Energy Conservation and Waste Heat Recovery

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Lecture – 11
Entropy

Hello, everyone welcome back to the lecture on Energy Conversion and Energy sorry Energy Conservation and Waste Heat Recovery. We were discussing second law of thermodynamics and then I wanted to show you the ideal heat engine cycle or reversible heat engine cycle or a Carnot cycle on a T S plane its significance. So, if we go back to our slide which we are discussing it is like this.

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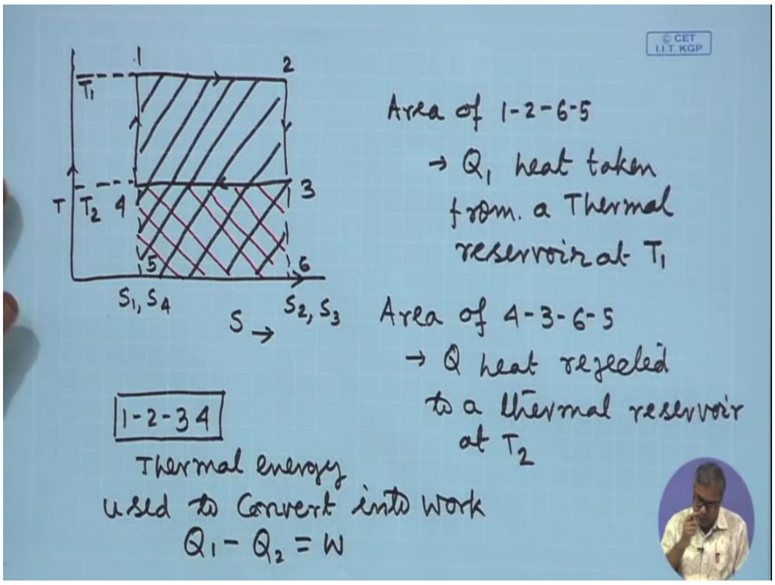

Area of 1-2-6-5
→ Q_1 heat taken from a Thermal reservoir at T_1

Area of 4-3-6-5
→ Q heat rejected to a thermal reservoir at T_2

$\boxed{1-2-3\,4}$

Thermal energy used to Convert into work

$Q_1 - Q_2 = W$

I have taken T S coordinate temperature and entropy coordinate and then I have shown 1 to 2 that is the heat addition process which has taken place at a constant temperature T 1. The heat rejection process has taken place at a constant temperature T 2.

So, heat which is added at constant temperature T 1 that is given by the area 1 2 6 5 that is Q 1 and then this shaded area that represents the heat which has been taken by the cycle from a high temperature reservoir. Heat which is rejected by the cycle to a low temperature reservoir at temperature T 2 that is given by the area, so I can write area of 4 3 6 5 that gives Q 2 heat rejected to a thermal reservoir at T 2.

So, then there is one area which is left some area is common between these two, but the area which is left which is not common that is 1 2 3 4. So, 1 2 3 4 that is thermal energy used to convert into work that is equal to Q 1 minus Q 2 work W. So, this is a very useful concept which we can get from your from the T S diagram and obviously, utilizing the concept of ideal cycle.

Now, let us go back to the example which we have taken well and we will try to see the example which we have taken for recovery of waste heat how we can graphically represent. See this is the example we have taken 2 sources of waste heat both the sources had 24 kilowatt of thermal energy.

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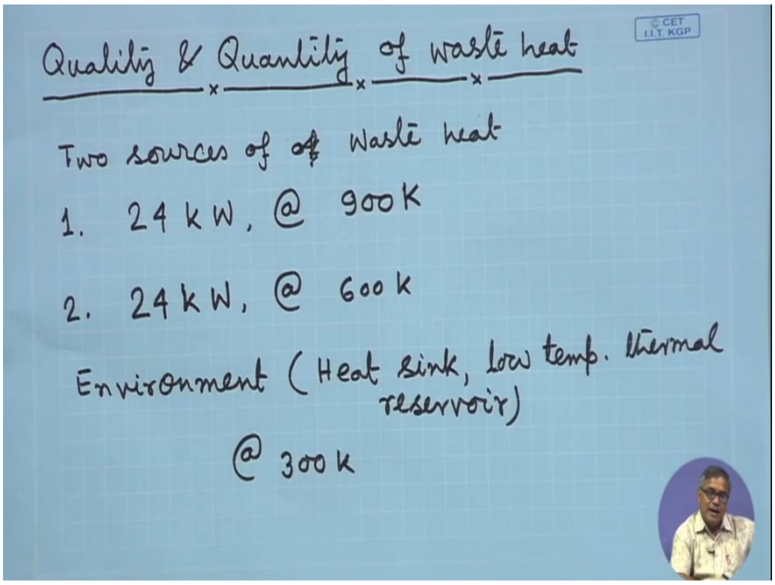

Quality & Quantity of waste heat

Two sources of of waste heat

1. 24 kW, @ 900 K

2. 24 kW, @ 600 K

Environment (Heat sink, low temp. thermal reservoir)

@ 300 K

The first source is at 900 Kelvin and the second source is at 600 Kelvin and the ambient is at 300 Kelvin. So, graphically if I try to represent this.

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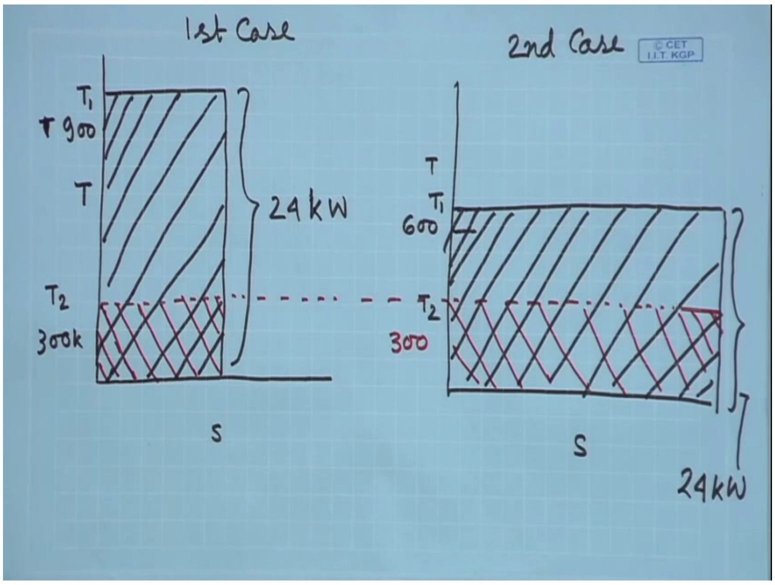

It is like this, let us have side by side 2 figures first case and then it is the second case this is your temperature coordinate temperature and entropy coordinate and in the first case in both the cases we are having T 2 T 2 that is at some 300 Kelvin. So, let us say this is at 300 Kelvin in the first case we are having T 1 that is at T 2 let us say T 2 300 k even in the first case we had at 900 k if you recall.

So, this is your 900 let us put T here and in this case T 1 is 600. So, both the cases we had 24 kilowatt of thermal energy available from the waste heat source. So, 24 kilowatt of thermal energy that will be represented like this and the way we have done earlier let us put some sort of shading or hatching. So, this is the energy available in the first case. Here also 24 kilowatt energy is available, but how it will be represented let us say from here. So, it will be something like this here also let us put the hatching.

In the first case heat will be rejected. So, heat rejection is at 300 Kelvin and let us see, let us say this is represented by this hatching. In this case also it is 300 Kelvin, so let us. Now if we compare these two figures. So, this is your first case this is your second case in both the cases this is 24 kilowatt, this is also 24 kilowatt, but obviously, in the second case we can see we are rejecting much more heat to the atmosphere to the ambient or environment.

So, now you can understand that what we have told that quality of waste heat source with some sort of a figure number I have explained it, now I am explaining it with I mean in form of graphical representation and what we can see that first source is having a higher quality compared to the second source. And this is possible with T S diagram where entropy is one of the ordinate of the thermodynamic plane. So, I hope you have understood what is quality and quantity of a waste heat source.

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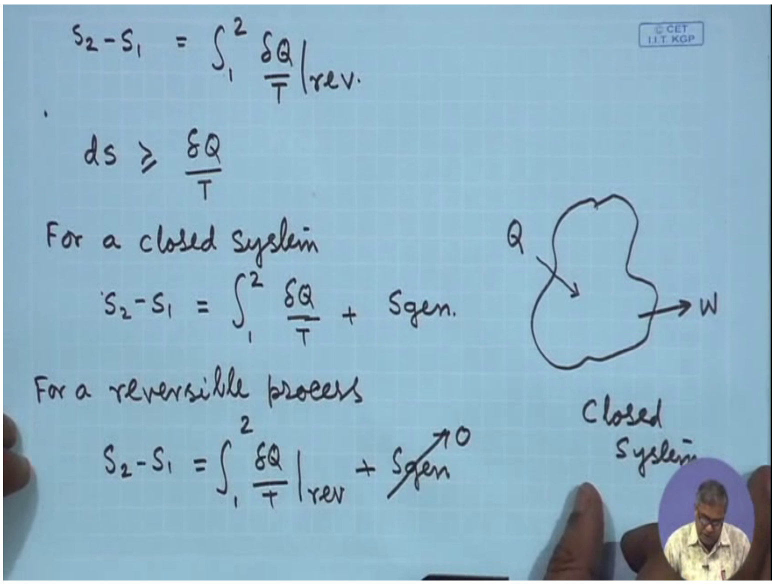

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T}\Big|_{rev.}$$

$$ds \geq \frac{\delta Q}{T}$$

For a closed system

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen.}$$

For a reversible process

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T}\Big|_{rev} + \cancelto{0}{S_{gen}}$$

Now, let us go into our important property which just now we have been introduced to that is entropy and entropy the basic equation is S 2 minus S 1 that is equal to 1 to 2 d Q by T reversible, now if you small thing I just like to recapitulate and ask you to recapitulate from our thermodynamics regarding entropy relationship. So, we can write this that ds in general is greater than equal to d Q by T. So, I am not writing d Q by T reversible when it is d Q by T reversible ds is equal to d Q by T, when the process is not reversible, but there will be some heat transfer and the entropy change has got some relationship with the a heat transfer. The relationship will not be an equality relationship that will be given by an inequality relationship. So, ds is greater than equal to d Q by T.

For a closed system, for a closed system we can write S 2 minus S 1 that is equal to integration 1 to 2 d Q by T plus S generated. So, let us take an example let us say this is a closed system when we are telling that it is a closed system it means there is no mass coming inside the system or going out of the system and there is of course, heat interaction and there is work interaction. This heat interaction can take place at different point.

What is the significance of telling that heat interaction can take place at different point? The significance of telling that heat interaction can take place at different point means of course, that there could be heat addition and heat rejection that is of course, one point, but more than that what is important that there could be heat interaction at different part of the system boundary at different temperature. So, for a closed system like this we can write the entropy, entropy balance equation S 2 minus S 1.

What is S 2? Suppose the closed system has undergone a process the initial point the starting state of the system is given by 1 and the final state of the system that is given by 2. So, S 2 minus S 1 gives the change of entropy for the process to go from state 1 to state 2 for executing the process and going from a state point 1 to 2 there is a change of entropy and that is given by S 2 minus S 1. So, that is equal to integration 1 to 2 d Q by T plus S generated.

So, here you see one new term has been introduced that is called S generated, entropy generated, it is like this that the process we are considering is a general process; that means, the process need not be a reversible process it could be either a reversible process or an irreversible process. If it is an irreversible process apart from the change of property which may take place from going from one point to another point there could be some generation of entropy. So, in most generalized case considering both reversible and irreversible process there will be a term called S gen.

So, if the process is reversible then of course, this S gen will be equal to 0 and we will get for a reversible process S 2 minus S 1 is equal to 1 to 2 d Q by T reversible plus S gen that is equal to 0. So, this is one of the very important equation sometimes we call it a entropy balance equation.

So, you see in first law as we have got some sort of energy balance equation in this case we are getting some sort of entropy balance equation and this entropy balance equation essentially will contain one term which is called S generate S gen that is entropy generated because during the processes most of the processes because most of the processes are irreversible process. So, if it is irreversible process there will be some entropy generation. And the causes of irreversibility I have already discussed. So, if those type of causes are, so there will be some sort of entropy generator. So, what we have got?

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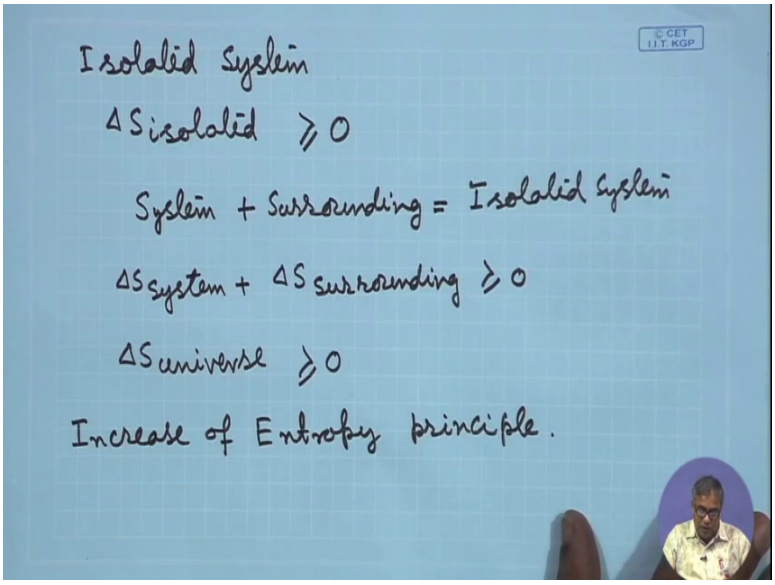

Isolated System

$\Delta S_{isolated} \geqslant 0$

System + Surrounding = Isolated System

$\Delta S_{system} + \Delta S_{surrounding} \geqslant 0$

$\Delta S_{universe} \geqslant 0$

Increase of Entropy principle.

Let us say there is an isolated system. So, delta S isolated delta S isolated means the there is some sort of change I mean we are observing that isolated system for some time, initially let us say the state point is equal to 1 or and finally, the state point is equal to 2 and for that process we want to calculate what is the change in entropy. So, delta S isolated that will be greater than equal to 0. For an isolated process the change of entropy that is greater than equal to 0.

So, isolated system isolated system means that it is not interacting with anything outside the system either in terms of mass exchange or in terms of a energy exchange. In that case what happens if we take a system plus surrounding, we can we are encompassing everything then this become an isolated system.

So, then you see delta S system plus delta S surrounding that is greater than equal to 0. So, this is again another useful concept and I can proceed just one step further like to proceed one step further it is like this if we consider system and surrounding then we are encompassing everything; that means, this is your universe. So, one can write delta S universe is greater than equal to 0. So, this is called increase of entropy principle. So, if a system is left to itself in an isolated manner, so its entropy will try to increase and ultimately maximize. So, you can consider universe to be an isolated system.

So, for the universe also entropy is continuously increasing. And in the book of thermo in the books of thermodynamics you can find some sort of elaborate discussion on this. But for the present course it is only it suffice if we understand appreciate and remember these two things. From first law what we say that the total amount of energy that remains constant it can only change from one form into another the picture is becoming complete if we take the concept from the second law then for a system if it is not interacting with anybody else it is isolated then its entropy will tend to increase and ultimately it will try to maximize.

So, this is the conservation of energy principle and increase of entropy or maximization of entropy principle now with this of course, we get certain good insights those insights are very important for our engineering practice. What are those insights? So, let us say that delta S for isolated system we have consider and we understand that it will go on increasing continuously and try to maximize and in that actually there is some sort of contribution for S gen and S gen if we consider separately, S gen generation of entropy.

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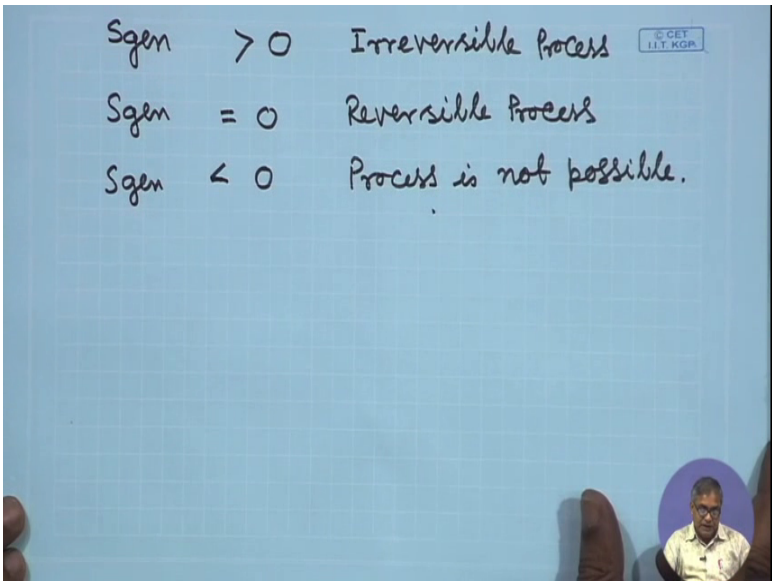

$S_{gen} > 0$ Irreversible Process

$S_{gen} = 0$ Reversible Process

$S_{gen} < 0$ Process is not possible.

So, this is a non negative quantity why it is a non negative quantity if it is greater than 0 if it is a non negative quantity then it is greater than 0 and in most of the cases we will find that S gen is greater than 0.

So, this denotes the process is irreversible. Then S gen is equal to 0 this is reversible process S gen less than 0 process is not possible. So, as I have told S gen which I have already introduced that is a non negative quantity S gen greater than 0 positive value it will be reversible process S gen equal to 0 that is reversible process and S gen when it will be negative process is not possible or in other words it is not possible to have a negative value of S gen. So, this is another important thing important concept we get from our entropy principle and entropy generation.

Though it will be available in most of the books of thermodynamics, but just a couple of minutes I like to spend on how one can calculate the change in entropy during a process for let us say for different substances. The relationship combining first law and second law one can get let me start with new slides and let me call it determination of change of entropy; how do we do that?

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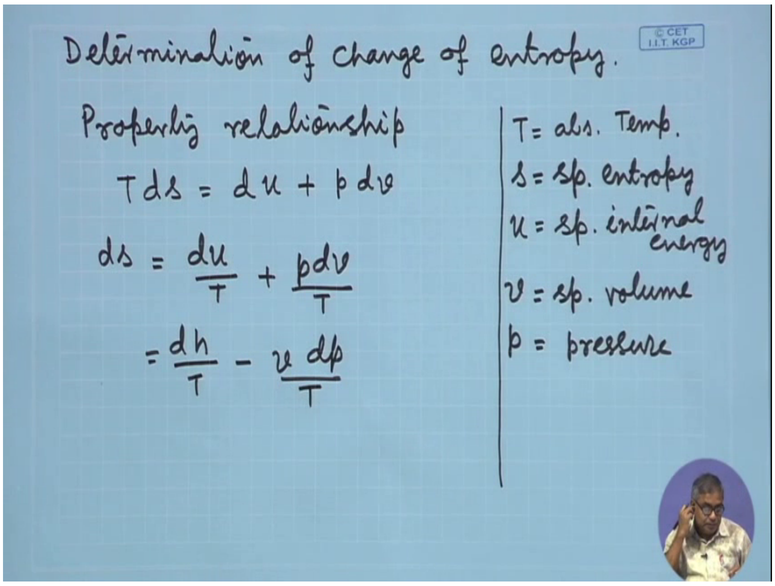

Determination of change of entropy.

Property relationship

$$T\,ds = du + p\,dv$$

$$ds = \frac{du}{T} + \frac{p\,dv}{T}$$

$$= \frac{dh}{T} - \frac{v\,dp}{T}$$

T = abs. Temp.
s = sp. entropy
u = sp. internal energy
v = sp. volume
p = pressure

Combining first and second law property relationship one can get T ds is equal to du plus p dv T already we know this is absolute temperature s specific entropy you see I have used lot of small letter for S you have I have used small letter u, I have used small letter and v, I have used small letter these are specific property, s is the specific entropy u is specific internal energy v that is specific volume and p that is equal to pressure. So, you see we get combining first and second law T ds is equal to du plus pdv and you remember that this is a relationship of property which is dependent only on n states and that is why we do not talk anything about the type of the process whether it is reversible process or irreversible process that is not relevant over here. Now ds then can be obtained as du by T plus pdv by T and by some sort of algebraic manipulation one can get dh by T minus v dp by T.

So, these two relationships are very handy in determining change of property.

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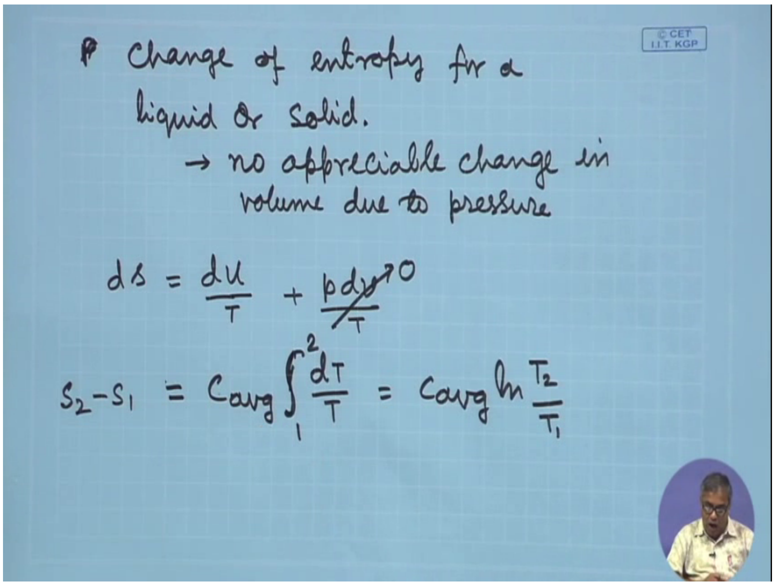

Change of entropy for a liquid or solid.

→ no appreciable change in volume due to pressure

$$ds = \frac{du}{T} + \cancel{\frac{pdv}{T}} \rightarrow 0$$

$$S_2 - S_1 = C_{avg} \int_1^2 \frac{dT}{T} = C_{avg} \ln \frac{T_2}{T_1}$$

Let us say we are considering change of entropy for a liquid or solid. So, in that case what happens for liquid and solid, what happens that we will not have much liquid and solid - no appreciable change in volume due to pressure, due to the application of pressure there will not be any appreciable change in volume. So, ds is equal to d u by T plus pdv by T and for this condition one can have this is equal to S 2 minus S 1 is equal to c average sorry c average dt by T that is equal to c average ln T 2 by T 1, 1 to 2.

So, what I have written let me explain it to. So, internal energy first thing is the second term of this equation will become 0 and then this internal energy we can write as u can be written as c into T for liquid and solid there is some sort of a specific heat multiplied by temperature. And well in general the specific heat will be a function of temperature, but if we take it some average value if we take that some average value can be taken for the process from 1 to 2 and that can be taken out of the integration sign. So, we will get this equation.

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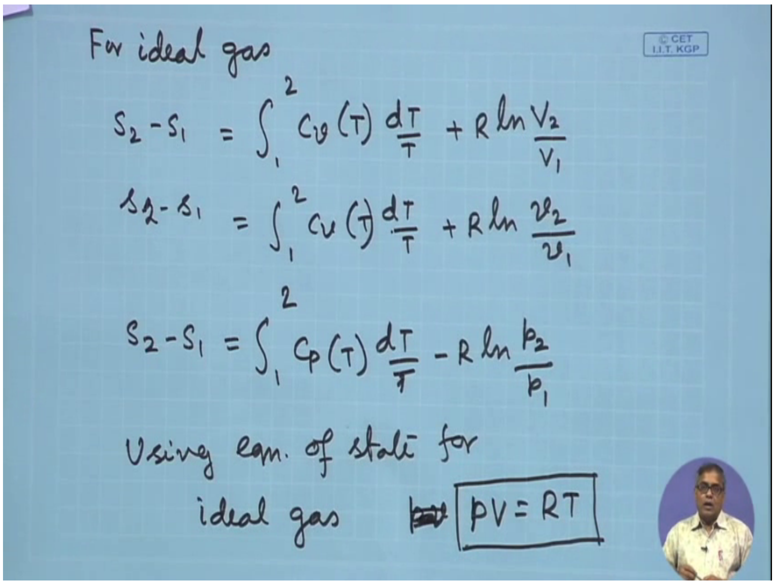

For ideal gas

$$S_2 - S_1 = \int_1^2 C_v(T)\,\frac{dT}{T} + R\ln\frac{V_2}{V_1}$$

$$s_2 - s_1 = \int_1^2 c_v(T)\,\frac{dT}{T} + R\ln\frac{v_2}{v_1}$$

$$S_2 - S_1 = \int_1^2 C_p(T)\,\frac{dT}{T} - R\ln\frac{p_2}{p_1}$$

Using eqn. of state for ideal gas $\boxed{pV = RT}$

Similarly, for ideal gas S 2 minus S 1 that is equal to 1 to 2 c v which is a function of T dt by T plus R that is your gas constant ln v 2 by v 1 here I have written for as extensive property I have written the entropy change I can write it as intensive property also S 2 minus S 1 is equal to 1 to 2 cv T dt by T plus R ln v 2 by v 1. So, this also I can write there is another expression S 2 minus S 1 is equal to integration 1 to 2 c p T dt by T minus R ln p 2 by p 1.

So, either in terms of specific heat at constant volume or specific heat at constant pressure I can write and as you can understand that when I have derived this equation for ideal gas I have used the equations of state for ideal gas using equation of state for ideal gas which is nothing, but pv is equal to or PV is equal to RT. So, this equation I have used. So, with this we have the idea how entropy change how entropy change for different substance solid liquid and ideal gas can be done real gas we are not covering, but I think it is not a course of thermodynamics.

So, people who are interested they can refer any standard book of thermodynamics. So, with this we will be able to calculate the entropy which will be needed again for some analysis of energy conversion systems and systems for waste heat recovery. So, thank you we will proceed from here in the next class we will take up some examples again from the domain of waste heat recovery and we will try to demonstrate how the principles of thermodynamics can be utilized for designing, planning, getting details of waste heat recovery systems.

Thank you.