Applied Thermodynamics for Marine Systems

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Lecture No - 03

First Law of Thermodynamics (Open System)

Good afternoon, everybody. We will continue with what we have learnt in our last lecture. In our last class, we have seen that whenever a fluid is entering a control volume through a control surface, it has to do some extra amount of work. This work we have termed as flow work or flow energy. I will repeat this.

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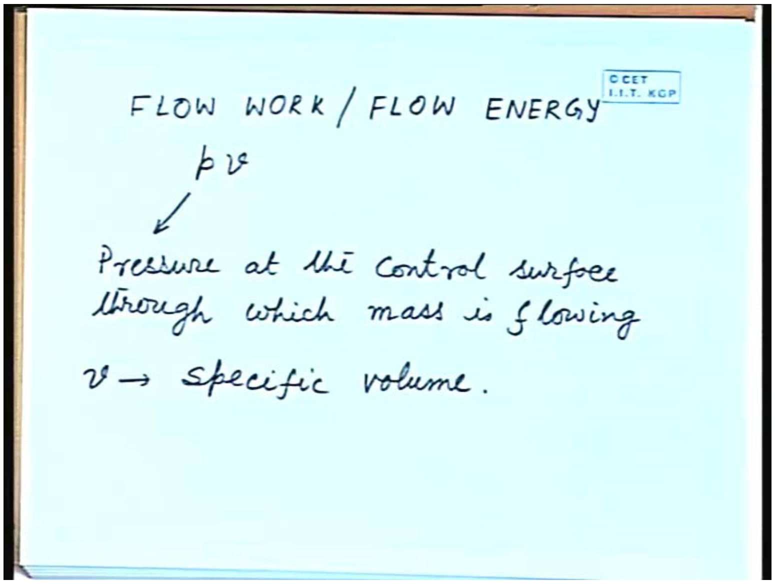

Flow work or flow energy, you have derived it. This is given by p into small v, where p is pressure at the control surface through which mass is flowing, v is specific volume. We are getting this flow work or flow energy by the product of two quantities; one is pressure at the control surface and another is the specific volume.

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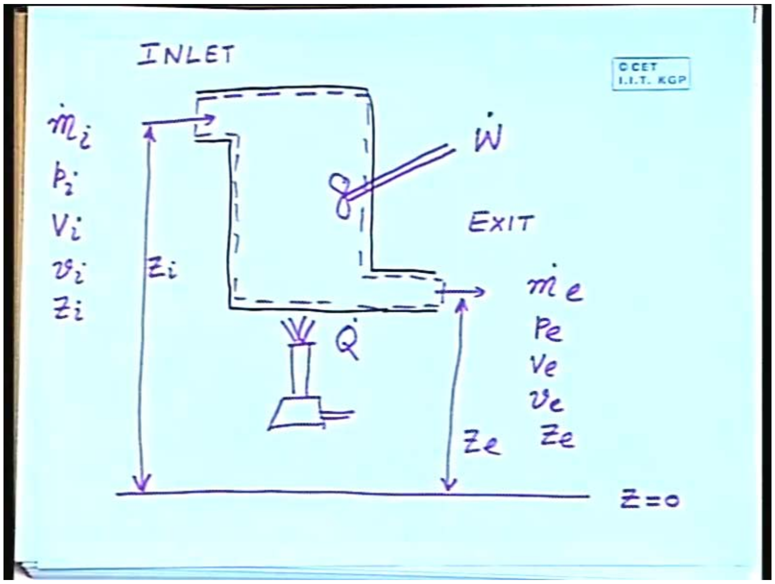

If we go back to our previous diagram of the control volume, it was like this - control volume of any arbitrary shape and we had the control surface like this. This is our inlet, where the mass is entering and this is the exit where mass is going out. Let us say that the mass flow rate at the inlet is given by m dot i; the mass flow rate through the exit is m dot e, pressure here is p_i, velocity is V_i, specific volume is v_i and the height from the datum level is Z_i. We have also selected a datum plane at Z = 0. This is Z_i and this is Z_e. The corresponding quantities at the exit are p_e - pressure, V_e - velocity, small v subscript e - specific volume and Z_e that is the height from the datum level. Over and above that, we also had some work interaction. Let us say that the rate of work interaction is W dot. We had some heat interaction; the rate of heat interaction is Q dot.

If we think of the energy balance for this particular control volume, let us see what are the quantities entering here? With the incoming mass, some amount of kinetic energy will enter the control volume, some amount of potential energy will enter the control volume and we will also have internal energy u_i plus the flow work or flow energy. The energy which will be leaving the control volume is the kinetic energy associated with the mass, the potential energy associated with the mass, internal energy associated with mass and the flow work or flow energy. Over and above that, we have work transfer and heat transfer.

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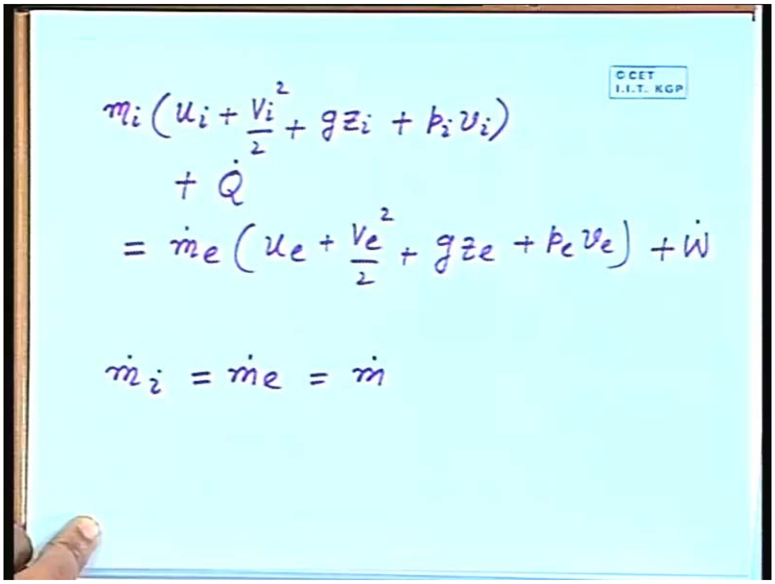

Keeping the sign convention intact we can write, m_i into u_i, u_i is internal energy plus V_i square by 2, that is the kinetic energy; gZ_i potential energy plus p_i v_i flow work or flow energy. With this the amount of heat interaction will come. This can be equated with m dot e u_e plus V_e square by 2 plus gZ_e plus p_e v_e plus W dot that is the work transfer. This equation can be written only under the condition of steady state steady flow process where m dot i is equal to m dot e is equal to m dot.

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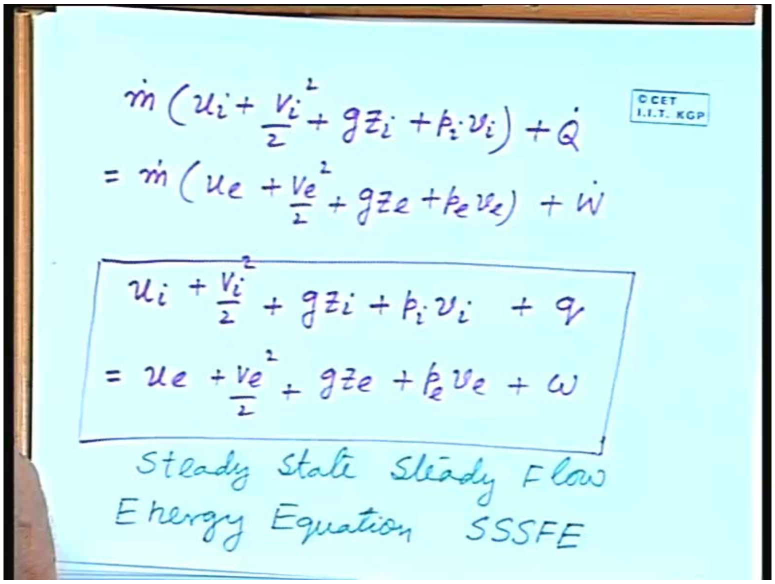

With this, we can finally write m dot u_i plus V_i square by 2 plus gZ_i plus pi v_i plus Q dot this is equal to m dot u_e plus V_e square by 2 plus gZ_e plus p_e v_e plus W dot. It is customary to divide both the sides with the mass flow rate. We will get one equation where all the quantities are specific or per unit mass. If we do that, we will get u_i plus V_i square by 2 plus gZ_i plus p_i v_i plus q that is equal to u_e plus V_e square by 2 plus gZ_e plus p_e v_e plus w. So, small q and small w are the heat transfer and work transfer per unit mass respectively.

All the quantities in this equation are specific quantities or quantities per unit mass. We can write the steady state steady flow equation in this particular form. This equation I will put in a box. It is termed as steady state steady flow energy equation or in short SSSFE. This equation is a very useful equation for the analysis of engineering systems and different devices. We will take up different examples in a few minutes and we will see how we can apply this equation for different systems and devices. Before that, we will do some more simplification.

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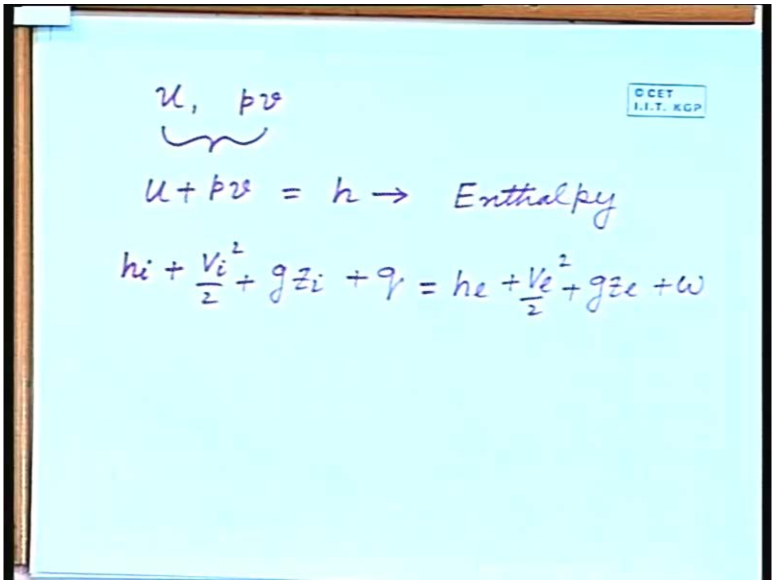

Both in the right hand and in the left hand we are getting quantities like internal energy u and flow work or flow energy pv. This is one intensive property, internal energy is one intensive property; pressure and specific volume they are also intensive properties. We can combine these two things and we can ultimately express this quantity with a new intensive property, which is known as enthalpy. This is denoted by h and is known as enthalpy. This is a property that is why it is a state variable; at a particular state, we will have a particular value of enthalpy. Introducing enthalpy, we will have our equation like this: h_i plus V_i square by 2 plus gZ_i plus q that is equal to h_e plus V_e square by 2 plus gZ_e plus w. This will be the form of our steady state steady flow energy equation.

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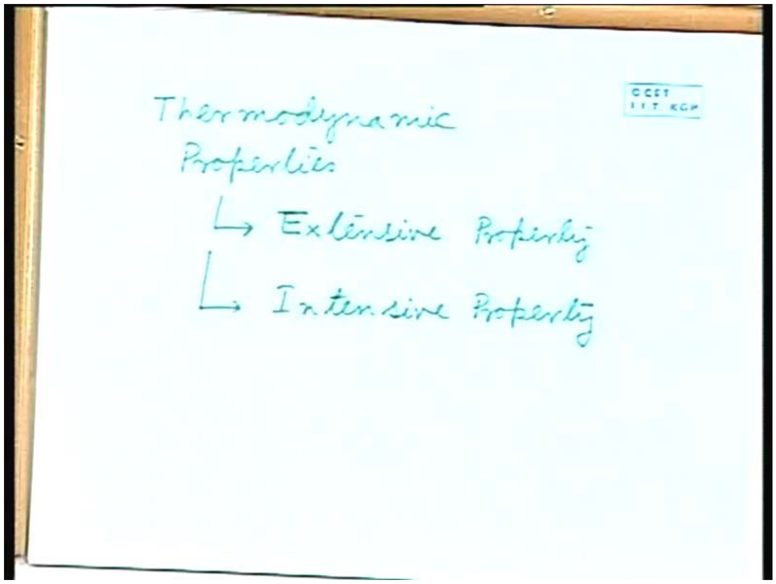

Let us see how we can apply the first law of thermodynamics for different systems and processes. First, we will take examples of some closed systems.

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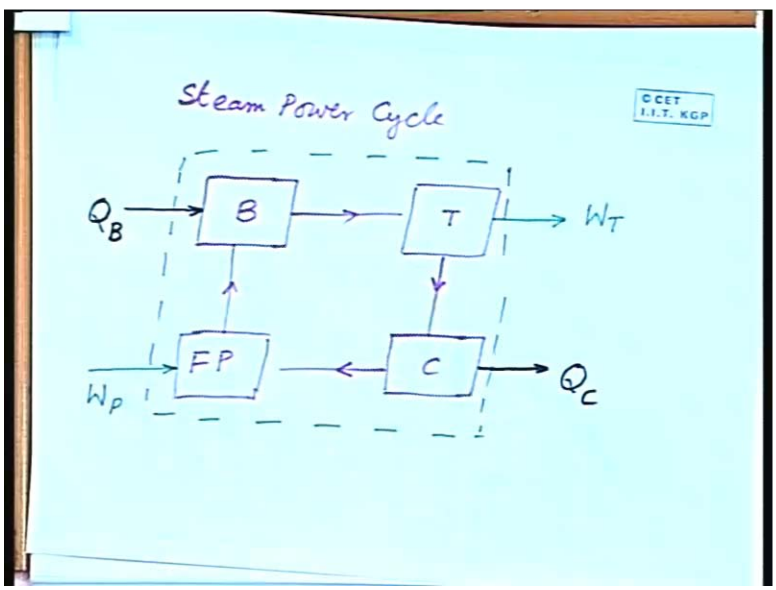

Let us say we are taking the example of a cycle - steam power cycle. Schematically, steam power cycle will have 4 components. This is the boiler denoted by B. Then, we will have turbine, this is denoted by T. After the turbine, we will have condenser denoted by C and finally we will have feed pump which is denoted by FP. The working substance which is either water or steam will execute a cycle between all these 4 components. In the boiler, we will have supply of heat from outside. Let us denote this thermal energy or heat as Q_B. In the condenser heat will be rejected and let us denote this quantity as Q_C. Similarly, in the turbine, it will do some external work; let us say this is W_T. In the feed pump, we have to supply some amount of work from outside to run the pump, so let us denote it as W_P. Recognize that these are all the quantities associated with different components of the steam power plant and we can also have some sort of a control volume identified as shown by this dotted line. If this is our control volume, we can see that there are a number of interactions in terms of heat and work. There is work input in the pump. The control volume is doing some work on the surrounding, that is the turbine work; there is heat supply to this control volume and there is heat rejection from this control volume.

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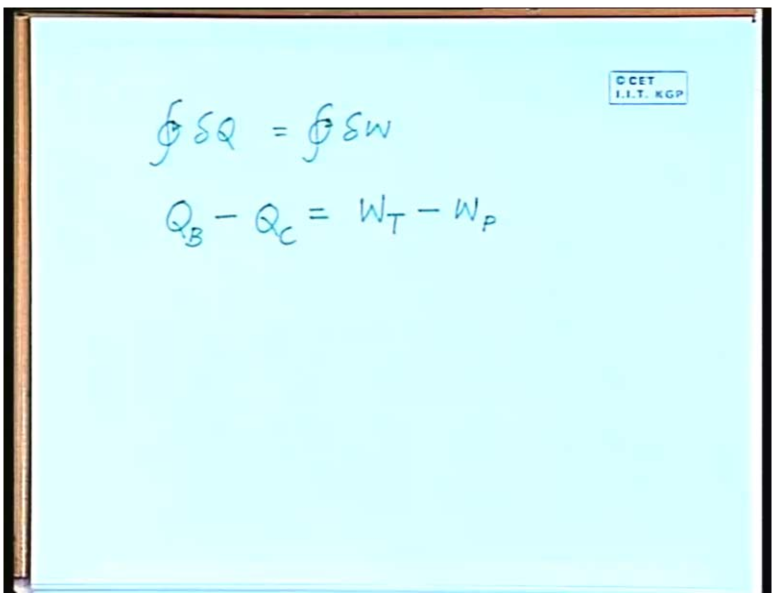

If we write down now the first law of thermodynamics, for a closed system, we have cyclic integral of dQ is equal to cyclic integral of dW. Basically, for this steam power cycle, considering all this work transfer and heat transfer, we can write Q_B, this is a positive quantity as heat is supplied to the control volume, minus Q_C, this is being rejected by the control volume; this is equal to W_T, work done by the control volume on the surroundings, so it is positive and then minus W_P, work which is required to run the pump, so which will be a negative quantity. I have taken a very simple example. This is how we can apply first law of thermodynamics taking the steam power plant as a whole to be our control volume.

This is the application of the first law of thermodynamics for a closed system because the way we have defined our control volume, if we take the steam and water to be the working fluid, then no mass is entering the control volume or no mass is leaving the control volume because steam or water is the working fluid for our example.

Next, let us take some examples where we have got flow process and we have got mass entering the system and leaving the system.

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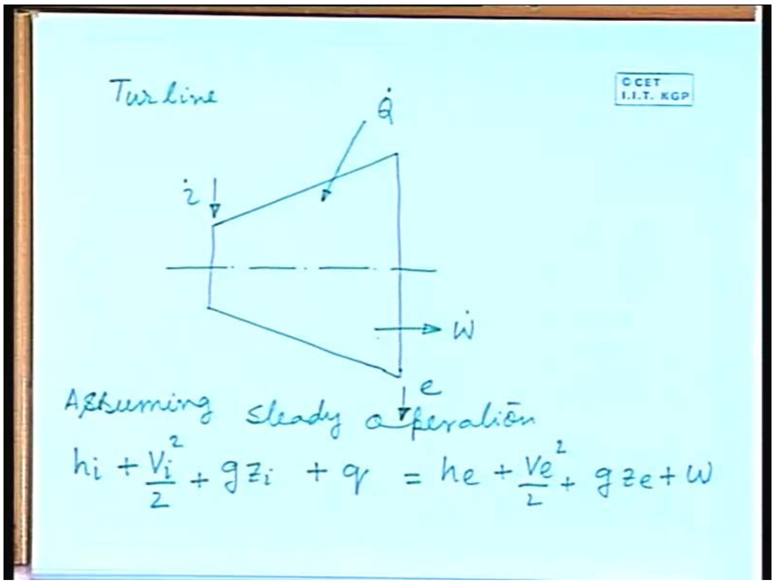

Let us take the example of a turbine. Either it can be a steam turbine or it can be a gas turbine. Schematically, it is represented by an inverted cone like this because in a turbine there is expansion. There is a change in specific volume in the direction of flow. This is the inlet, this is the outlet. Again, there could be heat transfer and work transfer. This is Q dot; it can have any direction, I have shown an arbitrary direction. Assuming steady operation, if we assume that it is operating under steady state, one can write, this is inlet and this is exit; h_i plus V_i square by 2 plus gZ_i plus q that is equal to h_e plus V_e square by 2 plus gZ_e plus w. This is the equation we can write for the turbine. This is a very generalized equation. For a turbine used in practice, we can see the number of terms which we have written here. Some of them are significant while contributions of some of the other terms are not that significant.

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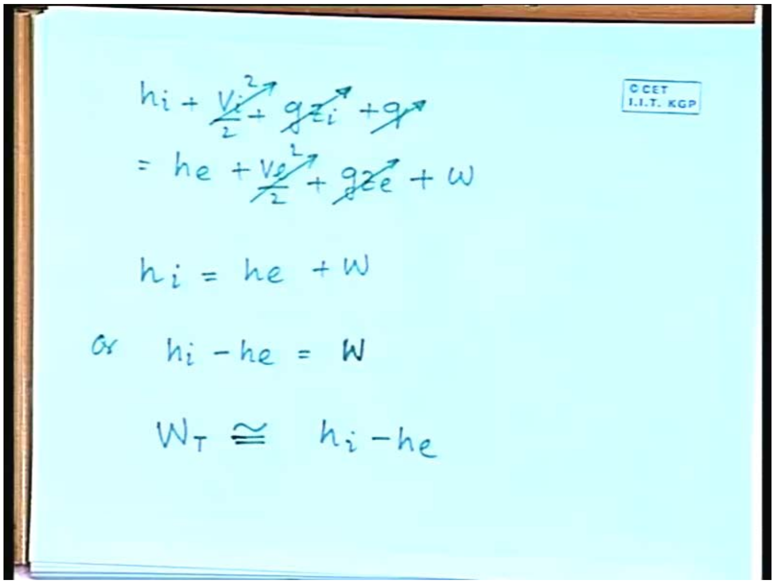

If we repeat this equation h_i plus V_i square by 2 plus gZ_i plus q that is equal to h_e plus V_e square by 2 plus gZ_e plus w. Generally, in a turbine a compressible fluid is entering and leaving the turbine. The change in potential energy is small. So, these two terms can be neglected. From the turbine, there could be some heat loss but generally, this is small compared to other quantities, so this term also can be neglected.

The changes in kinetic energy or contribution of the kinetic energy term is relatively small compared to the change in enthalpy or contribution of enthalpy, so one can neglect the change in kinetic energy also. We will have h_i is equal to h_e plus W, or in other words we can have h_i minus h_e is equal to W. Basically when the fluid is entering a turbine, its enthalpy will reduce and that will produce the work or the mechanical work which is supplied by the turbine, which is done by the control volume on the surrounding that is coming due to the change of enthalpy. The enthalpy at the inlet minus the enthalpy at the outlet is the specific work done by the turbine. Finally, we can write W_T is approximately equal to h_i minus h_e. If we take the example of a compressor, what will we get?

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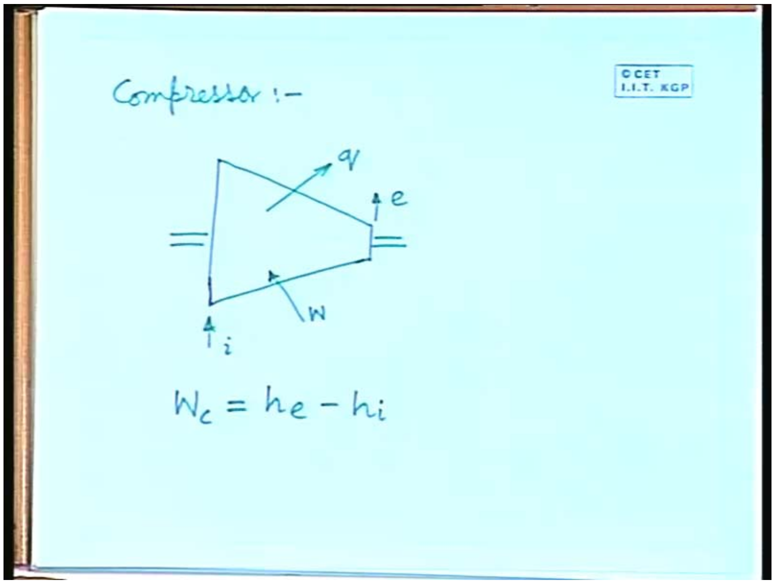

The compressor is a device where the fluid will be compressed. There could be different design of compressor either it could be a reciprocating compressor or it could be a roto-dynamic compressor. But, in both the cases there will be a compression of the fluid or the pressure of the fluid will increase while it will pass through the compressor. The fluid will be energized and we have to supply certain amount of work from outside. In general, one can represent it like this. There is an inlet through which mass is entering, there is an exit through which mass is going out. Again, one can have work interaction and heat interaction and one can easily recognize that it is a device to some extent reverse of turbine. Here, we are supplying work from outside and we are energizing the fluid whereas in the turbine we have extracted energy from the fluid and produced certain external work.

Here, I will not go into the details of it. One can do the analysis just like in the previous case. Some of the terms like kinetic energy, potential energy are negligible compared to others. One can write down the work of compression or compressor work again in terms of enthalpies. What will it be? It is h_e minus h_i. These two examples that I have shown, one should remember that in these cases we have neglected the heat transfer, the contribution of kinetic energy and potential energy. There are certain cases where it may be mentioned that the compressor or the turbine is having certain amount of heat transfer or having certain amount of change in kinetic energy. In those cases we need to consider those terms, otherwise in general those are negligible.

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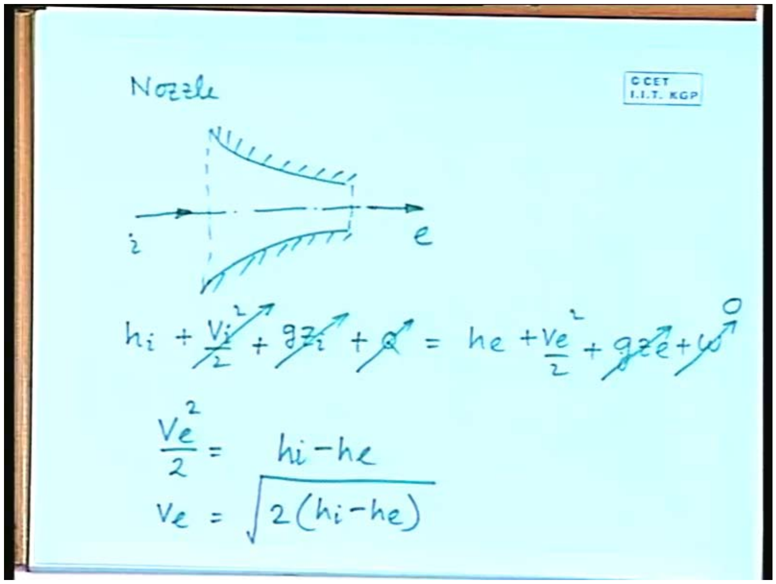

We can think of another mechanical device which is also used for the production of power; that is a nozzle. Schematically, one can show a nozzle like this. A nozzle is used for increasing the velocity of the fluid. Let us write down. This is the inlet of the nozzle and this is the exit of the nozzle. Let us write down the steady state steady flow energy equation for the nozzle. We will have h_i plus V_i square by 2 plus gZ_i plus Q that is equal to h_e plus V_e square by 2 plus gZ_e plus W. Generally, the fluid enters with a small velocity, with a very low velocity into the nozzle. The kinetic energy of the incoming fluid can be neglected. Generally, the nozzle is a small device and a fluid which is passing through it that experiences a very small change in elevation, so change of potential energy is very small. We neglect these two quantities. This is a stationary device and there is no work interaction with the surroundings. The work done is equal to zero. The way I have drawn it, the nozzle is insulated, so there is no heat transfer.

In certain cases, there could be a certain amount of heat transfer. But, generally, it is small compared to the other terms so we are also neglecting the heat transfer term. The exit velocity V_e square by 2 is equal to h_i minus h_e or V_e is equal to 2 h_i minus h_e and within a square root. This is how we can determine what the exit velocity of the nozzle will be or let us say we need to have certain amount of exit velocity of the nozzle. So, at what condition will the fluid be supplied to the nozzle that can be designed from the first principle.

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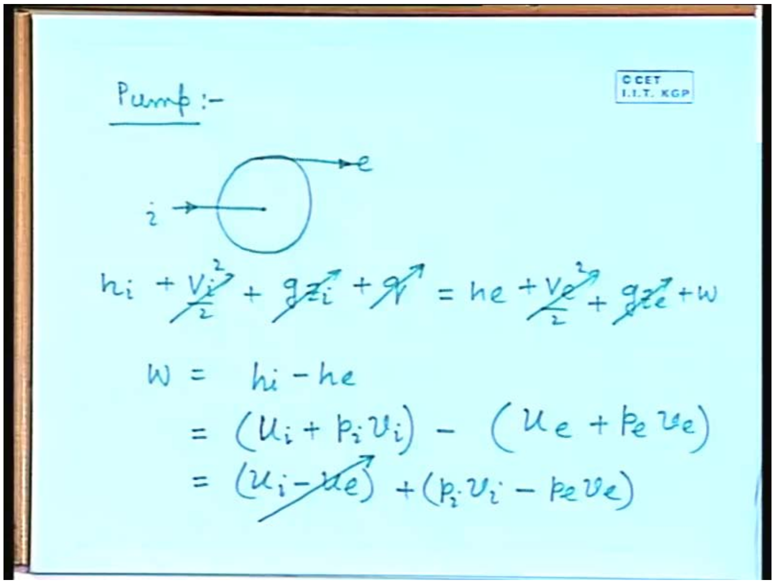

Let us take the example of a pump. It is slightly different compared to a compressor because in a compressor the working fluid is a compressible fluid, whereas in a pump the working fluid is incompressible. The fluid is entering the pump. This is our inlet and this is our exit. The fluid is going out of the pump. Again, let us write down the steady state steady flow energy equation. This is the potential energy term plus q that is equal to h_e plus V_e square by 2 plus gZ_e plus W.

Now, just like before if we try to analyze the process, there is no heat transfer. A very small change of temperature will occur when a fluid will pass through a pump. As the fluid is being churned inside the pump, there could be certain amount of temperature rise but that is negligibly small, so heat transfer is neglected here. Again, between the inlet and outlet of the pump one can neglect the change of potential energy. The change in kinetic energy can also be neglected. It can be like this; if we are having the same diameter of the pump suction pipe and discharge pipe, the kinetic energies will be the same here because, it is an incompressible fluid, the mass flow rate is remaining same. The kinetic energy at the inlet and kinetic energy at the outlet or exit are the same and they will cancel each other. There can be a variation in the suction pipeline diameter and discharge pipeline diameter. There will be some contribution from the change of kinetic energy but generally, that is small. So, we can neglect these two terms. Basically, what we are getting W is equal to h_i minus h_e. Again, let us write this down in terms of internal energy and flow work. If we do that, we will have u_i plus p_i v_i minus u_e plus p_e v_e. We can see this is the internal energy at the inlet; this is the internal energy at the outlet.

The internal energy is a property of the fluid and is dependent to a very great extent on the temperature of the fluid. We know that between inlet and outlet there is very small change in temperature. Basically, there will not be a very appreciable amount of change in internal energy in the case of a pump. We can neglect the quantity u_i minus u_e. Let me write it in two steps: u_i minus u_e plus p_i v_i minus p_e v_e. The first term is very small, we can neglect it.

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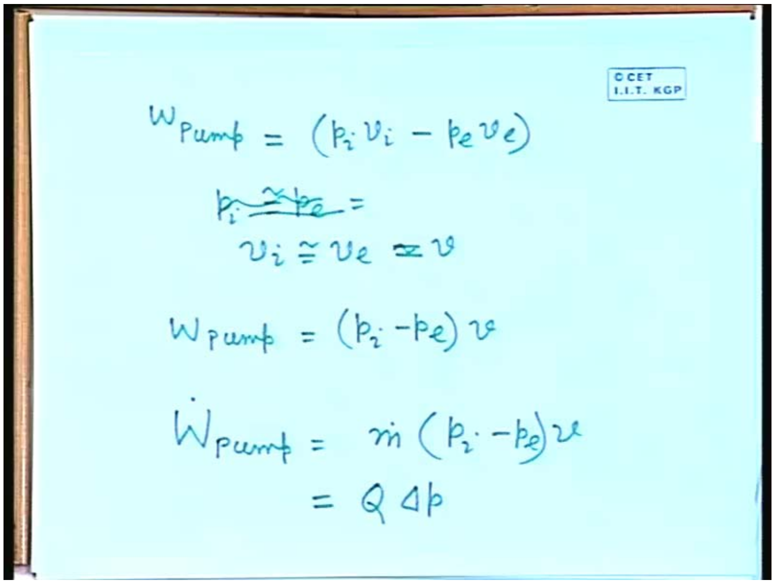

Ultimately, we are writing W_{pump} is equal to p_i v_i minus p_e v_e. Again, this specific volume as the fluid is incompressible fluid there will not be appreciable change in specific volume. We can write v_i is equal to v_e and this is denoted by v; so W_{pump} is p_i minus p_e into v. What is W_{pump}? This is the work transfer associated with unit mass, which is going through the control volume which is now our pump. What are we getting here? This quantity is equal to inlet pressure minus exit pressure multiplied by this specific volume.

In this quantity p_i inlet pressure, which is called suction pressure, this is less; exit pressure is higher compared to the inlet pressure. This quantity will be a negative quantity, which means that we have to supply work to run the pump for pressurizing the liquid. Basically, if we are interested in the magnitude only one can again reformat the expression and one can write p exit minus p inlet into v. W dot pump one can write m dot into p_i minus p_e into v or Q into delta p. We are familiar with this formula. Is there any difficulty? This is the specific volume per unit mass, and this is multiplied by m dot, so we will get this expression.

Let us take some other example, which is again interesting. Let us take the example of a throttling process.

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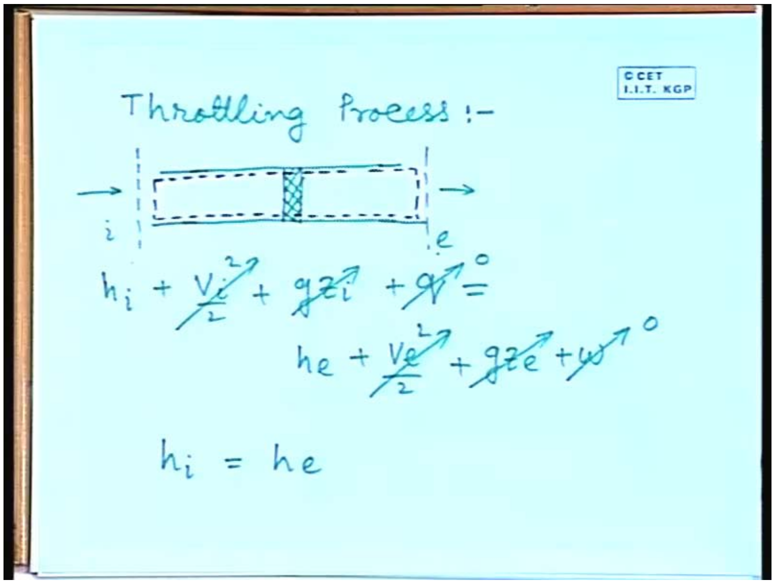

A throttling process is a process in which a compressible fluid is made to pass through a narrow aperture. This narrow aperture could be a porous plug, could be a very small opening like orifice or could be a small opening of a valve. Basically, we are having a pipeline. In the pipeline, we are having a very narrow opening and this change in cross sectional area, the pipeline has got a larger area; we are having a narrow opening so it is having a small area. This change in cross section is abrupt. There is an abrupt change in cross section, an abrupt constriction is there. Let us say, that this is your inlet plane and this is your exit plane. This is i and e; flow is taking place in this direction.

Our control volume is something like this. We have taken a sufficiently long or large control volume and we have encompassed this narrow aperture or narrow opening inside this control volume. Now, we can apply our first law of thermodynamics for this particular process. We can have h_i plus V_i square by 2 plus gZ_i plus q that is equal to h_e plus V_e square by 2 plus gZ_e plus W. Let us concentrate only in the inlet plane and outlet plane. This is a constant area term or constant area pipeline. It is a steady state steady flow process; mass flow rate remains constant. There will not be any change in kinetic energy. So from both the sides this kinetic energy term can be cancelled. There will not be any change in potential energy, so this can also be cancelled from both the sides.

There is no work interaction with the surroundings. So W, this term, can be made equal to 0. The duct or pipeline must be well insulated so there is no heat transfer and we can make q is equal to 0. So, for the throttling process we can write h_i is equal to h_e.

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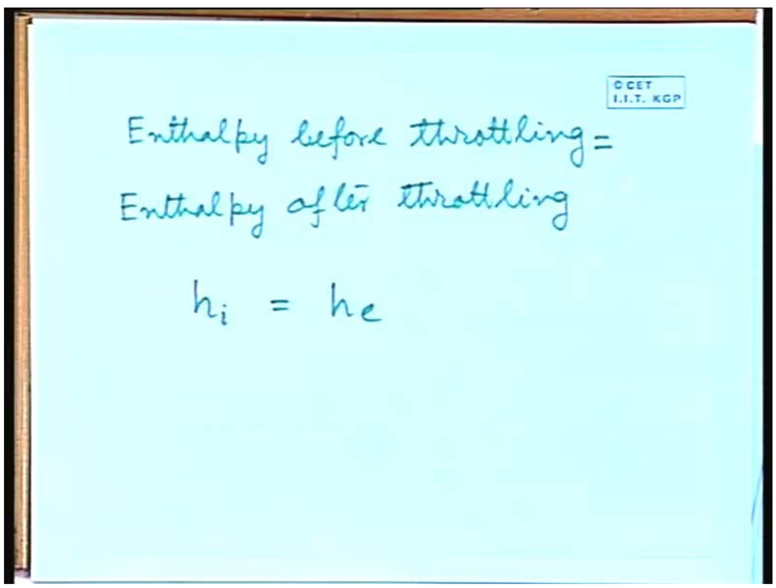

If we want to give a verbal description, we can write: enthalpy before throttling is equal to enthalpy after throttling. The throttling process is such that enthalpy before throttling is equal to enthalpy after throttling. This we get from the first law of thermodynamics but it has got some far-reaching significance. The throttling process is used for production of low temperature. We know that in our domestic refrigerator or air conditioner, we use a throttled valve or a throttling device. The throttling device could be some sort of expansion valve or some sort of a capillary tube through which the fluid is throttled. If certain conditions are maintained, then we can see that due to throttling, low temperature can be produced or low temperature effect can be produced. That is why the throttling process is very important. But, there we will have this derivation, and that means, what we have derived is valid in throttling process - the enthalpy before throttling and enthalpy after throttling will be identical.

If I elaborate this, actually h_i is equal to h_e. Let us elaborate it a bit further. Though h_i and h_e are identical, they are not at the same state. They are at different states. That means for h_i, the pressure and temperature are not identical with the pressure and temperature of the fluid after throttling. There is a fall in pressure, because the fluid is experiencing a sudden expansion and due to this sudden expansion there is a fall in temperature. We are interested in those situations. One can see that if it is an ideal gas, then there will not be any change in temperature. In case of real gases there are cases when there will be a fall in temperature. We are interested in those applications because using those applications we can have our refrigeration cycle. This process is known as Joule-Thompson expansion process. The throttling process when we have, enthalpy before throttling and after throttling identical; this process is known as Joule-Thompson expansion process.

I will take another example where we can apply the first law of thermodynamics. So far, we have considered that there is only one inlet and one outlet but the control volume need not have only one inlet and one outlet. There could be multiple inlets and multiple outlets.

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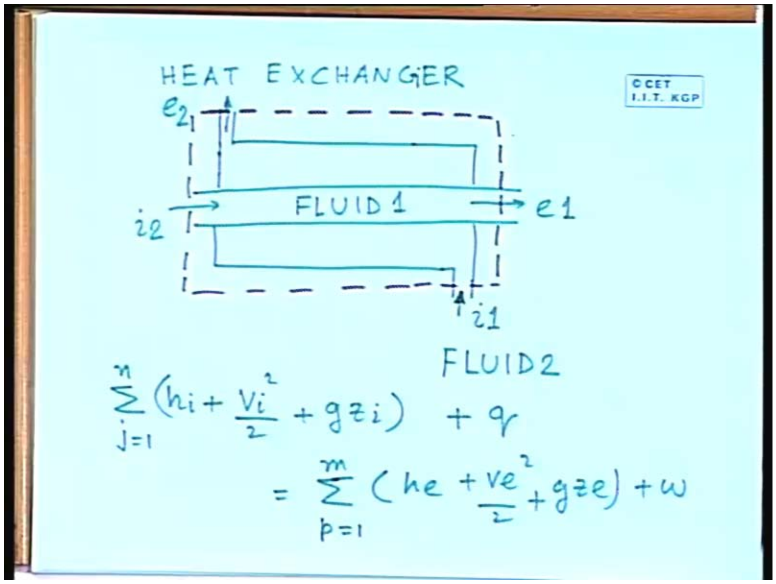

We can take the example of a heat exchanger. Let us have a very simple heat exchanger which is known as double pipe heat exchanger or tube in tube heat exchanger. Basically, there is a central tube through which one fluid flows and over this central tube, there is another tube which makes an annular passage and through this, another fluid flows. This is fluid 1 and this is the second fluid, fluid 2. If we take this device to be our control volume, we can see that the control volume has two inlets and two outlets. Let us say this is i_1, one inlet; this is i_2, second inlet. This is exit one - e_1 and this is e_2, exit two. There are two exits and two inlets. One can select or one can take example of some other control volume where there could be more number of inlets and more number of exits.

How can we analyse this particular system? There are different ways of analyzing it. What one can do is, first one can take only fluid 1 to be the control volume and then, one can see its interaction with fluid 2 because if we take fluid 1 to be our control volume then fluid 2 becomes the surroundings. One can arrive at the final equation or one can do the analysis the way I have drawn the control volume taking both the fluids inside the heat exchanger to be our control volume. If we adopt the second method then one can write sigma h_i plus V_i square by 2 plus gZ_i. This is j is equal to 1 to n, there are n number of inlets, plus q that is equal to sigma; let us say there are p number of outlets, p is equal to 1 to m; p is any arbitrary outlet and there are m number of outlets, then h_e plus V_e square by 2 plus gZ_e plus w. We can write it in this particular form. For this particular heat exchanger, we have two inlets and two outlets.

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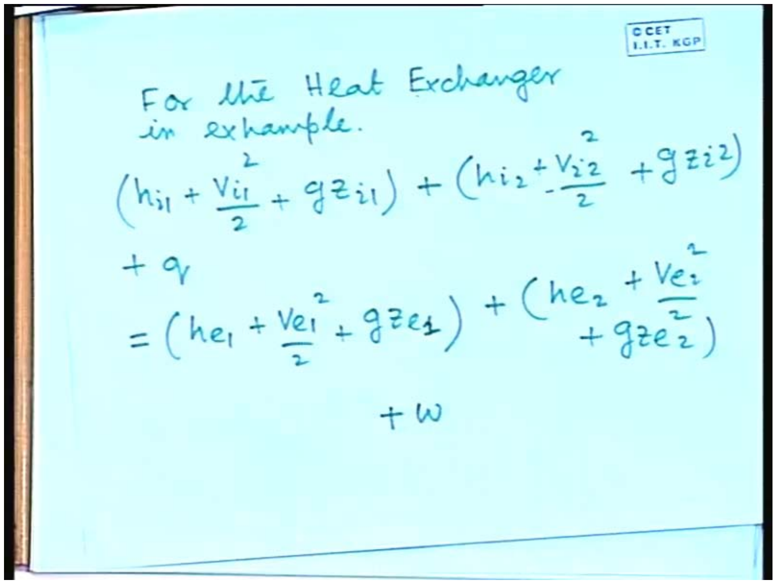

We have taken fluid 1 and fluid 2, so we can write h_{i1} plus V_{i1} square by 2 plus gZ_{i1} plus h_{i2} plus V_{i2} square by 2 plus gZ_{i2} plus q that is equal to h_{e1} plus V_{e1} square by 2 plus gZ_{e2} plus h_{e2} plus V_{e2} square by 2 plus gZ_{e2} plus w. So one can write it like this.

I think we will take a break here and we will continue from this in our next lecture.