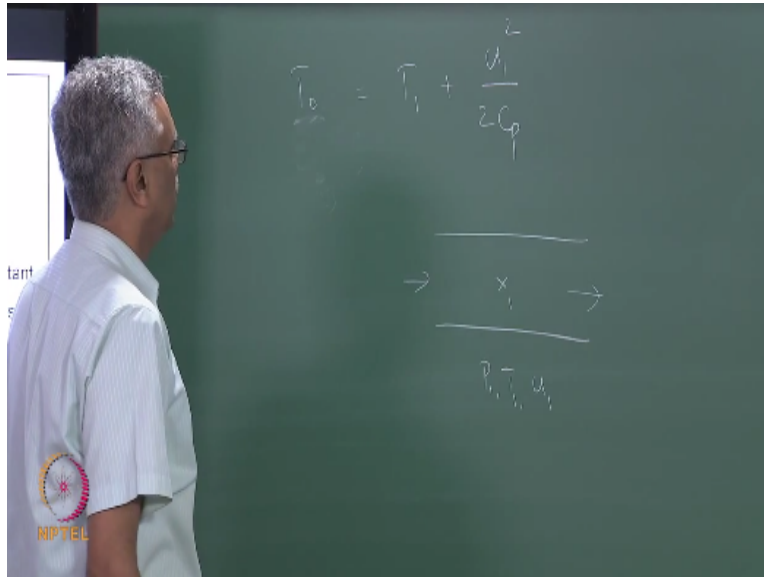


**Gas Dynamics and Propulsion**  
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**Lecture – 04**  
**Fundamental Ideas**

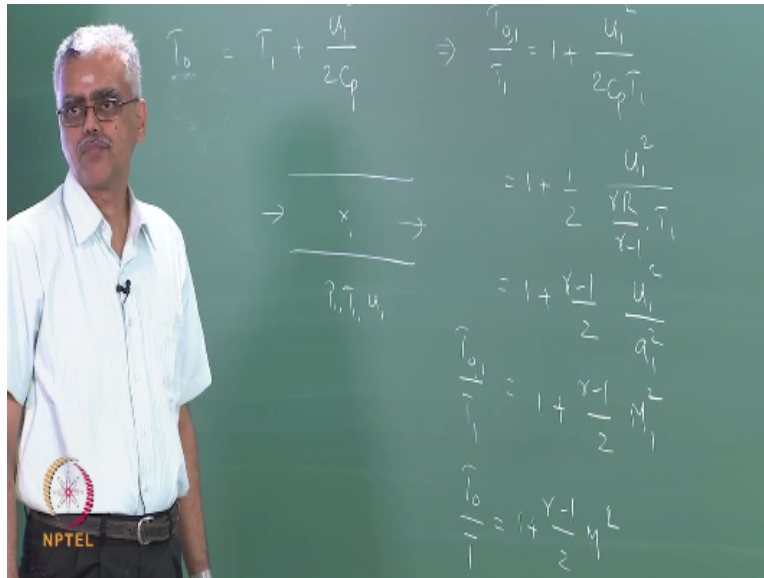
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In the last class, we derived the following relationship between the stagnation temperature and static temperature for a flow. So, let us see what it looks like. So, we showed that  $T_0 = T_1 + U_1^2 / 2C_p$ . So, we are looking at one-dimensional flow situation. So, let us say that we have a flow that is going through. So, we looked at a particular point in the flow which we labeled as state 1 and at this state, we know pressure  $P_1$ , we know temperature  $T_1$  and we know velocity  $U_1$ .

So, given these quantities what we were trying to do is to calculate the corresponding stagnation temperature, stagnation pressure and stagnation density. So, this gave us the stagnation temperature. In fact, it would be more convenient to write this relationship in terms of Mach number.

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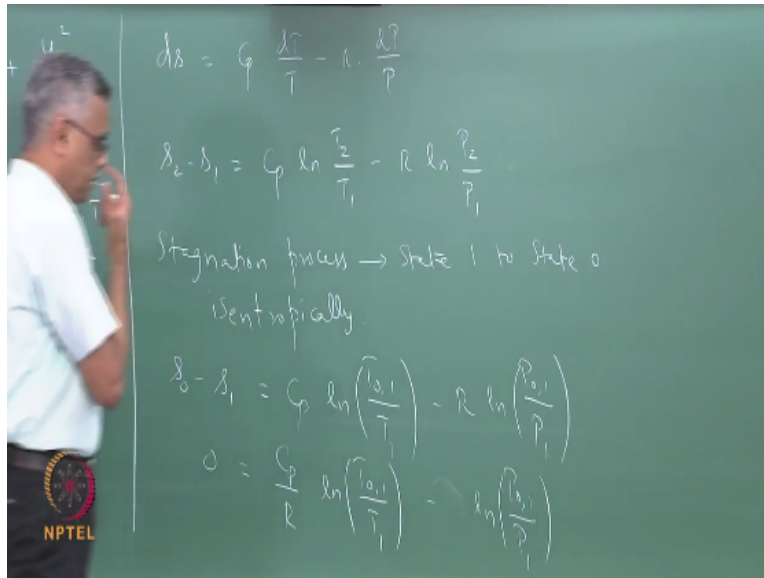


So, if I take this equation and if I divide through by the static temperature on both sides, I can write this as  $T_0/T_1 = 1 + u_1^2 / 2C_p T_1$  and if I recognise the fact that  $C_p$  is going to be  $1 + \gamma R / \gamma - 1$ , I can write this as  $u_1^2 / T_1$ . Now, I recognise the fact that this  $\gamma R / T_1$  is nothing but square of the speed of sound at that point. So, I can write this as  $1 + \gamma - 1 / 2 * u_1^2 / A_1^2$ .

$A_1$  is the speed of sound corresponding to state point 1 and this we can recognise as the square of the Mach number. So,  $T_0/T_1 = 1 + \gamma - 1 / 2$  times  $M_1^2$ . So, this is a very convenient form in which we can actually use this relationship, okay. So, once I know these three quantities, I can evaluate  $M_1$ , I can evaluate  $T_0$ . In fact, as we did yesterday, we want to be very specific and add subscript 1 to this to denote that this is the stagnation temperature corresponding to static state 1, okay.

So, the stagnation temperature corresponding to any static state can be written. If you drop the subscript 1, I can write this as  $T_0/T = 1 + \gamma - 1 / 2$  times  $M$  square. So, this is the stagnation temperature corresponding to any static state, okay. Now, when we wrote down the expression for entropy change, we wrote the following expression. Let us take a look at that and we will derive the expression for stagnation pressure based on this.

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If you remember, we wrote down that change in entropy =  $CP \cdot dT/T - R \cdot dP/P$  and if you integrate this, we are able to show that  $S_2 - S_1 = CP \cdot \ln(T_2/T_1) - R \cdot \ln(P_2/P_1)$ . So, this was the entropy change between any 2 states 1 and 2. Now, if I apply this equation between state 1 and state 0. For example, in the stagnation process, we are going from state 1 isentropically to state 0, right/


So, if I apply this. If I calculate the entropy change for such a process, so stagnation process takes us from state 1 to state 0 isentropically which means that if you apply this equation between state 1 and state 0, I get the following. I get  $S_0 - S_1 = CP \cdot \ln(T_{01}/T_1) - R \cdot \ln(P_{01}/P_1)$ . Since the process is isentropic,  $S_0 = S_1$ , so that means the left hand side becomes = 0, so  $0 = CP/R \cdot \ln(T_{01}/T_1) - \ln(P_{01}/P_1)$ .

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$$\frac{P_{0,1}}{P_1} = \left( \frac{T_{0,1}}{T_1} \right)^{\gamma/\gamma-1} = \left( 1 + \frac{\gamma-1}{2} M_1^2 \right)^{\gamma/\gamma-1}$$

$P_1$  - static pressure,  $P_{0,1}$  - stagnation pressure.

$P_{0,1} = \rho_{0,1} R T_{0,1}$   $\rho_{0,1}$  = stagnation density



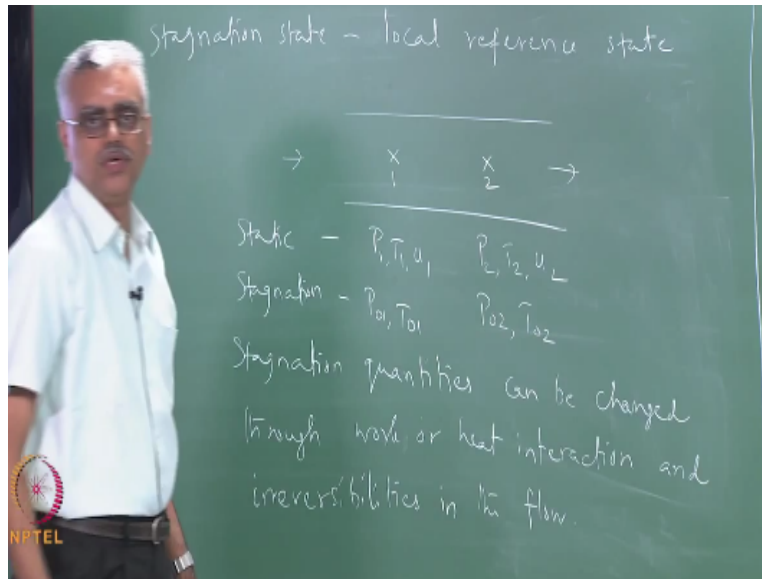
Once again, if you realize the fact that CP is  $\gamma R / \gamma - 1$ , I can simply this equation and write the following,  $P_{01}/P_1 = T_{01}/T_1$  raise to the power  $\gamma / \gamma - 1$ . Once again, if I wish to write this in terms of Mark number, I can substitute for  $T_{01}/T_1$  from here. So, I have  $T_{01}/T_1$  here. So, I can substitute for that from this equation. I can substitute for that from here and write this as  $P_{01}/P_1 = 1 + \gamma - 1/2$  times  $M_1$  square raise to the power  $\gamma / \gamma - 1$ .

So, given the static pressure  $P_1$ , we can calculate the stagnation pressure using this relationship. Notice that this is the static pressure. Now, we will again explicitly state static and stagnation pressure. So,  $P_1$  is the static pressure and  $P_{01}$  is the stagnation pressure. It is important to realize that when we calculated the stagnation temperature, we never really made use of the fact that in going from state 1 to state 0, the process is isotropic.

We never really used that information when we derive the expression for stagnation temperature. However, when we derive the expression for stagnation pressure, we are explicitly making use of the fact that it is an isotropic process when we go from state 1 to state 0 and that is how we arrive at this, okay. Now, the stagnation density can be calculated by using the following relationships. So,  $P_{01} = \rho_{01} R T_{01}$ . So, using this, the stagnation density can be calculated.

Now, let us take a quick look at the stagnation quantities and their implications on irreversibility work condition and heat addition in a flow that is what we are going to do next.

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So, we are looking at one-dimensional flow situation. So, the flow is going through and let say that this is state 1. This is the static condition  $P_1$ ,  $T_1$  and  $U_1$ . Now, the stagnation condition corresponding to this is  $P_{01}$  and  $T_{01}$ . These are the stagnation condition. This is the study condition.  $P_{01}$ ,  $T_{01}$  and  $\rho_{01}$  which we can calculate easily. Now, the stagnation quantities,  $P_{01}$  and  $T_{01}$  at this point depend upon what we did before, okay.

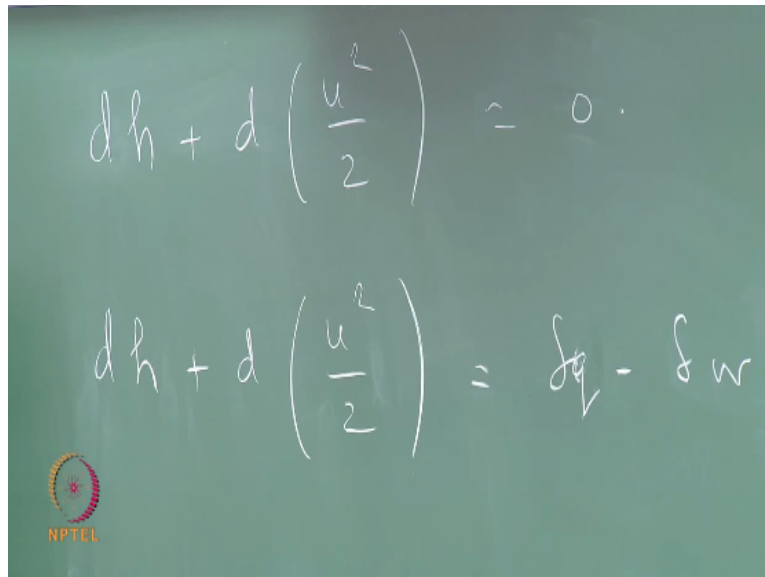
The two things that are important unlike the sonic state, the stagnation state is calculated for this static state, right which means that the stagnation stage is a local reference state because a stagnation state is calculated for a particular static state. So, it is a local reference state from that perspective. Let say, if I look at another point 2 along the flow direction, now what will the stagnation pressure temperature and stagnation density at this point be, will it be the same or will it be different that is the next question.

So, the stagnation condition at a given point depends upon what interaction the flow has upstream of the point, okay. So, if in between point 1 and 2, let say I add heat to the flow or I do some work on the flow. Let say it is a compressor or extract some work from the flow it is a turbine. So, depending upon the interaction, heat or work interaction that I have or irreversibility, the stagnation state at point 2 can be different from stagnation state at point 1, okay.

So, it depends upon the interaction that I have. So, stagnation quantities can be changed through work or heat interaction and irreversibilities in the flow, okay. Remember, the stagnation process is isotropic. As I said earlier, the flow itself need not be isotropic. There can be irreversibilities in the flow or the flow can also be isotropic, it does not matter, okay. Now, let us see how  $P_02$  and  $T_02$  are related.

So, the static state corresponding to state 2 is  $P_2$ ,  $T_2$ ,  $U_2$  and the stagnation state corresponding to that is  $P_02$ ,  $T_02$ . So, we want to see how  $P_02$  and  $P_01$  are related, if they are related and how  $T_02$  and  $T_01$  are related, that is what we are going to see next.

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$$dh + d\left(\frac{u^2}{2}\right) = 0.$$
$$dh + d\left(\frac{u^2}{2}\right) = \delta q - \delta w$$

Now, notice that or you should recall that when we calculate a stagnation temperature, we use the energy equation alone for calculating the stagnation temperature. So, if you go back to the energy equation. If you remember, we wrote it like this. This was the energy equation that we had written down and if there is heat or work interaction, then the energy equation has to be modified to that into account.

For example, if I have heat or work interaction then, I would write this energy equation as  $\delta q - \delta w$  where we are following the usual convention in thermodynamics that heat given to a system is positive and work done by a system is positive. So, you can see that stagnation temperature can be changed by changing either giving heat to the system or having a heat

interaction with the system or having a work interaction with the system. So, when I do either one of these, the stagnation temperature will change, okay.

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$$\frac{T_2}{T_1} = \left( \frac{T_2}{T_{0,2}} \right) \left( \frac{T_{0,1}}{T_1} \right) \left( \frac{T_{0,2}}{T_{0,1}} \right)$$

$$\frac{P_2}{P_1} = \left( \frac{P_2}{P_{0,2}} \right) \left( \frac{P_{0,1}}{P_1} \right) \left( \frac{P_{0,2}}{P_{0,1}} \right)$$

Next, we need to look at stagnation pressure. So, for example, if I add heat to the system, then the stagnation temperature will increase or across a compressor where work is being done on the system, again stagnation temperature will increase proportional to work and across the turbine where work is extracted, stagnation temperature will decrease because we are extracting energy from the turbine, right. Now, let us see how we can relate the 2 stagnation quantities.

So, if I take these two states and recognise the fact that  $T_2/T_1$  I can write as  $T_2/T_{0,2} * T_{0,1}/T_1 * T_{0,2}/T_{0,1}$ . So, I have taken  $T_2/T_1$  multiplied and divided appropriately by  $T_{0,2}$  and  $T_{0,1}$  to arrive at this, okay. That is one thing and I can write  $P_2/P_1$  similarly. So,  $P_2/P_1 = P_2/P_{0,2} * P_{0,1}/P_1 * P_{0,2}/P_{0,1}$ . So, we have this relationship. Notice that in this relationship  $T_2/T_{0,2}$  can be written in terms of the Mark number, right.

That is nothing but  $1 + \gamma - 1/2 * M^2$  square. Similarly, this can also be written in terms of Mark number and these terms can also be written like this, okay.

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The image shows a hand pointing to a chalkboard with the following equations written on it:

$$s_2 - s_1 = R \cdot \ln \left[ \left( \frac{T_2}{T_1} \right)^{\gamma/\gamma-1} / \left( \frac{P_2}{P_1} \right) \right]$$

$$s_2 - s_1 = C_p \ln \left( \frac{T_2}{T_1} \right) - R \ln \left( \frac{P_2}{P_1} \right)$$

$$= \frac{\gamma R}{\gamma-1} \cdot \ln \left( \frac{T_2}{T_1} \right) - R \ln \left( \frac{P_2}{P_1} \right)$$

An NPTEL logo is visible in the bottom left corner of the chalkboard image.

Now, we calculate, we write  $s_2 - s_1 = R \ln \left( \frac{T_2}{T_1} \right)^{\gamma/\gamma-1} / \left( \frac{P_2}{P_1} \right)$ . Notice that all I have done here is re-written the earlier equation that we wrote down. For example, the earlier equation looked like this. So, the earlier equation, if you remember, look like this  $s_1 - s_2 = C_p \ln \left( \frac{T_2}{T_1} \right) - R \ln \left( \frac{P_2}{P_1} \right)$ , right and  $C_p = \gamma R / \gamma - 1$ . So, if I take the R outside and take the gamma over gamma-1 to the exponent here, I arrive at this equation.

So, I have done is I am calculating the entropy change between state points 1 and 2 in the flow. So, I am calculating entropy change between state points 1 and 2 in the flow with the objective of relating, the stagnation states corresponding to these two static states, that is what I am trying to do there. So, now I have this relationship and I can substitute for  $T_2/T_1$  and  $P_2/P_1$  from here, right and I also recognise the fact, remember we have already written down the following equation, right.

**(Refer Slide Time: 17:42)**



The image shows a chalkboard with the following handwritten equations:

$$s_2 - s_1 = C_p \ln \left( \frac{T_2}{T_1} \right) - R \ln \left( \frac{P_2}{P_1} \right)$$

$$= \frac{\gamma R}{\gamma - 1} \ln \left( \frac{T_2}{T_1} \right) - R \ln \left( \frac{P_2}{P_1} \right)$$

$$\frac{P_0}{P} = \left( \frac{T_0}{T} \right)^{\gamma / (\gamma - 1)}$$

Then, a boxed equation is shown:

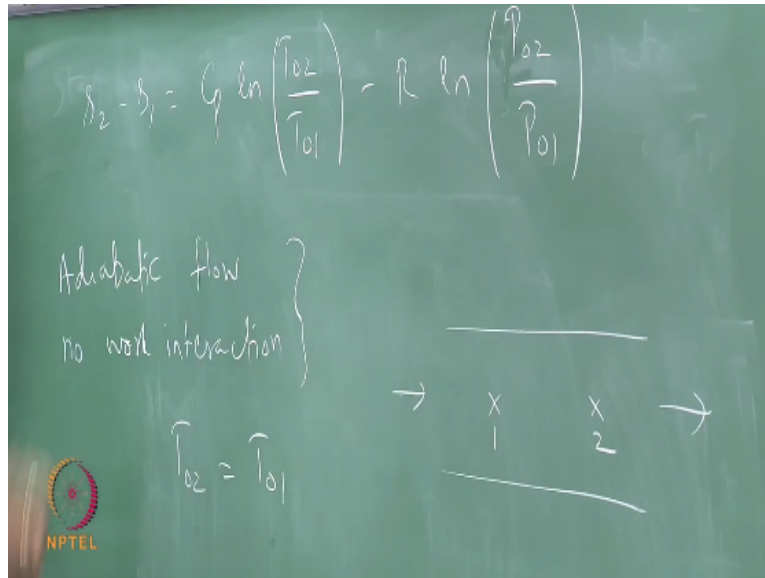
$$s_2 - s_1 = C_p \ln \left( \frac{T_{02}}{T_{01}} \right) - R \ln \left( \frac{P_{02}}{P_{01}} \right)$$

An NPTEL logo is visible in the bottom left corner of the chalkboard image.

We have written down the fact that  $P_0/P = T_0/T$  to the power  $\gamma/\gamma-1$ . So, if I use this relationship and these relationships in this equation, I can arrive at the following expression finally. I get the following expression  $s_2 - s_1 = C_p \ln T_{02}/T_{01} - R \ln P_{02}/P_{01}$ . Notice that by using this relationship, we have eliminated the static states from this equation completely. So, now we have an equation which relates the stagnation states corresponding to static state 1 and static state 2.

That is why we wrote this expression like this because this raise to the power  $\gamma/\gamma-1$  and this will cancel each other and we substitute, so we are left with an equation which relates only the stagnation states. This is an extremely important equation in gas dynamics and we will look at the implications of this equation next.

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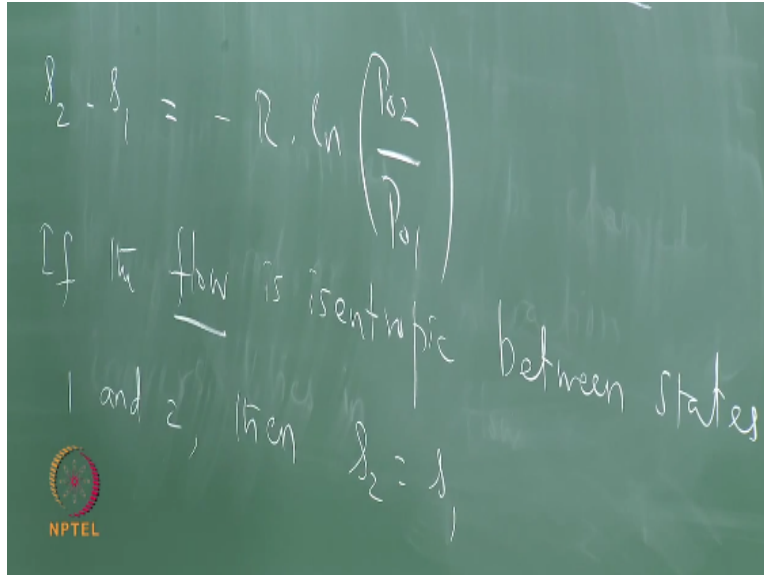


So, we are going to look at the implications of this particular equation. Let us re-write that equation over here and we are actually looking at a scenario a one-dimensional flow or even call one-dimensional flows is also okay as long as we have only one velocity component. So, we have a flow situation like this. This is state point 1, this is state point 2 and we can look at different scenarios.

Let us assume that the flow is idiomatic, that we do not have any heat or work interaction. If there is no heat or work interaction, then what happens to the stagnation temperature. Is there any change in the stagnation temperature. Remember, any heats interaction will go into the energy equation. So, if there is no heat or work interaction, idiomatic flow. So, we are looking at an idiomatic flow, now work interaction.

So, these two conditions together will lead to the fact that  $T_{02}=T_{01}$ . There is no change in stagnation temperature in such a case, right. Remember stagnation temperature can be changed either by the addition of heat or by the addition of work or removal or work or extraction of work. That is the only way we can change the stagnation temperature. If both of these things are absent, then  $T_{02}=T_{01}$ .

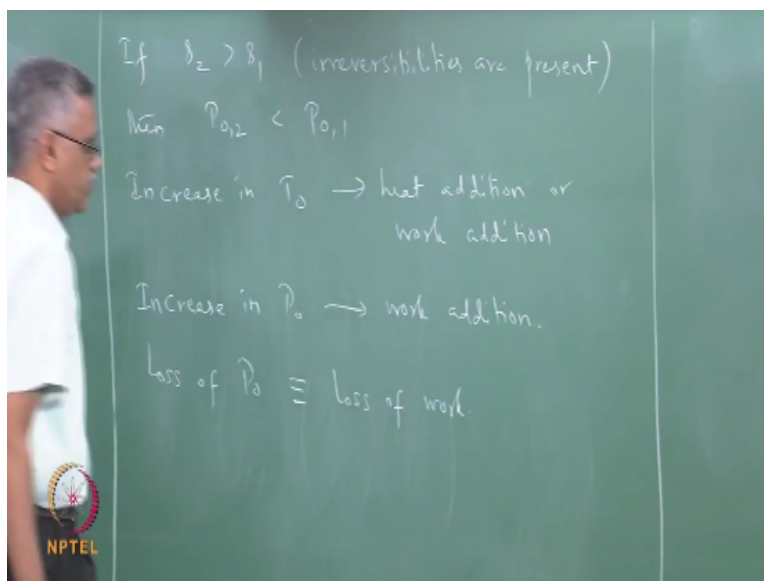
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From this equation we see that  $s_2 - s_1$  in this case  $= -R \ln(P_{02}/P_{01})$ . Now, if the flow between 1 and 2 is isentropic meaning there are no irreversibilities, then  $s_2 = s_1$ , so it follows that  $P_{02} = P_{01}$  correct. So, if the flow, remember here the important thing is I am saying, if the flow is isentropic between state 1 and 2, then  $s_2 = s_1$ , right. So, it follows that  $P_{02} = P_{01}$ , okay. So, there is no heat interaction.

There is no work interaction and the flow is isentropic, then we have  $T_{02} = T_{01}$ ,  $P_{02} = P_{01}$  which is the case in most of the kind of flows that we are going to look at, okay.

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What if there is an irreversibility between states 1 and 2. So, meaning irreversibilities are present.

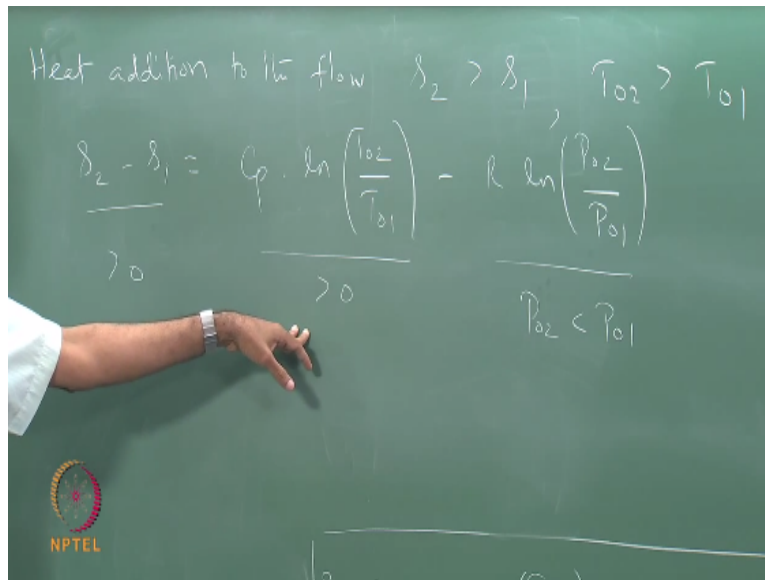
Remember we are saying that the flow is isentropic. So, the entropy change can only be positive or = 0. So, we already looked at the case and it is = 0, so if it is positive that means there are irreversibilities, then  $S_2 > S_1$  and from this equation, if  $S_2$  has to be  $> S_1$ , there is a negative sign here that means  $P_02$  has to be  $< P_01$ .

If you remember, if you recall we said earlier that increase in stagnation temperature. Let us write it down, increase in  $T_0$  is possible through heat addition or work addition. Similarly, increase in  $P_0$  is possible through work addition. So, if there is reduction of  $P_0$ , we can say that it is equivalent to a loss of work, right. So, any loss of stagnation pressure is equivalent to a loss of work or loss of energy and so it is not desirable, okay.

So, any compressible flow, loss of stagnation pressure must be avoided because that is equivalent to loss of work. So, we can see that loss of stagnation pressure is equivalent to loss of work and so must be avoided at all costs, because it represents irreversibilities in the flow field which must be avoided.

**“Professor - student conversation starts”** Sir. Yeah. What is the effect of heat addition on  $P_0$ ? The effect of heat addition on  $P_0$ , we can infer indirectly from this equation. Let us take a look at the next. We can only get an idea about it, we cannot calculate it exactly, okay. Let us take a look at that next. **“Professor - student conversation ends”**.

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What happens if you add heat addition? So, in the case of heat addition to the flow. Heat addition to the flow must cause an increase in entropy, right.  $S_2$  will be  $> S_1$  because we are adding heat to the flow. The increase in entropy is not due to irreversibility even if the heat addition process is reversible, still it results in an increase in entropy. So, heat addition to the flow makes  $S_2 > S_1$  and as we saw earlier  $T_{02}$  is also  $> T_{01}$ . This is very easy to see, right.

$T_{02}$  being  $> T_{01}$  is very easy to see. So, if you go back to our original equation,  $S_2 - S_1 = C_p \ln(T_{02}/T_{01}) - R \ln(P_{02}/P_{01})$ . So, this is a positive quantity and this is increasing, this is  $> 0$  and since  $T_{02} > T_{01}$ , this is also a positive quantity. Now, this as you can see from here, this can either be 0 or it has to be negative, right.

That is the only way this negative sign and this will act together to give a positive number which tells me that heat addition can probably keep the stagnation pressure the same or there must be a reduction in stagnation pressure, so that if  $P_{02} < P_{01}$ , this becomes positive and we can add to this, otherwise we cannot get an increase in entropy. This would start decreasing the entropy because entropy increases in heat addition process.

We know that any increase in entropy must result in a loss of stagnation pressure. So, in this case also,  $P_{02}$  will be  $< P_{01}$  because of the increase in entropy due to the heat addition, okay. We can actually illustrate this much more clearly when we demonstrative the states graphically, okay.

Since the entropy increases,  $P_02$  cannot be  $= P_01$ .  $P_02$  has to be  $< P_01$ .

So, even if you have heat addition in a reversible process, even a reversible heat addition process will cause an increase in entropy and loss of stagnation pressure that is unavoidable. This is what thermodynamics tells us. This is not due to any inefficiency or irreversibility in the process. So, this is an extremely important consideration for combustors, because in combustor we want to add heat. So, if you remember the picture of the aircraft engine that we drew earlier.

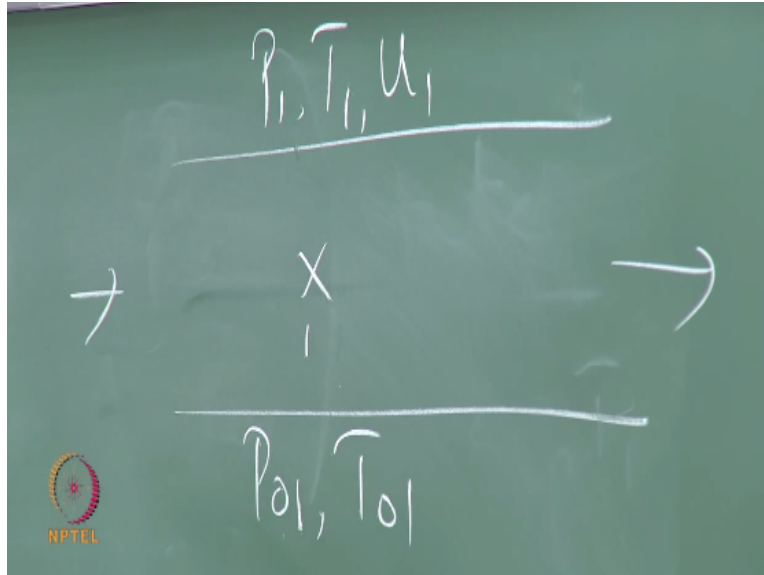
The air is compressed before being sent to the combustor. So, we have to add heat in the combustor but the heat addition process in the combustor also causes a loss of stagnation pressure which means whatever work you put in, some of the work that you put in into the compressor is now being lost in the combustor because of the heat addition process, that is inevitable. There is nothing that we can do about it.

Now, how do we increase the efficiency of the combustion process and you have a combustor. How do we make sure that the combustion process is very efficient? We need to make sure that the fuel and the air are mixed thoroughly, so that they can burn very well. Mixing as you know is also a thermodynamically irreversible process. So, as you keep improving the efficiency of the combustor, the loss of stagnation pressure will also increase.

So, these are two conflicting considerations. How do we minimise the loss of stagnation pressure while maximising the combustor efficiency. These are two completely conflicting requirements and so we need to optimise, okay. That is why I said that this equation is probably one of the most important equations in gas dynamics, okay, alright. What we are going to do next is we have looked at states mathematically. We have derived equations for this.

Now, we are going to actually depict processes graphically on T-S and P-V diagrams, so that more insights can be drawn into the process, that is very useful way of depicting the flow and that is what we are going to do next.

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So, we are going to discuss T-S diagrams and P-V diagrams in compressible flow. So, depicting flow processes in T-V and P-S diagrams can be extremely useful and give us a lot of insights into the nature of the flow, irreversibilities and other things, how the states are changing. It can give us a lot of useful information and that is what we are going to do next. So, when you draw a T-S diagram, what we want to show on a T-S diagram or lines of constant  $V$  or lines of constant  $P$ , that is what we want to show.

So, these are the four variables that we are looking at, okay. If you remember, we said that a one-dimensional flow each state is characterised by static pressure, static temperature and velocity, in addition, stagnation pressure and temperature. So, these are the quantities that we want to illustrate. So, let us say that we want to illustrate a state in a T-S diagram as we are looking at a one-dimensional flow situation which looks like this and we have state point 1 in this flow.

State point 1 if you remember was characterised by  $P_1$ ,  $T_1$  and  $U_1$ , in addition  $P_{01}$  and  $T_{01}$ . So, I want to show all this information on a T-S diagram. Let us say that is the first thing that we want to do. We would also want to show all this information in a P-V diagram next. First thing is T-S diagram. So, to do a T-S diagram, first thing that we want to do is look at lines of constant  $V$  and constant  $P$  and we start with the following equation.

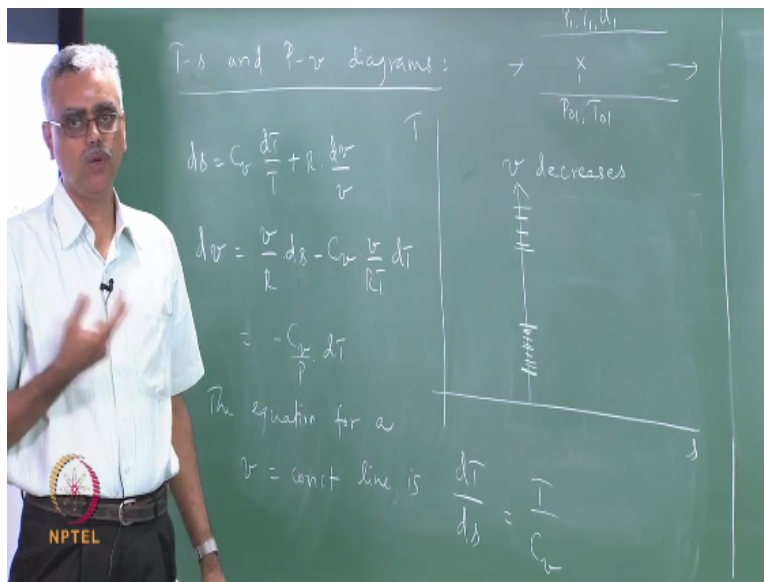
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$$ds = C_v \frac{dT}{T} + R \frac{dv}{v}$$

$$dv = \frac{v}{R} ds - C_v \frac{v}{RT} dT$$


If you recall, we wrote down  $ds = C_v dT/T + R \cdot dv/v$ . Now, if I rewrite this equation. I am going to rewrite this equation like this,  $dv = v/R \cdot ds - C_v \cdot v/RT \cdot dT$ , okay.

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T-s and P-v diagrams:


$$ds = C_v \frac{dT}{T} + R \frac{dv}{v}$$

$$dv = \frac{v}{R} ds - C_v \frac{v}{RT} dT$$

$$= -\frac{C_v}{p} dT$$

The equation for a  
 $v = \text{const line is } \frac{dT}{ds} = \frac{T}{C_v}$

$v$  decreases



So, on a T-S diagram, as you can see, if I move in the vertical direction, say a direction like this, so a move in a vertical direction, what is  $ds$ ,  $ds$  is 0. If I move along a vertical direction, so this tells me that as I move along the vertical direction,  $dT$  is positive, so this tells me that the specific volume decreases when I move along the vertical direction,  $dv$  is negative.

This is positive, positive, positive, positive. So, that means specific volume  $dv$  is negative, so that means specific volume decreases when I move in this direction. So, that is the first piece of



information that we can get from this, okay. Is this clear? right. So, that is the first piece of information. Now, I want to over look at  $v = \text{constant}$  lines. Before, I even do that look at this, as I move in a vertical direction, this becomes  $ds=0$ . So, I can write this as  $-C_v \frac{v}{rT}$  is nothing but,  $v/rT$  is going to be, remember  $Pv=rT$ , so  $v/rT$  is  $-C_v/P*dT$ .

This also tells me that for a given change in temperature, let us say  $dT$  is 10 Kelvin. So, for a given change in temperature, right; at low values of pressure, the change in specific volume is much higher than at high values of pressure. We will show next that pressure increases in this direction. So, what this tells me is for low values of pressure, for a given change in temperature. So, for example let us denote the given change in temperature like this.

So, this is a change in temperature right at a low value of pressure, same change in temperature at a higher value of pressure. So, we have used the same change in temperature in both these cases. This is  $dT$ . So, for this value of  $dT$  at a low value of pressure, the change in specific volume is very high which tells me that  $v = \text{constant}$  lines are bunched close together here whereas  $v = \text{constant}$  lines are spaced farther apart here.

So, this tells me that  $v = \text{constant}$  lines look like this here, like this and  $v = \text{constant}$  lines look like this here. So, the lines are bunched close here so that for the same  $dT$  I get a large change in specific volume here but a smaller change in specific volume here, right. So, this information we can get from this equation. Now, if I say that the equation for  $v = \text{constant}$  line, so the equation for a  $v = \text{constant}$  line can be obtained from here by simply setting,  $v$  is constant then I simply say  $dv=0$ .

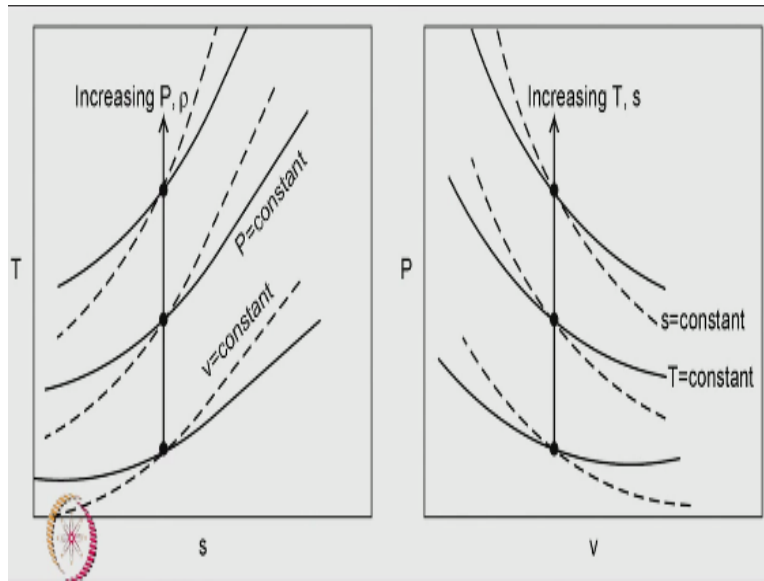
So, if I say  $dv=0$ , then I can re-write this equation and show that for such an equation,  $dT/ds=T/C_v$ . This is the first order differential equation, right.  $DyDx = \text{some function of } x$ . So, this is the first order differential equation. So, this gives me the equation for  $v = \text{constant}$  line. I am not going to solve this equation. We are just going to sketch that  $v = \text{constant}$  lines qualitatively, okay.

So, we already know certain things about the  $v = \text{constant}$  line. This is the spacing between the

lines. This tells me about the slope, okay. Notice that at low values of temperature, the  $v =$  constant lines the slope is very small, so that means the lines are shallow at low values of temperature. As the temperature increases, the slope also increases. Slope is not constant first of all, these are curves. Although we keep calling them lines, they are actually curves, right.

Slope also changes from point to point. At low values of temperature, the lines are shallow. At high values of the temperature, the lines are steeper and the spacing of the lines looks like this. They are closely spaced here and farther apart here, right and the slope is also positive which means the lines are all oriented like this.

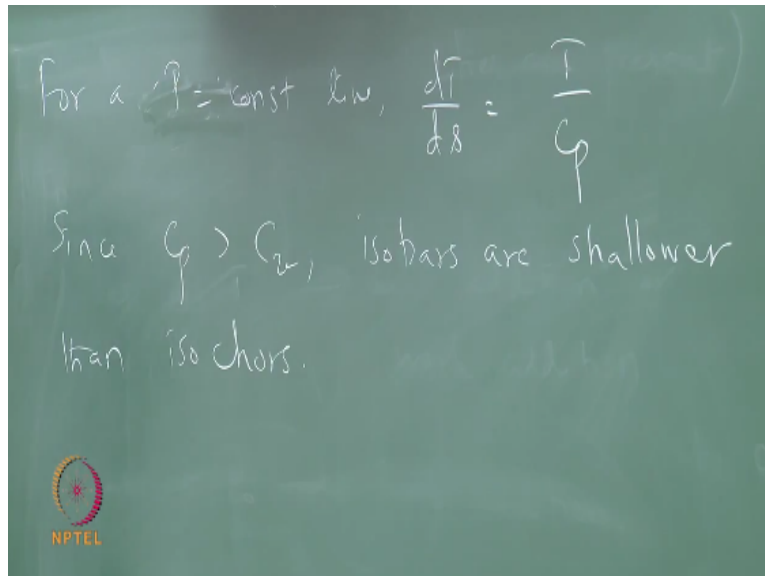
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Slope is positive throughout, shallow here and steeper here, right. So, shallow here positive, shallow here and becoming steeper as we go along, right. So, shallow and becoming steeper as we go along that is what is depicted in the figure in the left in this diagram. So, if you at the figure on the left, notice that  $v =$  constant lines are shown dashed and you can see that slope is shallow, low values of temperature, they become steeper as the temperature increases, okay.

So, all the information that we have discussed is shown here graphically, okay. The next is the T-S diagram, so now we know how  $v =$  constant line behaves.

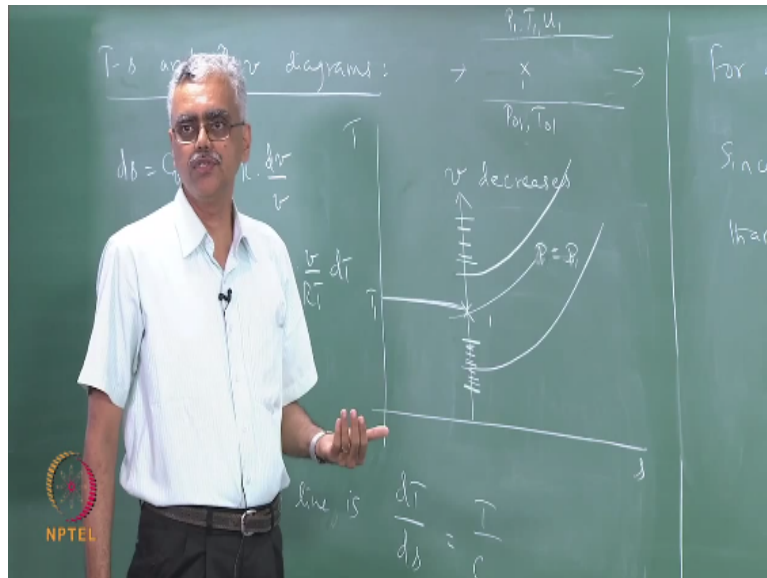
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The next thing that we want to do is to see how  $P = \text{constant}$  line shows. So, for a  $P = \text{constant}$  lines using similar arguments, I can show the following for a  $P = \text{constant}$  line. I can show that  $dT/ds = T/C_p$  using very, very similar arguments, okay. Now, look at this equation. Once again I can say that the slope for the  $P = \text{constant}$  lines isobar is positive and for low values of temperature, once again it is shallow and for high values of temperature it becomes steeper, that much I know.

Now, if I compare the slope of this with this which  $T/C_v$ , which one is steeper compared to these two, I can make that also since  $C_p > C_v$  isobar are shallower than isochores, right. So, that information is also shown in this diagram. We can see that  $P = \text{constant}$  lines are shallower for low values of temperature and the slope keeps increasing as we walk and you can also see that the  $v = \text{constant}$  lines are steeper than the  $P = \text{constant}$  lines passing through the same state point, okay. That information is depicted here.

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So, with this information, any of this can be transferred over here. So, all I do is if I have a particular  $P_1$  and  $T_1$ , I can go and look at the  $P_1$ . Let us say that this is my  $P=P_1$  line and for the given value of temperature, I simply take this  $T_1$ , this is pressure  $P_1$ , this is state point 1. So, the information from here  $P_1$  and  $T_1$  have been transferred here, okay. I have to now worry about how do I get this information in here and this information in here, right that we will do as we go along, okay.

So, this talks about  $P$  and  $V$ . Next, we have to look at drawing this on  $P$ - $V$  diagram. So, we have looked at this on a  $T$ - $S$  diagram, we have look at this on a  $P$ - $V$  diagram next.