Engineering Thermodynamics

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Lecture – 15
Laws of Thermodynamics: Revision. Cycles. Second Law statements. Clausius inequality.

Good afternoon to everyone, this is the second lecture of the second module.

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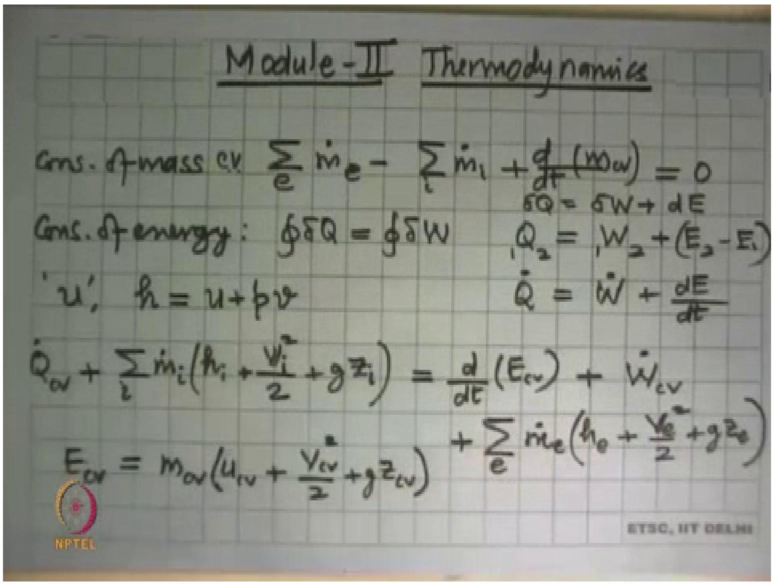

Module-II Thermodynamics

Cons. of mass CV $\sum_e \dot{m}_e - \sum_i \dot{m}_i + \frac{d}{dt}(m_{cv}) = 0$

Cons. of energy: $\oint \delta Q = \oint \delta W$ $\quad \delta Q = \delta W + dE$

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

'u', $h = u + pv$ $\quad \dot{Q} = \dot{W} + \frac{dE}{dt}$

$$\dot{Q}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i\right) = \frac{d}{dt}(E_{cv}) + \dot{W}_{cv} + \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

$$E_{cv} = m_{cv}\left(u_{cv} + \frac{V_{cv}^2}{2} + gz_{cv}\right)$$

And yesterdays lecture we covered the 1st law of thermodynamics preceded by the conservation of mass. What we will do today is, look at statements of the 2nd law of thermodynamics and start exploring the concept of entropy and the Carnot cycle.

So, a quick revision of what happened. Yesterday at the end if we ask you know what was the important things that, we have learned then this one sheet that I am putting up here is showing everything we have learnt about the conservation of mass for a control mass it is that the mass is always constant and for a control volume, we derive this equation from first principles, which said that outflow rate of mass minus inflow rate of mass plus rate of accumulation of mass in the control volume is equal to 0.

Measure of the equation we got for the control volume, we just want to conservation of energy and we said the 1st law of thermodynamics statement is that, cyclic for a system undergoing a cyclic process the cyclic integral of heat is equal to cyclic integral of work and then we took it out further and said what will happen if there is a process. And then said while for control mass it is this expression here denoting that Q 1 2 is a inexact differential here or delta Q is equal to delta W plus d E and I write equation we got Q dot is equal to W dot plus dE by dt.

And then when we continued working on this to get the equation of a process, we came across a property which is defined as specific internal energy mu and we acceptably also during the mass flow of terms we are looked at, we got a product of terms called the pressure and specific volume this we called as the flow work and the sum of flow work. And into energy is specific enthalpy this also came out when we derived.

This long equation which is the statement of the 1st law for a control volume, that heat transfer rate into the control volume plus rate of inflow multiplied by specific enthalpy plus kinetic energy plus potential energy for each inflow summed up over for all inflows equals the rate of energy accumulation or depletion in the control volume plus work done by the control volume plus energy out flow which is M dot e into h e plus V square plus gZ.

And in this equation the energy of the control volume is given by this term; mass of the control volume, multiplied by a specific internal energy in the control volume plus its kinetic energy plus its potential energy. So, we came to this point in that these equations are universally applicable, there is no ifs and buts in this it does not matter what the application is it does not matter what the working substance is. These are universally true and that is why we are saying that look, before we get into solving any problems whichever which is the equation which is always applicable to solving those problems and that is what we have done.

So, the next thing we will now take up is, we look at this thing called a cycle thermodynamic cycle or a system undergoing a cyclic process.

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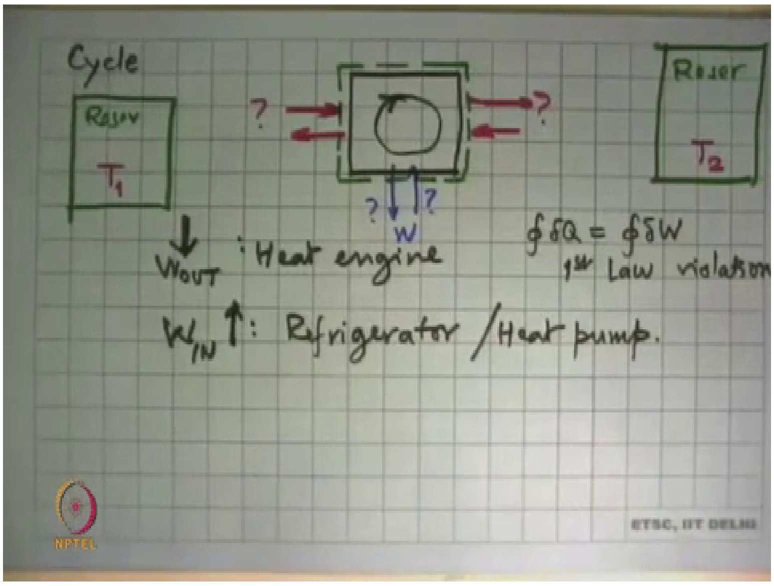

The symbol that we will use is that we put up a square with a circle in it and put an arrow here. So, this is the system boundary, this will include all of this. This system boundary the working substance is undergoing a thermodynamic cycle and how we can achieve a thermodynamic cycle was shown in yesterday's picture which we will see again now.

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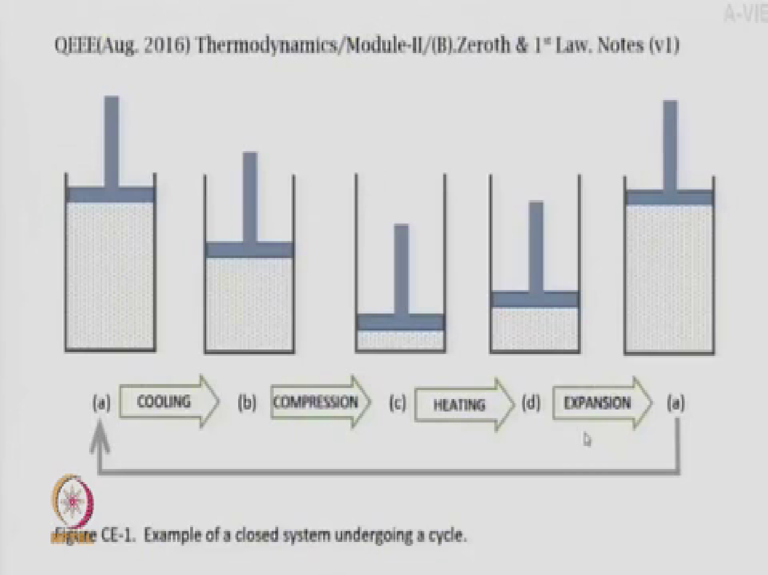
QEEE(Aug. 2016) Thermodynamics/Module-II/(B).Zeroth & 1st Law. Notes (v1)

Figure CE-1. Example of a closed system undergoing a cycle.

Here we have a cylinder and piston arrangement with a closed system and we can see that it starts with state a goes to some process comes to b, another process comes to c another process brings it in state d and another the fourth process brings it back with state a.

So, it can then go back and start this process all over again. So, it can go there and come back here and now we can repeat this thing. So, what is happening is that, it takes a finite number of time for each one of these to happen. So, whatever is the I mean interest in this particular cycle whether it is cooling, whether it is compression or heating or expansion it will happen once in all these (Refer Time: 05:49) processes. So, it is not a continuous process in that sense, but you are able to repeat it again and again at a high speed and the rate at which we do it multiplied by the energy or transfer that took place in each process will be the rate at which we get energy from the system that this was the closed system undergoing the cycle.

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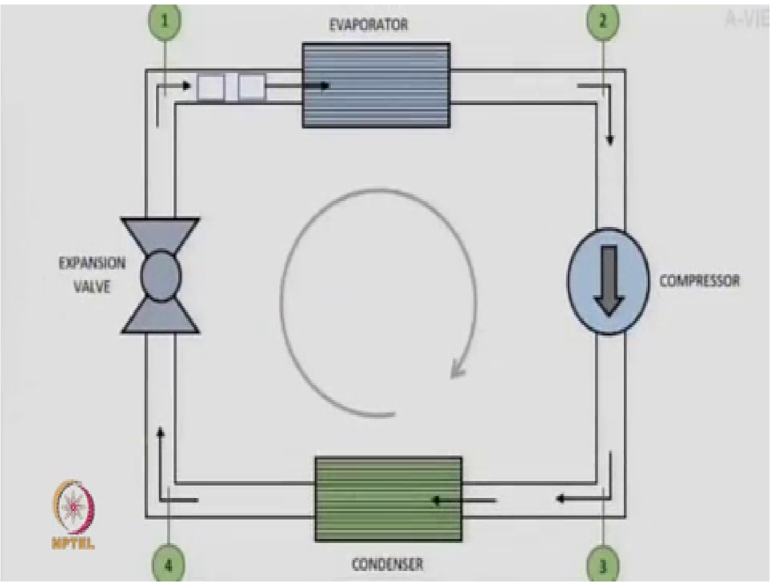

And the second one that we looked at is a four system and what was happening here is that we put four devices in which four different processes take place they are connected by pipes or tubes through which a substance flows and as it is shown here, it flows through the evaporator, it one process happens on it, then it comes into the compressor another process happens on it.

It goes through the condenser, another process happens, goes to the expansion valve another process happens and it comes back to its initial state. So, that is the element that is executing a thermodynamic cycle and that is what we show here as an arrow. So, this is very simple way of showing something which goes a cyclic process.

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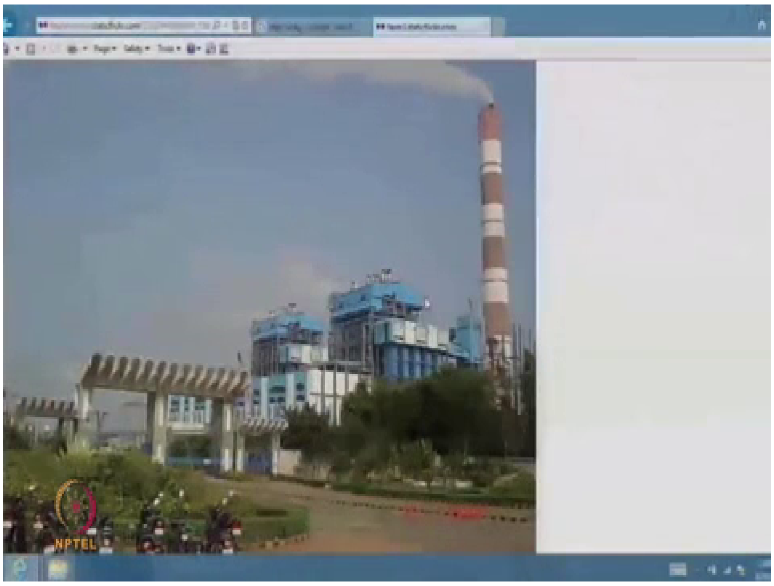

And in reality, but the time we get everything done we could see something like this. What you are seeing here is a photograph of or a thermal power station in which this whole thing here is the boiler in which coal or oil and gas is being burnt and somewhere here in the building there is a turbine condenser, where the electricity is generated and at the back you see this chimney through which the smoke is being thrown out.

So, this huge thing I am to get an idea this height of this building here, this is about like 60 metres. So, that comparable to the height of Qutub Minar which is 72 metres and this stack or the chimney is probably three times as tall. So, this huge thing that we have made is actually a practical rendering of that simple cycle that we just saw few minutes back, the analysis of this follows all the laws that we have learnt ok. So, this is what the cycle is and we now add two more things on this, there is one thing here and we will put a second thing here and these are reservoirs or thermal reservoir through with which this can interact and it can also produce work either of these can happen.

So, there is there could be heat transfer to this or heat transfer from this or heat transfer to this or heat transfer from this and work in or work out any of these permutations and combinations is theoretically possible. So, what we can add is this was work in and out and on this side you have 2 reservoirs this would be at some temperature say T 1 this is at another temperature T 2 and you could have this or this cutting the system boundary and any of these combinations can happen.

So, this is the most general type of a cyclic process that we are looking at and we begin by saying what are the laws according to 2nd law that governs this. The 1st law statement tells us that for this control volume system is in this cyclic process. So, cyclic integral of heat should be equal to cyclic integral of work and we can figure of what are each one of these individual elements, add them up and make sure that this condition is satisfied. If this condition is not satisfied it implies that there is the 1st law violation.

And so, there is no need to proceed to looking at what the 2nd law is telling us. The 2nd law comes into play only after we are certain that the 1st law is valid and obeyed by the system that is an important thing to remember and preceding that of course, is that the conservation of mass has to be there. So, far there is no mass transfer across this boundary so, that is not an issue. So, now, we look at the 2 statements of the law (Refer Time: 11:04) you show that a cycle that has a net output of work.

This we will call a heat engine and a cycle where the net work is in into a system, this we will call a refrigerator or a heat pump, with now we go back and check what are the statements of the 2nd law?

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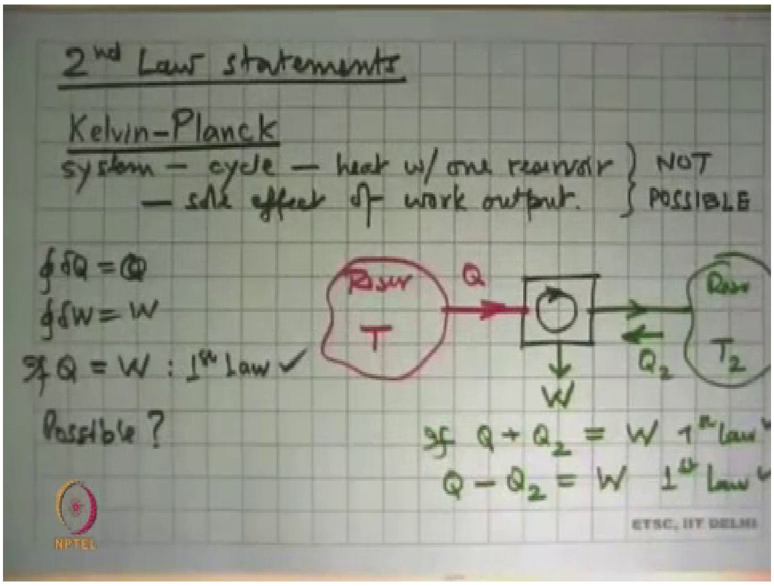

2nd Law statements

Kelvin-Planck

system – cycle – heat w/ one reservoir } NOT
– sole effect of work output. } POSSIBLE

$\oint \delta Q = Q$

$\oint \delta W = W$

If $Q = W$: 1st law ✓

Possible?

If $Q + Q_2 = W$ 1st law ✓

$Q - Q_2 = W$ 1st law ✓

And there are 2 statements the first we will look at is the Kelvin Planck statement and the Kelvin Planck statement says that, it is not possible to make a system that operates in a thermodynamic cycle exchanges heat with one reservoir and has the sole effect of work so, what it is telling is say work out.

So, say this cycle this type of a cycle not possible. And what it is telling us is that, we make a system then accord what they are telling us is that if there is a reservoir, this is a reservoir whatever temperature it may have; from here the system has a net heat to it Q and the only thing that the system gives is W, that is what the statement says is not possible. But before you get there let see whether this obeys the 1st law, then we would be able to apply the 2nd law.

So, cyclic integral of heat is Q, cyclic integral of work is W both are one is positive this way this is also positive the 2 are equal; that means, that if Q is equal to W 1st law is ok so, no problems with the 1st law the system obeys the 1st law. The problem is that the Kelvin Planck statement tells is this law is not possible this type of a cycle is not possible.

So, we say well if it is not possible, what are my options from which I can make this thing into a possibility not possible means scientifically not possible, so, the real machine cannot be made. So, do not even think about making a machine that is what it is, we can think of making something in the real world only when thermodynamics tells us that the cycle is possible. So, these are the question, what will make it possible?

And we say that the answer lies in the statement which says that system operates in a cycle we have to have that, sole effect is going to be work we want to have that heat with only one reservoir not possible. So, let us say we are going to put a second reservoir. So, we say well if I put a second reservoir and this is at some other temperature say T 2 and if the system exchanges heat with this then this statement is not violated.

So, make a connection there and we have two options here, we could have an arrow going this way or the arrow going that way. We take the second case where the arrow is this way then if now same cyclic integral of heat becomes Q plus this Q we will say call it Q 2, if this is equal to W then 1st law is ok. So, there is something stating that is taking heat from both and still producing work provided this is the case. The second option if this was the case, then you have Q minus Q 2 since energy leaving the system minus Q 2 this is equal to W and if this is obey then also the 1st law is not in violation.

So, we have two possibilities and clearly looking at this point, the 1st law does not tell you that this is not possible in the Kelvin Planck statement does not tell you that this is not possible we need to have something else, which you will get in a few minutes it will tell you which one of these is possible ok. So, this is the Kelvin Planck statement of the 1st law, that you cannot have a cycle the system that undergoes a thermodynamic cycle exchanges heat with only one reservoir, under sole effect is work output or raising of a weight that is not possible now we look at the second statement and this is the Clausius statement.

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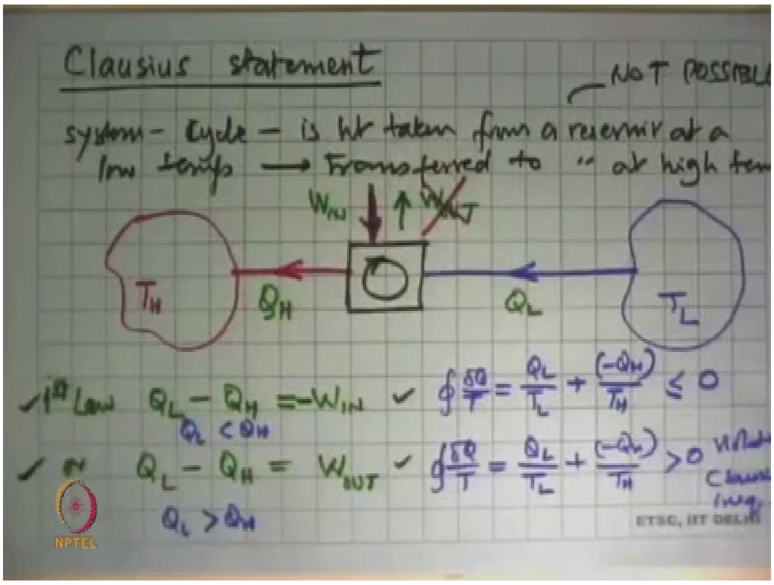

Clausius statement

NOT POSSIBL

system - cycle - is ht taken from a reservoir at a low temp → transferred to " at high tem

✓ 1st Law $Q_L - Q_H = -W_{IN}$ ✓ $\oint \frac{\delta Q}{T} = \frac{Q_L}{T_L} + \frac{(-Q_H)}{T_H} \le 0$

$Q_L < Q_H$

✓ or $Q_L - Q_H = W_{OUT}$ ✓ $\oint \frac{\delta Q}{T} = \frac{Q_L}{T_L} + \frac{(-Q_H)}{T_H} > 0$ Violat Claus ineq.

$Q_L > Q_H$

So, this statement says that you cannot have a system undergoing a thermodynamic cycle, where the sole effect is heat taken from a reservoir or a body at a low temperature and transferred to another reservoir at a high temperature. In very simple terms this is saying that heat cannot flow by itself from a low temperature to a high temperature, but it is also little bit more than that in that sense even if I have a thermodynamic cycle by itself it cannot take heat from a low temperature reservoir and put it into a high temperature reservoir.

So, the cycle that now we are talking of this is a cycle there, it is in contact and exchanging energy with 2 reservoirs. So, there is a high temperature reservoir here T H and energy is being pushed into it, and we have a low temperature reservoir on this side and this is taking energy into it. So, this statement tells us that such a system is not possible ok.

So, this is not possible and again we ask the same question that we did for the Kelvin Planck statement, if this is not possible how can I what do I need to do to make this possible? And the answer for that lies that its already in exchange with 2 reservoirs, I have a option of either putting in work or taking out work.

So W in or W out and the 1st law says that in this first case if the energy going this way was Q L and this is Q H then cyclic integral of heat is Q L minus Q H and this has to be equal to the cyclic integral of work, which could be this case minus W in which is this case work transfer into the system is negative either this is satisfied or Q L minus Q H equal to W out this is satisfied ok. So, these are the two options that we have the work flow is negative here Q L heat transferred to the system positive this is negative.

So, now we have the question if these conditions were satisfied, then the 1st law is obeyed by both so, which one of these is possible that we do not know. So, we need something else to figure out which of these 2 or in the Kelvin Planck statement which of these 2 is possible and that comes to us in the form of what is called Clausius inequality.

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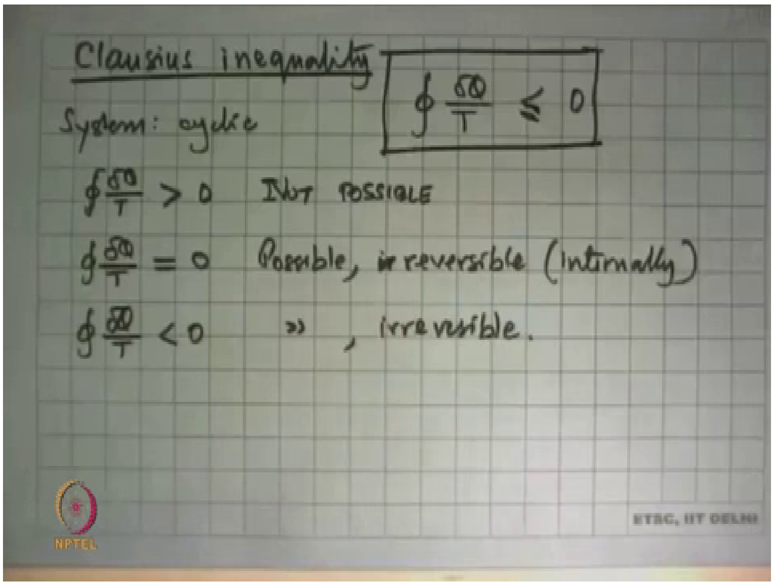

Clausius inequality

System: cyclic

$$\boxed{\oint \frac{\delta Q}{T} \leq 0}$$

$\oint \frac{\delta Q}{T} > 0$ NOT POSSIBLE

$\oint \frac{\delta Q}{T} = 0$ Possible, ~~ir~~ reversible (internally)

$\oint \frac{\delta Q}{T} < 0$ " , irreversible.

So, before I go there just a word here that these 2 statements although they are different one can prove that they have the same implication, that violation of one statement automatically leads to violation of another statement. I am not going to go into the detailed proof of that you can argue yourself by putting a few of these things together and see what happens.

Now, look at Clausius inequality and what it says that the system undergoing a cycle or a cyclic process, cyclic integral of delta Q by T is less than or equal to 0. Again its an inequality we have to do something else to see what comes out by making it equal so, this a very the statement is very far reaching consequences. So, we can put this at the beginning point of a lot of things to come. So, what it tells us is that if cyclic integral of delta Q by T is greater than 0 then the system is not possible; such a thing cannot be made.

Even if it obeys the 1st law, then it says in this if cyclic integral of delta Q by T is equal to 0 this is possible and the system should be irreversible system should be completely reversible. There should be no irreversibility in any of the processes that are running inside the system that is very important. So, theoretically yes possible to do it, practically, if I want to make a system when there are no irreversibility in the real world not possible.

So, we come to the third condition that delta Q by T less than 0 yes it is possible and this will have irreversibility. And that huge pic building I showed you about the thermal power plant, it obeys this inequality that is why works. So, that is the first thing that comes out and now we can go back and let us look at the 2 statements that we made a few minutes back and see what becomes possible. We said if Q plus Q 2 is W the let now ask the question what happens to if the system obeys Clausius inequality or not.

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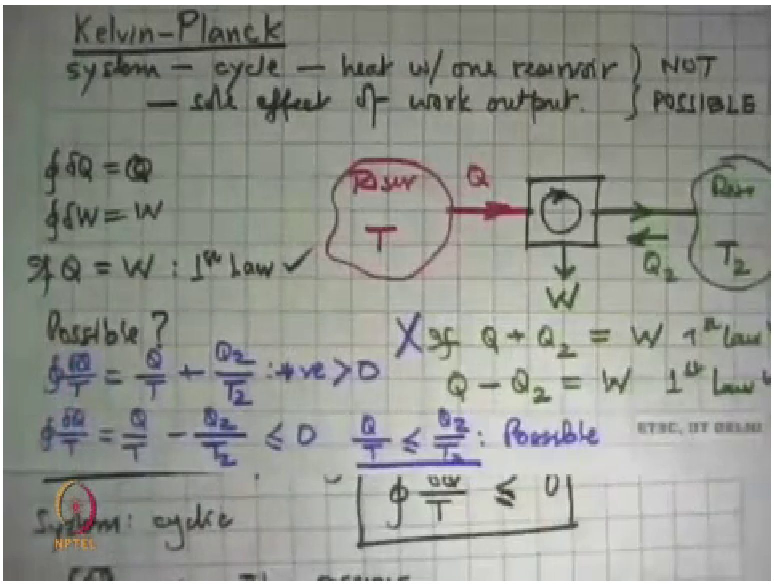

Kelvin-Planck

system – cycle – heat w/ one reservoir } NOT

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$\oint \delta Q = Q$

$\oint \delta W = W$

If $Q = W$: 1st Law ✓

Possible ?

$\oint \frac{\delta Q}{T} = \frac{Q}{T} + \frac{Q_2}{T_2}$: +ve > 0

X If $Q + Q_2 = W$ 1st Law

$Q - Q_2 = W$ 1st Law

$\oint \frac{\delta Q}{T} = \frac{Q}{T} - \frac{Q_2}{T_2} \leq 0$ $\frac{Q}{T} \leq \frac{Q_2}{T_2}$: Possible

$\boxed{\oint \frac{\delta Q}{T} \leq 0}$

System: cycle

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So, we said now cyclic integral of delta Q by T is this Q going associated with this temperature Q by T and this one also positive heat coming in this becomes plus Q 2 by T, remember temperatures are absolute temperatures so, this T so, it will be T 2. Both temperatures are positive numbers heat transfer is taking place into a system so, the Q and Q 2 are positive numbers. So, this whole thing is a positive number which means this is greater than 0 and Clausius inequality tells us that, cyclic integral of delta Q by t if it is greater than 0 this system is not possible. So, this obeyed the 1st law, but failed Clausius inequality it also obeyed the Kelvin Planck statement.

Now, look at the second statement that if this work was to be going out then what happens? So, in the this case we have cyclic integral of delta Q by T, this is Q by T as before, but now this is minus Q 2 by T 2. And it tells us that if this is less than or equal to 0 the system is possible we could make it. So, we have a condition coming up that Q upon T less than or equal to Q T upon T 2, then this system is possible. If this number turns out to be greater than 0, then also that system is not possible.

So, what we are saying is that, if there this is giving some heat and something else a little bit goes out here and the rest comes out as work according to the 1st law, even then this system although does not violate the Kelvin Planck statement does not violate the 1st law statement, but Clausius inequality tells us that such a heat engine is not possible.

It’s all it is possible only when this condition is satisfied. Now you look at the same thing with the Clausius statement. So, what have we ((Refer Time: 28:14) now that if I have to make a system that obeys Kelvin Planck statement and obeys Clausius inequality and obeys the 1st law, then this is not possible there has to be Q 2 over there. So, this is in there has to be some energy going there, this is there and under one particular condition which is this one under this condition this system is possible. And that brings us to the fact that you have a work producing device, it must take heat from a reservoir at a higher temperature and give out a minimum amount of heat to a reservoir at another temperature the balance of these two will come out as work.

So, this is a possibility that can be made is made and forms the basis of all analysis of heat power cycles. Now let us look at the Clausius inequality. We said there were 2 cases and we will do the same thing what we did a minute back with the other statement, we have to apply the Clausius inequality to this system. So, what do we have in this case?

Cyclic integral of delta Q by T we want to calculate and this will be this is the Q L coming from here with activated with temperature T L, this is heat transferred to the system. So, Q L is positive is divided by TLQ H is negative. So, we can put here minus Q H upon T H and we say if this is sorry we have a minus sign there. So, if this is less than or equal to 0, we can say that this system is possible.

In the second case here we say cyclic integral of delta Q by T is equal to Q L upon T L and again this is Q H upon T H and in this case Q L is greater than Q H in this case Q L is less than Q H. So, if we take these and check on these numbers here we find that one of these is not possible that we cannot have heat going this way or going out that way and just going out there.

So, the second statement this will violate Clausius inequality and so, the only way we can get heat transferred from body at low temperature to a body at high temperature is, by putting work into the system this would not work. And that gives us the basic foundation of how to make a realizable refrigeration system which by the way is the basis of air conditioner system also.

So, you have to if you want to transfer heat from a low temperature body to a high temperature body, you have to explain work doing that. So, we got now the basic processes of a heat engine and a heat pump, and which is that we will now write these 2 reservoirs there.

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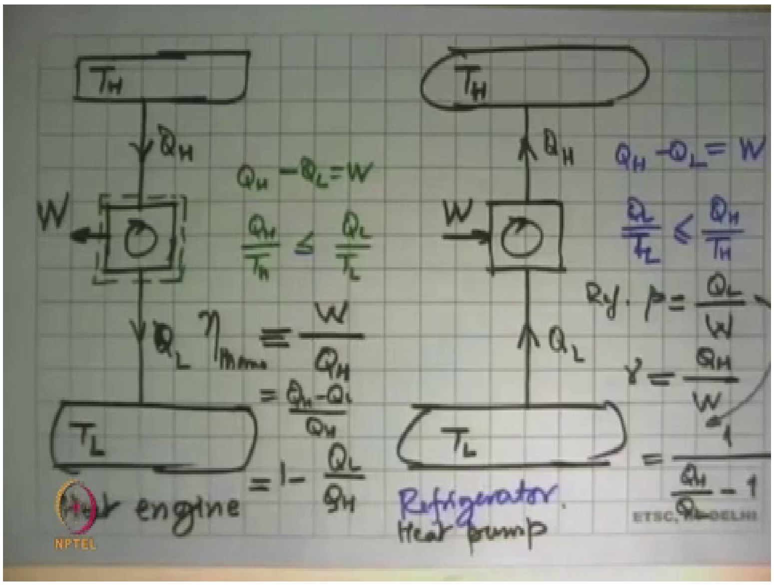

Again this is T H and our system is sitting there a low temperature is over there and if I have to make a heat engine, there has to be a heat transfer from the higher temperature reservoir to the system certain amount Q H of which some has to be rejected here which is Q L and the balance will come out as work.

So, we take this as the system boundary the 1st law, requires that Q H minus Q L is equal to W and Clausius inequality requires that both the equation we just saw that Q H upon T H should be less than Q L upon T L. And for a heat pump the higher temperature reservoir, a system undergoing a cyclic process a low temperature reservoir this takes heat from here Q L turns it out Q H and there is work input over there.

The 1st law tells us that we can make such a system possible provided Q H minus Q L is equal to W and we can get a similar expression for Clausius inequality over there which was that Q L Q L upon T L is less than or equal to Q H upon T H and this is a refrigerator these are realizable systems and all real systems actually are can be analysed in this way. And idealizing it we can get an upper limit or on the what we call the best performance and that is what we want to improve all the time.

So, how do we quantify the performance of these two? We will write two equations now. For a heat engine we define the thermodynamic efficiency as what benefit we get from it is W divided by what we pay for which is what we are paying is this high temperature energy there which is Q H. And in this case if it were a refrigerator we have performance indicator coefficient of performance where our useful thing is Q L we are taking heat out of a warm body and something we are paying for is this work which is W.

If it is a heat pump; that means, our objective is to pump this heat which is basically saying that in winter we turn the ac around and the hot air that it is throwing out is the one that is being now thrown into the room which you want to warm up. So, the benefit there is Q H so, then gamma this is defined as Q H upon W.

And so, if you look at this Q H will always be more than W because you are adding Q L which is heat taken out from the atmosphere which means that if you have a 1 kilo watt power consumption which is an electric heater in your room, you are getting heated in the room at the rate of 1 kilo watt, but if you put that 1 kilo watt into a heat pump then the amount of energy being dumped into the room is going to be more than 1 kilo watt. So, you get little more benefit then, what you got by using just a electric heater that of course, requires that you must have a refrigeration cycle operating in reverse principle.

So, we got the expressions for efficiency, for the heat engine and for the refrigerator. We can further simplify this, that W is Q H minus Q L upon Q H and so, this can be written as 1 minus Q L upon Q H and this beta we can take down W is Q H minus Q L and we divide it this becomes 1 upon Q H upon Q L minus 1. So, we have two expressions coming up and what it says that ((Refer Time: 37:52) want to increase the efficiency of the cycle the ratio here must become as small as possible and here this ratio should also be as close to 1 as possible, we cannot make them 0 because that would violate the Kelvin Planck statement.

So, if this becomes small and small our efficiency goes higher and higher in this case if Q H is slightly greater than Q L then our efficiency, this denominator becomes a small number the inverse of that becomes the big number so, we are in good shape. So, that is the direction in which things have to move and the inside of that comes up when we look at one step more and ask the question, what is the most efficient cycle either here or here that, we can make and that will give us an upper limit on the highest possible efficiency that we can get from this cycle or from this cycle.