Applied Thermodynamics for Marine Systems

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Lecture - 4

Second law of Thermodynamics

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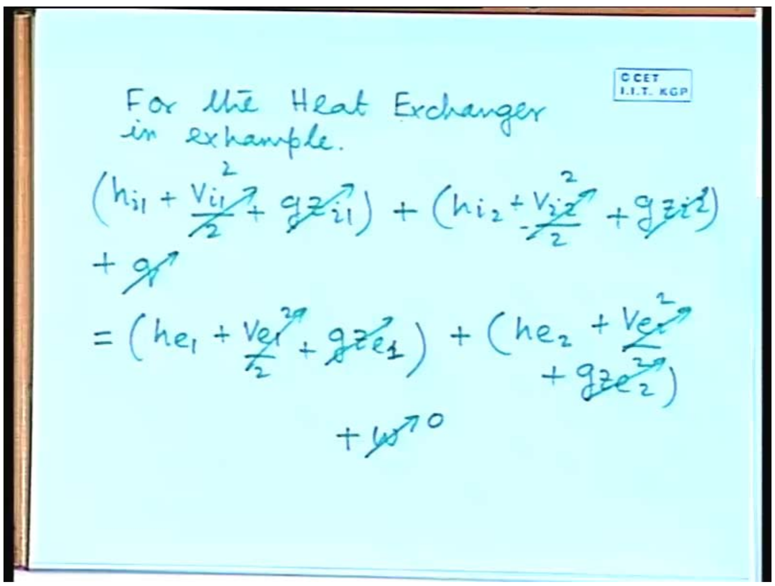

We are getting the equation for heat exchanger here and if we see the control volume, which we have drawn taking both the liquids together, there is no work interaction with the surroundings. We can put this particular term equal to 0.

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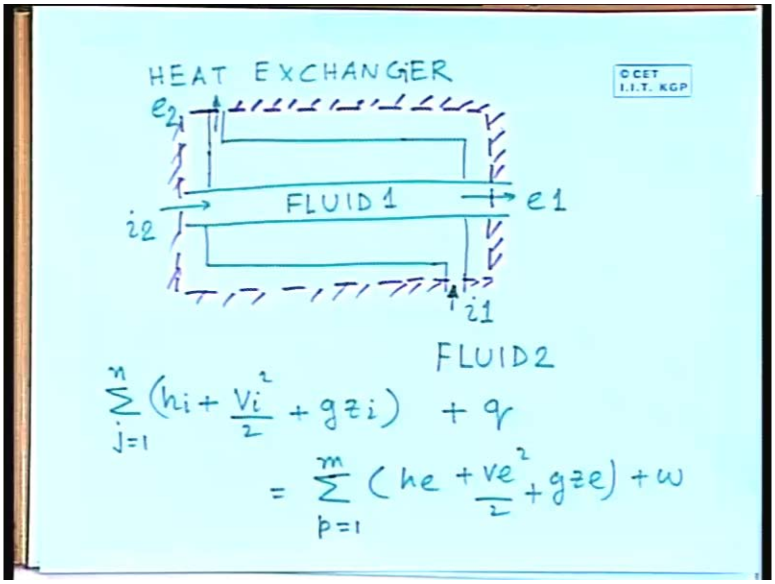

Again, if we consider this control volume, there is heat exchange between these two fluids. But, that is taking place inside the control volume and the control surface, which is given by this pink line can be assumed to be well insulated. What is meant by that is that, the heat interaction of the control volume with the surrounding is zero or that can be neglected from the final expression. So, we can neglect it. In a heat exchanger the changes in kinetic energy and potential energy those are also neglected. All the kinetic energy and potential energy terms are neglected. Then finally one can get h_{i1} minus h_{e1} plus h_{i2} minus h_{e2} is equal to zero.

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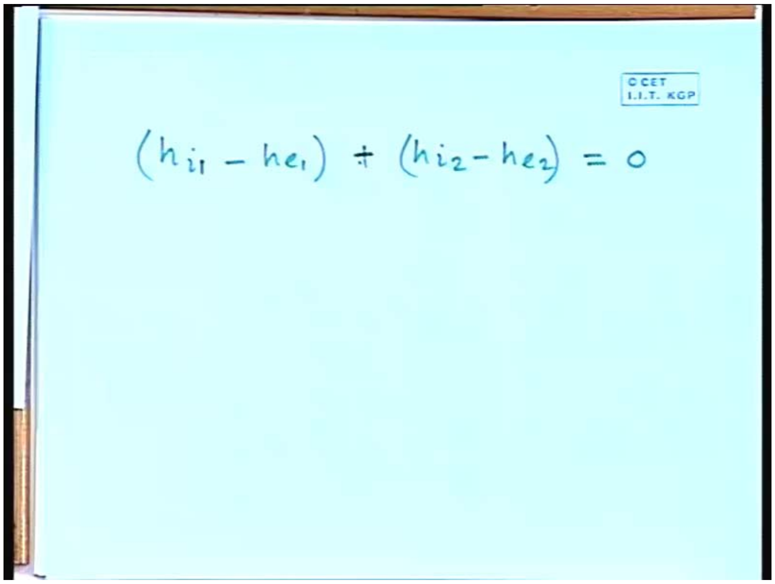

What will happen is one fluid will gain enthalpy and another fluid will lose enthalpy. That is what is coming out from this final expression for the heat exchanger example. Here, I like to recapitulate a few points once again and then I want to move to another topic. We started from the expression of the first law of thermodynamics, which has been derived for a closed system. Then, we have extended it to an open system. For the open system, we had a new terminology that is flow energy or flow work: whenever any fluid mass crosses a control surface there is some amount of extra work done by that fluid mass. When it is entering the control surface it is carrying this extra amount of energy into the control volume and when it is leaving the control volume it is carrying that amount of extra energy from the control volume and taking it to the surrounding. The expression of the flow work that is, p into v where p is the pressure at the control surface and v is the specific volume that gives the flow energy or flow work per unit mass.

Taking this quantity, one can write this steady state steady flow energy equation. Then, we have seen the application of steady state steady flow energy equation for different devices like pump, turbine, compressor etc. In all the examples, we have seen that certain terms can be neglected. Here, the designer or the operator or whoever is analyzing the problem he has to use his own judgment or he has to go very carefully through the specification which is given for an open system. Initially we have done thermodynamics for open system. But, we can now extend it for multiple inlets and multiple outlets. We have taken a specific example, which is the example for a heat exchanger where there are two inlets and two outlets. If the number of inlets and outlets are more than two, we have written the generalized expression; with that generalized expression we can analyze those situations. With this, we can go to the new topic or the next topic. In the next topic we like to see, what are the limitations of first law of thermodynamics?

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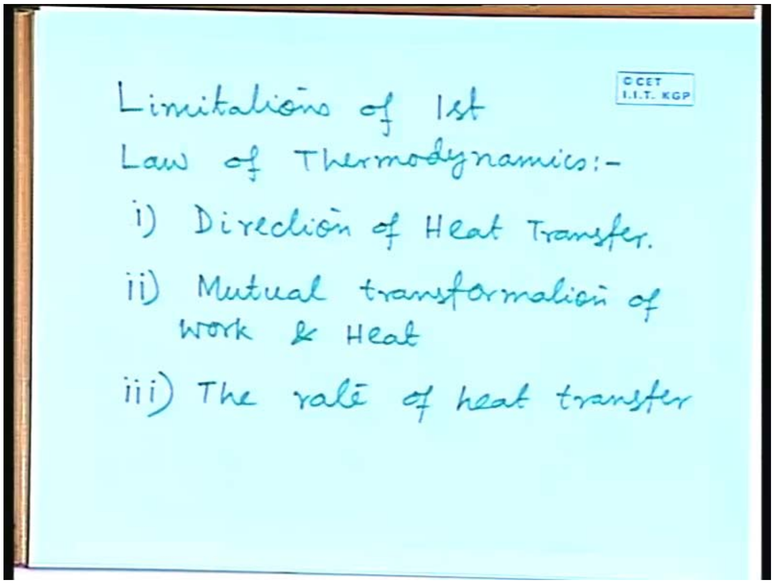

The first law of thermodynamics basically is the law of conservation of energy. If we want to describe this law, it is some sort of a book keeping law. It gives the account of the amount of energy and particularly there is a conversion of energy from one form to another form. The total amount remains constant, but to see how much of a particular form is transformed into another form of energy our first law of thermodynamics is utilized or useful. But, there are certain questions or certain issues regarding energy transformation, which the first law of thermodynamics fails to state.

What are those issues? The first issue is the direction of heat transfer. We know that there is a general tendency for heat transfer to take place from high temperature body to low temperature body. In first law, there is no hint about this preferred direction of heat transfer. Then the second issue is mutual transformation of work and heat. If we remember the statement of the first law it says that when a body executes a cycle, the cyclic integral of heat transfer is equal to cyclic integral of work transfer. That means, if somebody tries to visualize some sort of a device where the whole amount of heat can be converted into work, the first law does not pose any sort of a restriction to this postulation. But, from our day to day experience we know that though work can be totally converted into heat, heat cannot be totally converted into work. This is not stated by the first law, so this is one sort of limitation or one sort of incompleteness of the first law that we do not get this information from first law. Thirdly, the rate of heat transfer. From first law, though we get the idea of total amount of heat transfer, but at what rate the heat transfer will take place we do not get any idea.

Though the first law is very important, as far as transformation or conversion of energy is concerned, there are certain issues where the first law does not give any sort of information. To supplement this, we have got the second law of thermodynamics. Not that all the issues I have listed here are tackled by second law of thermodynamics. But, the second law of thermodynamics gives certain information, which supplements the first law to a very great extent. Particularly, we will see these first two topics; regarding them we get information in the second law of thermodynamics. So, now we move to the discussion of second law of thermodynamics.

Before doing that I like to discuss two very important devices, which are used in engineering very extensively and not only that the knowledge regarding those devices is also important for understanding the second law of thermodynamics.

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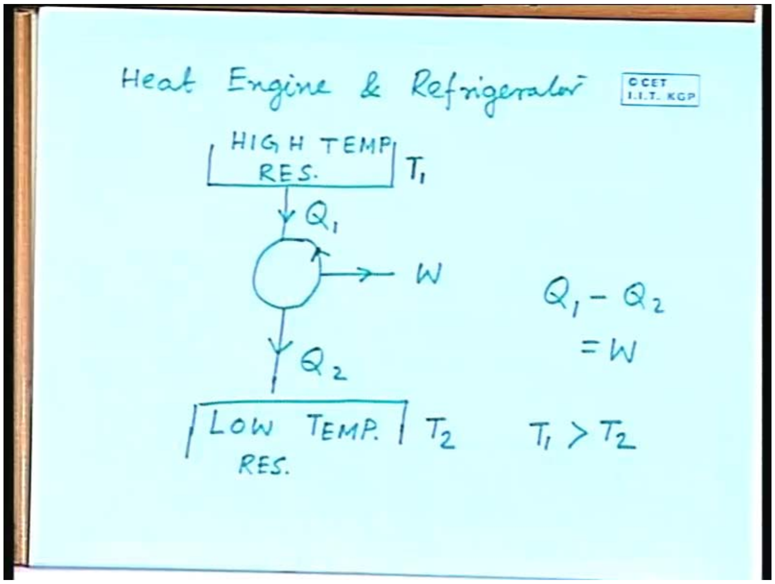

These two devices are heat engines and refrigerator. Let us first start with a heat engine. A heat engine is a device, which operates in a cycle and takes heat from a high temperature reservoir. Let us say that this is taking Q_1 amount of it and this high temperature reservoir is kept at a constant temperature T_1 converts part of it into work W and then rejects the rest, which is Q_2 to a low temperature reservoir. This is the schematic representation of a heat engine and from the first law we can write Q_1 minus Q_2 is equal to W. There is a flow of heat from the high temperature reservoir, which is kept at temperature T_1 through this heat engine to the low temperature reservoir, which is kept at a temperature T_2 and T_1 is greater than T_2. This device operates in a cycle.

Basically, one can think of different devices, which can be termed as heat engines. There is an internal combustion engine that can be termed as a heat engine, one steam power plant that also can be termed as a heat engine. If we take the example of a steam power plant, we have got let us say high temperature source, which is supplying heat to the boiler. Then, we have a low temperature sink which is our atmosphere where the cycle is rejecting heat and then there is a network done, which is turbine work minus the pump work. The steam power plant is operating in a heat engine cycle or as a whole the steam power plant can be termed as a heat engine cycle. We can think of a device, which is just reverse in arrangement to this heat engine cycle.

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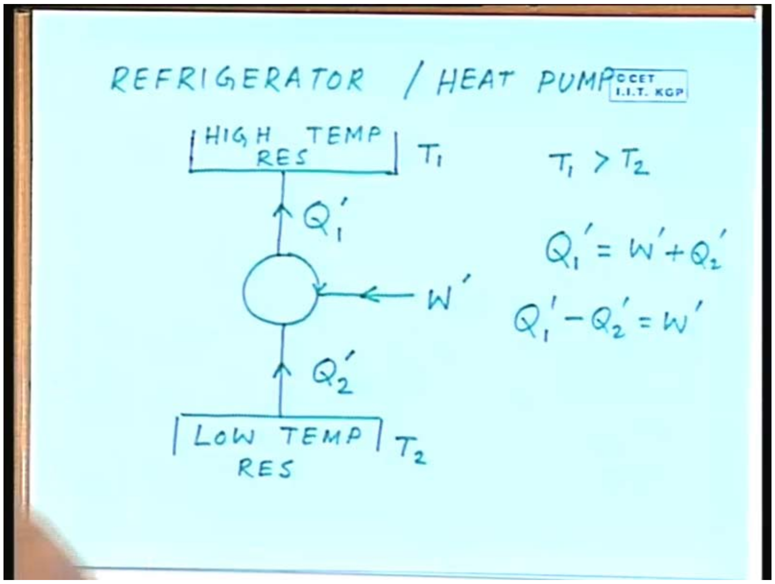

Here also we are having two reservoirs. This is a high temperature reservoir kept at a temperature T_1, this is low temperature reservoir kept at a temperature T_2 and a cyclic device is operating between these two, but the direction of flow of heat is just the reverse. So, this is taking some Q_2 dash amount of heat from here and it is supplying Q_1 dash amount of heat to the high temperature reservior, while this device needs certain amount of work to be supplied from outside and which is W dash. Again one can write down first law of thermodynamics for this device, we can write Q_1 dash is equal to W dash plus Q_2 dash or Q_1 dash minus Q_2 dash is equal to W dash. In this case also T_1 is greater than T_2.

This device can be termed either as a refrigerator or a heat pump, depending on what we want this device to do or what the end use of this device is. This device can be looked as a refrigerator and in that case what we are doing is we are supplying certain amount of work from outside and we are always extracting certain amount of heat from this low temperature sink, so that its temperature can be maintained at T_2 and ultimately that heat is being deposited into a high temperature source, which is maintained at T_1. If we are interested in extracting certain amount of heat from this low temperature reservoir, then we call it a refrigerator. The practical use could be such that we are interested to pump certain amount of heat to the high temperature source from this low temperature reservoir and in that case also we need certain amount of external work to run this device; in that case, we will call this device as a heat pump. Either, this can be seen as a refrigerator if we extract heat from low temperature source or it can be seen as a heat pump if we are pumping heat to the high temperature source.

If we compare between a heat engine and refrigerator, we can see that there are a lot of similarities. In both these cases we need a high temperature reservoir or a source, a low temperature reservoir or a sink and a cyclic device and there is work interaction with the surrounding. The only difference is the direction of heat transfer is reverse in these two cases and direction of work transfer is also reverse in these two cases. Now, we define certain merit of these devices.

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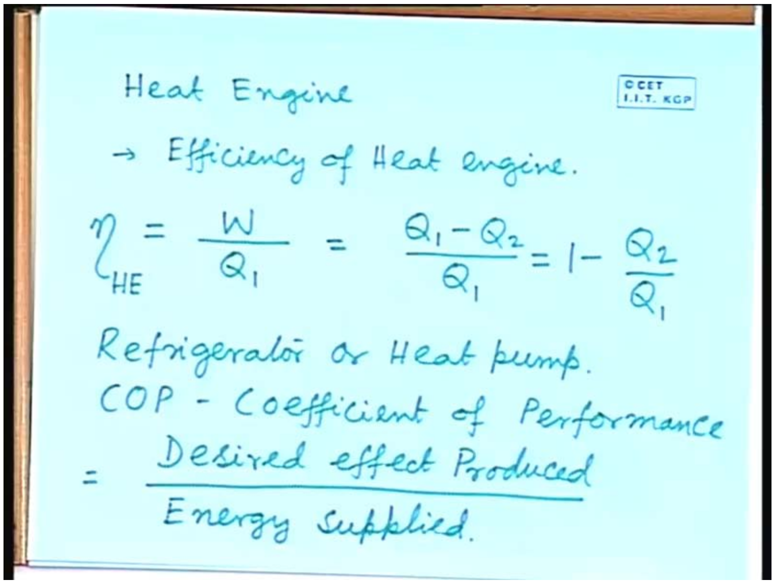

In case of heat engine, we define the efficiency of a heat engine. In general, efficiency is output divided by the input. We know in engineering sense this is the definition of efficiency and in case of heat engine also the same methodology is followed. In heat engine what is our output? What we are doing is, in the heat engine we are using thermal energy for conversion into mechanical work. Mechanical work or the work done that is the output. We can put W and for that we have to put certain amount of thermal energy which is equal to Q_1. This is our efficiency of heat engine; eta heat engine is W divided by Q_1. If we apply the first law of thermodynamics, we can write this is Q_1 minus Q_2 divided by Q_1 and after simplification one can write 1 minus Q_2 by Q_1. This is the efficiency of the heat engine. In case of refrigerator or heat pump instead of efficiency we introduce another term, which we call coefficient of performance or COP. We have COP, which is coefficient of performance. This is defined as desired effect produced divided by energy supplied. As the desired effect produced is different in refrigerator and in heat pump we will have different expression for COP in these two devices.

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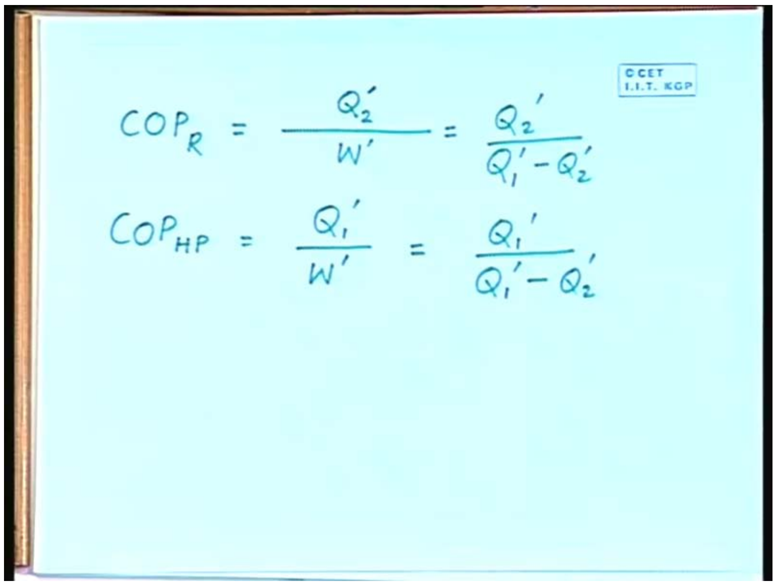

First, let us see the device. This is our refrigerator or heat pump, here in this device the external energy supplied is in the form of work or W dash. The desired effect produced is different in case of refrigerator and in case of heat pump. In case of refrigerator, we want to keep the low temperature source at a temperature T_2. For that we have to extract certain amount of heat, we have to extract Q_2 dash amount of heat. So, this Q_2 dash is our desired effect produced. While, in case of heat pump, we want to pump a certain amount of heat to the high temperature reservoir. So, Q_1 dash is the desired effect produced. Accordingly, I will write COP refrigeration cycle that will be W dash and Q_2 dash is our desired effect produced. We can write Q_2 dash by Q_1 dash minus Q_2 dash. COP heat pump, we can write, Q_1 dash is the desired effect produced and energy supplied from outside that is W dash or we can write Q_1 dash by Q_1 dash minus Q_2 dash. These are the two expressions for our COP of a refrigeration cycle and a heat pump cycle.

With this background of refrigeration cycle and heat pump cycle, we can go for our second law and we can give the formal statement of second law. One thing I would like to mention is that for the second law of thermodynamics there are different statements. All these statements, if we analyze a bit carefully, we will see that they mention the same phenomenon or same physical law of universe. All these statements they have the same meaning. For engineering thermodynamics, we have got two very important or classical statements for second law of thermodynamics. These statements I will write down for you and we will see that both of them mean the same thing.

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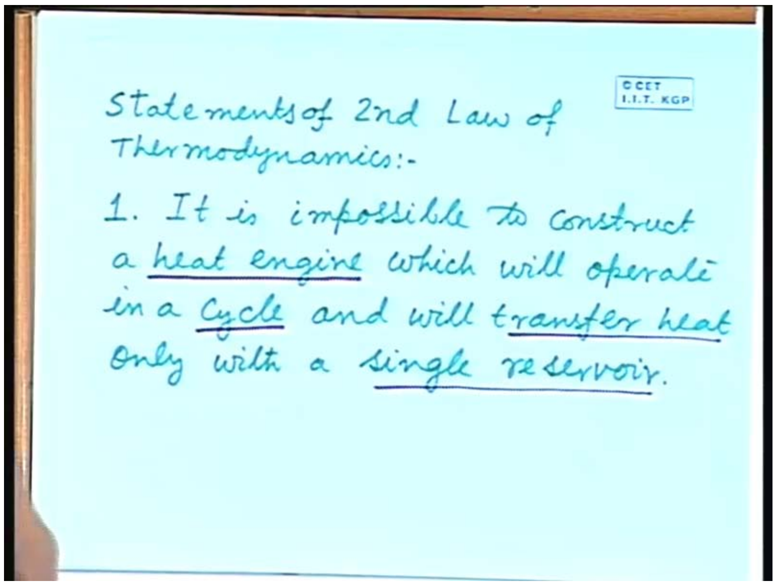

The first statement is like this: Statements of second law of thermodynamics: It states that, it is impossible to construct a heat engine, which will operate in a cycle and will transfer heat only with a single reservoir. Here, a few important points are there; heat engine which will operate in a cycle and will transfer heat only with a single reservoir. What is stated by the first statement of the second law of thermodynamics is like this. We know that, heat engine is a device, which converts thermal energy into work. So, what the second law is stating is like this.

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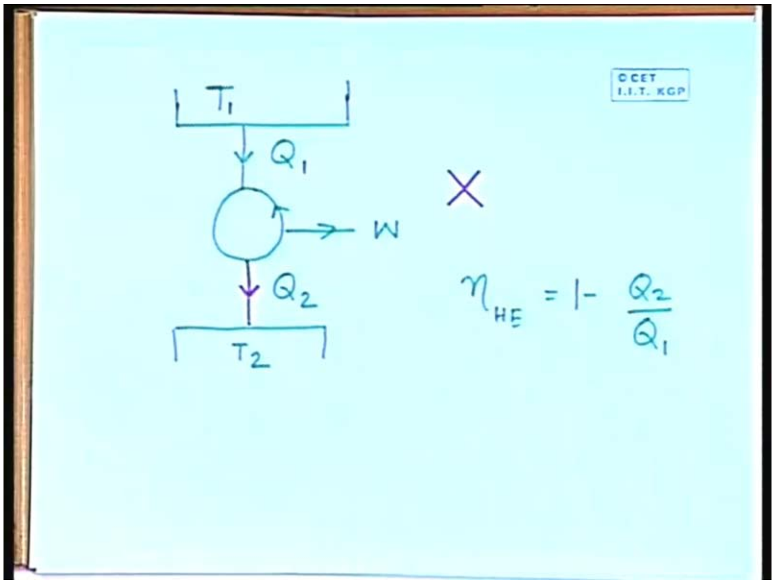

Let us say that, we have got a thermal reservoir, which is at a temperature T_1 and we are having a cyclic device, which is converting thermal energy into work. Let us say, this is Q_1 and this is W. Second law of thermodynamics says that this is impossible. Then, what is possible? Possible is this one; it is transferring heat, exchanging heat with two different reservoirs, which are at different temperatures. That means when we have got two reservoirs at two different temperatures, when there is a heat flow from one reservoir to another reservoir only then we can convert part of the thermal energy into work or if we put it in other words, it is like this. You cannot convert the full amount of thermal energy obtained from a reservoir solely into work. Only part of it you can convert into work. The rest of it you have to deposit or give to another reservoir or if we like to state the second law of thermodynamics in terms of efficiency, we know efficiency of heat engine is like this: 1 minus Q_2 by Q_1, where Q_2 is the heat rejected to the second reservoir. This Q_2 you can never make it into zero or you can never have 100% efficiency of the heat engine. This is what is stated by the first statement of second law of thermodynamics that, if you want to convert thermal energy into mechanical work by a cyclic device which is very important then a part of the thermal energy you have to leave or you have to give off to a low temperature body and rest of it you can convert into mechanical work. Then let us go to the second statement.

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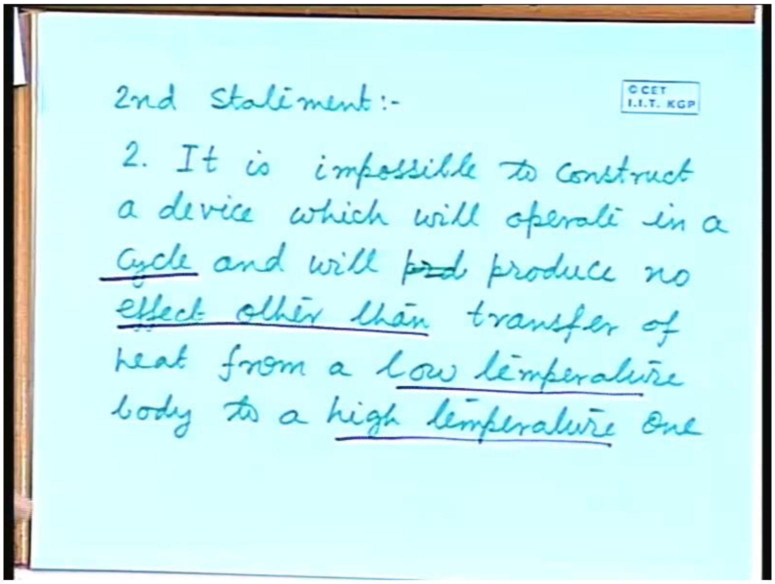

The second statement is like this: it is impossible to construct a device which will operate in a cycle and will produce no effect other than transfer of heat from a low temperature body to a high temperature one. So, here also a few important words are there. First thing, it is talking of a device which will operate in a cycle. In both the cases we see that cyclic operation is very important or continuous operation that is very important and will produce no effect other than, this is very important; this is another important phrase, transfer of heat from a low temperature body to a high temperature body. These are the important points. It is talking of a device which will operate in a cycle and will produce no effect other than transfer of heat from a low temperature body to a high temperature one. So just like the previous case let us try to make a sketch of it.

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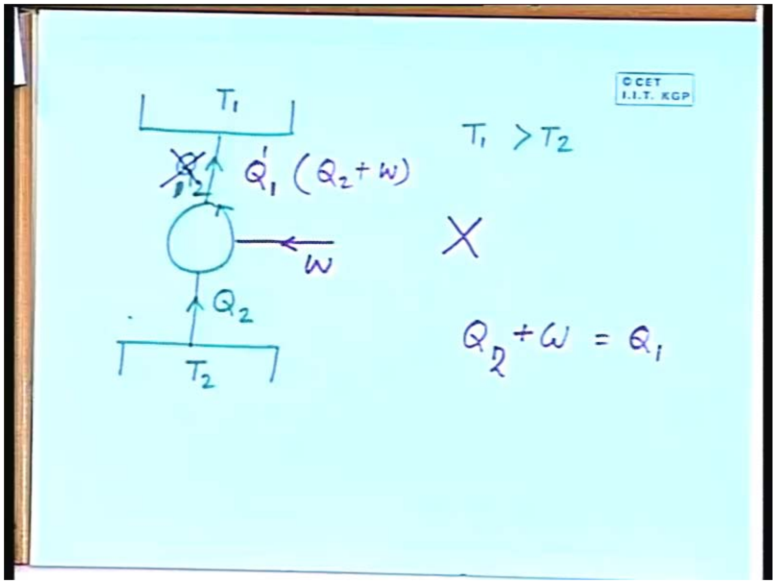

We have got two bodies at different temperatures. This is at temperature T_1 and this is at temperature T_2. T_1 is greater than T_2. We have got some device which is operating in a cycle and it is transferring heat in this direction. Here, it is Q_2 and here also it has to be Q_2. But second law says that this is impossible. Then what is possible? You cannot do it like this, but you have to have some other effect which could be in the form of supply of external work. Let us say this is W so this has to be also changed this is Q_1 which is nothing but Q_2 plus W. We can write, applying first law of thermodynamics, Q_2 plus W is equal to Q_1 and that is what has been written here also.

We know, from our day to day experience that heat flows from a high temperature body to a low temperature body and this is again restated in our second law of thermodynamics that the general tendency of heat flow is from high temperature to low temperature. You can make heat flow from a low temperature body to high temperature body by a cyclic device, only when you have some other external effect like the supply of work from some external agency. This device which is operating in a cycle and which we have seen is known as a refrigerator or a heat pump depending on what your end use is. Again, this particular statement can be restated in terms COP. How can we state it in terms of COP? If we see the expression of COP, we had the expression of COP like this. The first one is the COP of a refrigerator and the second one is the COP of a heat pump.

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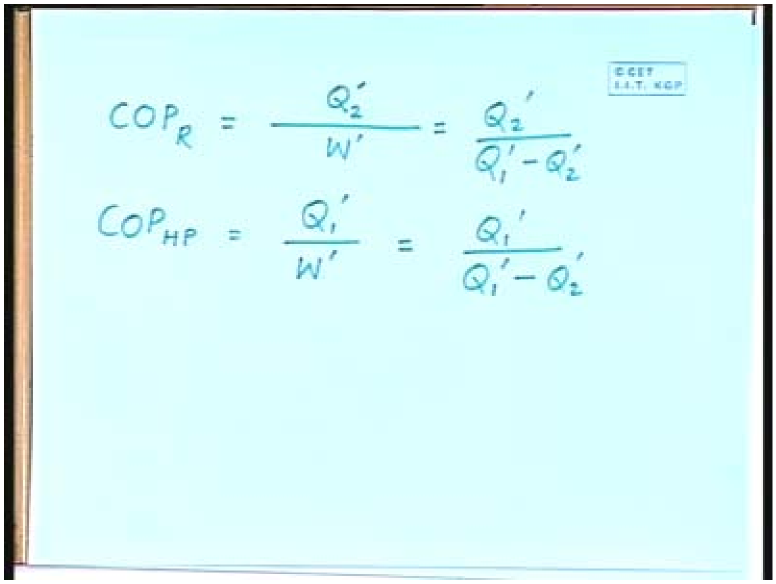

We have seen in this example that this external work W can be only a finite positive quantity; it can never be zero. In terms of the COP, we can say that the COP of a refrigerator or a heat pump can never be infinity. If W is not equal to 0 from our second law then the COP_R or COP_{HP}, heat pump they can never be infinity. We have seen the two classic statement of second law of thermodynamics and it can be shown that violation of one statement means the violation of other statement also. The proof of this particular thing, that means, the violation of one statement is the violation of other statement, is not very difficult. It is easy and it is given in any standard text book of thermodynamics. I think for the present course we are not going to do it due to lack of time. One can see it from any standard book of thermodynamics and one can take it that as the violation of one statement gives the violation of other statement, these two statements are identical and they are meaning the same physical law of the universe. Once we know that we cannot construct a heat engine which will have efficiency equal to 1 which is the highest achievable efficiency, then the next question that comes to our mind is that what best we can construct?

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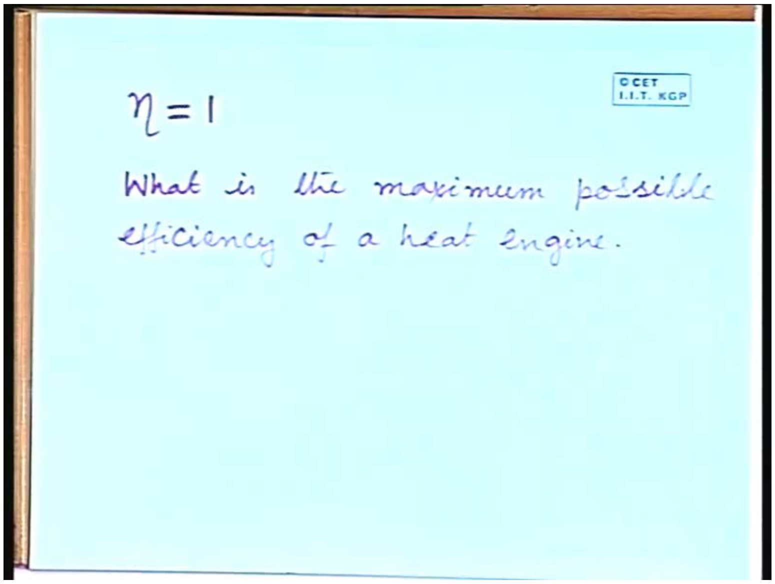

What could be the maximum possible efficiency that we can achieve from a heat engine? That is a very logical question and this question is of engineering interest also. Now, let us try to see what the maximum possible efficiency of a heat engine is. One can argue in the same line. We have seen that second law puts a restriction to the COP value of a refrigeration cycle or a heat pump cycle. We have seen that we cannot have infinite coefficient of performance for a refrigeration cycle or for a heat pump cycle. One can logically put one question. The COP of these devices will not be infinity but what is the maximum value of COP that we can have for a refrigeration cycle or for a heat pump cycle? Again, from observations the scientists have seen that the maximum possible efficiency can be achieved from a heat engine.

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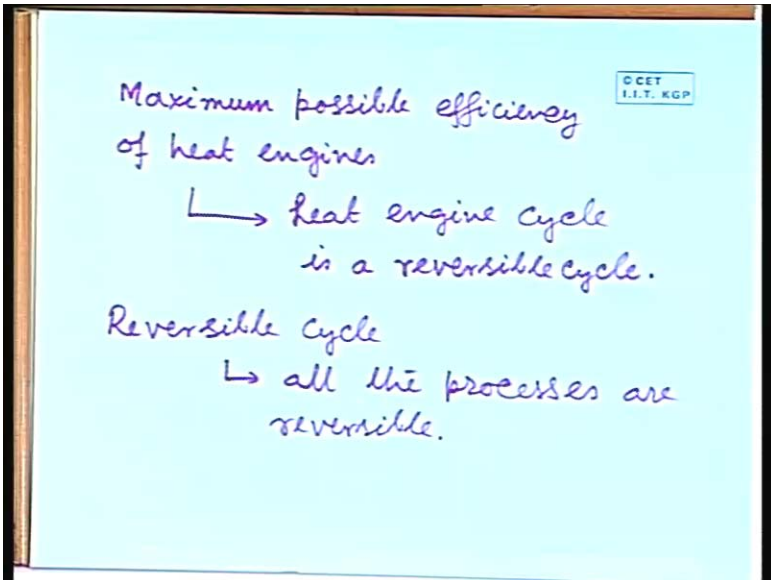

The maximum possible efficiency of heat engines can be obtained if the heat engine cycle is a reversible cycle. What is a reversible cycle? If all the processes of the cycle are reversible processes then we call it a reversible cycle. The next question that comes is, what is a reversible process?

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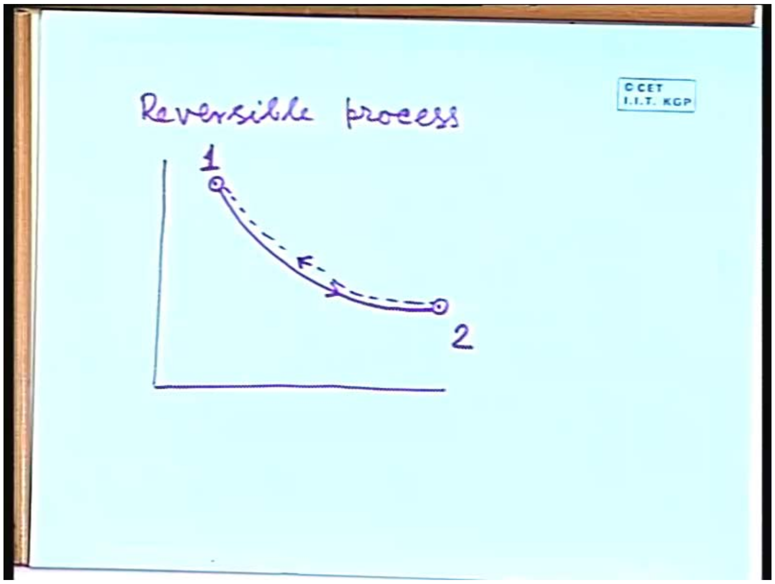

A reversible process, if we want to understand, let us take any example. Let us say this is a thermodynamic plane and we have got two state points. This is state point 1 and this is state point 2 on this thermodynamic plane. We can have any arbitrary process between state point 1 and state point 2. If it is a reversible process then, we can go from state point 2 to state point 1 or we can reverse the process and by doing so there will not be any change either in the system or in the surrounding. Then only we will call the process to be a reversible process, if by reversing it we do not produce any change either in the system or in the surrounding. We have started from state 1 we have gone to the state 2 by the forward process. If we can come back to state 1 without producing any net change in the system and in the surrounding then we will call that 1 to 2 is a reversible process. One has to remember that no natural processes are reversible process. However small it may be, there will be some change …. either in the system or in the surrounding. But there are certain processes which are highly irreversible process or there are certain effects, which are highly irreversible and that make the process highly irreversible process. If those effects are there, in your heat engine cycle or in the heat pump cycle, the efficiency or the COP of those cycles will be low. Let us try to identify the causes of this irreversibility.

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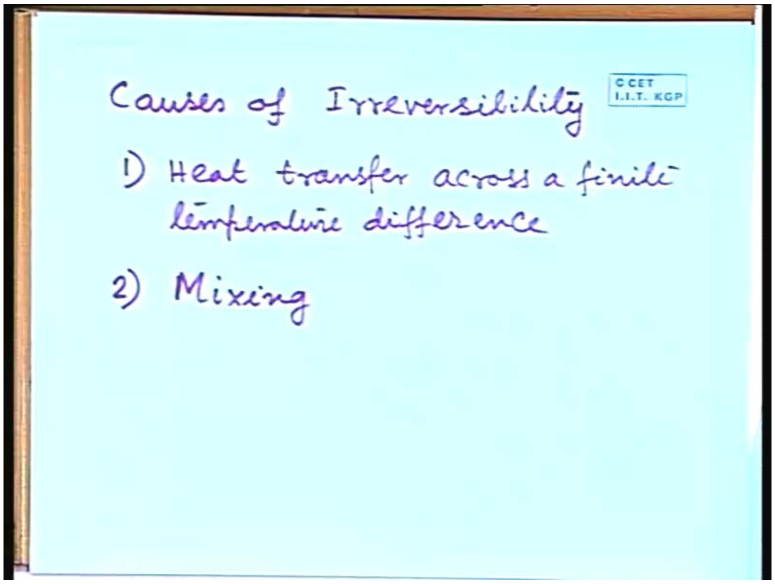

There are a number of causes of irreversibility. I cannot list all of them or we cannot discuss all of them, but some of them which are very important we will discuss it here. We will see not only from our day to day experience but also in this discussion, which will follow, that when these causes are there then the cycle efficiency will be lower. The first one is heat transfer across a finite temperature difference. Let us take some examples.

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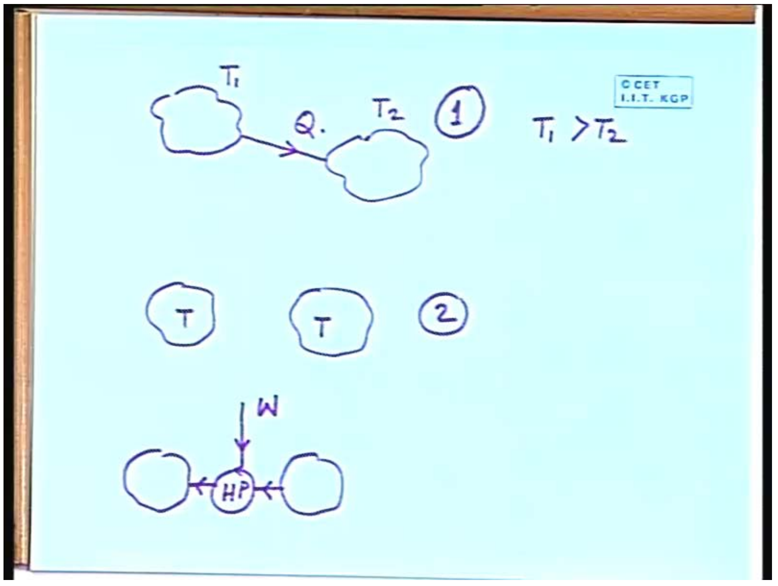

There are two bodies; this body is in temperature T_1 and this body is in temperature T_2. If they are thermally insulated then there will not be any heat transfer. But, if the thermal insulation between these two bodies is removed then there will be heat transfer. If T_1 is greater than T_2 then heat transfer will be there from the high temperature body to this low temperature body. The heat transfer will continue till the bodies assume some thermal equilibrium or they have the same temperature. This process is a highly irreversible process. If we have to bring back the initial condition that means after the heat transfer process we have got these two bodies, both are at temperature T. Let us say this is our state 1, this is our state 2. If I have to bring back again to state 1 from the state 2, then what we have to do? We have to put some sort of a heat pump in between them.

This heat pump what it can do? Both of them are at the same temperature. We can do like this. There is a heat pump, HP and it will take heat from this body and it will pump to the first body. But for running this heat pump what I have to do is, I have to supply some work from outside. It is not impossible to go back to state 1. We can go back to state 1. So, the system will be brought to its initial state, but what about the surroundings? From the surrounding we have taken some amount of work for running the heat pump, so there will be a certain change in the surroundings. The heat transfer across a finite temperature difference is a process which causes irreversibility. In our cycle if we have such type of a process definitely we will have a low efficiency of the cycle. The mixing of two materials is again an irreversible process.

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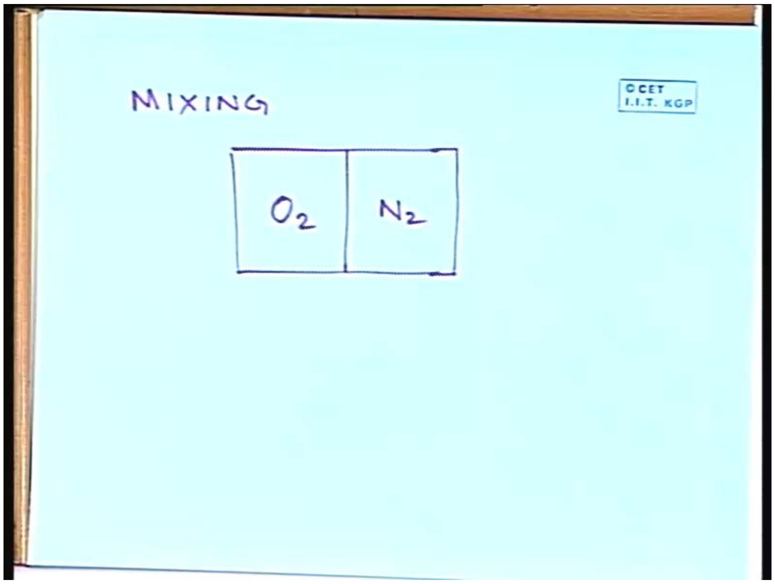

For example, there are two different species of gas kept in two compartments. Let us say this is oxygen and this is nitrogen and this is a mixing process. They are partitioned. If I remove the partition, due to the diffusion process, oxygen molecule will diffuse into nitrogen and nitrogen molecule will diffuse into oxygen and this process will continue until we get some sort of a homogeneous mixture. Once we get the homogeneous mixture, if we want to bring back to this condition, we have to have some sort of a device which can pump or which can separate the oxygen molecules and nitrogen molecules. We need certain energy inputs from outside and there will be certain changes in the surrounding if we want to bring back the system to its initial condition. We will have an irreversible process if we allow mixing between oxygen and nitrogen. I think we will stop here and we will take other examples in our next class and we will see what the other different causes for irreversibility are. Thank you.