Engineering Thermodynamics
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Lecture – 37
Applications. Problem Solving: Nozzle. Diffuser. Expansion valve. Pipe/duct flow.

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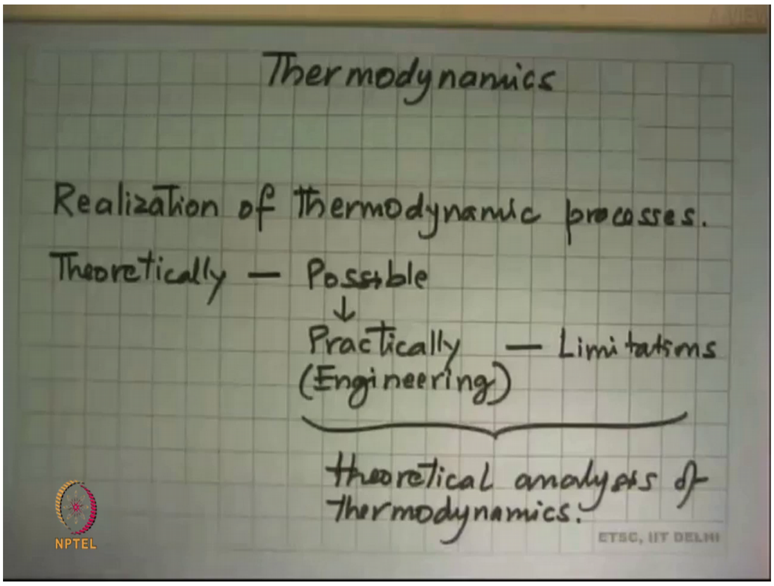

Good morning, this is the second lecture of the 4th module. And let us recap what we did yesterday. We started looking at several devices to which we do thermodynamic processes, and those devices were selected, because that is what we have in real life that if we need to make a machine, we would make combinations of those and put it together.

So, theory tells us that there are lot of things possible. In practice, there are some things possible and on that also there are certain restrictions in their use. So, we will continue with that, and then we will look at how we can use all of that knowledge of what is possible, what is theoretically possible, but what is practically realizable. And then we will look at how we can what the closest one can come to creating a Carnot cycle. After that we would have also gained experience in saying that if these are the devices on which I want to make a solution or a problem is given, what is the way in which we go about solving it.

And so the first part of it is what we have now done. Tomorrow, I will take up examples, where we will start actually putting some numbers, and see a variety of problems over there. So, this is what we have been looking at, realization of thermodynamic processes, what are the types of devices that we have. These are theoretically impossible. And practically from the world of engineering, there are limitations. And what we have done is given with those limitations, we have seen what are the implications of both limitations on the thermodynamic performance of these devices.

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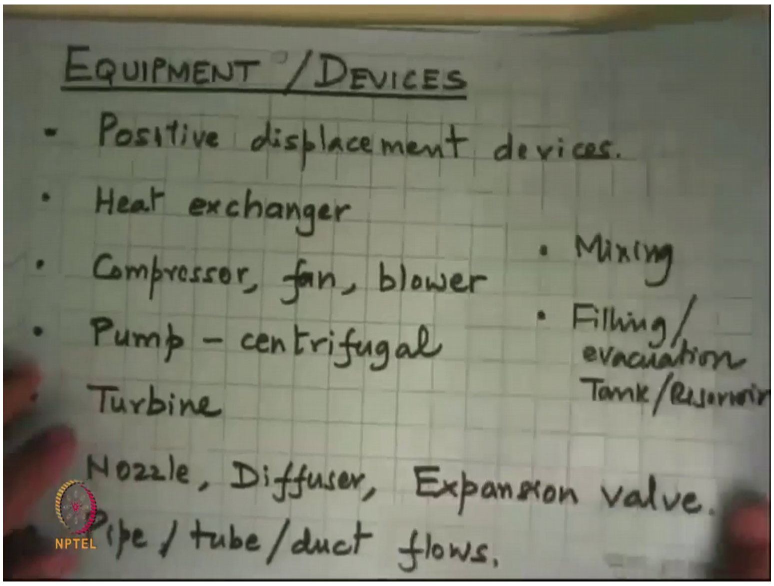

So, yesterday we looked at these devices, a positive displacement devices in particular something that keeps coming up, and we will look at it again a similar piston arrangement, closed system in which as working substance and various things. Then we look at the idea of what the heat exchanger, and we learned that a major assumption, we make in heat exchangers is that heat transfer processes, what they are flowing through a tube the fluid there assume to be constant pressure processes, so that is possible.

Then we looked at compressors, where we take an ideal gas and increase a special relatively in large amounts and fans and blowers, where the pressure raise is relatively small, and flow rates are high. And both pv set are work input devices. And in the ideal case, we said that this would be a best isentropic. And you also saw that the way we get these machines, we do not add heat into these devices. In reality if it is running about temperature, then we have a little bit of heat loss from the surface to the ambient air.

Then we looked at pumps, it said these are devices that take a liquid, and pump it to a higher pressure on a continuous basis. So, here is also work input is there, and we said that the ideal case for isentropic like the compressors fans and blowers. And what will be the real case, where this entropy increases. And we looked at the last machine class yesterday was the turbine, and looked at gas turbine, we looked at steam turbine, hydro turbines, and we said these are work producing devices.

And the most efficient way that we can get them thermodynamics tells us that they should be an isentropic process at these turbines. And we said that if this were real machines, when there is some irreversibility in the flow, then operating between the same pressures, what does the process look like. So, these were the things we looked at.

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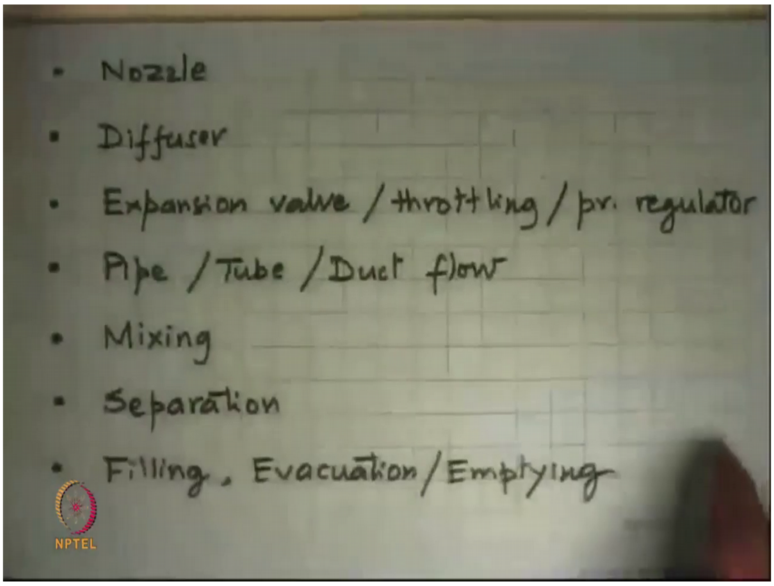

So Today, now we will look at another list of a thing, we will continue some of the side put up the yesterday will now look at a nozzle, then we look at the diffuser, then expansion valve or something in between takes place a pipe tube or duct flow just to plain flow. Then they look at mixing mixing of the same substance not mixtures of two different substances. Then we will look at separation particularly in a wet region. And finally, we look at unsteady processes like filling or evacuation, and emptying of a tank or a reservoir.

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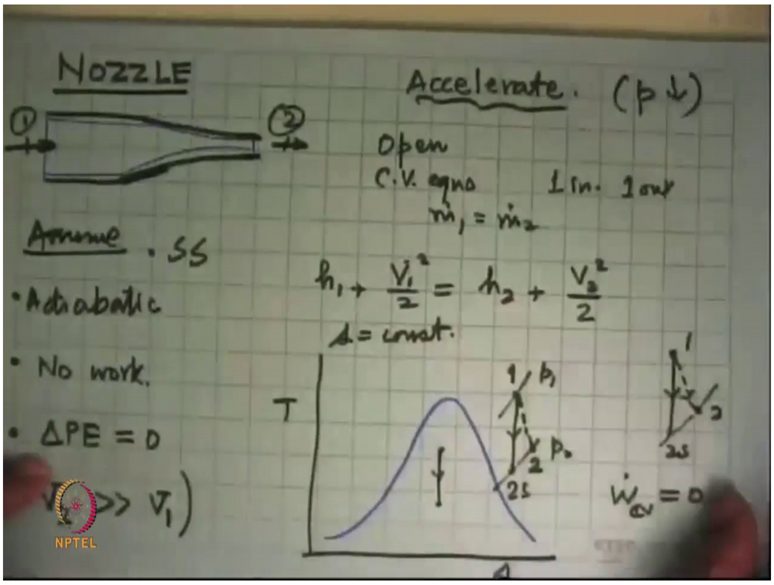

So, let us start with the nozzle. So, this is a device, which accelerates a fluid in the process the pressure drops. And a typical sketch of this would look like this in which the working substance enters here, and exit over there. And we make this as a system saying that the system boundary is everything that is inside this nozzle, and in that we apply various laws.

So, once you make the system boundary, we see that there is something moving in here, something moving out. So, our first step in the analysis is to decide, whether it is the body of the system boundary, we did that because is a open system or a closed system, this is an open system. And then whichever now I have to apply equations, which are the control volume equations. We have one inflow and there are one out flow. And that tells us that this is state 1, we call this state 2 that m dot 1 is equal to m dot 2, and then whichever what does the energy equation tell us.

It tells us that in this case, we make the important assumptions there that first it is a very very small device, and we try to insulate it if possible. So, this is adiabatic. There is no heat transfer, during this process. Then we also say that there is no work transfer happening across this, so there is no work and until, so there are the things are happen. But, the size of this is relatively small so that means that we can simply assume like delta change in potential energy is 0.

And the very first assumption, like we did yesterday in all the analysis steady state that means, nothing changes with time. So, we said delta PE is 0, but because this is the device that accelerates a fluid, there is no why we can assume that kinetic energy changes are small.

So, in this case what is here is that V 2 the velocity is greater than the inlet velocity which is V 1. If one of these value will given say V 1 is given, then we do not need to make this assumption, but the important thing then becomes that if we solve the energy equation and simplify, then we get h 1 plus V 1 square by 2 is equal to h 2 plus V 2 square by 2, this is what we get.

If V 1 is given, and the conditions states 1 and state 2 are known, then h 1 and h 2 are known, we can calculate V 2, so that is the analysis of a nozzle. And this does not matter, whether it is an ideal gas or vapor, the processes are the same. And you have to show it on a T s diagram. If we are looking at something which is in the wet state like that, then a nozzle ideally would be without any irreversibility's, so this would be s equal to constant or an isentropic process inside this.

So, if the initial state is there, you can say that ideal case it comes down to this pressure, so this was p 1, this is p 2, and this is what the nozzle would do. A real nozzle is isentropic part, a real nozzle would be irreversibility's, and it would come this part. We would have put a nozzle there also, and accelerated to fluid there. If you are far away from this dome in the ideal gas region say somewhere here, then also it is the same thing, this is 1, this is 2, and the gas is accelerated. If there are irreversibility, that gas will then reach this point. This dome will not appear, but this is the process.

So, the process actually looks the same as that of a turbine, but the difference is that in the case of a turbine, there is work output in this case w dot c v, the work output or input in this this is 0. And the drop in enthalpy goes to increase the velocity at the outlet. So, the such devices are used in turbines compressors and many other applications that you want to isolate the fluid and get some benefit out of that, so that is a nozzle.

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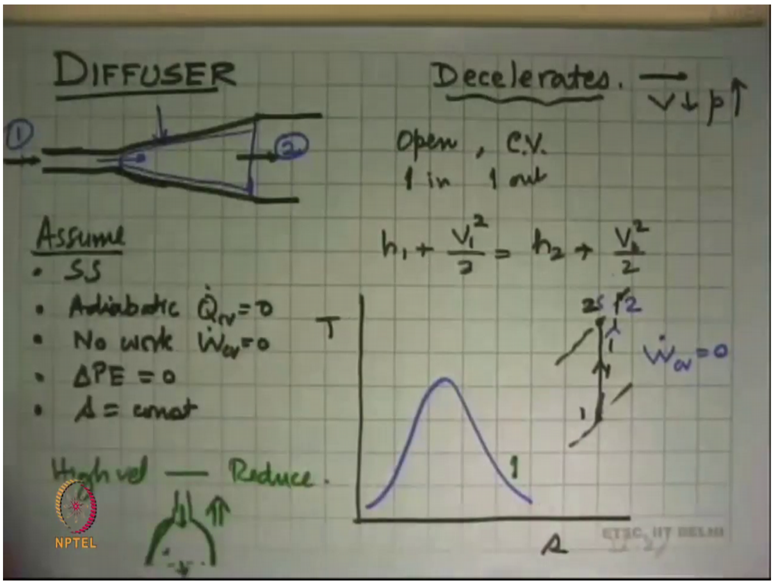

And the opposite of the nozzle is what is called a diffuser. So, generally look at what is the diffuser now. So, this is a thing which decelerates the fluids that means, in the direction of flow, the velocity goes down and pressure goes up. So, what is happening here is that we have a flow coming in, and then there is the area opening up, and the flow goes out over there.

So, we say that the diffusing part is the one, where the area is large. So, we said this is our diffuser control volume. So, this is a system boundary you can say, and there is one in flow taking place here. So, this is state 1, in flowing to the system. Out flow is there, state 2. So, with that we put thing together, and say that first this is an open system. So, we have to apply the control volume approach, and we use the flow equations that we have developed, this is 1, this is 2, entry and exit.

Again like a nozzle, here also we assume something first steady state. The second assumption is that there is no heat transfer, so this is adiabatic Q dot c v equal to 0. There is no work W dot c v equal to 0. And changes in potential energy, these are very small is there, but because the primary job is to decelerate a fluid, it means that velocity changes are substantial that is the main purpose of the device. So, kinetic energy change being 0 is not a assumption for the diffuser.

So, there is one inflow, one out flow, and the equation energy equation becomes exactly the same what was there earlier or the nozzle, this is v 2 square by 2. And so in the direction of flow, the enthalpy will change and you have decrease in the velocity. So, if you plot it on a T s diagram, if it is an ideal gas, they will be a state there. It is ideal case, if we assume this is that s is constant isentropic. So, it starts from here, and it will go stay there state 1, state 2.

If it is a real case, and this is the isobar, this is the isobar here entropy has to increase, so this will go over there. And you can check from the T s diagram that what it means is that this it has been taken to same pressure, but now the temperature has gone up. So, this was two isentropic, this is the two real cases. The process looks very similar to that of a compressor, but the difference is that here work transfer is 0. The only change that enthalpy difference does is because of the velocity change that is the difference.

And if you were near the dome, same thing would happen that if you have initial state is over there, then you would like to bring it up there, and increase the pressure here, so that is what diffusers do. And you use diffusers in places, where you have very high velocity which you want to reduce. And one of the place, where such a device is use is the exhaust of a turbine, where as the gas goes through and expands its velocity also increases, but we cannot increase the area so much that the velocity can be kept low.

So, what happens is the exit velocities are high, and then we do not if you want the kinetic energy to be recovered for some purpose, we can then put a diffuser there, recover some of that energy, and then through the gas vapour. You will also see this in rockets, where at the bottom you will see a device looking like this. When you got high velocity fluid coming in, low velocity fluid goes out in the process the pressure increases, and this is what generates the trust on rockets. So, this is a very important part in the design of propulsion systems.

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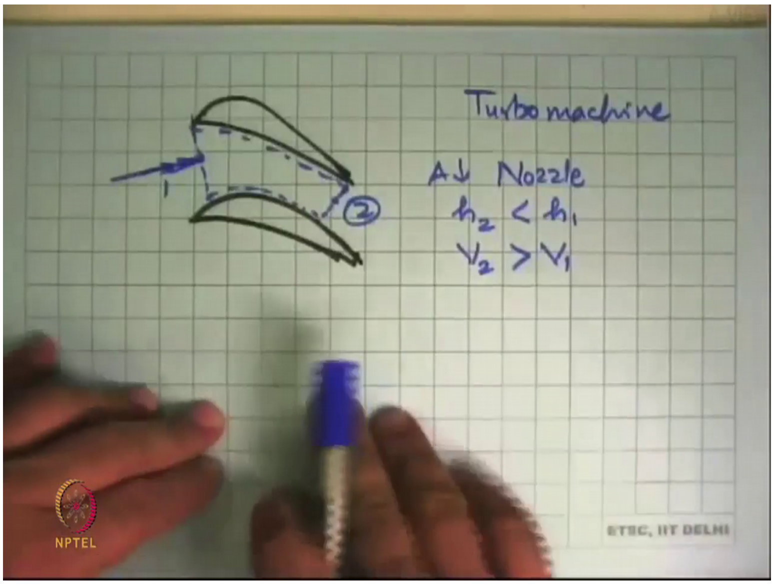

The way we achieved nozzles and diffusers, although I have drawn it here as a pipe in turbo machines, we achieve this as making a asset between two consecutive blades. So, if it look at two blades, and we draw the shape there like this. So, this is a one blade, and this is a second blade, then the purpose of this is that as the gas or the steam flows through this. We take this as a system here, and what I have drawn is a blade of this cross section which is normal to the plane of the paper, and there are many such things on a shaft.

So, they make a circular thing, it looks like a turbo machine rotor or the nozzle. But, the thing is that when this enters here, it sees this much area, normal to the paper, the height is the same. So, this is the inlet plane. At the outlet, this has decreased. So, these two things together produce a flow passage, where the area decreases. And this would mean that this would act like a nozzle that will accelerate the fluid, so between this inlet state 1, and the exit state 2. h 2 will be less than h 1, and the velocity at 2 will be greater than velocity at 1, so that is what one does in turbines, where we have high pressures say steam or gas decelerated.

And then we pass it over or rotating set of blades which imparts momentum to it, and that is what causes the power output from a turbine. The opposite has done, when we look at compressors. So, you have the same shape, but now you are putting in from this side and you decelerate the fluid. So, this is the realization on turbo machines. The idea is that we create passages, it does not necessarily have to be concentrate, it does not have to be straight, it would be of any shape, and you can get this type of performance from this (Refer Time: 17:10) device.

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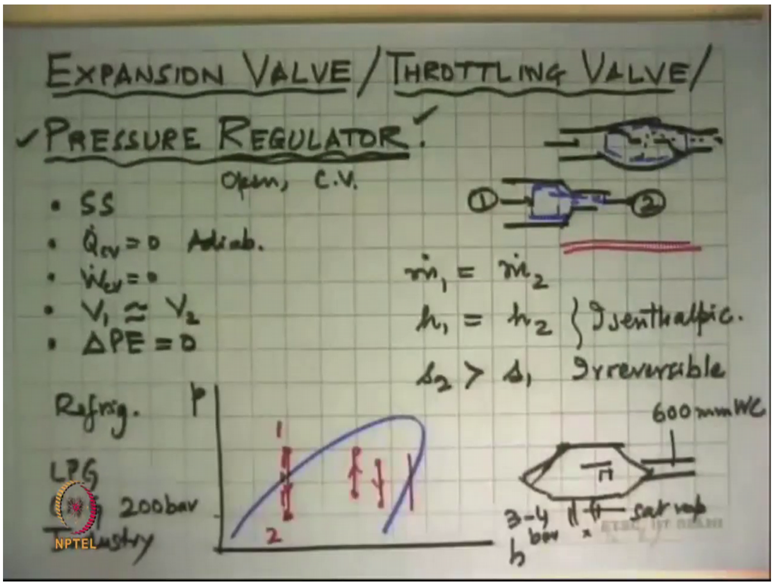

The next thing we are going to look at is a device, which we call something we call the throttling valve, but some plays also known as an expansion valve, and popularly we also see these as pressure regulators. So, all of them in construction would be slightly different, but in all these cases what we have done is that we just have a small cost construction in the flow.

And this flow could be passage through a valve, which means that there is a body into which it enters from one side, and we have a small construction there. As the fluid goes through this, there is a big pressure drop, and that is all happens over at the outlet, this is a small device. So, what one does is that we assume that this is a steady state system, the control volume would be like this or in this case, it could be like that.

And here we have something coming in going out, this is state 1, this is state 2. So, this is an open system, and we have to apply the control volume approach. We assume that it is steady state, there is no heat transfer. Adiabatic, there is no work transfer. It is just a simple stationary device nothing moving, then we also say that here velocity at the inlet and outlet are comparable, they are not very drastically different. So, it is not like a nozzle in any sense. And of course, it is a very small device in most cases, and we can say that changes in potential energy are 0.

So, the conservation of mass equation tells us that m dot 1 is equal to m dot 2, and the conservation of energy tells us that h 1 is equal to h 2. And so this type of a process is isenthalpic, inlet outlet enthalpies are the same. But, what we have done is we had a higher pressure higher temperature here, we got them at lower pressure on the outside.

We would know from the second law analysis that s 2 is greater than s 1 throttling is a hugely irreversible process, which would also mean that you would like to avoid it as much as possible, but then there are certain practical aspects of the throttling process which are very very nice, and where do we see throttling taking place.

Firstly, you can see that in all their refrigeration cycles, where what we have done is that is the ph diagram, and on this we can plot the dome. And after sub cooling the liquid from the condenser, we have to bring it down to this pressure. One option is that let us put a small turbine, generate some work and come to this state. Entirely, possible thermodynamically, it is nothing can be is it is entirely feasible.

Practically, for the size of the machines that we have refrigerators, and air conditioners at even large of devices like central air conditioning plants. The work output of this will be so small, the machine is complicated. And second somewhere it is handling a liquid, somewhere it is handling liquid plus vapor that makes the machine very very practically impossible to make in the engineering world.

So, we do not have work transfers taking place like this. And as we saw with turbines in general and pumps, we do not want any work producing device that operates like this or operates like this or there or there. We want work producing devices to either handle only a vapor or a gas or only handle a liquid not mixture from of these two such machines cannot be made ok. So, in the refrigerator, we cannot put a turbine. The second option, we just learned why not put them nozzle, we can accelerate it, it is an isentropic process. But, the trouble is that by the time you drop the pressure the velocities are so high, it becomes difficult to manage the machine.

So, the next easiest thing one does is to just throttle it. And throttling is the irreversible process, we do not know exactly what happens in the intermediate states, but it brings us from there to there. And that can be done either through a valve what we put it put the refrigerant suddenly throw a very very narrow tube, where there is a very large pressure drop that is all it does. In the process, as sub cooled liquid becomes a saturated state and the wet mixture that you get here, so that is what we use throttling for in all refrigeration systems.

The second application that you would all have to actually seen is your LPG stove. Here on the top of the cylinder, you have a small device something looks like this. And this is sitting attached to the top of the cylinder, and from one side of this, there is a tube going out, that is the pressure regulator we does that we cannot use the LPG regulator, what it does is in that there is a very small opening over here, which is controlled by an automatic spring device which senses the pressure over here, it senses the pressure over here.

And depending on the difference of the pressures it adjusts the position of this, so that inside here which is saturated vapor at the 3 bar, 4 bar something like that that is reduced and brought down to a pressure of 600 millimeters of water column that the throttling process. So, we are just throttled it from say 3 bar or 4 bars, somewhere in there to 600 millimeters of water column that is how much lower pressure.

So, this is a very small opening like a millimeter in diameter or so through which this vapor passes, there is a lot of friction that it goes. And it pressure drops, but enthalpy remains the same, there is not much change in velocity, potential energy changes are very very small and you get constant pressure over here. So that is the device of this, and that is why it is called a regulator that no matter how much gas you are using, whether your gas on low flame or on high flame, this will always put out by adjusting itself 600 millimeters of water column pressure here, where it begins to have a problem, in fact when the cylinder is getting empty, and the liquid is all gone.

Then 3 bar pressure as you keep drawing the gas, we start decreasing in which case after some time this regulator cannot do its job, this pressure begins to fluctuate. And you see that the stove is now giving an unstable flame, and that is a good indication that cylinder is about to go empty.

So, pressure regulator is another very important device not just here in LPG, but you can see any machine which operates on CNG as CNG operated bus or auto or rickshaw or taxi, cylinder pressure is 200 bar cannot put that into the engine. So, there is a pressure regulator maybe 1or 2 state pressure regulator, they are bring it down from here pressures could be as high as 200 bar, and brings it down to again something like this pressure few 100 millimeter (Refer Time: 25:06) of water column.

So, these are also used in industry, there you say that I need to help say steam coming into a device at 10 bar, but your supply comes anywhere between say 11 and 13 bar, you always give some margin there. And so you do a small amount of throttling so that outlet pressure is always 10 bar to the device that you want. So, these are very commonly used because of this very precision movement inside this, these are very very sophisticated devices.

And the engineering of this is quite a challenge, but the fact is that these are commercially availables and lot of these available for many different applications, and they are used very frequently in process industry ok. So, this is the idea of throttling valve or a pressure regulator or an expansion valve, it need not even be evolved as I mentioned in refrigerator, it could just be a long very thin tube. So, which are the refrigerant goes because of the frictional pressure drop, it achieves the purpose of throttling ok, so that was what happens in a pressure regulator or an expansion valve.

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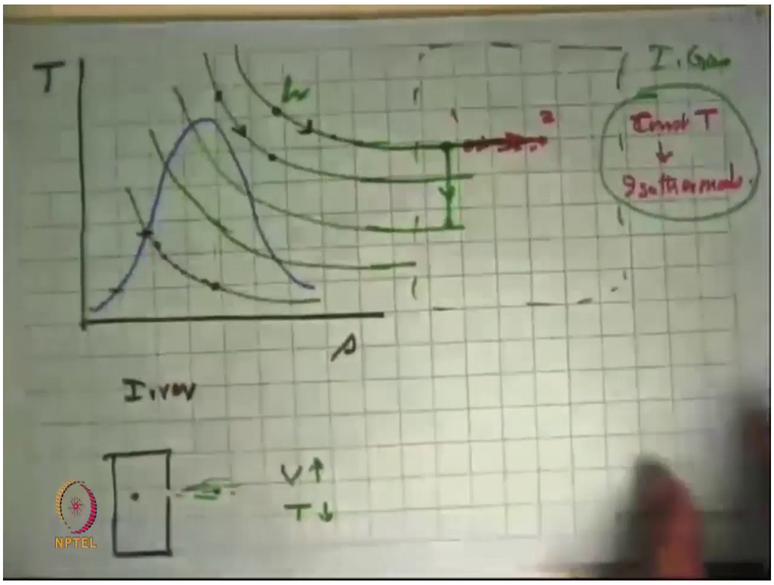

And it is a hugely irreversible process, so I have to show this on a T s diagram. And the saturation dome is say somewhere there, the constant enthalpy lines, they run like this.

These are constant enthalpy lines. So, the throttling process on the pH diagram which looked like a straight line say between this pressure and this pressure, it will actually follow apart and come finally to this state. So, this would be a throttling on the T s diagram in the case of the refrigerator.

But, if you are throttling superheated steam, then it could come from there to there or maybe there to there. So, in a every case it goes only in one direction, it is an irreversible process, so the opposite process is not possible unlike say nozzles unlike diffusers, turbines, pumps all of those ideally we assume to the isentropic process which means that we could exactly do everything in the opposite side, and run it in the other mode. Here it is not possible, this is usually irreversible.

And the only other thing that comes out to be interesting is that the constant enthalpy lines further away become constant, and so this region which is the ideal gas behavior. These lines are constant, which tells you that if you throttle an ideal gas from there to there, this should be a dotted line so irreversible process. Throttling is a constant temperature process isothermal, and that means that is only when the velocity changes are very small.

Other examples of throttling is like you suddenly let out steam from a pressure cooker or there is a puncture in a tire. So, what you have there is a say a vessel or a device which has a very small opening, and through which the fluid is leaking out in this case. We all know from experience that if a air leaks out and comes out here at high velocity, it also feels cold that means compared to this the temperature has freezed.

So, this is opposite to what we have just seen over here, and the reason why that happens is that here velocity has increased quite a lot. So, there is part of it has some of it is like a throttling process, some of it is like a nozzle. In a nozzle if you increase the velocity of a gas, which would happen here to there, you could see a drop in temperature, and that what we see happening over here.

So, this idea is exploited in gas based air conditioning systems, where you expand the gas and you produce cooling. And an example where that type of a cooling is used is all aero planes. So, inside the plane, the air is either heated or cooled, if it is hot outside on the ground, it is to be cooled, so that is what is done. And when you are up flying at 10,000 meters that air temperature outside is minus 40 degrees Celsius in which case that compressed air which is at a higher temperature is slightly throttle, and put inside the passenger cabin to make it nice and cozy. So, those are not entirely throttling process, you are partly using the effect of a nozzle also ok, so that was throttling.

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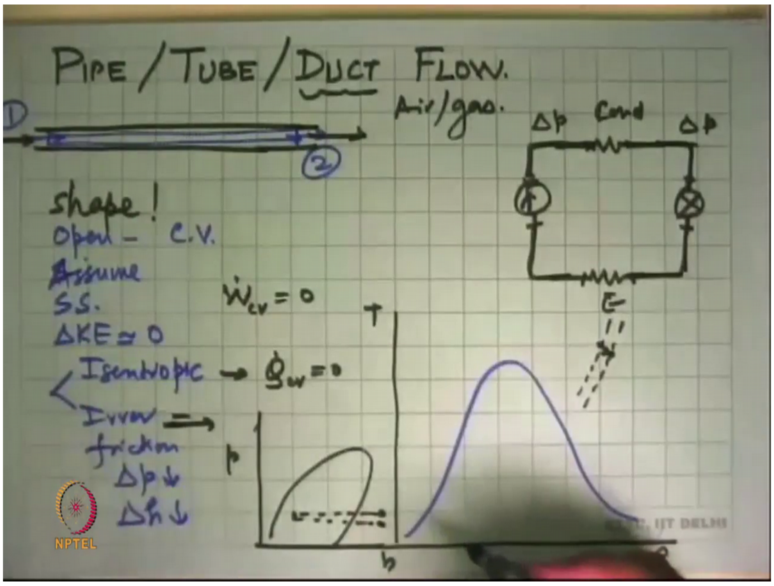

Now, we come to something which is somewhat trivial, you would really find that being discussed in many books, but this is essential to completing a flow cycle. And what it is if flow through a pipe or flow through like water flowing in a pipe or steam flowing in a pipe or hot pipe flowing in a pipe or through a tube, tube means basically inside diameter is relatively small, pipes inside diameters could be very large. All the way up to meter one and a half meters two meters tube plus small in diameter few millimeters 5 millimeter to 8 millimeters pipe and ducts.

So, duct is the term used into which we have a gas or an air flow. So, if you have seen air conditioning buildings, and you have big square or round things moving around through which air is going those are ducts. Now, why do we need these, so there yesterday, when I started off, I made a picture of a refrigeration system.

And I said that there are four items there, there is an evaporator, there is say a condenser which gets compressed gas from there. And evaporator expansion valve, this could also be a symbol for it. And the thing is these devices, we have just seen now, what is the thermodynamics of that. To make a system practically, we have to connect them in a right sequence. And this is essential to all flow systems and flow servers.

So, what we are showing here to here is a pipe, here to here there is another pipe, here to here this is another pipe here, to here is another pipe. And how do we treat these in the thermodynamic analysis that is what we are going to be looking at now. So, ideally what we have, if you can make a pipe and we say that well, if it perfectly but what is the system boundary? And the system boundary we say is just this much, all the fluid inside the pipe over a certain length.

And it tells us that there is inflow happening here, this is state 1. Outflow happening here, this is state 2. And this immediately tells us that first and foremost, this is an open system which means that we have to apply the control volume approaches for analyzing this, which tells us that one in assume. First we assume steady state, and then we can say that changes in kinetic energy are pretty much 0, the pipe is neither accelerating or decelerating the fluid ideally speaking.

And in two cases, ideal case we can say this is isentropic. In the real case, when it is irreversible, it is because of friction in the fluid and between the fluid and the valves of the pipe because of which there the pressure drop because of which there is the enthalpy drop, so that is what real pipes do. And we know that there is a pressure drop in that the theory of this you learn in a course in fluid mechanics. But thermodynamics tells us that under these assumptions, this is what would happen in a pipe.

And if we either assume that this is isentropic, there is no work transfer in this, so W dot c v equal to 0, in the ideal case Q dot c v is also 0. But, even if this is 0, internal irreversibility is for there, this could cause a drop in pressure. So, what we do in and treating pipes in a thermodynamic system is that if that is the thing, and you are looking at a T s diagram.

What we are saying is that if a flow is taking place, then the state will remain the same. But, if it is a real flow, then this was the isobar through which this point was there. There will be a pressure drop, it will come here. Pressure dropping is an irreversible process, and since there is no heat input output enthalpy is remaining same. This sort of a throttling type of a thing happening here, this state here will come down, that is what will happen in the real pipe.

On the ph diagram, when we have the dome there, we say that we are pumping it from the through the evaporators from here to there. Ideally, we assume it to be constant pressure process. Practically, it will the pressure will be slightly less, and so the process will actually be something over there. So, practical design of these type of system, we will take care of pressure drop in these in every one of these pipes with most of them are insulated. So, we say well insulation is there, and we can as the first approximation, we can say there adiabatic Q dot c v is 0.

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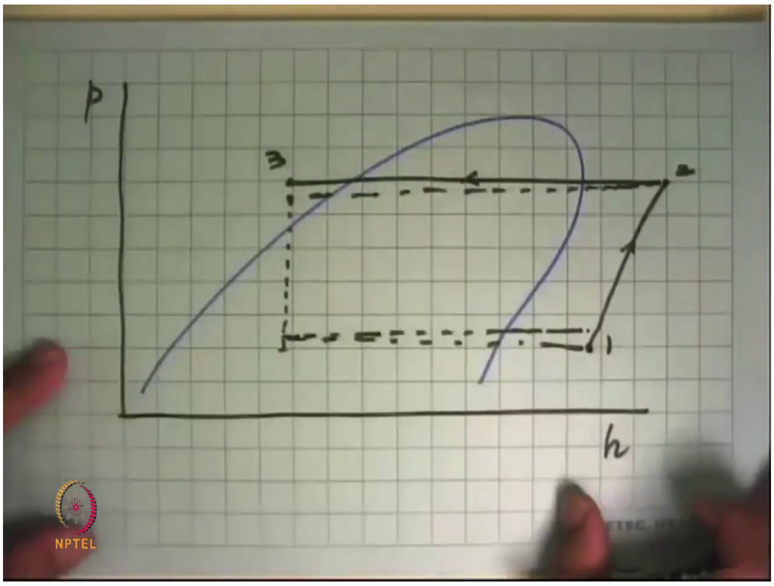

And then the diagram is look very simple will actually start looking a little more complicated, I will just make one diagram at the illustration, and this is on the ph diagram. So, this is the dome, and the ideal cycle says this is the compressor outlet, this is the compression process, this is inlet, this is outlet.

And we assume that the condenser ideal condenser would be like this, the real condenser it will be it will get to a slightly lower pressure than this. And so the process then have to be shown by this line. Throttling of course did reduce the pressure and this process though if you want to come back to this point, you would then have to go through this, this would have been the ideal case. But, because the pressure drop takes place, it will come over there, so that is sort of a changes that happen to the diagram, when we do the analysis of real service.

We will not go into the full details of that part right now here, at the fact that we will do analysis of the ideal cycle there, assuming that there is no pressure drop in the pipes. We should know that if I have to treat the pipe, there is a very simple way by which the thermodynamics tells us what we should treat it as, and we can factor that into the cycle manages.

Ducts are nothing but air flowing through them; and the same theory applies to ducts also, where this is important for pressure drop enough. All these pressure drops have to be ultimately taken up by the work input device which in this case is the compressor. If it is a water system and all the pressure drop in the pipe has to be taken care of by adequate pressure build up in the pumps. So, you have pump design, a compressor design, the fan design, they depend on the design of the pipes, and also pressure drops which will take place within the say that cooling coils or some heating coils or some other tubes, so that is where that this is important.