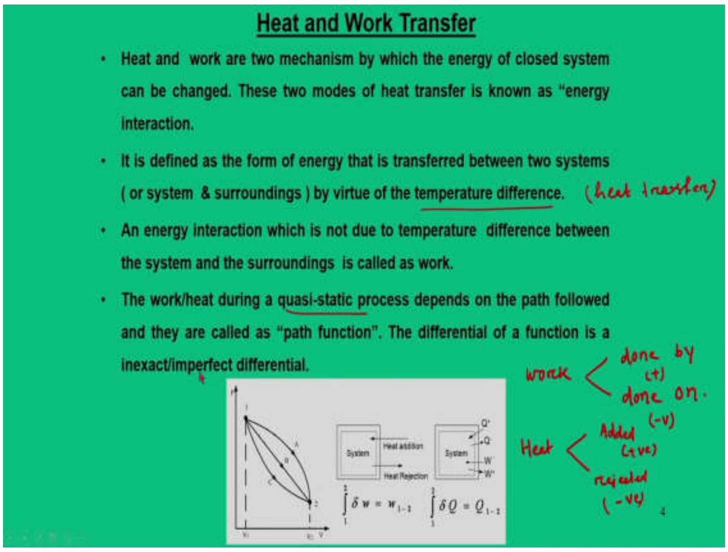

Heat and Work Transfer

- Heat and work are two mechanism by which the energy of closed system can be changed. These two modes of heat transfer is known as "energy interaction.
- It is defined as the form of energy that is transferred between two systems (or system & surroundings) by virtue of the temperature difference. (heat transfer)
- An energy interaction which is not due to temperature difference between the system and the surroundings is called as work.
- The work/heat during a quasi-static process depends on the path followed and they are called as "path function". The differential of a function is a inexact/imperfect differential.

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

work < done by (+) / done on. (-v)

Heat < Added (+ve) / rejected (-ve)

So, let me start the first topic that is heat and work transfer. Now, here, heat and work these are the two terms of energy. Although, they are two terms of energy, but their philosophy of looking at the situation is different. So, basically, these are the two mechanisms by which energy of a closed systems can be changed and these two modes of heat transfer is known as energy interactions either it can be a work mode or heat mode.

And the first one which is the heat transfer, it is the form of energy that is transferred between the systems and surroundings by virtue of temperature difference. So, the temperature difference means it is due to heat transfer. Now, any interactions which does not involve the temperature difference, we recognize it as a work transfer.

So, the thermodynamic definition of energy interaction is by two modes either heat or work. If it is a temperature difference, the mode of interaction is heat and anything that is not due to temperature difference, that we call this as a work transfer.

In fact, in a closed system if you look at the terminology that we are going to use either it can be heat addition or it can be a heat rejection. When it is a heat addition, we say Q is positive. When it is a heat rejection, we say Q is negative. Side-by-side if you look at the work transfer, when heat is added to systems and the system delivers some work so, in that situation we say it is a work done by the system so, it is a positive.

And when heat is rejected from a system side-by-side due to the work interaction, then in that case we can say when Q is negative, work is positive, Q is positive work is negative. So, those terminology we will be using in our applications.

So, it is very important to recognize when the heat transfer is consider as a positive at that time we have to take the work interaction as negative. If it is so, there are two terms used, work done by the system; work done on the system.

So, when it is work done by the system so, we recognize this as a positive, when it is work done on the system, we recognize this as a negative. Similarly, for heat may be added so, we say it is a positive, when heat rejected, it is recognized as negative. So, these terms we are going to use.

Another important similarity between heat and work transfer is that both are recognized as a path functions so, it depends on the path. So, if you look at the PV diagrams, a system undergoes a change of state from 1 to 2 in three different paths A, B, C and of course, when you define them as a path function, the process needs to be a quasi-static one and since they are path functions so, they are not exact differential.

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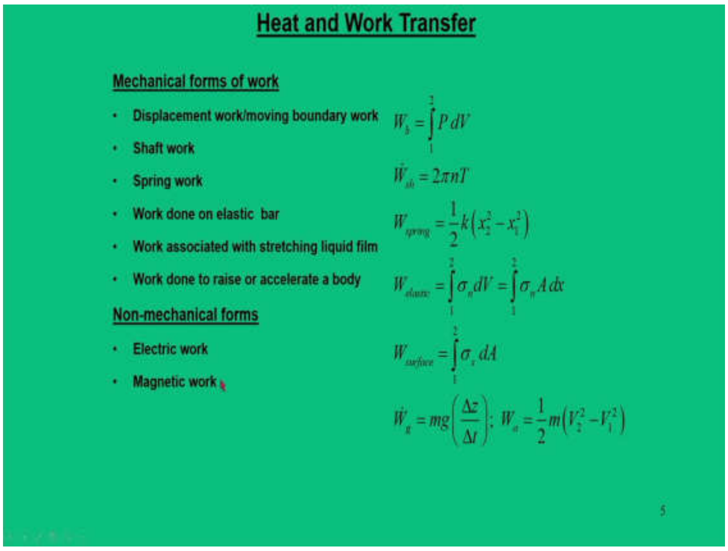

Heat and Work Transfer

Mechanical forms of work

- Displacement work/moving boundary work
- Shaft work
- Spring work
- Work done on elastic bar
- Work associated with stretching liquid film
- Work done to raise or accelerate a body

Non-mechanical forms

- Electric work
- Magnetic work

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

$$\dot{W}_{sh} = 2\pi n T$$

$$W_{spring} = \frac{1}{2}k\left(x_2^2 - x_1^2\right)$$

$$W_{elastic} = \int_1^2 \sigma_n\,dV = \int_1^2 \sigma_n A\,dx$$

$$W_{surface} = \int_1^2 \sigma_s\,dA$$

$$\dot{W}_g = mg\left(\frac{\Delta z}{\Delta t}\right);\ W_a = \frac{1}{2}m\left(V_2^2 - V_1^2\right)$$

Now, once we say recognize energy interaction as heat, then what else we can recognize as a work? So, there are thermodynamic way we recognize this work. So, we can have a mechanical form of work or non-mechanical form of work. The mechanical form of work means displacement work or moving boundary work, shaft work, spring works, work done by the elastic bar, work associated with stretching a liquid films, work require to raise and accelerate the body, raising the body or accelerating the body.

So, these are the different forms of work. Now, accordingly, one can find out the work transfer in these kind of applications. So, of course, when you recognize this work, these are the different applications what you see here.

First one maybe we are mostly using by the shaft work, it is mostly used in thermodynamics or IC engines. Spring work when the system is getting compressed or expanded through spring, there is a work done in the elastic bar so, normally this work we are using in the topic solid mechanics.

Work associated with stretching a liquid film, this is normally used when you deal with the bubbles formations and that is due to the capillary actions and we are using it in the fluid mechanics, work done to raise the system or raise a body so, it is due to potential energy, work required to accelerate a body so, we require a thrust. So, all these forms of energy we can compute the work transfer.

However, apart from this mechanical work, we also have non-mechanical form of work which we are not at all using in this course. So, they are like electric work or magnetic work.

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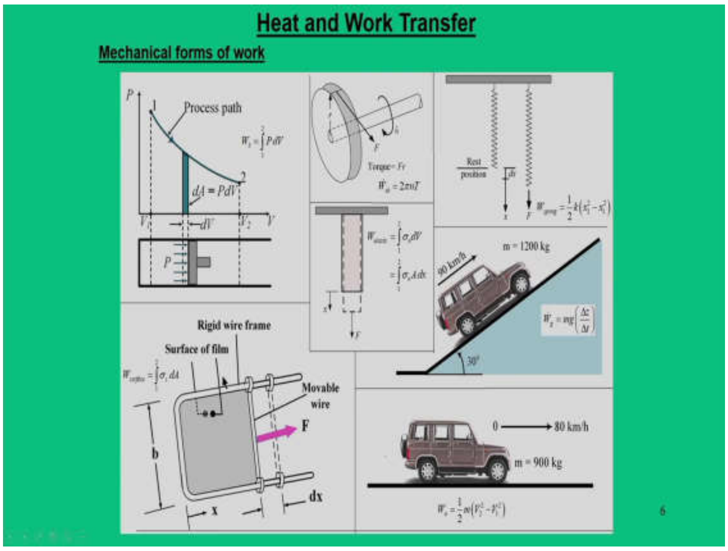

Heat and Work Transfer

Mechanical forms of work

So, these are the some examples which has been given like this particular situation is piston motion within a cylinder so, we can recognize this as a PdV work and the rotation of a shaft, we can say it is a shaft work. So, elongation of a spring we can call this as a spring work. Elongation of an elastic bar, we can call it as a elastic work. The soap bubble expansion in a liquid film is known as a surface tension work.

When we are going in an off hill that means, we are going in an inclined path so, we are raising a body so, we require a gravitational work. Then, when we are moving on a horizontal surface in a vehicle so, we can say it is a work to be done due to the change in the kinetic energy so, you say acceleration work. So, all these kind of mechanical form work we are commonly used in our day to day life.

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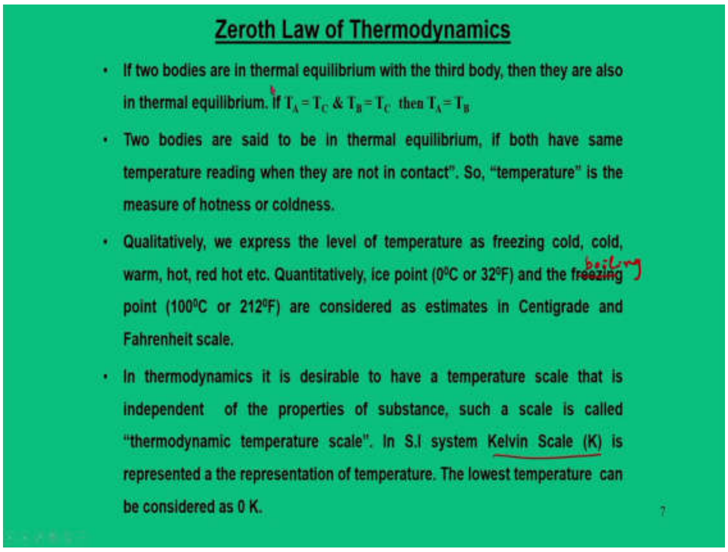

Zeroth Law of Thermodynamics

- If two bodies are in thermal equilibrium with the third body, then they are also in thermal equilibrium. If $T_A = T_C$ & $T_B = T_C$ then $T_A = T_B$
- Two bodies are said to be in thermal equilibrium, if both have same temperature reading when they are not in contact". So, "temperature" is the measure of hotness or coldness.
- Qualitatively, we express the level of temperature as freezing cold, cold, warm, hot, red hot etc. Quantitatively, ice point (0^0C or 32^0F) and the ~~freezing~~ boiling point (100^0C or 212^0F) are considered as estimates in Centigrade and Fahrenheit scale.
- In thermodynamics it is desirable to have a temperature scale that is independent of the properties of substance, such a scale is called "thermodynamic temperature scale". In S.I system Kelvin Scale (K) is represented a the representation of temperature. The lowest temperature can be considered as 0 K.

Now, having recognized these things, now let us move to laws of thermodynamics. The first law is which is known as zeroth law of thermodynamics. So, this particular laws has a significance which gives the indication of a temperatures. So, it talks about temperature is one of the property and it says that if two bodies are in thermal equilibrium with the third body.

Then they are also in thermal equilibrium that means if temperature body A is equal to temperature of body C and temperature of body B is equal to temperature of body C, then temperature of A and B are equal. Now, when we are talking this as a thermal equilibrium, then we have to say that both have same temperature readings when they are not in contacts.

So, the basic significance of zeroth law it gives the indication of a temperature which is nothing but the measure of hotness and coldness. Now, to quantify these temperatures, we require some scale, temperature scale and the temperature scales are quantitatively defined through ice point or steam point in two coordinates, one is in the degree centigrade, other is in the degree Fahrenheit.

So, ice point in the centigrade scale is recognized as 0°C or 32°F similarly, boiling point of water is recognized at 100°C in centigrade scale and 212°F in the Fahrenheit scale.

So, these are the estimates, but one important thing here that when you keep measuring of the temperature, we require a working fluid, but the temperature scale and Fahrenheit scale does not be represented without any working fluid. So, to counteract these, we have another scale which is known as Kelvin scale of course, this Kelvin scale came of when we have second law of thermodynamics that means, this Kelvin scale came off after we recognize the second law of thermodynamics.

And here, the temperature scale is independent of properties of the substance. So, this is one of the significant scale and we call this as a thermodynamic temperature scale and in fact, till date, the lowest temperature that we have is 0°K. So, this is what we have zeroth law of thermodynamics, it gives the sense of temperature.

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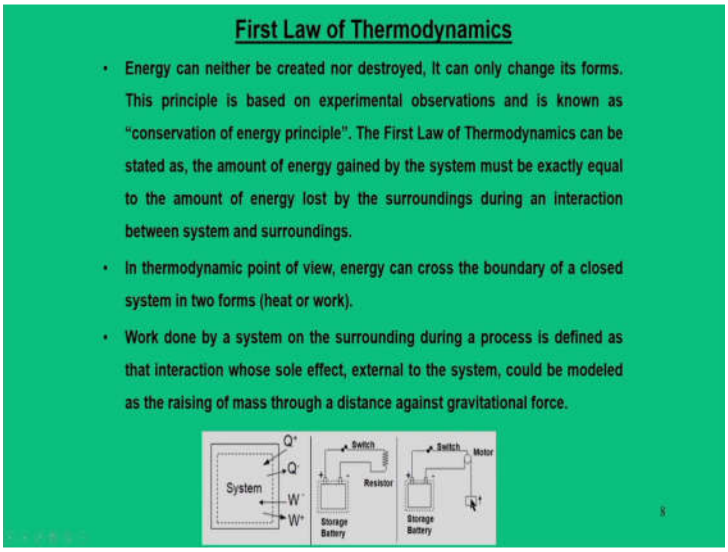

First Law of Thermodynamics

- Energy can neither be created nor destroyed, It can only change its forms. This principle is based on experimental observations and is known as "conservation of energy principle". The First Law of Thermodynamics can be stated as, the amount of energy gained by the system must be exactly equal to the amount of energy lost by the surroundings during an interaction between system and surroundings.
- In thermodynamic point of view, energy can cross the boundary of a closed system in two forms (heat or work).
- Work done by a system on the surrounding during a process is defined as that interaction whose sole effect, external to the system, could be modeled as the raising of mass through a distance against gravitational force.

Now, moving on to first law of thermo dynamics so, we all know from our basic instinct that energy can neither be created nor be destroyed, but it can change only its form. So, this particular principle is based on the experimental observation so, we call this as a conservation of energy.

So, based on this conservation of energy, we say that amount of energy gained by the system must be equal to the amount of energy lost to the surroundings during an interaction process between system and surroundings. So, since we are dealing with thermodynamics, this interaction is only by two modes, heat or work.

So, this particular example have given that when we have heat interaction and some situation, we have work interaction for a close systems. But with a viewpoint of work and heat, we say particularly work, when we view that by definition of work is that this interaction must be such that it can be viewed as a rising or falling a body or certain mass.

For example, if you have a source of electrical energy which is in the form of storage battery, and we have a resistor so, in this way we are consuming the electrical work, but this particular situation can be viewed that resistor can be replaced with a motor and that motor can be used to raise or fall a weight or body. So, that means, these particular things we can view it as a work transfer. So, that is the reason all these electrical application, we can view in thermodynamically, we call this as a work transfer.

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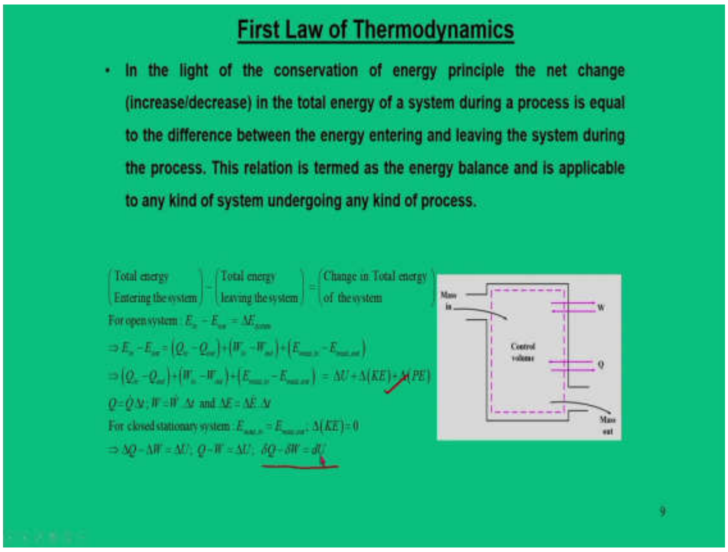

First Law of Thermodynamics

- In the light of the conservation of energy principle the net change (increase/decrease) in the total energy of a system during a process is equal to the difference between the energy entering and leaving the system during the process. This relation is termed as the energy balance and is applicable to any kind of system undergoing any kind of process.

$$\begin{pmatrix}\text{Total energy}\\ \text{Entering the system}\end{pmatrix}-\begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix}=\begin{pmatrix}\text{Change in Total energy}\\ \text{of the system}\end{pmatrix}$$

For open system : $E_{in}-E_{out}=\Delta E_{System}$

$\Rightarrow E_{in}-E_{out}=(Q_{in}-Q_{out})+(W_{in}-W_{out})+(E_{mass,in}-E_{mass,out})$

$\Rightarrow (Q_{in}-Q_{out})+(W_{in}-W_{out})+(E_{mass,in}-E_{mass,out})=\Delta U+\Delta(KE)+\Delta(PE)$

$Q=\dot{Q}\,\Delta t;\ W=\dot{W}\,\Delta t$ and $\Delta E=\Delta\dot{E}\,\Delta t$

For closed stationary system : $E_{mass,in}=E_{mass,out};\ \Delta(KE)=0$

$\Rightarrow \Delta Q-\Delta W=\Delta U;\ Q-W=\Delta U;\ \underline{\delta Q-\delta W=dU}$

Now, let us see that when we are going to deal with the first law of thermodynamics, how energy of a system can change. So, when we are looking at the energy balance or first law of thermodynamics when we are going to apply for energy balance system in an open or control volume system. So, by control volume I mean that there is a possible work transfer, there is a possible heat transfer in addition to these, we will have also mass can come in and can go out.

So, this is most generic definition or general definition that how energy can come into a control volume, but whereas, when we deal with the close systems, we do not have mass interactions so, it is a very general way that normally, when you deal with the energy balance equations, we take a control volume approach.

So, if you look at this particular figure so, we have work interactions W, we have heat interaction Q and side-by-side there is some mass which is coming up and there is some mass is going out and in a practical situation, there may be multiple entry of mass and multiple exit of mass. Similarly, there are multiple entries of work transfer and multiple entries of heat transfer as well so, all sorts of things that can be summed up.

So, very basic equation that can be derived from this first law of thermodynamics is that a total energy entering the system minus the total energy leaving the system is the change in the total energy of the system. Now, that means, $E_{in} - E_{out} = \Delta E$. So, what is this E$_{in}$ and E$_{out}$? $E_{in} - E_{out}$ can be from $\left(Q_{in} - Q_{out}\right) + \left(W_{in} - W_{out}\right) + \left(E_{mass,in} - E_{mass,out}\right)$.

So, when we sum it up these things, then we can get the left-hand side of this equation in this form of heat, work and E$_{mass,in}$ and E$_{mass,out}$, but what is the delta ΔE_{system} ? System can change its internal energy U, it can change its kinetic energy, it can change its potential energy. So, this is the very basic definition or energy balance equation based on the first law.

Now, when we apply for a closed systems so, we are restricting the mass interactions. So, there is no mass interactions and of course, when if system is stationary so, there is no change in the kinetic energy. So, it takes a very simple form between work, heat and internal energy that is $\Delta Q - \Delta W = \Delta U$.

So, in a small differential form, we can say $\delta Q - \delta W = dU$. So, here if you see since heat and work are path function so, it is represented as inexact differential whereas, U is a property that is internal energy; so, it is represented in the exact differential.

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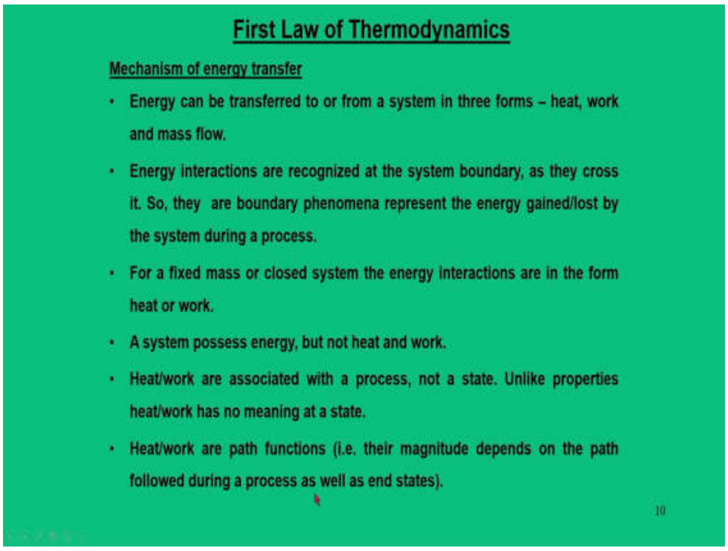

First Law of Thermodynamics

Mechanism of energy transfer

- Energy can be transferred to or from a system in three forms – heat, work and mass flow.
- Energy interactions are recognized at the system boundary, as they cross it. So, they are boundary phenomena represent the energy gained/lost by the system during a process.
- For a fixed mass or closed system the energy interactions are in the form heat or work.
- A system possess energy, but not heat and work.
- Heat/work are associated with a process, not a state. Unlike properties heat/work has no meaning at a state.
- Heat/work are path functions (i.e. their magnitude depends on the path followed during a process as well as end states).

So, these particular things that mechanism of energy transfer, I have already told that energy interactions are recognized when the energy crosses the boundary; so, it is a boundary phenomena. So, for a fixed mass system or closed systems, it is in the form of heat and work. So, a system possesses energy, but we cannot say system possesses heat or system possesses work because these are boundary phenomena.

So, heat and work associated with a process not a state. Unlike properties heat and work has no meaning at a states. So, it is wrong to say that heat at a state one and last one is that heat and work are path functions because their magnitude depends on the path followed by a process as well as its end state.

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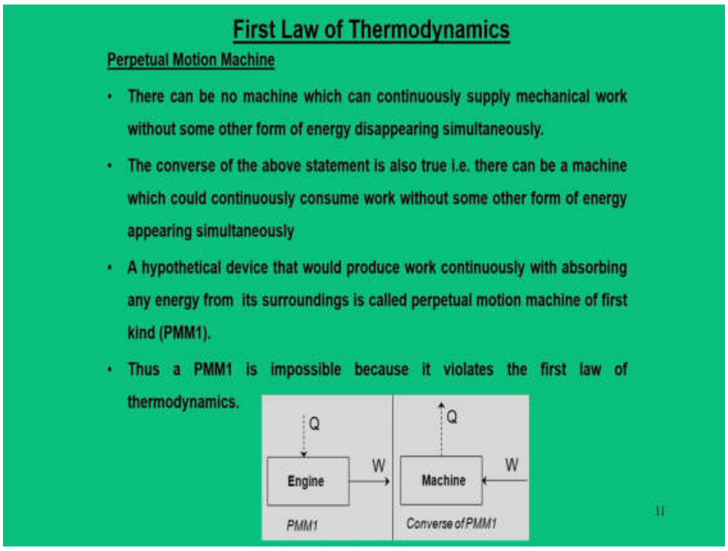

First Law of Thermodynamics

Perpetual Motion Machine

- There can be no machine which can continuously supply mechanical work without some other form of energy disappearing simultaneously.
- The converse of the above statement is also true i.e. there can be a machine which could continuously consume work without some other form of energy appearing simultaneously
- A hypothetical device that would produce work continuously with absorbing any energy from its surroundings is called perpetual motion machine of first kind (PMM1).
- Thus a PMM1 is impossible because it violates the first law of thermodynamics.

So, there is another concept called perpetual motion machine and in fact, this is hardly used word. So, the very basic philosophy is that if till date, we have said that in fact, all first law of thermodynamics is an experimental observations and none of the system has violated this particular law till date. So, that means, it is an experimental observations and side-by-side till this point of time, every system that agrees the first law of thermodynamics.

Now, the concept or hypothetical term that is used perpetual motion of machine; means it is a device that would produce work continuously with absorbing any energy from its surroundings. So, we cannot keep on producing work continuously for lifetime, for infinite time so, in such cases we say PMM1 is impossible. So, it is a very hypothetical term.

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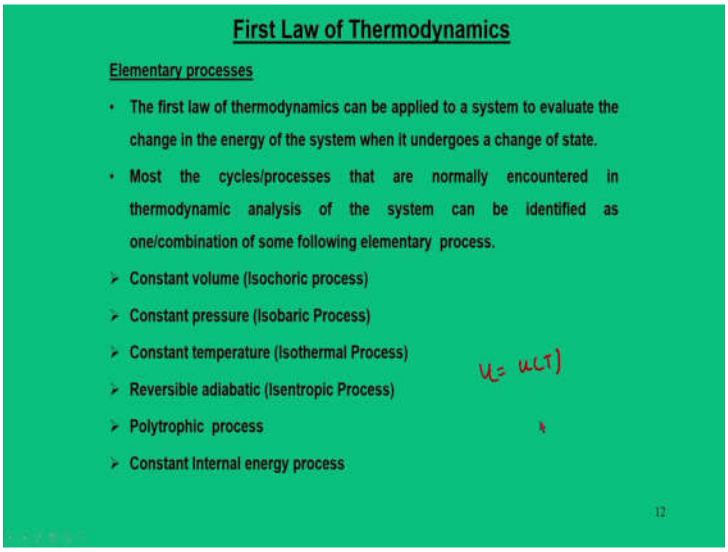

First Law of Thermodynamics

Elementary processes

- The first law of thermodynamics can be applied to a system to evaluate the change in the energy of the system when it undergoes a change of state.
- Most the cycles/processes that are normally encountered in thermodynamic analysis of the system can be identified as one/combination of some following elementary process.

- Constant volume (Isochoric process)
- Constant pressure (Isobaric Process)
- Constant temperature (Isothermal Process)
- Reversible adiabatic (Isentropic Process)
- Polytrophic process
- Constant Internal energy process

$u = u(T)$

Now, after understanding this, let me tell about some elementary processes that are we are used in the thermodynamic systems and in fact, these elementary processes are very vital for subsequent applications in the steams, in refrigeration, in the gas cycle, in the IC engine cycles; so, all these processes are routinely used.

So, what are the processes? So, basically there are constant volume processes, we call this as isochoric process, constant pressure process, we say isobaric process these are mostly used in the IC engines. Constant temperature process which is a isothermal process, it gives a indication that the process is very slow because a process has to take in a very slow manner to make the temperature constant so, it is a isothermal processes.

We also have a reversible adiabatic or isentropic process and side-by-side we can also have a non-reversible process or simply adiabatic process. We have polytrophic process; polytrophic process is something gives a very general definition which can take care all types of thermodynamic processes and last one is a constant internal energy processes.

So, here I will make an emphasize here that when we have constant internal energy because till this point of time, we say u is a function of temperature. So, it means that whenever temperature remains constant, internal energy also remains constant, but in some situations, the internal energy in a non-reversible situation maybe constant, but temperature need not be. So, I will tell you some examples in the subsequent slide.

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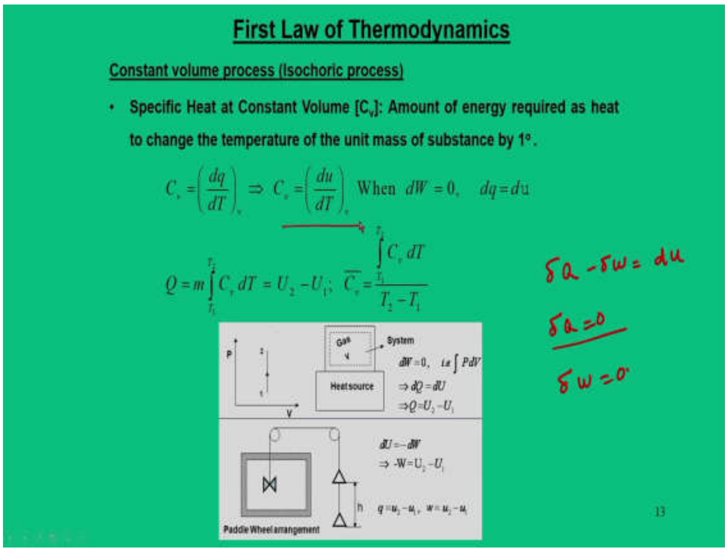

First Law of Thermodynamics

Constant volume process (Isochoric process)

- **Specific Heat at Constant Volume [C_v]: Amount of energy required as heat to change the temperature of the unit mass of substance by 1°.**

$$C_v = \left(\frac{dq}{dT}\right)_v \Rightarrow C_v = \left(\frac{du}{dT}\right)_v \quad \text{When } dW = 0, \quad dq = du$$

$$Q = m\int_{T_1}^{T_2} C_v\, dT = U_2 - U_1; \quad \overline{C}_v = \frac{\int_{T_1}^{T_2} C_v\, dT}{T_2 - T_1}$$

$dW = 0$, i.e. $\int PdV$

$\Rightarrow dQ = dU$

$\Rightarrow Q = U_2 - U_1$

$dU = -dW$

$\Rightarrow -W = U_2 - U_1$

$q = u_2 - u_1, \ w = u_2 - u_1$

$\delta Q - \delta W = du$

$\delta Q = 0$

$\delta W = 0$

So, let me say first one is constant volume processes so, it is a isochoric processes. So, a typical example is that when you draw this isochoric processes, it is a vertical straight line in a PV diagram. So, process undergoes from 1 to 2; so, in this process, your volume does not change. Typical example could be that we have a heat source and a system containing a gas of certain volume V is taking this heat.

So, in this process, what happens? There is no work transfer that is dW is 0, but it is getting heat. So, dQ that means, entire heat is getting utilized in changing its internal energy or in the form of temperatures. So, when we are adding heat, so, obviously, temperature of the gas is going to rise.

Another way of looking at the thing is that here, when you have no heat interactions like in this case, there is a paddle wheel arrangements; so, we have a pulley and by raising or falling this particular mass, we are regulating what is going to happen within this container or the system.

So, what happens here? There is no heat interactions, but the work which is being used through this mass is getting utilized in changing its internal energy. So, basically speaking, if you look at dQ - dW = dU, then one situation your ΔQ is 0, other situation is ΔW is 0.

So, if you have this ΔQ is 0, then W can be represented as $U_2 - U_1$. If ΔW is 0, then q can be represented as $U_2 - U_1$ and of course, when we deal with the constant volume process, we must recall that there is a term which you are using called as specific heat at constant volume that is amount of energy required as heat to change the temperature of unit mass by 1°C. So, that way, we can define the $C_v = \left(\frac{du}{dT}\right)_v$.

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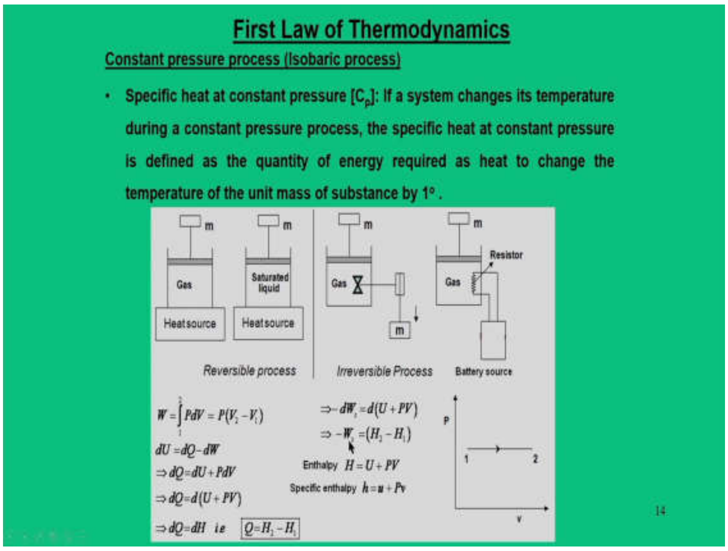

First Law of Thermodynamics

Constant pressure process (Isobaric process)

- Specific heat at constant pressure [C_p]: If a system changes its temperature during a constant pressure process, the specific heat at constant pressure is defined as the quantity of energy required as heat to change the temperature of the unit mass of substance by 1° .

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

$dU = dQ - dW$

$\Rightarrow dQ = dU + PdV$

$\Rightarrow dQ = d(U + PV)$

$\Rightarrow dQ = dH \;\; i.e \;\; \boxed{Q = H_2 - H_1}$

$\Rightarrow -dW_s = d(U + PV)$

$\Rightarrow -W_s = (H_2 - H_1)$

Enthalpy $H = U + PV$

Specific enthalpy $h = u + Pv$

The next process that we are going to discuss is about constant pressure. So, in a constant pressure process, in PV diagram it is a horizontal straight line. So, here there are two situations which is given in this example, one could be a reversible process. So, in the reversible processes, we can have a heat source and this heat source is utilized to heat a gas or saturated liquid and this particular system is in equilibrium with a mass m at certain positions.

So, in first case, when we are talking about this $dU = dQ - dW$ so, when we can write this dW as PdV, PdV means that when we are using this heat, the piston keeps on raising or falling depending on the amount of heat is getting added or rejected.

So, side-by-side the volume of the gas or this particular liquid keeps on changing. So, we can represent that in the form of PdV. So, that is here it is written $dQ = dU + PdV$ and when U + PV you can merge in a single term as a differential and we give a name as enthalpy that is H = U + PV so, dQ becomes dH.

So, in a constant pressure process heat addition is nothing but the difference in the total enthalpy and we also can have another situation define that specific enthalpy we can define in this manner. This is what we get in a heat addition process.

Now, when there is no heat additions; so, similar expression also can be drawn here where the gas is controlled or the temperature of the gas is controlled through raising or falling mass system and these particular things when you do is basically instead of heat we are doing work transfer in the form of shaft work. So, here this work transfer is recognized as the difference in the enthalpy.

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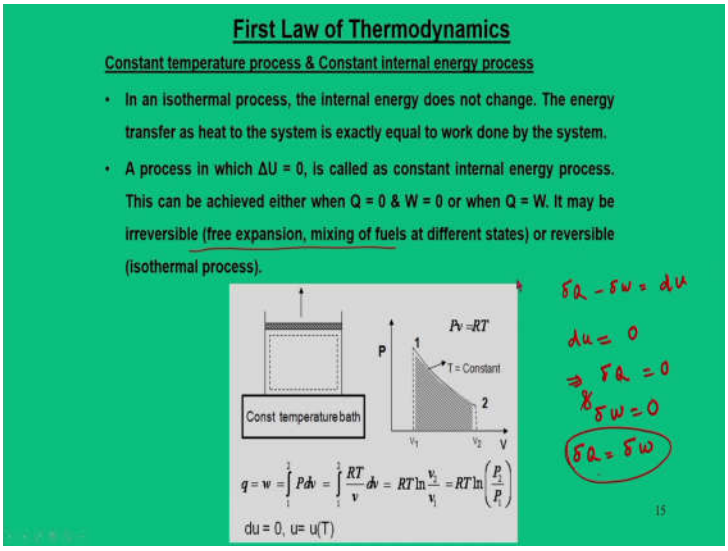

First Law of Thermodynamics

Constant temperature process & Constant internal energy process

- In an isothermal process, the internal energy does not change. The energy transfer as heat to the system is exactly equal to work done by the system.
- A process in which ΔU = 0, is called as constant internal energy process. This can be achieved either when Q = 0 & W = 0 or when Q = W. It may be irreversible (free expansion, mixing of fuels at different states) or reversible (isothermal process).

$$q = w = \int_1^2 P\,dv = \int_1^2 \frac{RT}{v}\,dv = RT\ln\frac{v_2}{v_1} = RT\ln\left(\frac{P_1}{P_2}\right)$$

du = 0, u= u(T)

$\delta Q - \delta W = du$

$du = 0$

$\Rightarrow \delta Q = 0$

$\& \ \delta W = 0$

$\boxed{\delta Q = \delta W}$

Then moving further, we are now in the constant temperature and constant internal energy processes. So, in some situation what happens? Let us check when you have a constant temperature process normally, we call this as a isothermal processes.

So, it means in an isothermal processes, temperature do not change so, internal energy does not change. The energy transferred to the heat is exactly equal to work done by the systems. So, this is represented $q = w = \int_1^2 p dv$ so, accordingly, q or w we can find out by integrating the system which undergo change of state so, $RT \ln\left(\frac{p_1}{p_2}\right)$, this is one aspect.

But another aspect is that when you deal with the constant internal energy processes so, for example, in that case, you are saying that ΔU is equal to 0 it is a constant internal energy process and this can be achieved either Q is equal to 0 so, if you take $\delta q - \delta w = dU$ and if dU can be 0, this will implies either dQ is equal to 0 or dW is equal to 0 or dQ = dW. Both Q and W are 0 is very hypothetical or dQ = dW.

So, on such cases, but here it has nothing to do with temperature if you see here, it is comes from first law, it has nothing to do with temperature when dQ is equal to dW, what is the situation? There are some situation, the processes which are irreversible for example, free expansion, mixing of two fuels at different states. So, these are the some of the irreversible processes where we are recognized as a constant internal energy processes whereas, isothermal processes is a reversible one.

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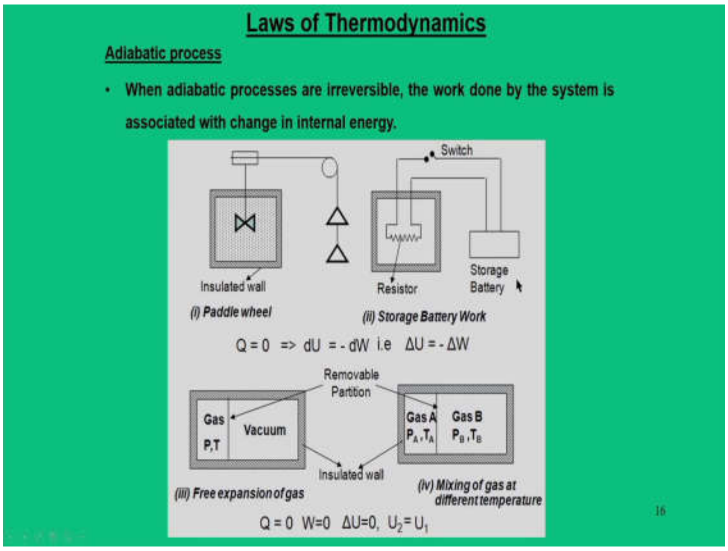

Laws of Thermodynamics

Adiabatic process

- When adiabatic processes are irreversible, the work done by the system is associated with change in internal energy.

$Q = 0 \Rightarrow dU = -dW$ i.e $\Delta U = -\Delta W$

$Q = 0 \quad W = 0 \quad \Delta U = 0, \; U_2 = U_1$

Then, this is the example that talks about that how we can have a free expansion of gas. So, we have a gas in a container and this particular gas is separated by two entities, one at certain pressure press P and T other is in the vacuum. Now, if you remove this partition, suddenly gas comes into contact. So, in this process, there is no heat transfer, there is no work transfer, so, internal energy is equal to 0.

Another situation could be mixing of gas at two different temperature gas A, gas B at different conditions. So, in that case finally, U2 becomes U1. So, these are the some situations where we can recognize a constant internal energy or a constant isothermal processes.

Another process it can be adiabatic. So, adiabatic process is a irreversible one. So, the work done by the system is associated with the change in the internal energy. So, mostly most of our systems are adiabatic, when we say there is no heat interactions. So, that means, the work done by the system is associated with the change in the internal energy.

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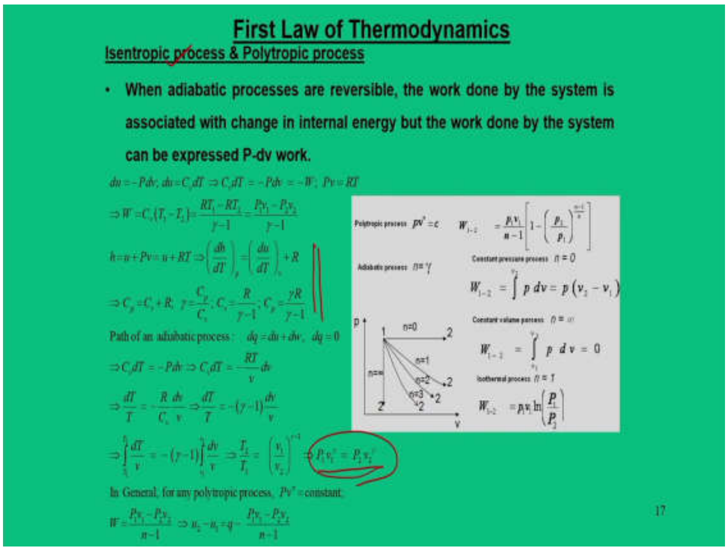

First Law of Thermodynamics

Isentropic process & Polytropic process

- When adiabatic processes are reversible, the work done by the system is associated with change in internal energy but the work done by the system can be expressed P-dv work.

$du = -Pdv;\ du = C_v dT \Rightarrow C_v dT = -Pdv = -W;\ Pv = RT$

$\Rightarrow W = C_v(T_1 - T_2) = \frac{RT_1 - RT_2}{\gamma - 1} = \frac{P_1v_1 - P_2v_2}{\gamma - 1}$

$h = u + Pv = u + RT \Rightarrow \left(\frac{dh}{dT}\right)_p = \left(\frac{du}{dT}\right)_v + R$

$\Rightarrow C_p = C_v + R;\ \gamma = \frac{C_p}{C_v};\ C_v = \frac{R}{\gamma - 1};\ C_p = \frac{\gamma R}{\gamma - 1}$

Path of an adiabatic process : $dq = du + dw,\ dq = 0$

$\Rightarrow C_v dT = -Pdv \Rightarrow C_v dT = -\frac{RT}{v} dv$

$\Rightarrow \frac{dT}{T} = -\frac{R}{C_v}\frac{dv}{v} \Rightarrow \frac{dT}{T} = -(\gamma - 1)\frac{dv}{v}$

$\Rightarrow \int_1^2 \frac{dT}{v} = -(\gamma - 1)\int_1^2 \frac{dv}{v} \Rightarrow \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma - 1} \Rightarrow P_1v_1^{\gamma} = P_2v_2^{\gamma}$

In General, for any polytropic process, $Pv^n = \text{constant}$

$W = \frac{P_1v_1 - P_2v_2}{n - 1} \Rightarrow u_2 - u_1 = q - \frac{P_1v_1 - P_2v_2}{n - 1}$

Polytropic process $pv^n = c$ $\quad W_{1-2} = \frac{p_1v_1}{n-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]$

Adiabatic process $n = \gamma$

Constant pressure process $n = 0$

$W_{1-2} = \int_{v_1}^{v_2} p\,dv = p(v_2 - v_1)$

Constant volume process $n = \infty$

$W_{1-2} = \int_{v_1}^{v_2} p\,dv = 0$

Isothermal process $n = 1$

$W_{1-2} = p_1v_1 \ln\left(\frac{P_1}{P_2}\right)$

Now, moving to adiabatic and there is a another term if you use the word reversible in its prefix so, we call this as reversible adiabatic, then we say the process becomes isentropic processes and this isentropic processes why we are recognizing because it gives lot of important information means that when we say it is an isentropic processes so, that means, Q is 0 so, $du = -Pdv$. So, this $du = C_v dT$. So, from this, we can get what is work transfer W.

So, work transfer can be evaluate in the form of pressure and specific volume and of course, we also know another information that $h = u + Pv$ and from this, we can get for an ideal gas a definite relations that the specific heat at constant pressure, specific heat at constant volume, we can frame a relations C_p, C_v and R.

And they are recognized by this $C_p = C_v + R$, gamma is equal to that is specific heat ratio that is $\gamma = \frac{C_p}{C_v}$ and $C_v = \frac{R}{\gamma - 1}$ whereas, $C_p = \frac{\gamma R}{\gamma - 1}$. Why I am saying this? Because this isentropic processes has many information that we are going to use routinely in our all applications.

Now, in PV diagrams, we can recognize this path of an adiabatic processes, and we can describe the system as $Pv^\gamma = \text{constant}$ and these derivations also comes from the first law. So, the first law for an isentropic processes has very important implications.

Now, after recognizing this particular thing $Pv^\gamma = \text{constant}$, a more generic way of representing a system is a polytrophic processes. So, instead of saying $Pv^\gamma = \text{constant}$, we normally say $Pv^n = \text{constant}$. So, for a quasi-static processes which undergoes change in pressure and specific volume is represented as $Pv^n = \text{constant}$.

Now, let us see what is its significance. Now, if you draw it in a PV diagram, so, when n=0; so, it represents a constant pressure process. If n = ∞, it represents a constant volume processes. If n = 1, it is equal to Pv = constant, it is an isothermal processes and side-by-side n can be 2 and when n = γ, it becomes adiabatic processes.

So, likewise n has any number that can be specified for a given thermodynamic process, but however, elementary processes has definite value of n. So, this is how we recognize these polytrophic processes as one of the base to understand many elementary processes.

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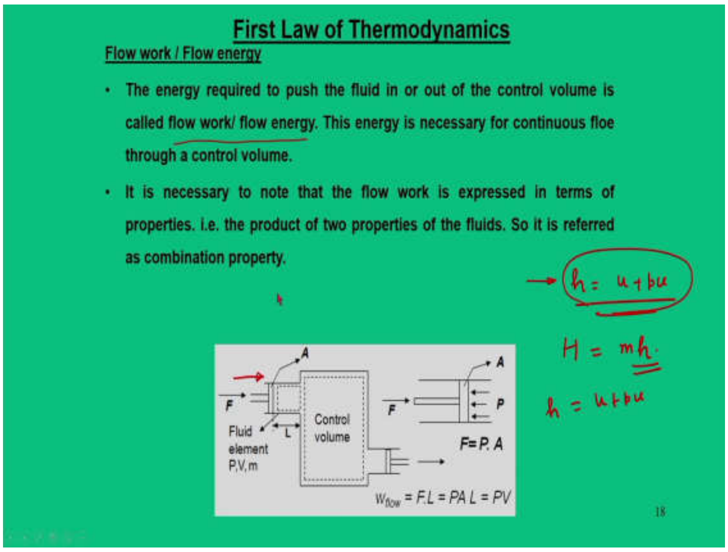

First Law of Thermodynamics

Flow work / Flow energy

- The energy required to push the fluid in or out of the control volume is called flow work/ flow energy. This energy is necessary for continuous floe through a control volume.
- It is necessary to note that the flow work is expressed in terms of properties. i.e. the product of two properties of the fluids. So it is referred as combination property.

$\rightarrow \boxed{h = u + pv}$

$H = mh.$

$h = u + pv$

The first law of thermodynamics gives another indications that what is this flow work. It is nothing but the energy required to push the fluid in and out of a control volume is known as flow work or flow energy. Normally, when you say the first law or mechanism of energy transfer, mass entering and mass coming out from a control volume has certain kind of energy.

Now, what is that amount of energy that you are going to require; that means, how much that mass which enters or leaves carry the energy, so that particular term in thermodynamic sense, we view or call as a flow work or flow energy and and it is a combination of two properties.

And in fact, when some mass comes in; so, we represent this as a term enthalpy $h = u + pv$. And the flow work of course, can be computed for imagining this particular mass as if it moves a distance L. So, amount of force which requires is PA and this flow work can be nothing but PV, pressure into its volume.

But thermodynamically, we can represent this flow work by its enthalpy $H = mh$ and this $h = u + pv$. So, if you will see here this enthalpy has two terms, internal energy, pressure and specific volume. So, it is a combination of property. So, the flow work is normally a combination property.

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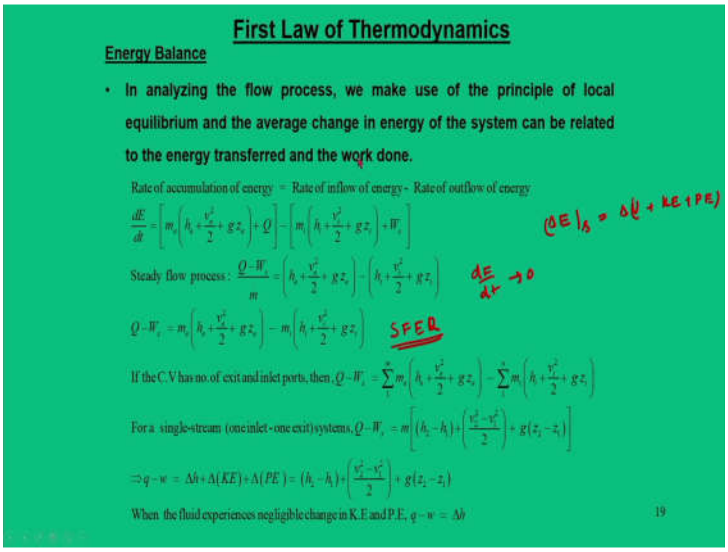

First Law of Thermodynamics

Energy Balance

- In analyzing the flow process, we make use of the principle of local equilibrium and the average change in energy of the system can be related to the energy transferred and the work done.

Rate of accumulation of energy = Rate of inflow of energy - Rate of outflow of energy

$$\frac{dE}{dt} = \left[m_e\left(h_e + \frac{v_e^2}{2} + g z_e\right) + Q\right] - \left[m_i\left(h_i + \frac{v_i^2}{2} + g z_i\right) + W_s\right]$$

$(\Delta E)_s = \Delta(U + KE + PE)$

Steady flow process: $\frac{Q - W_s}{m} = \left(h_e + \frac{v_e^2}{2} + g z_e\right) - \left(h_i + \frac{v_i^2}{2} + g z_i\right)$

$\frac{dE}{dt} \to 0$

$Q - W_s = m_e\left(h_e + \frac{v_e^2}{2} + g z_e\right) - m_i\left(h_i + \frac{v_i^2}{2} + g z_i\right)$ SFEQ

If the C.V has no. of exit and inlet ports, then, $Q - W_s = \sum_1^n m_e\left(h_e + \frac{v_e^2}{2} + g z_e\right) - \sum_1^n m_i\left(h_i + \frac{v_i^2}{2} + g z_i\right)$

For a single-stream (one inlet - one exit) systems, $Q - W_s = m\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right) + g(z_2 - z_1)\right]$

$\Rightarrow q - w = \Delta h + \Delta(KE) + \Delta(PE) = (h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right) + g(z_2 - z_1)$

When the fluid experiences negligible change in K.E and P.E, $q - w = \Delta h$

And moving further, we have another equations for a non-steady situations. When if you are going to deal with the energy balance, we make use of the principle that local equilibrium and average change in the property systems can be related to the energy transferred and work done that means, rate of accumulation energy is equal to rate of inflow of energy minus rate of outflow energy.

So, basically, we are using same equations of first law, we are interpreting in a different manner that is if the phenomena is a transient phenomena that is $\frac{dE}{dt}$ (change on the energy with respect to time). That energy that can come in either in the form of mass that is m_e and this is the total energy content that is its enthalpy, its velocity and its potential energy which is the exit plus Q and other kind of the energy that comes as mass from the inlet is m_i multiplied by its enthalpy, velocity and the gravity z and other kind of energy that we have is work transfers. So, this particular equation talks about rate of accumulation energy in the form of what we call as the energy of the system which is represented as $(\Delta E)_s = \Delta(U + KE + PE)$.

$$\frac{dE}{dt} = \left[m_e\left(h_e + \frac{v_e^2}{2} + g\,z_e\right) + Q\right] - \left[m_i\left(h_i + \frac{v_i^2}{2} + g\,z_i\right) + W_s\right]$$

So, when you have this, then this particular energy can be expressed in the form of mass, enthalpy, velocity and height. Now, for a steady flow process, we can take out mass as a common that means, $\frac{Q-W_s}{\dot{m}}$ so, $\frac{dE}{dt}$ becomes 0 so, we can represent in this form and finally, we can get a steady flow energy equations. So, this is a very fundamental equations in the thermodynamics and it has lot of implications.

$$Q-W_s = m_e\left(h_e+\frac{v_e^2}{2}+g\,z_e\right) - m_i\left(h_i+\frac{v_i^2}{2}+g\,z_i\right)$$

Now, this control volume can have a multiple exit and multiple inlet so, that way we can put the exit as 1 to m and entry as 1 to n. For a single stream that is one inlet-one exit systems, we can say there is only one mass that is mass flow rate remains unique or fixed and finally, when the working fluid experiences in most of the situations negligible change in the kinetic energy and potential energy; so, we can say $q-w = \Delta h$.

So, what has been seen here that starting from the very basic equations, we have changed the nature of the equations for variety of applications. So, this is what the main significance or main inference that we derive from the first law.

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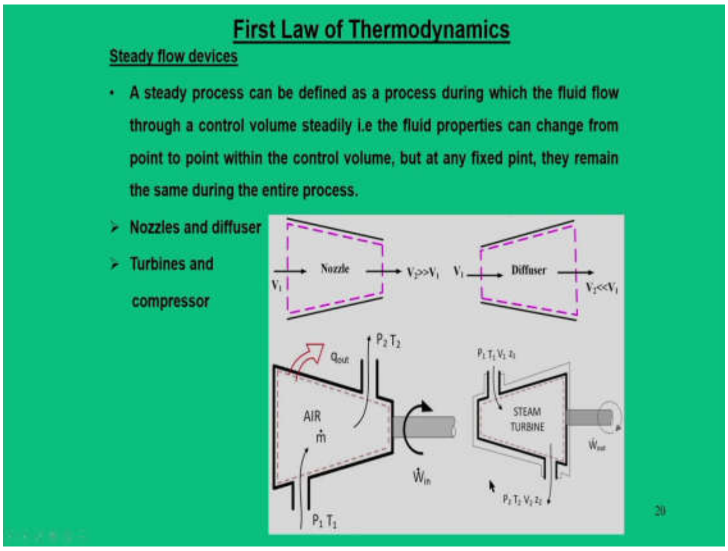

First Law of Thermodynamics

Steady flow devices

- A steady process can be defined as a process during which the fluid flow through a control volume steadily i.e the fluid properties can change from point to point within the control volume, but at any fixed pint, they remain the same during the entire process.

- Nozzles and diffuser
- Turbines and compressor

Now, why we are going to do this? Because we are going to discuss about steady flow devices that are commonly used. So, this steady flow energy equations can be simplified for variety of applications. So, first application we are going to use is nozzles and diffusers and usually, the purpose of the nozzle is to increases the velocity at the cost of pressure whereas, the diffuser performs the opposite phenomena where velocity is decreased.

Now, in same concept, we call this as a turbine and compressor. Normally, nozzles are used to generate thrust and instead of thrust if you looking at power, then same concept we can use it as a turbines and compressors. So, turbines gives the power output and compressor takes the power in as input. So, as a result, its pressure is increased, but in a turbine, the pressure drops.

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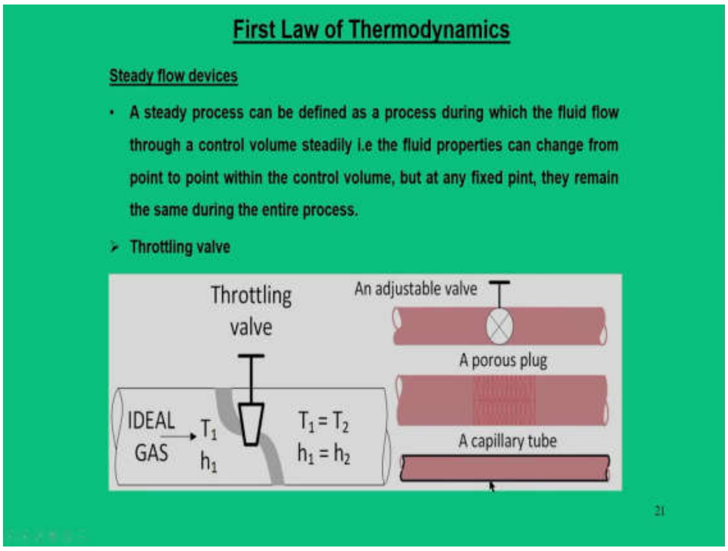

First Law of Thermodynamics

Steady flow devices

- A steady process can be defined as a process during which the fluid flow through a control volume steadily i.e the fluid properties can change from point to point within the control volume, but at any fixed pint, they remain the same during the entire process.

➢ Throttling valve

Another kind of steady flow devices, we can have a throttling valve. In fact, this throttling valve is used most of the refrigeration applications. So, there the throttling concept is that its enthalpy remains same. Enthalpy is a function of u and pv that means u is also a function of temperature.

So, basically, when enthalpy remains same, we can control the pressure, temperature such a way that we can regulate the flow of a gas through a valve by keeping enthalpy is constant and typical valve could be a porous plug, it could be a capillary tube, capillary tube means a very small tube or it can be a adjustable valve.

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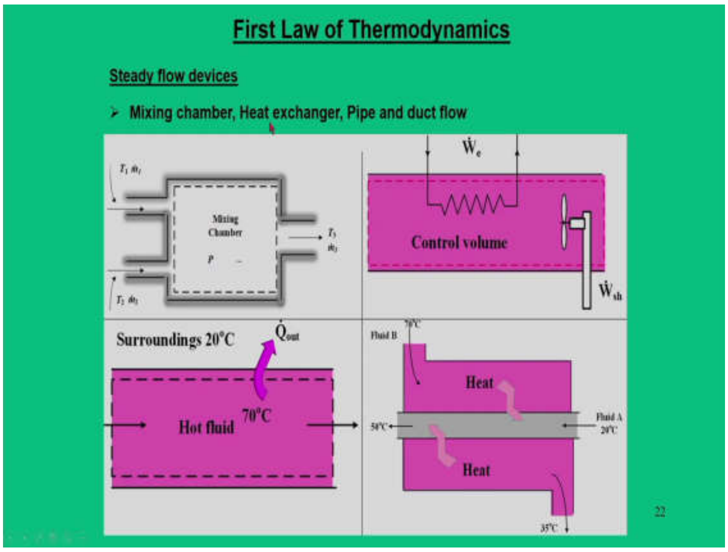

First Law of Thermodynamics

Steady flow devices

- Mixing chamber, Heat exchanger, Pipe and duct flow

Other type of steady flow devices are mixing chamber. Many a times, you use a mixing chamber when two fluids comes, mixes and finally, a single fluid goes out. So, we call this as a mixing chamber. We also can have a pipe or duct flow. So, this particular say that there is a pipe or duct and in which a shaft is rotating so that it sucks the air.

Normally, this is used in a typical wind tunnel where there is a fan that sucks the air from one end and throws it away to the other end, you can view it as a pipe or duct flow. And most importantly in the heat transfer, we are using very frequently the word heat exchanger. So, in the heat exchanger, there are interaction of hot fluids to the surroundings.

So, you can have a situation, there is a hot fluid passing through a tube and it is interacting heat with respect to surroundings. Other situation could be there are two fluids that is fluid A and fluid B. So, fluid A is entering in a pipe whereas, another entry fluid B is entering, but it is at higher temperature. So, as a result, there is a heat transfer between these fluids. So, such a device we call this as a heat exchanger.

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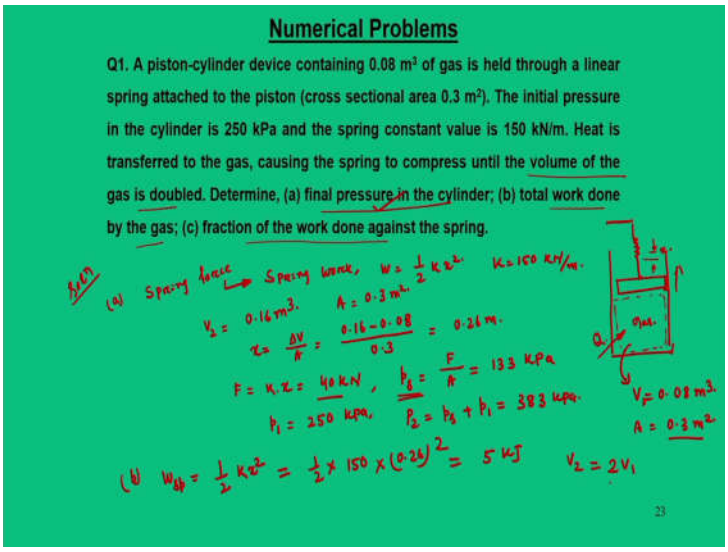

Numerical Problems

Q1. A piston-cylinder device containing 0.08 m^3 of gas is held through a linear spring attached to the piston (cross sectional area 0.3 m^2). The initial pressure in the cylinder is 250 kPa and the spring constant value is 150 kN/m. Heat is transferred to the gas, causing the spring to compress until the volume of the gas is doubled. Determine, (a) final pressure in the cylinder; (b) total work done by the gas; (c) fraction of the work done against the spring.

Soln

(a) Spring force → Spring work, $W = \frac{1}{2} k x^2$. $K = 150$ kN/m.

$V_2 = 0.16 m^3$. $A = 0.3 m^2$.

$x = \frac{\Delta V}{A} = \frac{0.16 - 0.08}{0.3} = 0.26$ m.

$F = K.x = 40$ kN, $p_s = \frac{F}{A} = 133$ kPa

$p_1 = 250$ kPa, $P_2 = p_s + p_1 = 383$ kPa.

(b) $W_{sp} = \frac{1}{2} k x^2 = \frac{1}{2} \times 150 \times (0.26)^2 = 5$ kJ $V_2 = 2V_1$

So, with this I conclude the topic for the today. So, we have dealt with the first law of thermodynamics and its application for the steady flow processes. Other topic interest that we come out that what are the different types of thermodynamic definition of work interactions.

So, based on this particular two important inferences, we are going to discuss some few couple of problems and the first problem is about a piston-cylinder devices in which there is a gas of certain volume 0.08m^3 and it is held in equilibrium through a linear spring. So, first let us draw the physical systems what it should be.

So, we have a piston-cylinder device, what we have is this particular piston is held by a spring and there is a gas. What happens? This gas has volume V as 0.08m^3 and this piston has cross sectional area 0.3m^2, and it is in equilibrium. So, what we do is heat is transferred to the gas. So, through some means we are transferring heat into the systems. So, heat is added to the systems.

So, obviously, this particular gas which is in this control volume or in this space, its temperature is going to rise so, when it rise, it tries to push this piston off. So, when this piston is pushed off, the spring gets compressed by a distance x. So, the question that was asked that what is the final pressure in the cylinder and what is the work done by the gas and fraction of work done against the spring.

We have to use basically the first law and we have to find out final pressure, work done and also you have to find out the spring work. So, what happens? When we are adding heat, we can recognize that this is V_1 and final volume V_2 becomes $2V_1$ because heat is added so that volume of the gas is doubled. So, final volume $V_2 = 2V_1$.

Let us try to solve first problem that is spring force. So, the spring force will give you the spring work. So, spring work is nothing but $w = \frac{1}{2}kx^2$. So, k is also known here 150 kN/m. To solve this particular problem, let me start what is V_2? V_2 is nothing but $2V_1$ so, it is 0.16m^3, and we have area 0.3m^2.

So, we can find out what is this compression in the spring x? $x = \frac{\Delta V}{A} = \frac{0.16 - 0.08}{0.3} = 0.26\text{m}$. So, when we have this, then we can find out force, spring force nothing but k times x. So, when we multiply 150 into 0.26, this number turns out to be 40 kN.

So, once we know the spring force, we can find out pressure induced that is due to the spring that is F spring force by area. So, area is 0.3 so, this number would be 133 kPa, but initial pressure p_1 was 250 kPa so, final pressure p_2 would be the spring force that is $p_s + p_1$. So, this number would be 383 kPa. So, we know the final pressure.

So, work done by the gas is nothing but spring work that is $w_s = \frac{1}{2}kx^2 = \frac{1}{2}\times 150 \times 0.26^2 = 5\text{kJ}$. So, the fraction of work that is done against the spring is 5kJ.

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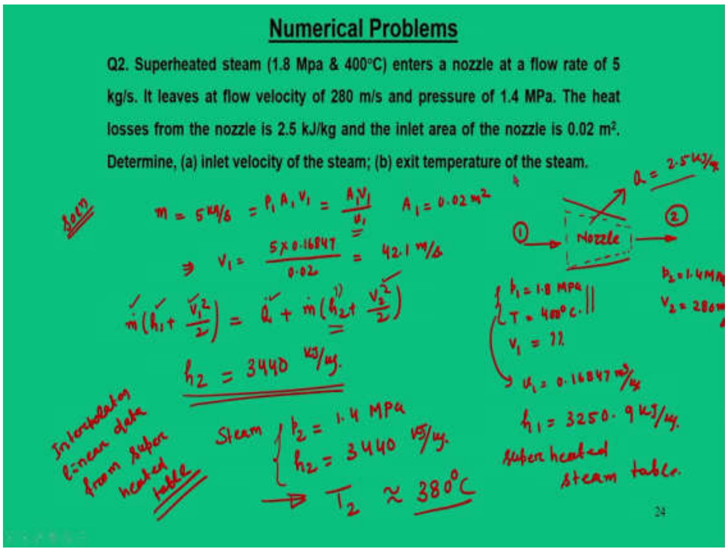

Numerical Problems

Q2. Superheated steam (1.8 Mpa & 400°C) enters a nozzle at a flow rate of 5 kg/s. It leaves at flow velocity of 280 m/s and pressure of 1.4 MPa. The heat losses from the nozzle is 2.5 kJ/kg and the inlet area of the nozzle is 0.02 m². Determine, (a) inlet velocity of the steam; (b) exit temperature of the steam.

Sol^n

$m = 5 \text{ kg/s} = \rho_1 A_1 V_1 = \frac{A_1 V_1}{v_1}$ $A_1 = 0.02 \text{ m}^2$

$\Rightarrow V_1 = \frac{5 \times 0.16847}{0.02} = 42.1 \text{ m/s}$

$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{Q} + \dot{m}\left(h_2 + \frac{V_2^2}{2}\right)$

$h_2 = 3440 \text{ kJ/kg}$

Interpolation linear data from super heated table

Steam $\begin{cases} p_2 = 1.4 \text{ MPa} \\ h_2 = 3440 \text{ kJ/kg} \end{cases}$

$\rightarrow T_2 \approx 380^\circ C$

$p_1 = 1.8 \text{ MPa}$

$T = 400^\circ C$

$V_1 = ??$

$v_1 = 0.16847 \text{ m}^3/\text{kg}$

$h_1 = 3250.9 \text{ kJ/kg}$

super heated steam table.

The next question is about a nozzle. So, we have come across a steady flow devices which is a steam nozzle. So, if you can draw a stream nozzle with its control volume, it can be represented in this manner. So, nozzle normally accelerates the flow so, its contour is like a contracting section.

So, the steam let us say that enters the nozzle that is condition 1, the steam leaves the nozzle at condition 2. So, when the steam enters the systems its p_1 is 1.8MPa, temperature was 400°C and it leaves at 1.4MPa and velocity is 280m/s. So, we have to calculate what is the inlet velocity of the stream and in this process, there is a heat loss Q that is 2.5kJ/kg.

To solve the problem, first thing we have to use the fundamental equations mass flow rate. So, mass flow rate which is given to us is 5kg/s that is $m = \rho_1 A_1 V_1 = \frac{A_1 V_1}{v_1}$, v_1 is the specific volume. So, from the steam table data, we can get v_1 at this super-heated condition as 0.16847m^3/ kg.

And area A_1 is 0.02m^2. So, this turns out to be from these equations, one can find out V_1. $V_1 = \frac{5 \times 0.16847}{0.02} = 42.1 \text{m/s}$. Now, once you have this, then you have to recall the steady flow energy equations for nozzle.

So, we can write this as $\dot{m}\left(h_1+\frac{v_1^2}{2}\right)=\dot{Q}_1+\dot{m}\left(h_2+\frac{v_2^2}{2}\right)$. So, here, from this first condition, we can find out the enthalpy for condition 1, that value would be 3250.9 kJ/kg that is from super-heated steam table.

So, in these equations, we have all the numbers $\dot{m}$ is known that is 5kg/s, h_1 is known, V_1 is 42m/s, Q is 2.5kJ/s, h_2 is unknown and V_2 is 280m/s. So, all the numbers are known except h_2. So, after solving, you can find out h_2 value as 3440kJ/kg.

So, enthalpy is known. So, remember that we are looking at a steam that leaves the nozzle at p_2 = 1.4 MPa and h_2 as 3440kJ/kg. For these conditions, you have to use the interpolation of linear data from super-heated table.

So, this table we can find out any of the fundamental books I have referred and here from this, we can find out temperature T_2 will be approximately equal to 380°C. So, that is the question that was asked what is the exit temperature of the steam.

So, with this, I conclude this lecture for today.

Thank you for your attention.