Applied Thermodynamics for Marine Systems

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Lecture – 2
First Law of Thermodynamics
(Closed System)

In the last class, we have learnt the definition of thermodynamics, different thermodynamics systems and control volumes; then important properties which we will need in the discussion of thermodynamics. Today, we will learn the different laws of thermodynamics. We will start with the most important law of thermodynamics, that is, the first law of thermodynamics.

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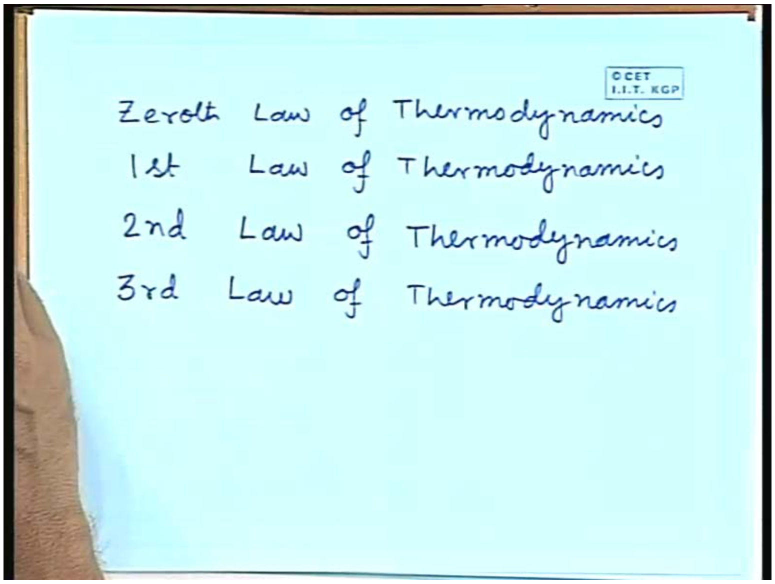

Zeroth Law of Thermodynamics
1st Law of Thermodynamics
2nd Law of Thermodynamics
3rd Law of Thermodynamics

In thermodynamics, there are four laws: the zeroth law of thermodynamics, then the first law of thermodynamics, the second law of thermodynamics and the third law of thermodynamics. Amongst them, the zeroth law of thermodynamics tells us or gives us a means for measurement of temperature. The first and second laws are very important as far as energy conversion is concerned. We will restrict our discussion in this particular course to the first three laws- the zeroth law of thermodynamics, the first law of thermodynamics and second law of thermodynamics.

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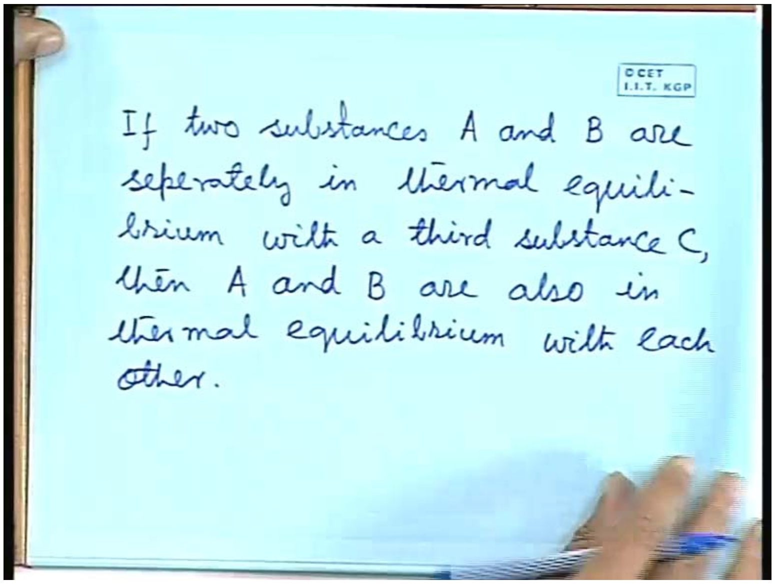

If two substances A and B are seperately in thermal equilibrium with a third substance C, then A and B are also in thermal equilibrium with each other.

The zeroth law of thermodynamics states that if two substances A and B are separately in thermal equilibrium with a third substance C, then A and B are also in thermal equilibrium with each other.

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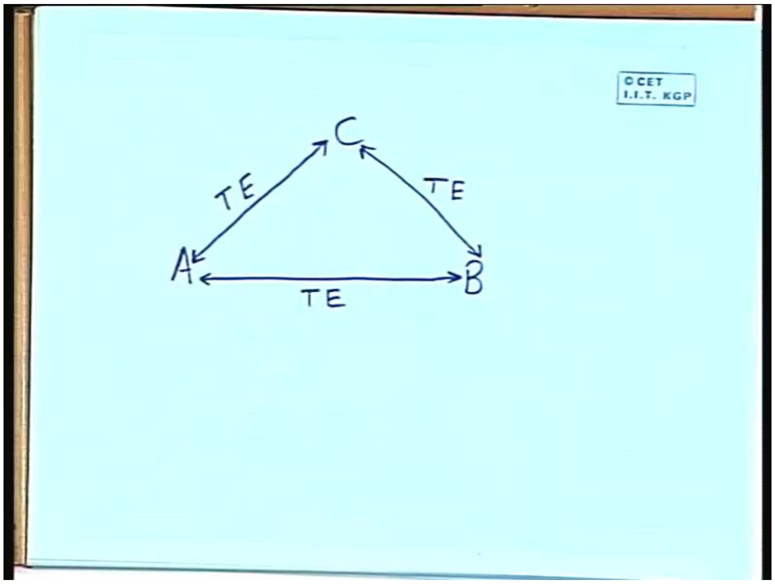

Symbolically, we can represent it like this. There are three substances: A, B and C. A and C are in thermal equilibrium. B and C are also in thermal equilibrium. According to the zeroth law of thermodynamics, A and B also are in thermal equilibrium. Symbolically, we can represent the law like this. Now, it gives us a very convenient method or convenient principle for the measurement of temperature. We can take a small example and then we can understand how it is possible.

Let us say the temperature of ice melting in water under atmospheric pressure is taken to be a standard temperature. If we take that as a reference, then with that reference, we can compare the temperature of other bodies. But, what we are doing is, when we are having a thermometer, first, we calibrate the thermometer by bringing it in contact with the melting ice at atmospheric pressure. Once the thermometer is calibrated, then, the temperature of any other body is measured with the help of the thermometer. Then, the third body is never taken in contact with the melting ice to see whether these two bodies are in thermal equilibrium or not. So, we can have a reference body or thermometer which is in thermal equilibrium with the melting ice and then onwards we do not require the melting ice to compare its temperature with other bodies. So, that is how we are applying the zeroth law of thermodynamics for the measurement of temperature.

It is interesting to note the laws of thermodynamics, if we see the history of their development, the first law and second law were invented or proposed much before the statement of zeroth law of thermodynamics was given. But, for the development of the idea regarding thermodynamics, the discussion of the zeroth law is needed prior to first law and second law. That is why we discuss zeroth law, prior to the first law and second law and then we go for first law and second law. Now, we will go to first law of thermodynamics.

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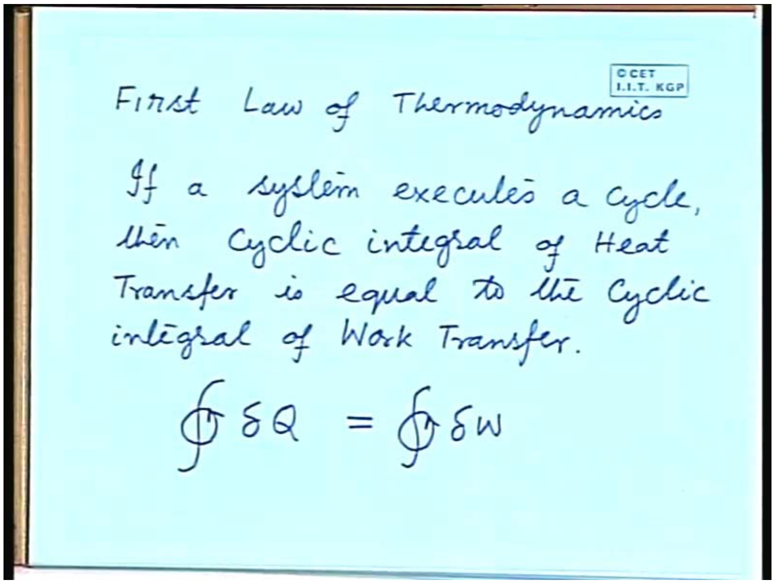

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First Law of Thermodynamics

If a system executes a cycle, then Cyclic integral of Heat Transfer is equal to the Cyclic integral of Work Transfer.

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

As it is known to us, the first law of thermodynamics basically states the conservation of energy. But, the way we have read the principal of conservation of energy in our physics books, it is stated in a slightly different manner in engineering thermodynamics. Classically, the statement of the first law of thermodynamics is like this: if a system executes a cycle, then cyclic integral of heat transfer is equal to the cyclic integral of work transfer. This is the statement of the first law of thermodynamics. Now, it needs some explanation, because it contains certain new terms, probably with which we are not familiar. Mathematically, we can write it like this. I would like to draw your attention to two aspects in this mathematical expression. First, I have put a cyclic integral, which means integration over the entire cycle, because we are considering a process in which the system undergoes a cycle. Probably, some explanation of cycle is needed here.

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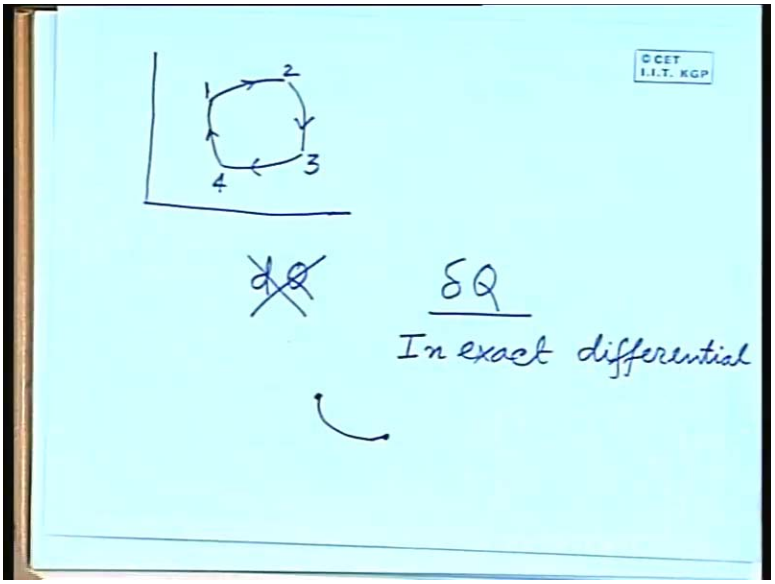

A cycle can be defined as a series of process between identical end states. Let us say, this is a thermodynamic plane. This is a representation of a thermodynamic process on a two dimensional plane. Any two independent thermodynamic properties have been taken for representing the process. We can have a series of processes, arbitrary processes, something like this. But, the processes are such that the end states are identical. There is 1 process 1 to 2, another process 2 to 3, 3 to 4, and again the last process is 4 to 1 which completes the cycle. So, the initial point or initial state for the cycle is 1 and the final state of the cycle is also 1. So, such a process we will call as a cycle. For this cycle, if we consider the heat transfer in all the processes and sum them up, then we will get the cyclic integral of heat transfers during the processes. That is what has been meant by the cyclic integral of dQ.

The second thing to which I would like to draw your attention is dQ and dW. I have used some sort of a different symbol, instead of the usual symbol which is used for representing a differential quantity. The usual symbol could have been dQ, but, instead of that I have used dQ because this is an in exact deferential. This quantity is an in exact differential. Physically, it means that the heat transfer or the amount of heat transfer does not depend on the end states only, but it also depends on the path which is taken by the process. So, that is why, to separate it, or make some sort of a difference between the property of the system and the quantity of heat transfers or the quantity of work transfer, we are using this in exact differential. It is important to keep in mind that heat transfer and work transfer not only depend on the end states, but they depend on the process between the end states.

Now, let us apply the first law of thermodynamics, which mathematically I have written as a cyclic integral of dQ is equal to cyclic integral of the dW for a cycle. Let us see what conclusion we can draw from that.

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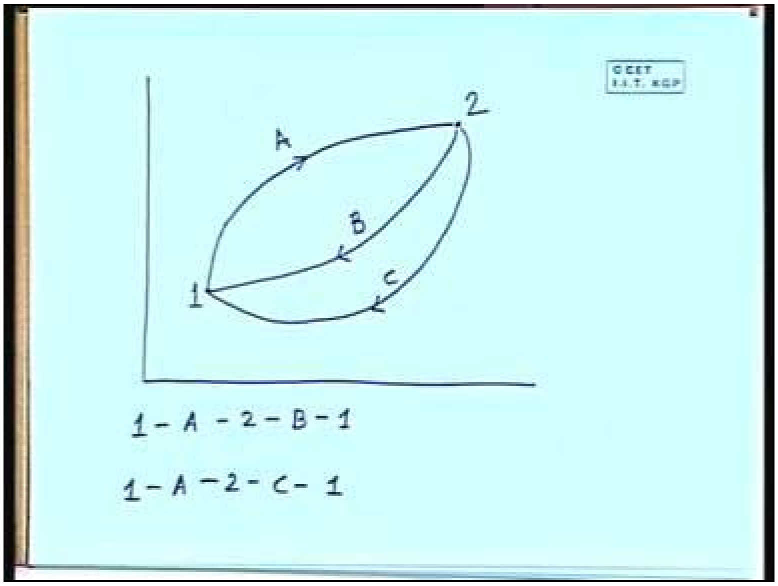

Again, I am taking a thermodynamic plane and there are two state points on this thermodynamic plane: 1 and 2. Let us say, we have some arbitrary cycle. To represent this path I am putting A here. So one process of the cycle is 1-A-2 and the other process by which the cycle is complete is 2-B-1. We can have another arbitrary path like 2-C-1. So, basically, in this diagram, we have two cycles - one cycle is 1-A-2-B-1 and another cycle is 1-A-2-C-1. Let us apply the first law of thermodynamics for these two cycles.

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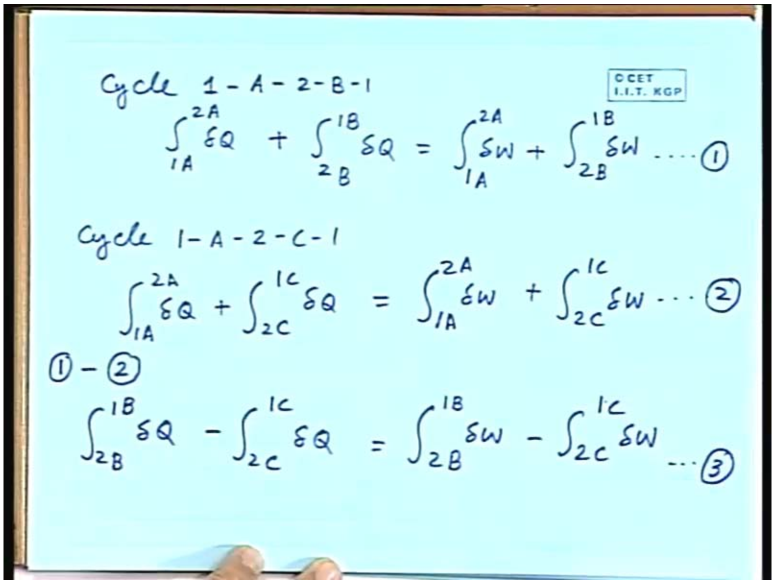

Cycle 1 - A - 2 - B - 1

$$\int_{1A}^{2A}\delta Q + \int_{2B}^{1B}\delta Q = \int_{1A}^{2A}\delta W + \int_{2B}^{1B}\delta W \quad \ldots\textcircled{1}$$

Cycle 1 - A - 2 - C - 1

$$\int_{1A}^{2A}\delta Q + \int_{2C}^{1C}\delta Q = \int_{1A}^{2A}\delta W + \int_{2C}^{1C}\delta W \quad \ldots\textcircled{2}$$

① − ②

$$\int_{2B}^{1B}\delta Q - \int_{2C}^{1C}\delta Q = \int_{2B}^{1B}\delta W - \int_{2C}^{1C}\delta W \quad \ldots\textcircled{3}$$

Cycle 1-A-2-B-1, for this cycle we will get integration 1A to 2A dQ plus integration 2B to 1B dQ is equal to integration 1A to 2A dW plus integration 2B to 1B dW. So, this is equation 1.

Cycle 1-A-2-C-1 that will give us 1A to 2A dQ plus 2C to 1C dQ is equal to 1A to 2A dW plus 2C to 1C dW. Let us denote this equation as equation 2.

Now, if we subtract any one of the equation from the other, what we will get? We subtract equation 2 from equation 1. So, we will get integration 2B to 1B dQ minus integration 2C to 1C dQ is equal to 2B to 1B dW, minus 2C to 1C dW. Let us say this is the equation number 3.

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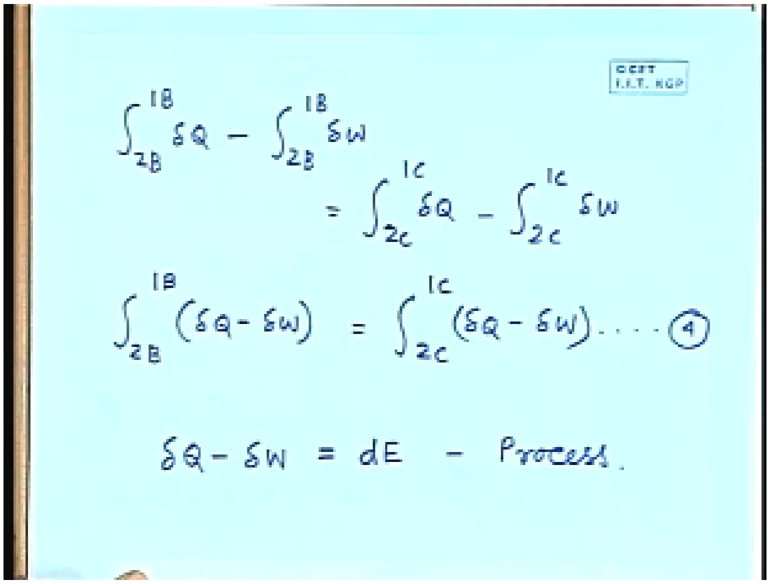

$$\int_{2B}^{1B}\delta Q - \int_{2B}^{1B}\delta W = \int_{2C}^{1C}\delta Q - \int_{2C}^{1C}\delta W$$

$$\int_{2B}^{1B}(\delta Q - \delta W) = \int_{2C}^{1C}(\delta Q - \delta W) \ldots\ldots ④$$

$\delta Q - \delta W = dE$ – Process.

Then, we can do a little bit simplification like this. Integration 2B to 1B minus 2B to 1B dW is equal to 2C to 1C dQ minus 2C to 1C dW. We can see that, in these 2 quantities the limit of integration is the same. So we can take them under one integral sign like this: 2B to 1B dQ minus dW is equal to 2C to 1C dQ minus dW.

So what is the implication of our final expression? Here, we can see the quantity is dQ minus dW. We have taken integration from 2 to 1 taking a path B. Here also we can see the quantity is dQ minus dW. We have integrated this quantity from point 2 to point 1 or from state 2 to state 1 taking another path, that is path C, but these 2 quantities are identical; that means they are independent of the path. Though, at the beginning, I have said that heat transfer or the quantity Q, work transfer or W, are path dependent, but we can find that dQ minus dW, this quantity is independent of path. But, what is this quantity? Q - heat transfer that is one energy, W that is work transfer, that is also another form of energy; both are energy in transit. So, definitely their difference will be also some kind of energy. Let us denote it by capital E. If we denote it by capital E, we can write for any process dQ minus dW, that is some kind of energy, that is dE. Now, I am using the symbol of exact differential, because it is dependent only on end points or states.

So, what have we achieved? We have started from the statement of the first law of thermodynamics, which is given for a cycle and from there we can write the statement of thermodynamics or we can have some sort of mathematical expression, when only a process is there. Now, we are getting the statement of thermodynamics or mathematical expression of thermodynamics for a process. We have started from a cycle, now we are getting the mathematical expression for a process. So this is for a process. Now, we like to look a little bit in detail as to what this quantity dE is.

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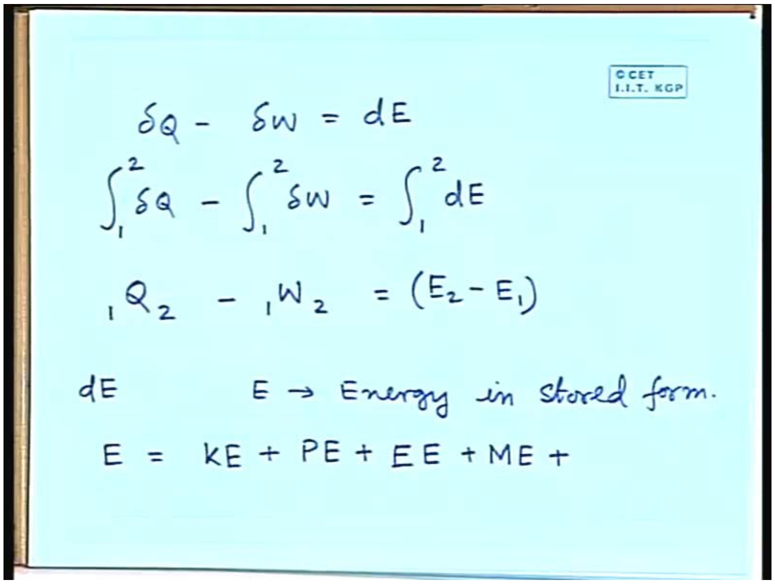

$$\delta Q - \delta W = dE$$

$$\int_1^2 \delta Q - \int_1^2 \delta W = \int_1^2 dE$$

$${}_1Q_2 - {}_1W_2 = (E_2 - E_1)$$

dE   E → Energy in stored form.

$$E = KE + PE + EE + ME +$$

Let us write down once again dQ minus dW is equal to dE. These are differential quantities. If it is a finite process, we can integrate it. If we integrate it, it will be like this. Let us say, we are integrating it from state 1 to state 2. So, this is dQ minus dW is equal to dE. If we remove the integration sign or if we do the integration, we will have Q 1 to 2 minus W 1 to 2 that is equal to E_2 minus E_1.

It is again important to note that I have written the heat transfer and work transfer in such a manner so that it indicates that it depends on the path or the process 1 2; whereas, the change in energy has been written in such a manner that it depends only on end states 1 and 2. This we will remember while we will study further the other topics of thermodynamics.

This is dE, where E is energy in stored form. We can have different forms of stored energy like, E can be kinetic energy plus potential energy plus, let us say in some application electrical energy is important and magnetic energy is important. Due to surface tension, there is some amount of energy; surface energy plus there can be many other forms which can remain in stored form inside the system. What other forms are important or which is the most important form for our discussion? Let us try to understand it with the help of a simple example.

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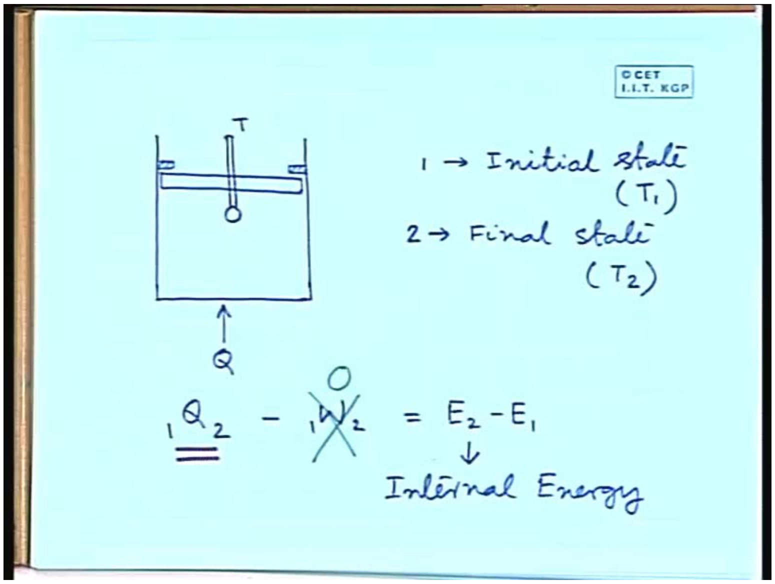

Let us say, this example or this type of application we will consider very frequently in future. We have taken a compressible fluid as the substance inside a piston cylinder arrangement. The movement of the piston is restricted with the help of a stopper like this and initially it is at cold state. Then we apply a certain amount of heat to this substance. After certain time, we remove the source of heat and to assess the change of state, we have got some measuring instrument. We have got a thermometer here. We know it was initially at one state. The initial state is denoted by 1 which is given by temperature T_1 and after heating, we are getting the final state which is given by temperature T_2. The system has undergone a process and we can apply first law of thermodynamics. We can write down the mathematical expression for the first law of thermodynamics which we have derived for a process. What will it be? It will be Q 1 to 2 minus W 1 to 2 that is equal to E_2 minus E_1, this we can write.

Let us say that somehow we know the amount of heat that has been supplied to this system. It is not very difficult. We have got electrical heating and we know how much electrical energy has been supplied during the process. This is a known quantity. What about our work transfer? As the movement of the piston is restricted, there is no work done by the system during the process. This is equal to 0. We have supplied certain finite amount of heat and we can see that there will be certain finite amount of change of stored energy of the system, for the process 1 to 2, or between the state points 1 to 2. Now, what is this energy? There is no gross movement of the system. So there is no change in kinetic energy. The system orientation has not changed. So there is no change in potential energy and the type of system which we have taken for that electrical energy, magnetic energy, surface energy, capillarity, etc., are irrelevant; those are not significant. Those types of energies have also not changed.

Then, there is some definite change in energy which is said by first law of thermodynamics. We can see there is a change of energy by doing a small experiment: if we remove these stops, then the piston will move in the upward direction. It will do some work. Definitely, there is some energy which is doing this work. What is this form of energy? This form of energy is known as internal energy. This is internal energy. If we look a bit deeply, when heat is transferred to the substance, then definitely at the molecular level there are some changes in the molecular motion. That is why at the molecular level, some amount of energy is stored. The manifestation of heat at the macroscopic level is our internal energy and we call it internal energy. This is very important, because in most of the thermodynamic systems which we will study, there we will see that internal energy is very important component of stored energy.

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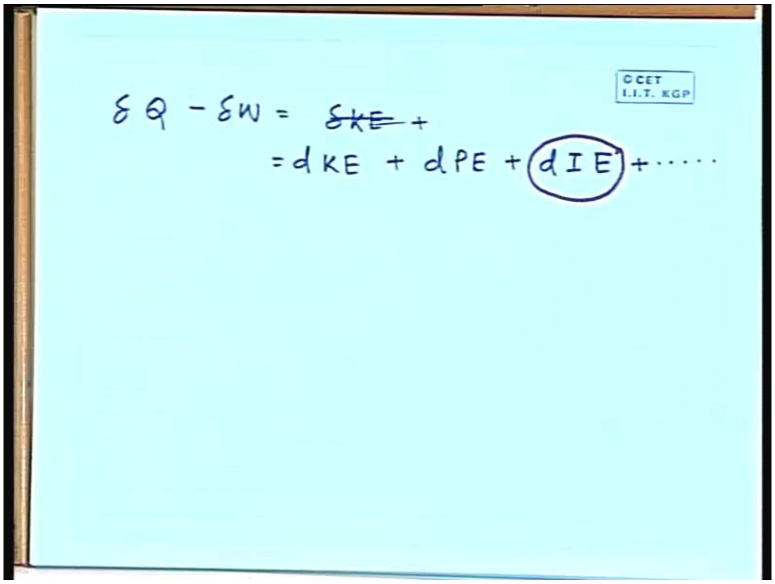

$$\delta Q - \delta W = \cancel{\delta KE} +$$

$$= dKE + dPE + \boxed{dIE} + \cdots\cdots$$

Basically, one can now write dQ minus dW is equal to dKE kinetic energy plus, one should use the other symbol like, dKE plus dPE plus d internal energy plus the other terms. This internal energy is very important for the type of systems which we are going to consider. In number of cases, we will see that probably kinetic energy and potential energy one can neglect; but internal energy, we have to take into consideration for compressible fluid or incompressible fluid which we will take into consideration while we will analyze an engineering system like turbine, compressor, boiler, etc.

Now, let us go for a slight extension of first law of thermodynamics.

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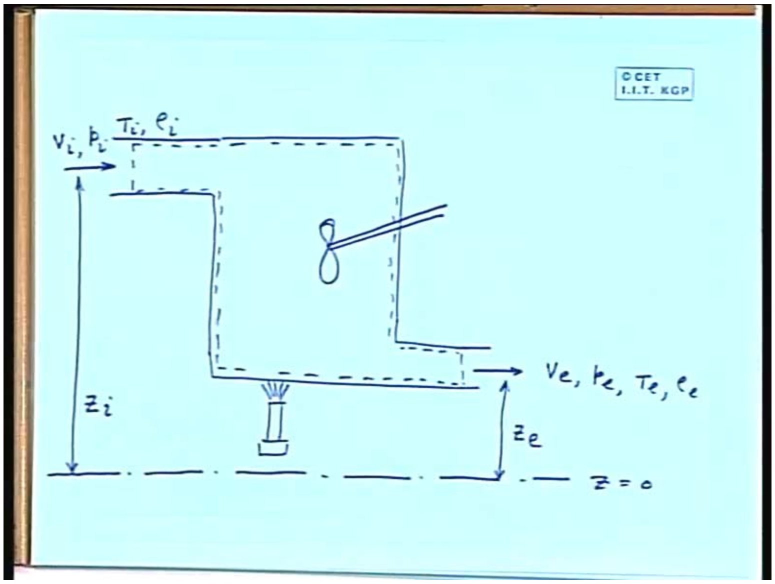

Let us say, we are focusing our attention to some control volume where there is a flow of mass. So, this is an arbitrary control volume. This is the inlet where mass enters and this is the outlet from which mass leaves the control volume. We have some datum plane. We have selected this datum plane where Z is equal to 0. Compared to this datum plane, the inlet has got a height Z_i and the exit has got a height Z_e and here, the average fluid velocity is V_i, average fluid velocity is V_e. The pressure here is p_i. At the exit, it is p_e and we can define the temperature T_i, density rho_i, corresponding quantities are T_e, rho_e, etc.

This control volume also interacts with the surroundings in terms of heat transfer and work transfer. Let us say, there is work transfer and there is also some amount of heat transfer. We want to analyze the energy interaction of this control volume with its surroundings.

What is the difference compared to the previous system? In the previous system, we have taken a closed system. Initially, we have considered a cycle and we really did not pay any attention to the mass transfer or to the transfer of material. But, here we can see that certain material is entering the control volume with certain velocity, pressure, temperature etc., and it is leaving the control volume with certain other velocity, pressure, temperature, etc., in general. So, we can see that a process is taking place and with time there is some sort of a change. Again, we can take care of our first law of thermodynamics for a process.

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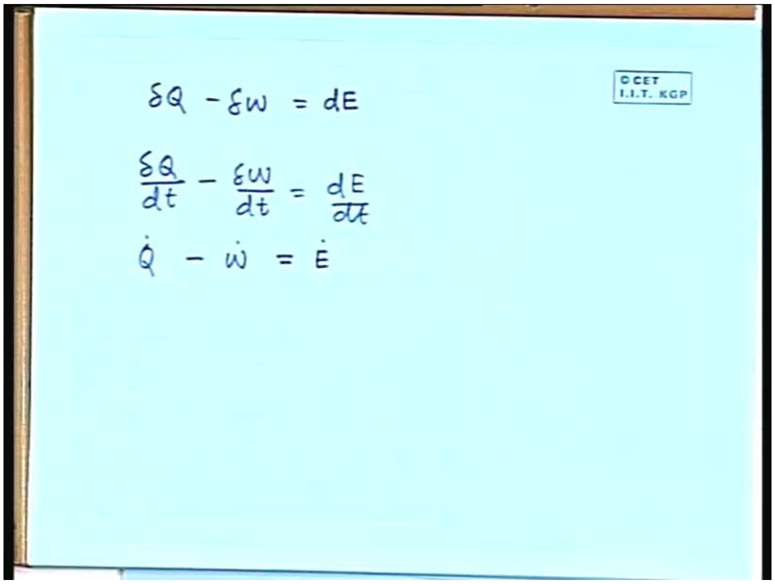

$$\delta Q - \delta W = dE$$

$$\frac{\delta Q}{dt} - \frac{\delta W}{dt} = \frac{dE}{dt}$$

$$\dot{Q} - \dot{W} = \dot{E}$$

The way we have written it, we have written it like this. dQ minus dW is equal to dE. If we are interested in what changes are taking place with time, then we can modify this equation. So, dQ by dt minus dW by dt is equal to dE by dt or Q dot minus W dot is equal to E dot. This is a rate equation. Here, we have considered the time rate of heat transfer, time rate of work transfer and time rate of energy change inside the control volume or system. This basic equation we will also use in the example which we have just now drawn.

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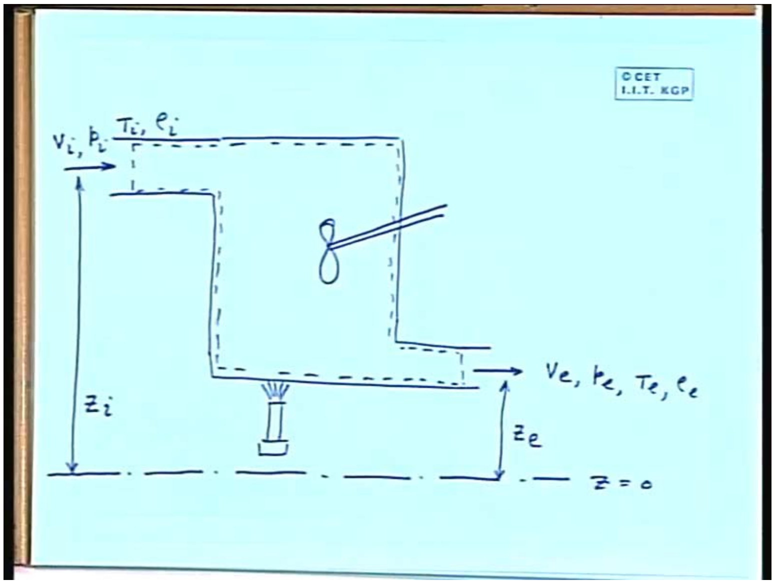

In this particular control volume, if we want to apply the rate equation of the first law, then, what we have to do? We have to identify one thing. What are the different forms of energy which are entering the control volume and what are the different forms of energy which are leaving the control volume? We have to consider that. The control volume which we have taken, this example could be very generalised, but for the present course, we will restrict our discussion to a slightly simpler system and we specify the system or process like this.

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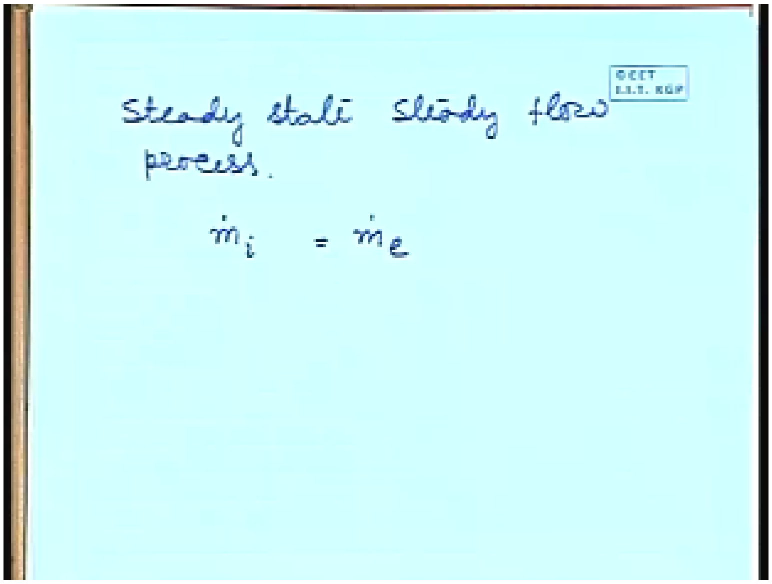

Steady state steady flow process.

$$\dot{m}_i = \dot{m}_e$$

We will analyse for a steady state steady flow process. Let me explain what a steady state steady flow process. First, let's take the steady flow process. A steady flow process means whatever mass is entering the control volume, the same amount of mass is going out of the control volume. We can write m dot i is equal to m dot e. There is no accumulation of mass inside the control volume and we will find there are a large number of applications in engineering where the flow rate of incoming mass is equal to the flow rate of outgoing mass. In general application when a compressor operates or when a turbine operates, the amount of air which enters the compressor the same amount of air goes out of the compressor. The amount of steam which enters the turbine is the same as the amount of steam that goes out of the turbine.

We will see that steady state steady flow process encompasses a large number of engineering applications. But, one has to remember that there are applications where steady state steady flow process is not applicable or steady flow process is not applicable. Suppose, we have a pressurized gas cylinder, if we open the valve, then a certain amount of gas will come out of the cylinder and if the cylinder is taken to be a control volume, the process is not a steady flow process. We will preclude those types of examples from our analysis. The steady flow process we have understood as the amount of mass which is coming in is the mass that is going out of the control volume.

Steady state, at any point of the control volume the property remains a constant during the process. From point to point, there is variation of property; but, at a particular point, the property remains constant.

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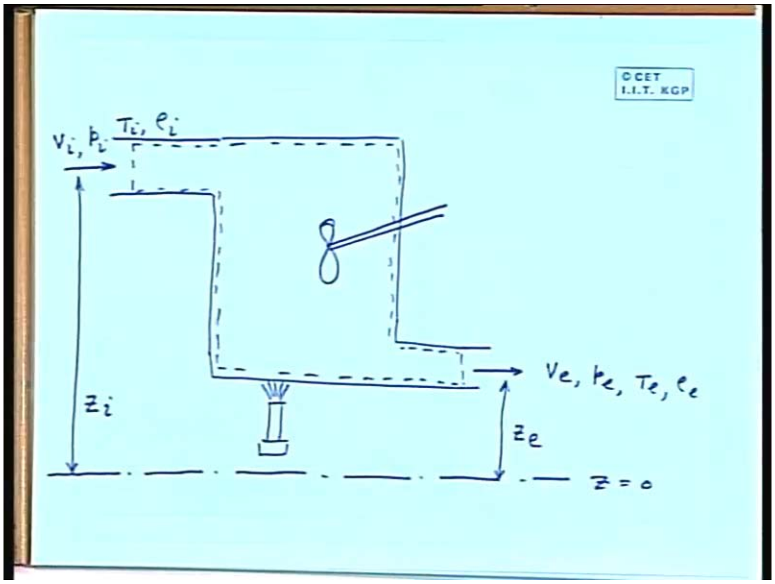

Again, let me take this example which I have drawn. At the inlet and outlet, if we consider then the properties are different. This property at the inlet does not change with time. These properties at the outlet, they do not change with time. So, we can take the example of the steady operation of a turbine. When steam is entering the turbine, it has a high pressure and temperature. When it is going out at the exit, it is having low pressure and temperature. But, with time we are supplying the turbine with the same quality and the same temperature of steam and if it is operating steadily, the steam with same properties is coming out of the turbine throughout the process. This is the meaning of steady state process. Steady state process also means that there is no accumulation of energy within the system.

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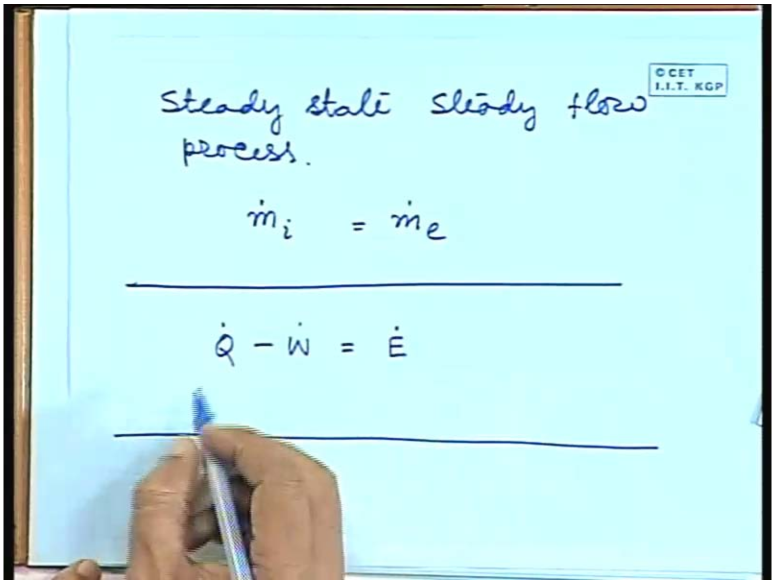

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Steady state steady flow process.

$$\dot{m}_i = \dot{m}_e$$

$$\dot{Q} - \dot{W} = \dot{E}$$

If we consider our first law of thermodynamics, for a process we have written it like this as a rate equation. This is the rate of heat transfer; this is the rate of work transfer and this is the rate of change of energy within the system. So, if it is a steady state steady flow process then the right hand term will become 0. That means, within the system or within the control volume, there will not be any storage of energy or any depletion of energy. The amount of energy within the control volume or within the system will remain a constant. That is what will happen in our example also. So, here also, there will not be any storage or depletion of energy if it is a steady state steady flow process.

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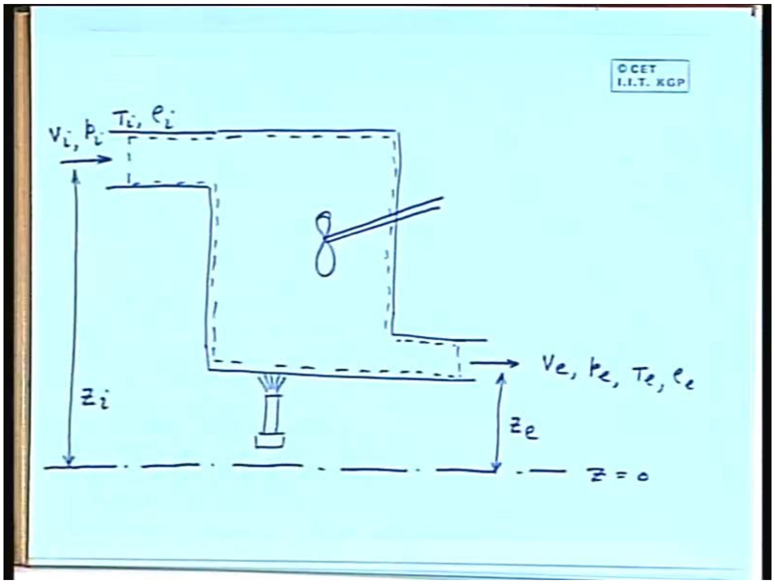

Then, from our common sense or from the knowledge of thermodynamics how can we write the energy interaction or energy equation of this particular control volume? Apart from the work transfer and heat transfer, we have to also consider what amount of energy is entering the system and what amount of energy is leaving the system. Now, there it is important to know energy in which form is entering the system and energy in which form is leaving the system.

What are the different forms of energy? If we take a compressible fluid to be our thermodynamic medium, then what are the different forms of energy? When the fluid is flowing inside, it is having some velocity, so it will have some kinetic energy. This is our datum plane. With respect to the datum plane, the height of the inlet is different. So, it will have some potential energy. As we have discussed earlier that internal energy is very important for the type of system which we are considering, it will have some amount of internal energy. It may have some electrical energy or magnetic energy etc., but for our application, generally those forms of energies are not present. So, we will not consider them, but kinetic energy is there, potential energy is there and internal energy is there.

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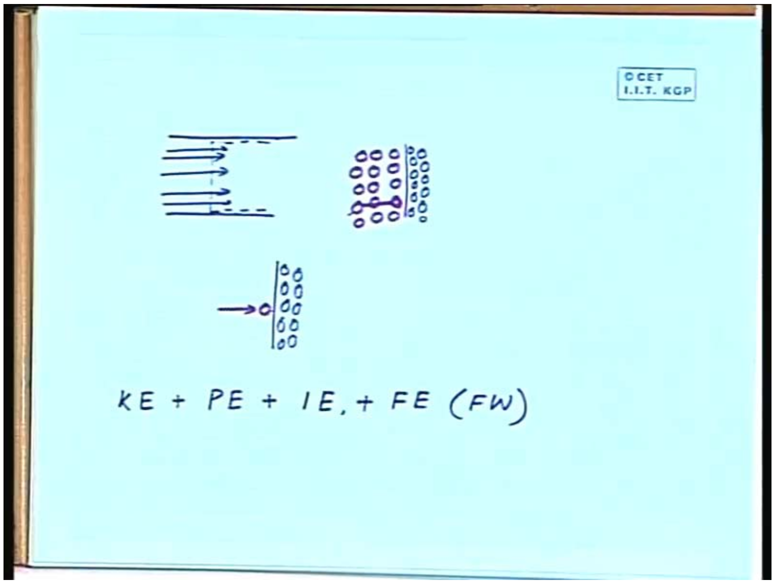

KE + PE + IE, + FE (FW)

Is there any other form of energy? Let us look a bit minutely as to what happens at the entry. Let us say this is the control surface at the entry. Basically, this is an imaginary line. There is no physical barrier, otherwise mass cannot enter. So here, the fluid particles are entering the control volume. When they are entering, they have to do certain extra amount of work, because here there are other particles. If we again take another figure, these are the fluid particles which are already there inside the control volume and these are the particles which like to enter the control volume. So, these particles, this violet colour particles, if they have to enter, they have to push the blue colour particles and then they have to get inside the control volume. So, they have to do certain amount of work.

If we look like this, there are a large number of particles. These particles have to push the front one inside the control volume. So, if this particle is pushing the front most particle then, it is doing some work and this work, where is it going? It is going inside the control volume. When some fluid is entering the control volume, it is doing some extra amount of work and that work is going to the control volume. This work is known as flow work. Apart from its own kinetic energy, it is also taking some amount of work, because it has to go inside a space where already gas particles or fluid particles are there. We can calculate this amount of work. This work is known as flow work or flow energy.

The reverse will happen when the particles are leaving the control volume. When the particles are leaving the control volume, outside the control volume, there will be other particles. Let us say this particle is leaving the control volume. So, it needs a push from its back and when it is going, it is taking this extra amount of work or extra amount of energy along with it out of the control volume. So, it will take away certain amount of work or energy from the control volume. Again, this is also flow work or flow energy. Basically, we will consider kinetic energy, potential energy, internal energy and flow energy. This is called flow work. Now, let us estimate what is our flow work or flow energy.

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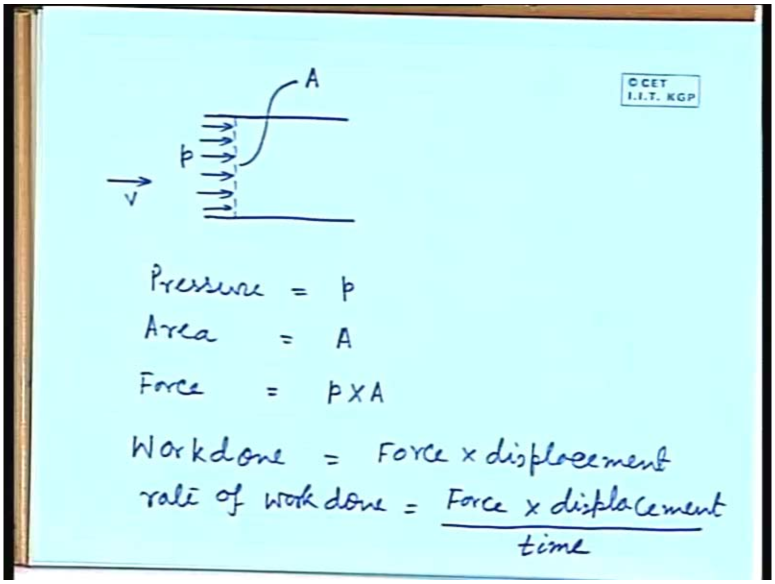

Pressure = p

Area = A

Force = $p \times A$

Workdone = Force × displacement

rate of work done = $\frac{\text{Force} \times \text{displacement}}{\text{time}}$

The fluid has a velocity v and here at this control surface, the pressure is p. This area is A. The pressure is p, area is A. So force is equal to p into A; that is the force. Work done is force into displacement and rate of work done will be force into displacement by time. Displacement by time, for this we can replace velocity. So, this will be force into velocity or p into A into velocity.

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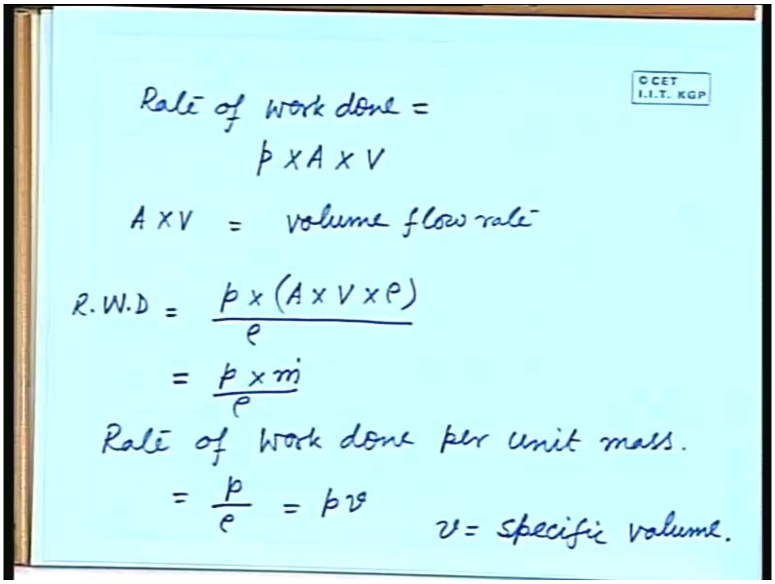

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Rate of work done =

$p \times A \times V$

$A \times V$ = volume flow rate

$$R.W.D = \frac{p \times (A \times V \times \rho)}{\rho}$$

$$= \frac{p \times \dot{m}}{\rho}$$

Rate of work done per unit mass.

$$= \frac{p}{\rho} = pv$$

v = specific volume.

If we do that, we can write rate of work done that is p into area into velocity. What is A into velocity? That is the volume flow rate. We can write A into V, is volume flow rate. How can we get mass flow rate? If we multiply volume flow rate by density; so, we can get p into A into V into rho, this is the mass flow rate and this divided by rho. This we can write as rate of work done. This is rate of work done that is equal to the p into A into V into rho divided by rho, because I have taken rho both in the numerator and denominator. We can write p into m dot by rho. So rate of work done per unit mass that will be p divided by rho; so that will be our rate of work done per unit mass. We will have the rate of work done per unit mass is equal to p by rho. Rho is the density. So it is the reciprocal of specific volume. We can now introduce specific volume and then we can write this is nothing but pv, where v is the specific volume. We have got the expression of flow work per unit of mass; that is nothing but p multiplied by small v which is the specific volume.

We will stop here, and in the next lecture, we will try to get the expression for first law for a control volume or for an open system. Today we have learnt how to calculate the flow work or flow energy and this is coming as p into v. Today's discussion if we summarize, we have seen the first law of thermodynamics for a cycle initially and then we have defined it for a process, and very importantly thermodynamic property that is internal energy, we have some idea regarding it. With this background, in our next class, we will move to deriving the first law of thermodynamics for an open system or control volume.

Thank you.