Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Engineering Thermodynamics

Lecture – 17
First Law of Thermodynamics for Steady Flow Processes

By
Prof. D. P. Mishra
Department of Aerospace Engineering

In the last lecture we derived a relationship for first law of thermodynamics that can be applied for open system.

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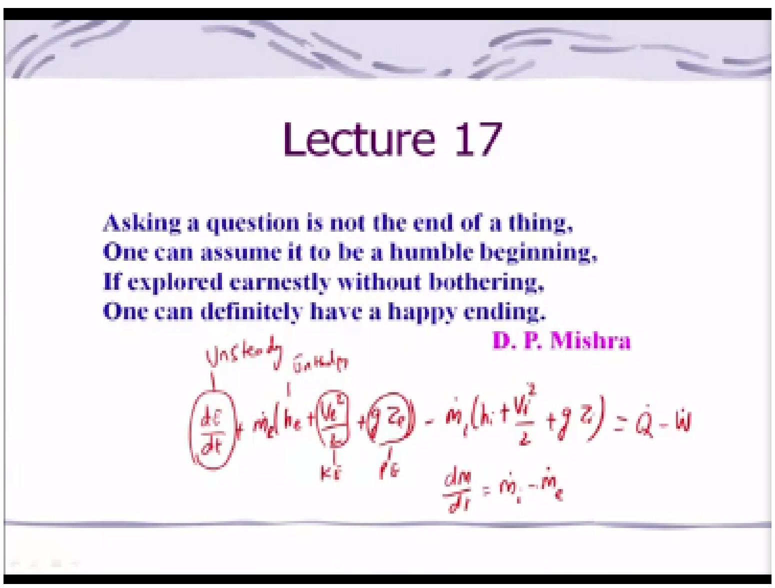

So if you recall the expression that is $dE / dT + m._E (h_E+V_E^2/2+gZ_E) - m._i (h_i+V_i^2/2+gZ_i)=Q.-W.$, so if you look at this, this is basically unsteady term and which indicates how much energy being accumulated in the system right and per unit and particular time it is basically unstated term. And this is your enthalpy and this term is if you look at kinetic energy term and this is your potential energy term, and similarly at the inlet this is about exit right, and this is about inlet, the enthalpy kinetic energy, and potential energy, and this is your heat interactions right, and this is your work interactions.

And not only that we need to look at this equation for energy conservation, but also we need to look at mass conservation equation which we have derived as $dM/dT = \dot{m}_i - \dot{m}_E$ that means the mass being accumulated is equal to mass in being you know entering into the control volume minus mass of the going out. Now what we will be doing this we will be applying this energy equation also the mass conservation equation for open systems and take some examples and then look at it and how we can apply what are the, you know assumption will be making and how we can simplify the problem those things will be looking at.

But that let us consider a steady flow process right and if it is a steady flow process you know then we can you know simplify this equation question arises whether any engineering device is there which we can consider as a steady, steady means nothing is changing with respect to time is it we can think of, because if you look at like let us say the fan is running right a fan which we use you know in our in summer season ceiling fan we use right.

So that is almost remaining constant moving at the same rpm right if there is no change in flow what you call voltage input voltage to the motor right, the flow will be coming in that will be almost constant you can assume right yes or no that we can there are several, you know like systems in engineering which we can assume very happily to be operated at steady condition. For example, power plant you might be knowing that you know Kanpur city is having a power plant yes or no that is your steam power plant. It is a power plant will be operating almost you know at a steady state.

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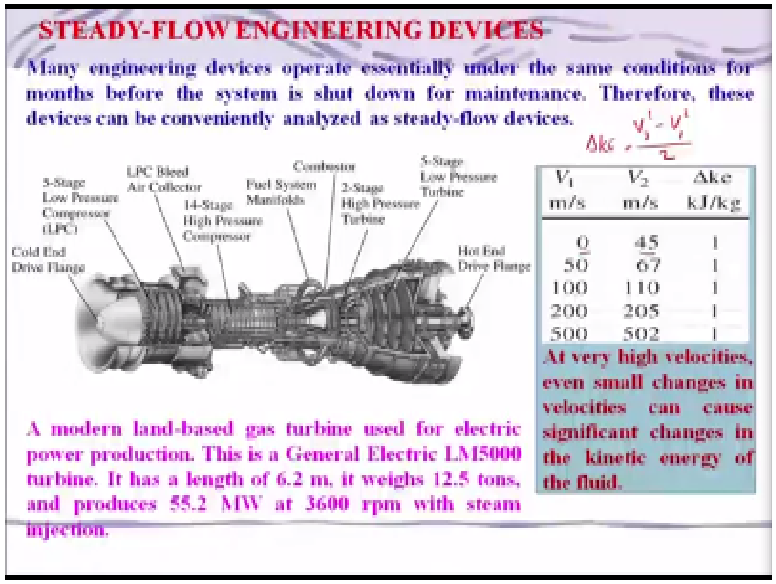

Similarly your heat exchangers and other thing several devices we can assume to be what you call up remaining almost same conditions for months you know together unless it is the system is shut down for maintenance you might have heard a lot of noise sometimes from our power plant which is located in pond key am I right we do here lot of noise will be coming continuous manner that is basically setting down of the system's kind of right.

So therefore these devices, you know like we can analyze it by assuming the flow to be steady okay. So let us consider you know gas turbine engine which is have quite complex you know it is having what you call compressors, it is having what we call combustion chamber there are various kinds of compressor here you know like you know low-pressure compressor, high-pressure compressor and you may have take out the air and there is a combustion chamber the turbine and the other thing.

So if you look at this very big gas turbine engine which can give you something power of 50 to 55.2 megawatt and it is rotated at 36,000 RPM with of course the steam injections and length is 6.2 meter, you know it is a very huge and weight of course is 12.5 ton okay. Now when we apply this kind of energy equation you know like we have looked at kinetic energy term. Now let us look at if the kinetic energy term you know if the velocity change whether we can neglect or not right.

You know velocity kinetic velocity goes by square if the change is a low-velocity, you know there is a change you know that change will be negligibly small, but whereas the higher it will be for example like if V1, you know 0 and V2 is 45 meter per second and if I take the change in kinetic energy terms right that is of course the specific energy that will be what $V2^2$-$V1^2$/2 that will happens to be 1 kilo joule per kg right this is your change in kinetic energy specific kinetic energy per unit mass you know.

But if you look at the change is 45 meter per second, but if I go for five hundred to five hundred two and the same amount of energy one kilo Joule per kg there are only two meter per second you know, but there is a hue so one has to be very cautiously you know neglect this term right, because keep in mind that at high velocity even a small changes in velocities can cause a significant change in kinetic energy of the fluid.

So we will be also making lot of assumption how where when we can neglect the potential energy term change in potential energy and the, you know work done by the system and then heat interactions also will be doing that.

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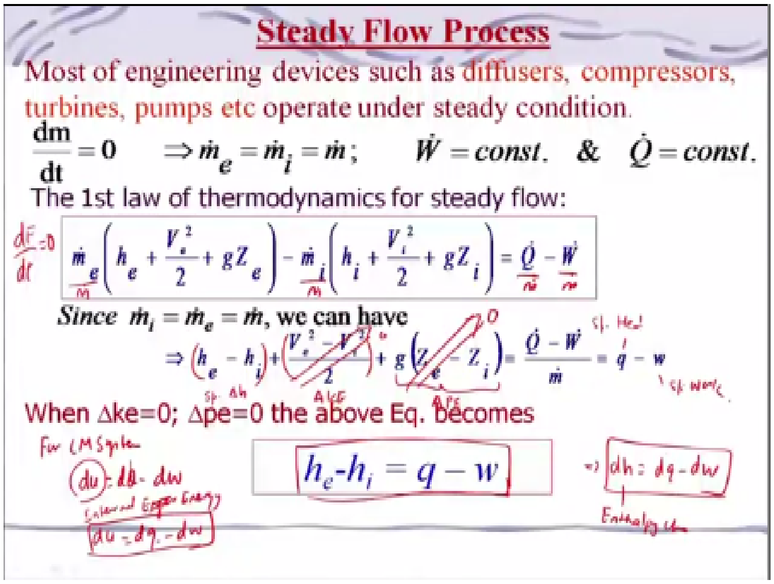

Let us consider a steady flow process as I told that most of engineering devices such as diffusers compresses turbine pumps extra operate under steady state conditions right. We can assume that without much so for that what we will be doing, we will be saying that dM dT=0 steady state means you know like there would not be any change you know accumulation of mass it will be coming and going so that and then the mass flow rate at the exit is equal to the mass flow rate at the inlet whatever is entering you know is going out at the and this is equal to m.

And in this problem with particular diffuser and the nozzle we can say there is no work done right, but whereas for the compression turbine we cannot say this is constant okay right, and heat interaction we can say it is what you call constant. Let us say that first law of thermodynamics for a steady flow process what it will be, you know m.T into this term that is your energy total energy minus at the inlet total energy is equal to Q.=W because in this case the if you look at dE/dT=0.

So therefore we are not considering the unsteady terms for the steady flow. And since this m.i = $m._E$.=m. that is from the mass conservation steady for the steady flow, so then we can divide this you know I can divide it by m. here, m. here, and m. here, and m. here, so what I will get, I will get a expression h_E-hi I have taken over this you know this term and there is a change in the kinetic energy right, and this term is nothing but your change in kinetic energy, and this term is basically change in potential energy.

And this keep in mind specific potential energy, this is specific kinetic energy and this is specific enthalpy change you know specific enthalpy change and is equal to this is specific you know like heat and then walk this is basically heat and this is specific heat, and this specific work done. So if I consider that, you know some problem where the change in kinetic energy is zero that means this term will be 0 and change in potential energy will be 0 this term will be 0, so then what will get you will get an expression that is equal to h_E-hi=Q-W right are you getting.

So this term you will be getting is it similar to that your first law of thermodynamics for control mass system yes or no, this is nothing but I can write down you know I can write down that this is basically you can write down as dH = dQ - dW yes or no, I mean this equation is similar to that right. but the first law of thermodynamics for a control for control mass system right what is that that is du is equal to dq - dw it is almost similar right it is not same only things that here it is internal energy this is your internal energy change energy and this is your enthalpy change and the same is a heat and war kind of thing so you can think of using that are you getting right of course this is for a unit mass and this also you can write down as a unit mass I can say this is basically per unit mass will be d u is equal to dq – dw right.

So you should keep this in mind that for a steady flow process the what we call the energy equation of the first law of thermodynamics is similar to that of the for the what you call control mass system except that only the internal energy in the control mass system is replaced by the change in enthalpy that is all okay so now we will apply this equation rather you know for some application let me tell you we are going to take an example where we need to consider the original equation right I will just tell you that.

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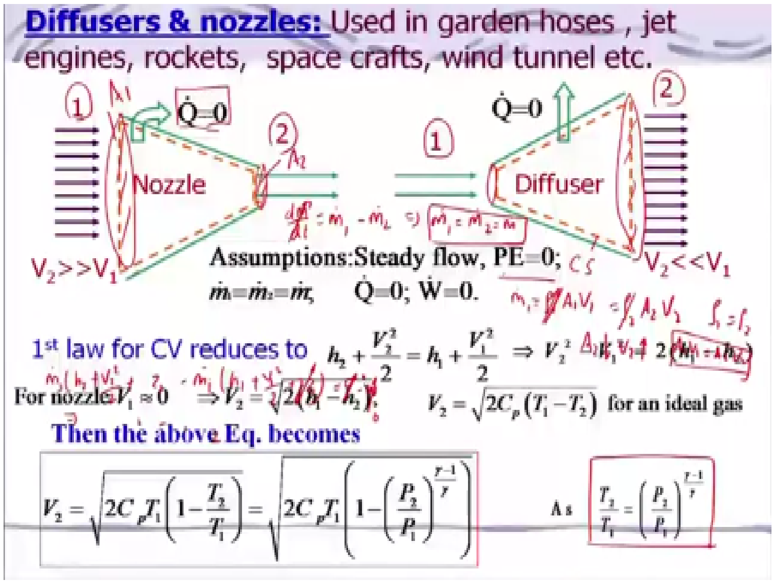

So let us consider the diffuser and nozzles use in your you know like you know nozzles do use in your garden hoses and jet engines rocket spacecrafts who internal several places nozzles and diffusers are being used right you might have you know played with your what you call garden hoses right yes or no because they are you know like suppose you want to you know send the water place for little away from the place what he will have to do right suppose you are putting water here in this and then you want to send to another one meter.

Let us say what you have to do in the host pipe will have to block the nozzle exit yes or no so that what will happen you will when you block the area will be decreasing and then so that your velocity will increase type so let us consider a case of a nozzle what you do like if the fluid is entering with a certain velocity let us say we won this is your station one we are considering and station 2 here and the fluid is entering with a certain velocity V_1 and then when it moves through the nozzle because there is a change in area.

Is higher at the station one and then it is low here you know people look at this is your are across-sectional area then what happens the velocity has increased as I told that area is decreasing at the exit of the nozzle therefore velocity will increase why it is so because we know from the word from the continuity equation yes or no okay we will discuss that and then similarly for the diffuser the fluid will be entering into the diffuser at a very high velocity and then the velocity will decrease because the cross-sectional area has increased here if you look at this is your cross sectional area right and you can take this as a control volume of the you know kind of thing dashed line this is your basically control surface.

You can say right now we want to analyze what is happening I want to find out let us say we will take a nozzle what will be the velocity exit velocity if I know the inlet velocity similarly in the diffuser and then for that we will have to apply the what you call mass conservation equation and then energy equation but what assumption we can do already we have made one assumption that is the heat is what you call transfer during this process when it is a fluid is moving through the nozzle is 0 why because the velocities will be very high and so that the residence time will very low to have this.

You know heat transfer to take place and we can assume similarly and is there any work done by this because there is no shaft work right so the work done will be 0 right so also the heat interaction will be 0 and the change in the potential energy if you look at because the elevation is almost similar in nature so we can say that the change in potential energy is 0 and for the steadiest flow process we have seen that you know why this vertical mass conservation equation them by dt is nothing but you m.1.

In this case – m.2 this is equal to 0 so therefore m.1 is equal to m.2 is equal to m. right and what is that M mass if you consider that is nothing but your mass flow rate that will be mass flow rate if I consider one is equal to rho 1 A_1 V_1 right that means rho 1 as a density a1is a cross-sectional area if I consider this is the cross-sectional area this is nothing but your A_1 and this area is A_2 right so is equal to Rho 2 A_2 V_2 if I consider that density is same not changing so what will happen this can be cancelled it out right if I am assuming row 1 is equal to rho 2.

So therefore I can write down A_1 A_1 V_1 is equal to A_2 V_2 if there is a decrease in the area A_2 is decreased so what will happen then V_2 in V_2 in what will happen increase if A_1A_2 is decreasing V_2 will increase so therefore you are getting higher velocity in case of a nozzle and diffusion just oppose it okay so now you know whether if you look at assumption wise we have you know assumed that change in potential energy is 0 can I say change in kinetic in a 0 I cannot afford to because you know we are either increasing velocity or decreasing the velocity so that we want to know so therefore and also it is will be very high at all right so we cannot really this thing and then we will apply the first law of thermodynamics and what you will be getting will be getting enthalpy at the station 2 + the V_2^2 divided by 2 is equal to h1 + V_1^2 divided by.

How we are getting this any idea right we have already seen that you know if you look at equation wise and this is a steady flow passes so therefore in this case it will be to S_2 + V_2 square by 2 + Z Z_2 - mi so 1 here one here into h1 + $v1^2$ by 2 + Z_1 Z_1 is equal to q - w so this is 0 this is 0 and this is neglected so then what will get you will get this expression that is & M_0 if I can divide this you know is equal to I can write down s2 + v_2^2 by 2 is equal to h1 + $v1^2$ by 2 so this is the expression we can get and we got that thing right.

So and so that we can write down this basically equal to $V2^2$ - $V1^2$ is equal to h1- s_2 so therefore we can say that this is basically if I say this V_1 is very small it is 0 so V_2 is equal to root over 2h 1 - s_2 and for an ideal gas you know like what we can write down is V_2 is equal to root over 2 CP T1 – T_2 right for the ideal gas we can say so the above equation becomes that is V_2 is equal to root over 2CP and T_1 I can take a bracket in the 1- T_2 by T_1 and if I assume the flow to be isentropic right.

Then I can relate this temperature T2 by T1 with respect to pressure by using the isentropic relationship that is T2 by T1 is equal to P2 by P1 power to the γ - 1divided by γ so that I can put It here and do that and in this case if you consider that it can be considered as an isentropic provided you know you assume there is no friction there is no friction you know on the wall right which is very unlikely but however we use this you know think for the isentropic considering item isentropic flow for the analysis.

Because of simplification and already we have assumed that heat loss you know from the system is 0 right so now we will take an example.

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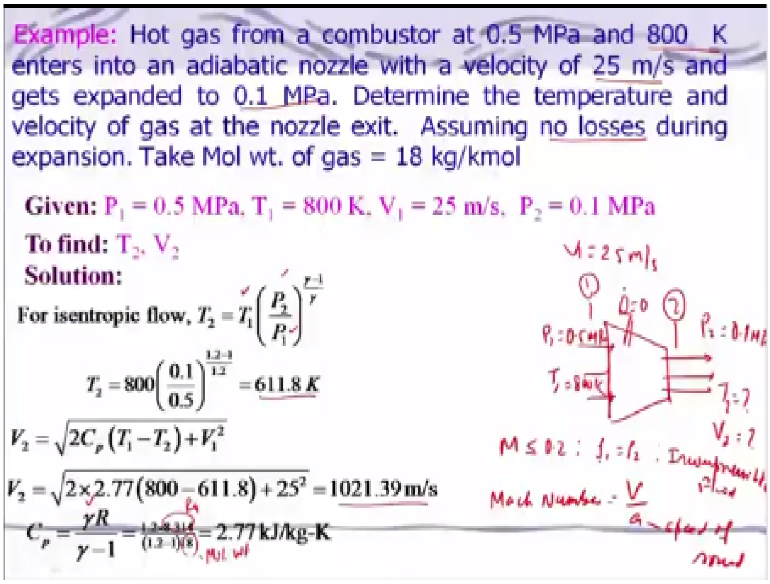

Like to how to compute and how to use this equation let us say hot gas from a combustor at point five mega Pascal you know like and 800 Kelvin enters into an adiabatic nozzle, adiabatic nozzle means there is no heat transfer from that nozzle we are saying with a velocity of 25 m/sec right, and gets expanded 2.1 mega Pascal's basically atmospheric pressure determine the temperature and velocity of gas at the nozzle exit assuming no losses during this expansion process and of course we can take a molecular weight of gases 18 kg/ per kmol.

So if you look at what are the given is the P1 so if you consider the nozzle you know let us say this is a nozzle where fluid is entering and leaving at a very high velocities and this we want station 1 and v1 is 25 meter per second and if you look at this is basically P1 0.5 mega Pascal and T1 is 800 Kelvin and this P to this is your station 2 P2 is 0.1 mega Pascal and I need to find out T2 and I need to find out V2 right, so this has to be found.

So what we will do we will have to apply the what you call the relationship what derived just now and we are assuming the flow to be article isentropic because it is already given there is no losses right and also given as the adiabatic that means this thing is 0 right, so therefore we can assume to be isentropic for isentropic flow we know T2 is equal to T1 P2/P1 and P2 is given to you what is that that is 0.5 mega Pascal, P1 is given so that is your 0.1 and T1 is given that is also and then γ is given so you just substitute those values and find out that you find that it happens to be 611.8 Kelvin it is reduced you know right.

And we can now find out the velocity we will find out to $V2\sqrt{2CP(T-T2)+V1^{2}}$ keep in mind that we had neglected in the last derivation that V1 is you know small or 0 so therefore but here we are we have retained it so that from the energy equation we can get and you can but now question arises how to evaluate this 2CP and we are saying this is the ideal gas that is an assumption we are making and from that we are finding out CP is equal to $\gamma R/\gamma-1$, γ is given and then we know this R is basically specific gas constant that is Ru, Ru is given here Ru and molecular weight right.

And you just substitute this value you get 2.7 kJ/kgK and then you know like put this all the values you here you know 2xCP values 2.77 and the T1 is 800 Kelvin T2 is 611.8 and 225 meter per second v1 you will get 1021.39m/s. Suppose I will assume that you know there is not much effect of this inlet velocity which is 25m/s because the exit velocity is 1021.39 m/s which is quite vertical high as compared to the inlet velocity right.

So if I you know assume that to be neglected then what kind of error I will make that you take is you know you can calculate that find out that error would not be much number one, number two if you look at velocity is very high right, now we have you know like consider that the flow the you know I did not mention that when the that we talked about the density at the inlet and the exit is same I have a signal in the when we are talking about mass conservation equation right, yes or no.

But actually here the velocity is very high right, whether it will be you know I can assume this density at the inlet and exit of a nozzle to be same provided it is incompressible fluid if it is compressible fluid then we cannot okay, are you getting my point. Now how we will know whether it is a compressible fluid or not for that you need to of course go for compressible factor from that you can find out the speed of sound right, and then you will have to find out Mac number you know like Mac number if you look at if I say this Mac number is equal to V/a a is the speed of sound right.

And if Mac number is very, very low then we call it as an incompressible bit around point to you know like kind of things then only we can you know say that density at station 1 and is equal to the density a station that means when M is you know less than equal to 0.2 right, I can say that $\rho 1$ is equal to $\rho 2$ because incompressible fluid right, fluid. But if it is more than that it is a compressible fluid where you cannot assume that ρ1=ρ2 you will have to take care of that density of fact right.

So you know that depends upon the, if you look at we have taken very simple example complexity of the problem also increases as you go on and kind of things.

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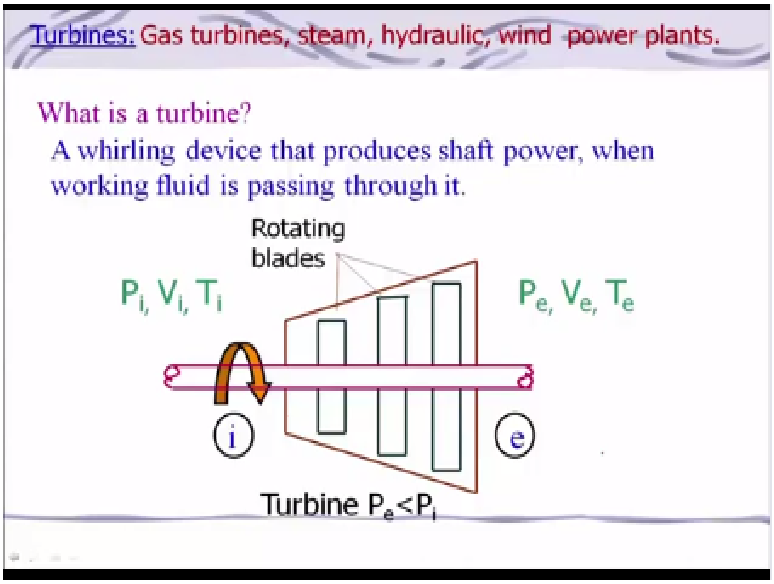

So let us look at how we will handle the gas turbine you know like if you look at turbines there are several kind gas turbine, steam turbine, hydraulic turbine, wind turbine you know like where we generate power and power is very important in your life particularly in modern life to have a comfortable life you know, so therefore but what is the turbine? Turbine is basically a willing device that produces shaft power when working fluid is passing through it.

As I told that you know like a turbine will be having several blades rotating blade, stationary blades and it should be designed properly you know so that you can extract the work from the fluid which will be you know at inlet of let us say entering at PIV I and TI and leaving with Pe, Ve and Te and then that power has to transfer to the shaft and then you can utilize that power mechanical power basically we are getting the what you call thermal power is converted into mechanical power here and you know like we will be also trying to handle the compressors.

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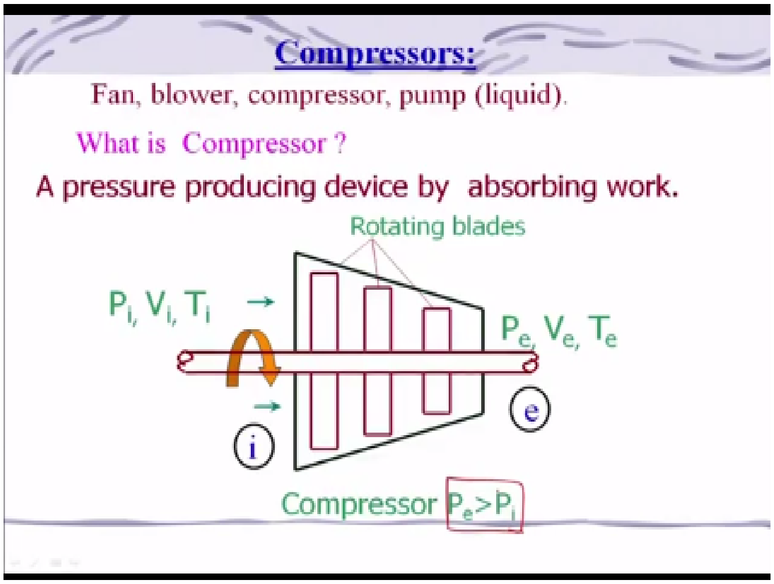

There are various kinds of compressors are there you know like okay what is the compressor, compressor is basically where you will be compressing the fluid so that is pressure will increase right, so if you look at your ceiling fan or the table pan whatever we use in summer can you call it as a compressor. Similarly let us say you know like there will be a blower you might have seen in your hostel it is there in you go to your keychain you know there is a blower right, you have seen that so if you have not seen you just see there is on the top there will be a blower which will be to suck out the hot gases and other things.

So compressor there and there is a pumper so whenever we use liquid we call it as basically the what you call a pump. Now the compressor if you look at is a pressure what you call it is a pacer producing device by observing the work in the turbine in case of a turbine the turbine will be producing the work okay, in this case this will be consuming work and then producing the pressure there the pressure you know will be what you call energy will be used to the produce the work.

And as I told there will be fan blow air compressor pump there are several kinds we use left and right in industrial applications so this the schematic looks like that it is having rotating blades and stationary blades not shown in this figure and it is you know like where pressure exit pressure is greater than the inlet pressure right, exit pressure is greater than the inlet pressure. And in the turbine it is other one exit pressure will be lower than the inlet pressure so how to handle these problems that we will see.

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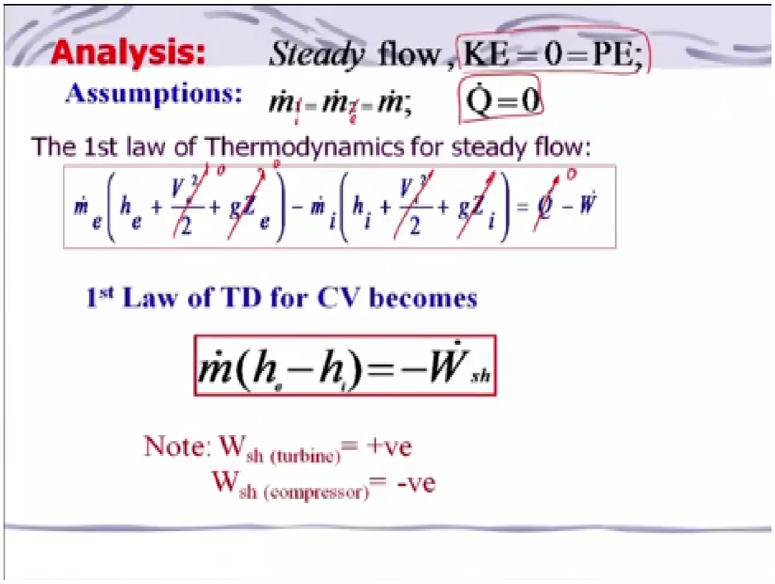

So what are the assumption will be making will be making this compressor all the turbine you know any one of them like is operated and under steady state condition that means the steady flow if it is a steady flow then by applying the mass conservation equation we can say the mass flow rate at the inlet or the one station is equal to the mass flow rate at the exit at the station 2 is equal to the mass flow rate and we are saying the change in kinetic energy and potential energy is 0 but not all the time okay.

We are just making assumption and the adiabatic system no heat is going out actually it will be dissipated during the either the compression work or the expansion work in a turbine in a compressor and turbine respectively. So first law of thermodynamics for a steady flow process we have already seen this expression right we have seen, so we can apply that what we will do we are basically saying this change in kinetic energy is zero.

So this is basically zero potential energy is zero right and this is zero because of adiabatic in nature right so if we look at then we can write it down as an expression m dot e h e minus H I because we have seen m dot 1is equal to m dot 2 is equal to m dot okay, so and keep in mind that this I am using basically inlet and this is exit okay one and two corresponding to inlet and exit so therefore it comes up work.

So this is the equation for what you call either compressor and turbine keep in mind that in some places we cannot afford to you know make this assumption what we have made see this assumption may not be valid okay, that we will see an example and see that and the what you call the shaft work is basically will be positive for a turbine because it is done by the control volume right and work done what we call input to the compressor is negative because it is you know you are giving externally to the controller so therefore that is will be negative.

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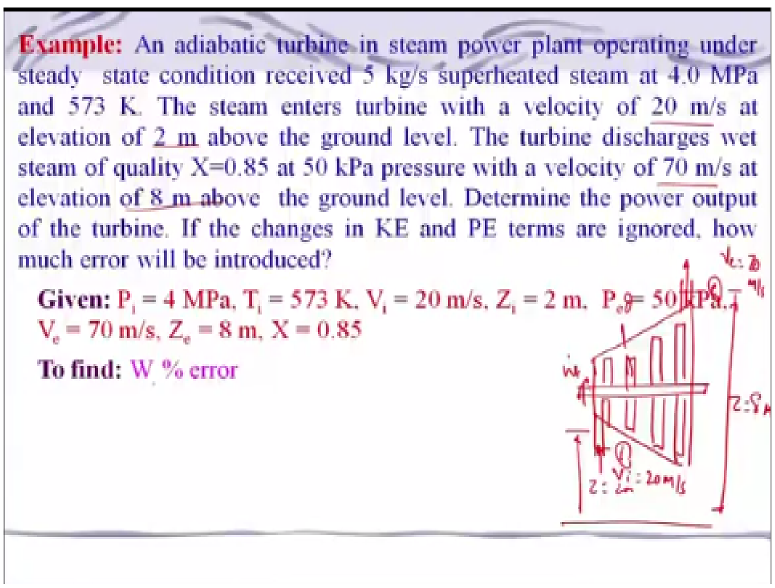

And let us take an example that an adiabatic turbine in a steam power plant operating under the steady state condition received five kg per second superheated steam at for mega Pascal pressure and 573 Kelvin temperature and the steam enters turbine with a velocity of 20 meter per second which is a very low at elevation of 2meter right and above the ground level and the turbine discharge the weight steam of quality x is equal to 0.5 at 50kilopascal pressure with a velocity of70 meter per second at elevation of 8meter per second above the ground level.

So if you look at there is a water color let us say this is your turbine there is a blades you know there is a SAP to work and this is zero and there is a inlet here let us say you know and from the elevation if I take you know this is something Z is equal to 2 meter at the inlet this is my Inlet and there is a exit and this is exit is what Z is equal to 8 meter okay, and this V exit is 70 meter per second and V inlet this is exit we inlet is 20 meter per second see in our problem or in the derivation we have neglected that change in kinetic energy and change in potential energy and derived.

But nowhere the data is given we need not to you know neglect it but we will have to see if we will neglect what will be the error that is the being asked how much error will be introduced if will neglect this you know so these are the data I have already mentioned about it and the pi is given for mega Pascal TI 573Kelvin and VI 20 meter per second Z 1is 2 meter per second and other things like a steam entering you know at x is equal to quality is point eight five and we will have to find out the work done and percentage of error if we now we will neglect or the terms kinetic energy and potential energy.

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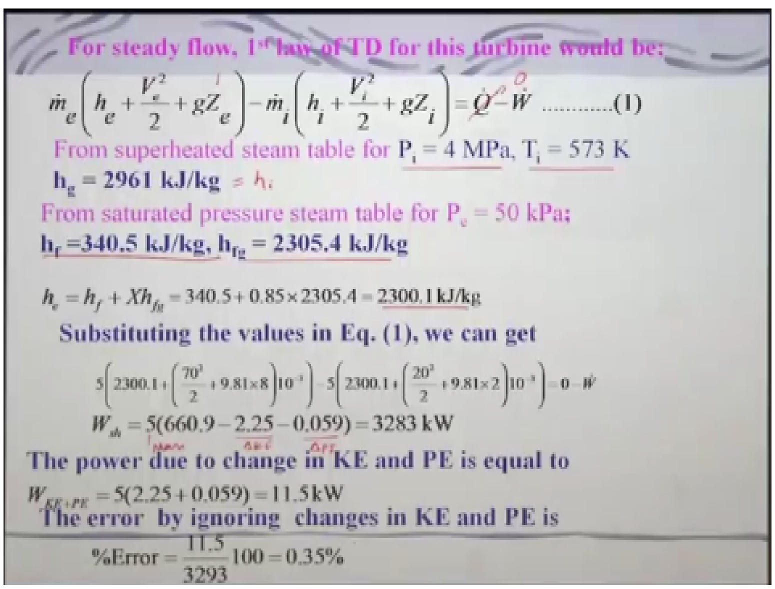

So and for this turbine problem we can apply the first law of thermodynamic considerations hast law of thermodynamics which is consists of the total energy term including the flow walk and the heat and the work interaction so what we will do we will basically take the data and from the superheated steam table at pressure pi/4 mega Pascal's and Ti 571 and that will get the enthalpy as 296 one kilo joule per kg and keep in mind that for the steady flow equation we had neglected the kinetic energy and potential energy term but here we are keeping the same.

However we will be what you call you know make it a 0 this term because it is adiabatic you know turbine, so let us then we will have to get the data from the saturated pressure steam table that is the exit pressure of 50kPa and that is HF is 340 point 5 kilo joule per kg and h FG is 230 5.4 kilo joule per kg and we know the quality of the steam which is you know at the exit of the turbine.

So that is 0.85, so we can find out from this data right and this enthalpy data’s responding to 50 kilo Pascal's we can evaluate the enthalpy at the exit that is HF into X this is the quality into enthalpy hfz and if you just substitute those values we will get something 23000.1 kilo joule per kg keep in mind that this enthalpy HE is between the hf and h FG because the quality is 0.85 that cross-checked one has to do while solving a problem sometimes you may make some mistake.

And what we will do we will basically substitute this H E and H or to call I which is a G is equal to H I and then what we will do we will basically we know the velocity is given to you we exit that is a 70 meter per second and JD is given to you that is something 8 meter and VI is given 20meter per second and Jed I is given to meter per second substitute those values here in equation one and then you can find out the shaft work as basically three to eight through three kilo watt.

If you look at this term is very, very low this corresponding to the kinetic energy change in kinetic energy term and this is corresponding to change in potential energy of course this is your mass now this is a quite a bit power being generated by this turbine now we need to find out what will be the error if we will neglect the change in kinetic energy and change in potential energy is I mean almost zero kind of thing.

So for that power due to change in kinetic energy potential energy can be evaluated very easily like taking this change in kind of 2.25 and change in 0.059 x 5 it is coming around to a 11.5 close which is very, very small as compared to 3283 kilo watt, so percentage of error if you calculate you will get basically percentage error is equal to 11.5 / 3293 in 200 this amount to be something 0.35 percentage which is negligibly small you know right.

And therefore we always neglect you know this term but however if in your problem it is given that you will have to evaluate please do that okay, so I mean we have seen why we are neglecting the kinetic energy and potential change in a turbine or compressor problem or any other problem also we can neglect provided it is a small quantity we will discuss some other applications of the first law of thermodynamics in the next class.

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