**Introduction to Aerospace Propulsion**

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**Module No. #01**

**Lecture No. # 09**

**First law of thermodynamics for open systems/flow processes**

Hello and welcome to lecture 9 of this lecture series on Introduction to Aerospace Propulsion. In the last few lectures, we have been discussing some of the basic concepts of thermodynamics. In the last lecture that was lecture 8, we discussed about the first law of thermodynamics applied to closed systems that is those systems, where there is no mass interaction between the system and the surroundings.

In this lecture, we are going to discuss about first law of thermodynamics applied to open systems; that is, how do we apply first law of thermodynamics to a system, which has mass as well as energy interaction with the surroundings.

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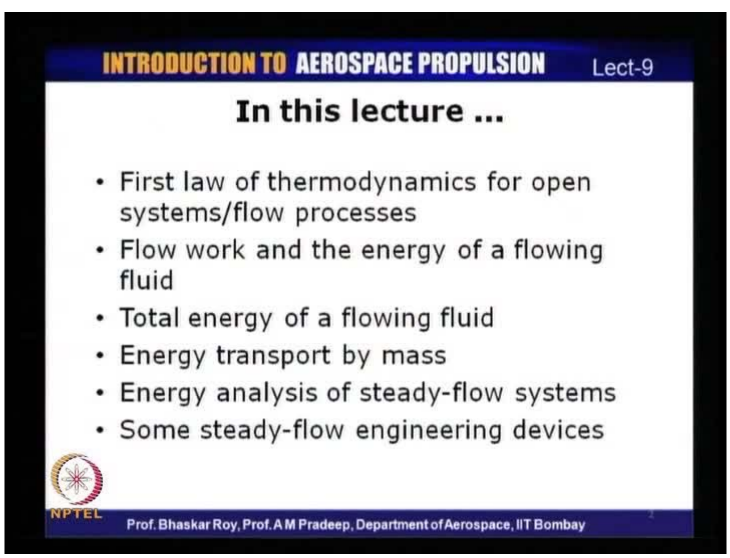

In this lecture, what we are going to discuss are basically the following: we shall be discussing about first law of thermodynamics as applied to open systems. Before we actually define it for open systems, we need to look at what is meant by flow work and the energy associated with a flowing fluid. This is basically applied only for those systems, where there is mass interaction between the system and the surroundings.

We shall then define what is meant by total energy of a flowing fluid. We shall subsequently define energy transport by mass and we shall carryout energy analysis of steady-flow systems. We will also define, what are steady-flow systems. We shall take up some examples of some steady-flow engineering devices; some commonly observed engineering devices. We shall derive the steady-flow energy equation for such devices.

Now, before we look into the first law of thermodynamics applied to open systems, we need to understand that there are 2 ways or 2 methods in which you can approach a particular problem. One is known as the Lagrangian approach and the other is known as the Eulerian approach. Depending upon how you would like to analyze a particular system, you can use either of these approaches. In the case of Lagrangian approach or system approach as it is called in the usual practice. You would track a particular particle and see what are the changes that particular particle or a fluid element undergoes as it moves within the system boundaries. In the case of the second approach, that is the Eulerian approach, or it is also known as the control volume approach. We only look at the system boundaries as a whole. We are not really interested about what is actually happening to certain fluid element or a group of particles. So, we are going to use the Eulerian approach for majority of discussions that we are going to have during this course. In some problems, we may also look at the Lagrangian approach as it might simplify the analysis in some sense.

Now, this is regarding the different approaches that you can have for analyzing a particular system. Now, besides this, a particular flow process could also be steady or it could be unsteady. The system you are looking at may have certain steady-flow process that is undergone by the system or it might have an unsteady-flow process. So, we shall look at what we mean by steady and unsteady-flow processes.

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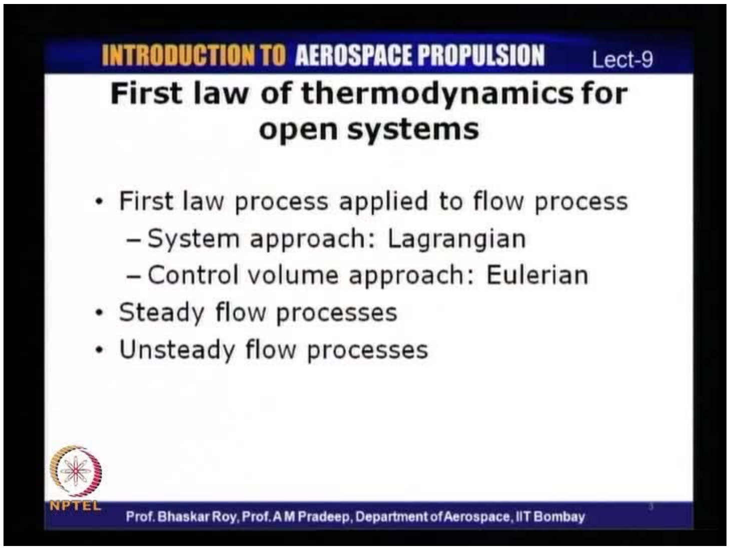


As I mentioned, we are going to discuss control volume approach for majority of the discussion. There are 2 types of processes - steady and unsteady. Now, in a steady-flow process, the rates of flow of mass and energy are constant across the system boundary. Some examples of steady-flow processes are turbines, compressors, heat exchangers and so on. We shall take up detailed analysis of some of these systems when we explicitly state the steady-flow energy equation or the first law of thermodynamics as applied to these systems little later in this particular lecture.

Now, a process could also be unsteady, if the rates of mass or energy are not constant across system boundaries. Some examples are like charging and discharging processes. If you are charging a tank with compressed air or some other compressed gas or you are charging a tank from a pipeline, which carries a certain compressed air or a certain fluid, it is basically an unsteady-flow process because the rates of mass or energy are not constant across the system boundaries.

We will not be covering any unsteady-flow process in this particular course as it is beyond the scope of the syllabus that we have. We shall definitely be analyzing the steady-flow processes and steady-flow process systems in this lecture because majority of the processes that we are interested as aerospace engineers can be approximated to be a steady-flow process. That is the reason why we shall not really go into details of the unsteady-flow process in this course.

Before we take up the first law of thermodynamics for open systems, we need to understand a very fundamental law of nature known as the conservation of mass principle. If you recollect, we had already discussed about the first law of thermodynamics for close systems. We stated that it is basically the conservation of energy principles stated in a different way to define the first law of thermodynamics for open systems. We also need to understand what is mean by conservation of mass.

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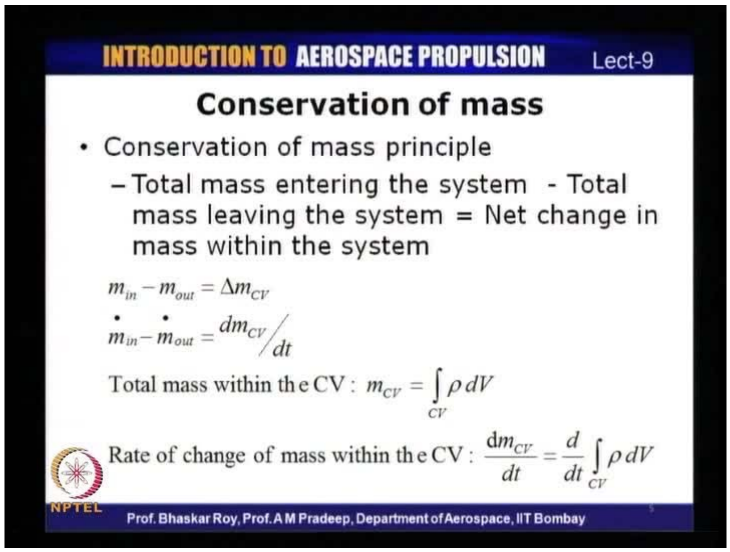


Conservation of mass law states that the total mass of a particular system will be equal to the difference between the total mass entering the system minus the total mass leaving the system and it will be equal to the net change in mass within the system. So, this is what basically the conservation of mass principle states. The total mass, which enters a system minus the total mass that leaves the system should be equal to the net change in mass within the system. It means that there is no creation or generation of mass within the system boundaries. It is basically the mass contained in the system; it is the net difference of the mass that is entering the system and the mass leaving the system.

So, stated in equation, we would have m subscript in minus m subscript out should be equal to delta m cv, where cv stands for the control volume. So, the mass in minus mass out is equal to delta m that is net change in mass of the control volume or rate of mass flow in minus rate of mass flow out is equal to dm cv by dt. Therefore, you can calculate the total mass within the control volume m cv as the integral of rho times dv, where row is density and v is the volume.

In the rate form, the rate of change of mass within the control volume is dm cv by dt, which is d by dt of rho dv and this is for a control volume. Basically, the conservation of mass states that there is a change in the mass of the system and that is attributed to the mass coming in and the mass that is going out.

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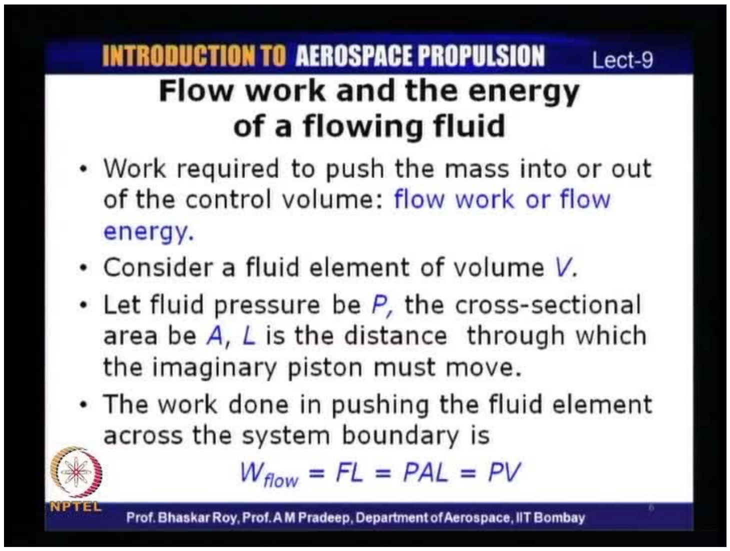


Now to understand flow process, we also need to understand or we should be familiar with the concept of what is known as the flow work or flow energy. If you are looking at a certain flow process, there is a certain mass entering a system and a certain mass leaving a system. It means that there is certain amount of work that is required to push a certain mass into a control volume or out of the control volume. This mass or this work that is required to either push in the mass or push out the mass of a control volume is known as the flow work or flow energy. This is the major difference between a closed system and an open system. It makes a lot of difference in the analysis of closed and open systems and that is because of the certain of work that is required for pushing in a certain mass of fluid into a system or pushing out certain mass out of the system. So, there is a certain work required.

Now to define or to understand this better, let us consider a certain system, which has a certain volume V. Let us say, the pressure acting on that particular control volume or particular fluid volume is P through an area A. We know that the work done for any particular process is equal to force times the distance .To understand this better, let us consider that there is an imaginary piston, which is pushing this mass flow into the control volume. The piston moves by, let us say, a distance of L and this requires a certain force, which is let us say, F. So, F times L will give you the work required. We also know that force is nothing but pressure times the area. Since we already know the pressure or we have defined the pressure as P and area as A. So, P times A will give you the force acting on the piston, multiplied by L will be equal to work. So, F into A into L will be the work and since A times L is volume, we get the net work done as equal to P times the volume PV.

Basically, the flow energy will come out to be the product of the pressure times the volume. This was some way obvious to you because in the last lecture or in the 2nd lecture, we had discussed about work and heat transfer. One of the major forms of work was displacement work. This is basically displacement work, but we are defining it in a different way here and that is basically known as the flow work or flow energy. So, if we were to look at it in a different way as I mentioned, we consider some fluid element of volume V. If the fluid pressure acting is P through a cross sectional area A, let us say, L is the distance through which an imaginary piston must moved. So, the work required or work done in pushing this fluid element across the system boundary would be F times L, where F is pressure times the area and therefore it is PA times L. Therefore, it is equal to PV and so work done during this process is PV.

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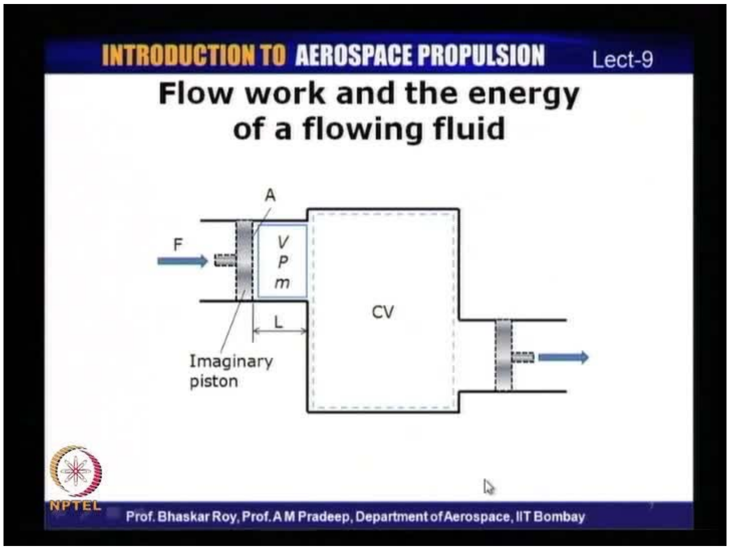


I have illustrated this in a in a small example here. What I was mentioning about this fluid element, which you can see here is - it has a certain volume of V, pressure acting is P and a mass m. This is the control volume, which has been indicated by dotted lines and the piston that is shown here is an imaginary piston. This is just to indicate that there is a certain force, which has to be acted upon this fluid element to push it into the control volume. So, this is the force acting, F and it is acting through an area A. As the piston moves by a distance of L, this much amount of fluid, which has a volume of V, pressure of P and mass of m goes into the control volume. Similarly, there is a certain amount of mass flow leaving the system.

The work done for this process is this force acting on the imaginary piston multiplied by the distance L through which it was displaced. So, force times L and force is pressure times area and PA into L and A into L is volume; area times the length is volume. Therefore, the work done for this process or the flow energy or the flow work is equal to P times V pressure times the volume.

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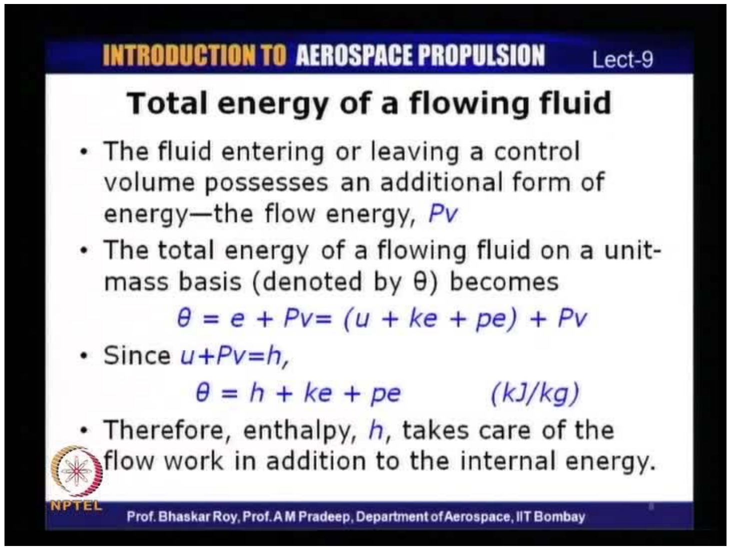


Now, we shall look at what is the total energy. Now, you have understood what is flow energy and we will now look at what is the total energy that is associated with a fluid that is flowing. Let us say, entering a system or leaving a control volume, it has a certain amount of additional energy. If you recall, we had defined total energy for closed systems as the sum of the internal energy plus kinetic energy plus the potential energy. Now, in the case of fluid, which is flowing there is an additional work or energy associated with it. It is given by the flow work or flow energy, which is the product of pressure times the volume.

So, the total energy of a fluid, which is flowing will be the sum of the internal energy u plus the kinetic energy plus the potential energy and the flow energy that is Pv. So, the total energy, which we normally represent for flow processes by theta will be equal to u plus ke plus pe plus Pv, which is the flow energy. Now, in one of the earlier lectures, I had defined a term, which is known as a combination property as enthalpy. We had defined enthalpy as the sum of internal energy u and the flow energy Pv.

The total energy is now equal to the sum of the enthalpy, the kinetic energy and the potential energy. So, for a flowing fluid, there are the total energy consists of 4 different terms - it is the sum of internal energy- u, kinetic energy, potential energy and the flow energy. For closed system, the total energy consists of 3 terms - the internal energy, kinetic energy and the potential energy. So, there is no flow energy associated with closed systems. It makes sense to define this term, combination property as enthalpy because enthalpy actually takes care of the internal energy as well as the flow energy. So, you do not have to worry about these 2 terms separately. Enthalpy has already taken into account for the internal energy and the flow energy. So that is the convenience of defining this combination property of enthalpy.

The total energy of an open system or a flow process will be the sum of enthalpy, which in turn is equal to u plus Pv, enthalpy plus kinetic energy plus the potential energy pe. So, the total energy associated with the flowing fluid is normally associated as h plus ke plus pe.

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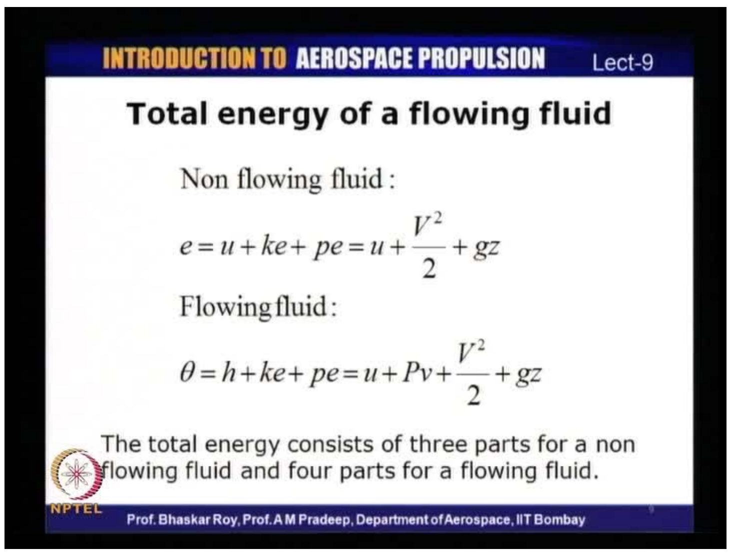


If you were define it in terms of an equation, the total energy of a flowing fluid is e and it is equal to the total energy associated with a non-flowing fluid. It is u plus ke plus pe and which is in turn equal to u plus V square by 2 and that is kinetic energy per unit mass plus g times z, which is the potential energy per unit mass.

For a flowing fluid on the other hand, theta is the total energy and it is equal to h plus ke plus pe and which is in turn equal to u plus Pv plus V square by 2 plus gz. So, you can see that the total energy consists of 3 parts for a non-flowing fluid. For a flowing fluid, the total energy consists of 4 components or 4 terms and that is the basic difference between a flowing fluid and a non-flowing fluid.

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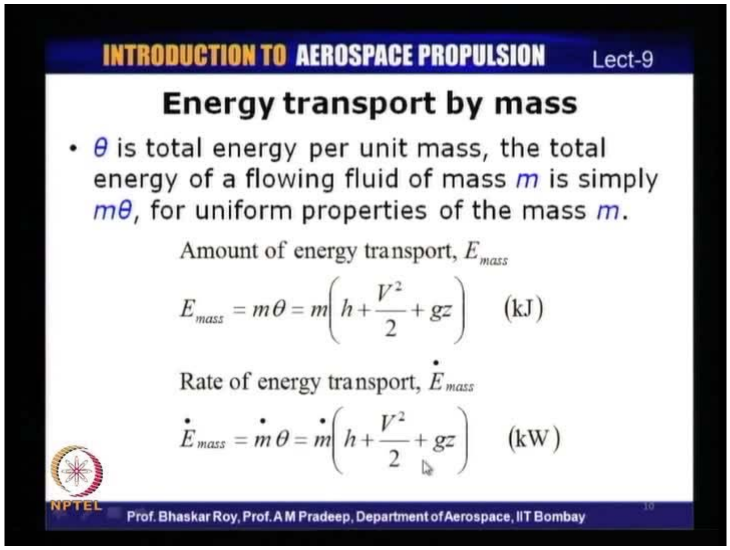


I have mentioned that for a process, which involves a fluid element crossing the system boundary. If there is a certain flow that is taking place, we can define the total energy per unit mass equal to the mass, which the flowing fluid multiplied by the energy itself. Therefore, the energy transport associated with the mass will be equal to m times of theta that is mass times the total energy.

We have already defined total energy for the flowing process, which was the sum of h plus kinetic energy plus potential energy. The amount of energy transported is E subscript mass is equal to mass times theta. Theta is the flow energy equal to h plus V square plus gz. If you were to look at this in the rate form, the rate of energy transport E dot mass is equal to m dot times theta, where m dot is the mass flow rate. So, the amount of energy transport E mass is in kilo joules and the rate of energy transport will be in kilo watts because you are looking at mass flow rate. So, you would get kilo joules per second, which is equal to kilowatts.

The amount of energy transport here will be the product of the mass. The total energy associated with this particular process and the amount of or the rate of energy transport will be equal to the product of the mass flow rate times the total energy. So, you would get m dot multiplied by h plus V square by 2 plus gz, where h is the enthalpy for the process, V square by 2 is the kinetic energy and gz is the potential energy per unit mass.

This multiplied by the mass flow rate would give you the total energy associated or energy transport associated with that mass in kilowatts.

The amount of energy that a certain fluid flow process carries depends on 4 terms - internal energy; which is u, the flow work or flow energy; which is P, the kinetic energy and the potential energy. So, this is the total energy associated with a flow process and this multiplied by the mass will give you the total energy transport associated with this particular mass flow process.

It is important for us to understand these flow processes because many of the engineering systems that we shall be discussing soon are basically involving flow processes and a certain mass associated with these flow processes. So, we need to understand the importance of flow processes and also how do you apply the first law of thermodynamics to different flow processes. We will take up some examples towards the end of this lecture on how you can derive first law of thermodynamics. So, energy equation for different steady-flow processes like turbines and nozzles etc, which we will take up towards the end of the lecture.

I mentioned in the beginning of this lecture that the flow process can be of different types. One of them is known as a steady-flow process and the other is an unsteady-flow process. I mentioned that steady-flow processes are those in which the mass and energy do not change across the system boundaries. So, what is the importance of understanding or analyzing steady-flow processes? Well, there is a lot of importance in understanding steady-flow processes because several engineering devices or systems can be can be well approximated as steady-flow systems. Some examples are turbine, compressors, nozzles etc. During a steady-flow process, the basic assumption is that no intensive or extensive property with in a control volume change with time. The element of time does not really appear in a steady-flow process. If there is a d by dt term in the steady-flow equation of the energy equation, it will become 0 because the rate of change of any of any intensive property or any extensive property with time will be equal to 0 and so that is the basic definition of a steady-flow process.

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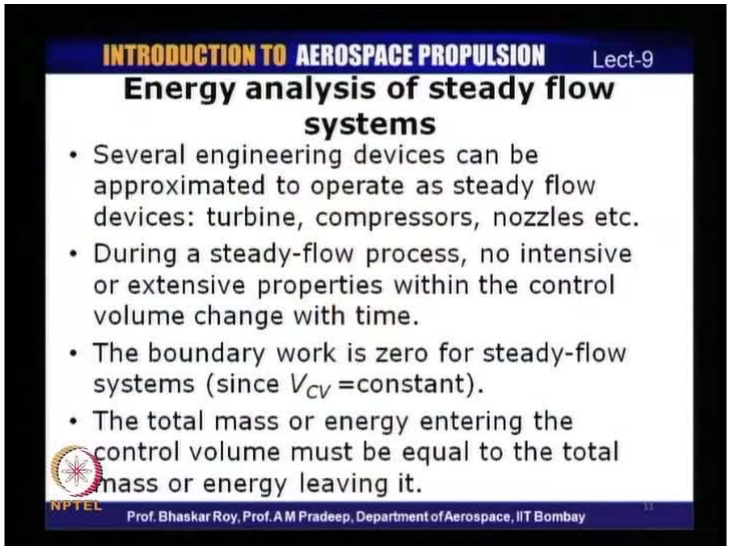


As I mentioned, there are many engineering devices, which we can approximate as steady-flow devices like turbines, compressors, nozzles etc. During a steady-flow process, we may discuss that the none of these properties like extensive or intensive properties would actually change with time. Therefore, the boundary work associated with a steady-flow system will be 0 because the volume of the control volume is fixed or constant and so boundary work associated with this process will be 0.

The other property with a steady-flow system is that the total mass or energy entering the control volume must be equal to the total mass or energy leaving the control volume. So, there is no accumulation of mass or energy within the control volume. If that was the case, it could become an unsteady process. I mentioned that we are not going to discuss about unsteady-flow process in this lecture. We shall be talking only about steady-flow processes during this lecture.

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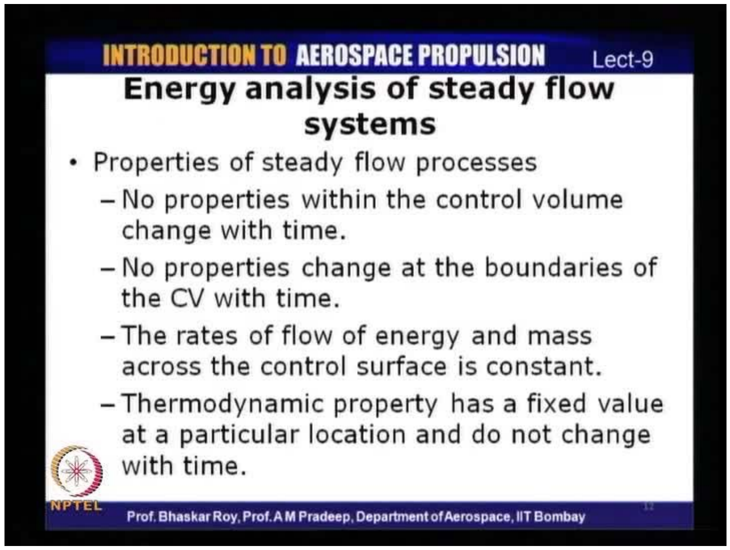


What are the properties of steady-flow process? Well, the basic properties of a steady-flow process are - none of the properties, whether they are extensive properties or intensive properties, they do not change within the control volume with time. Of course, the properties can change within the control volume itself, but there is no rate of change of the control properties within the control volume with time. It is also a fact that no properties will actually change at the boundaries of the control volume with time. The rate of change of mass or energy with time across the control surface is actually a constant, if the process is to be approximated as a steady-flow process.

The different thermodynamic properties like pressure, temperature etc has fixed values at a particular location. They do not change with time that is if you look at a system, it has to be approximated as a steady-flow system or a steady-flow process. Then the different thermodynamic properties of the system will have fixed values at different locations within the system. They do not change with time. So, these are some basic properties that need to be satisfied, if a particular process has to be approximated or if a process has to qualify as a steady-flow device or a steady-flow process.

Very shortly, we shall define the first law of thermodynamics for steady-flow devices. We shall apply the first law for some examples of steady-flow engineering devices. So, we need to keep these properties in mind, if we are going to approximate a particular process or a system as a steady-flow process.

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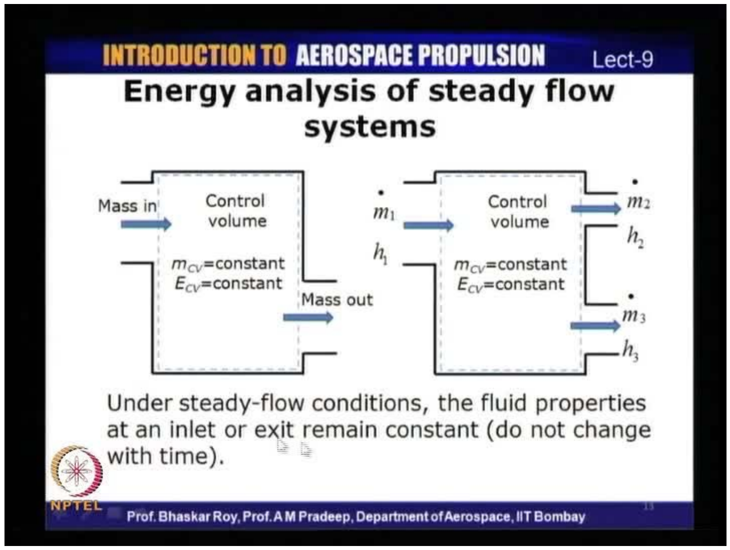


This is an example or just an illustration showing, what are the properties associated with steady-flow systems. For a steady-flow system, which has certain mass entering and a certain mass leaving the system, the net mass of the control volume is a constant. The net energy associated with this control volume is also a constant.

Now, the first one on the left hand side, what you see is an example of a single entry and single exit system. You could also have a system, which has multiple entries and multiple exits. The basic definition remains the same that if the net mass within the control volume is constant and the net energy of the control volume remains a constant, then we can approximate this process as a steady-flow process. Under steady-flow conditions, the fluid properties at the inlet or exit remain a constant. They do not change with time and so the element of time in the steady-flow energy equation would become equal to 0 because we are assuming that the properties do not change with time.

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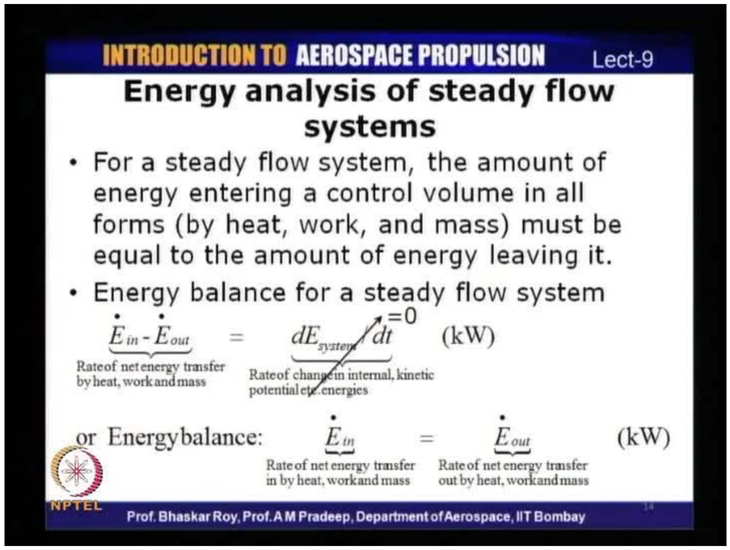


Let us now look how we can derive the energy equation for a steady-flow process. For steady-flow system, the amount of energy entering a control volume in all its forms, it could be energy transfer by heat, it could be energy transfer by work or it could be energy transfer by virtue of the mass flow itself. So, whatever energy is entering a control volume, it should be equal to the energy leaving the control volume because we have seen that energy of a control volume, whether it is single entry or multi entry, the net energy of the system within the control volume is a constant.

The total energy is entering in all its forms of heat, work and mass because these are the 3 modes of energy interactions, which a system can have with the surroundings. The net energy entering in all these forms should be equal to the net energy leaving the system. Energy balance for a steady-flow system would be equal to energy in minus energy out. The net is equal to rate of change of energy of a system. In the case of steady-flow processes, the rate of change of energy is equal to 0 because it is a steady-flow process. Therefore, energy in will be equal to energy out that is e in is equal to the rate of change of energy leaving the control volume.

Now, as I mentioned, energy in could be in different forms. It could be in the form of heat work or mass, but whatever the form of energy interaction, which the system has with the surroundings. The net rate of change of energy transfer by heat mass or work should be equal to rate of change of energy transfer out of the system by heat work or mass. This is basically the energy balance or the energy equation for a steady-flow process.

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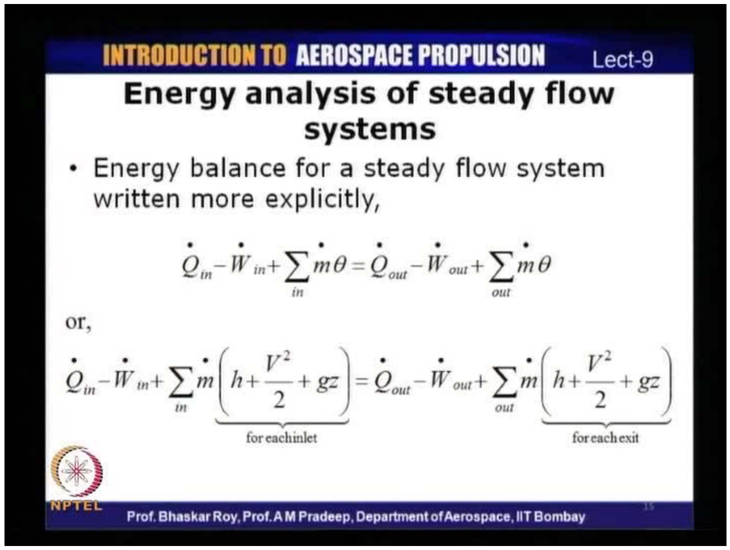


We can write this more explicitly. If you look at the steady-flow process, the energy equation is expressed in more explicit form. As I mentioned, energy transfer can take place in 3 modes – heat, work and mass flow. So, these are the 3 modes, which have been written here. Q in dot, which is rate of input of heat minus W dot in, which is rate of work input plus the mass flow input, which is equal to sigma in m dot theta. This sigma is for accounting the different multi input flow rates into the system. Since E in is equal to E out, this should be equal to Q dot out, which is rate of heat transfer out of the system minus W out dot, which is rate of work out of the system plus sigma out of m dot theta.

As we now discussed, the third term is the total energy associated with the flow process. It should be equal to Q in dot, which is heat transfer in minus W in dot, which is work input plus sigma in times mass flow rate multiplied by the enthalpy, the sum of enthalpy plus kinetic energy plus the potential energy. This is applicable for each inlet and this should be equal Q dot out, which is heat transfer out of the system minus W dot out, which is work done by the system, plus m dot out multiplied by the flow energy, which is h plus V square by 2 plus gz. So, this defines the general energy equation for steady-flow processes, which consists of 3 terms.

In a steady-flow energy equation, you have 3 distinct terms. One is the heat transfer term, the work done term and the flow work term. So, Q in minus W in plus mass flow rate times the flow work or flow energy should be equal to the same terms leaving out of the system. If the system consists of multiple entries and multiple exits, it will affect the third term that is the flow energy term. You have to calculate the flow energy for each of these entries and each of these exits from the system.

In general, steady-flow energy equation will consist of these 3 different terms, which have to be applied at the entry as well as the exit. You can now compare this steady-flow energy equation with the energy equation, which we had discussed in the last lecture. It was applicable for closed systems or closed processes. So, you might recall that we did not have this flow energy term in the first law of thermodynamics as applied to closed systems. For the first law as applied to closed systems, it was Q minus W is equal to delta e or delta u.

There was no flow energy in a closed system or closed process. So, energy equation can be written in the generalized form of energy equation. It can be expressed as Q dot minus W dot is equal to the difference between the mass flows entering the system and mass flows leaving the system or the flow energy associated with the mass leaving the system minus the energy associated with mass entering the system. So, Q dot would refer to the net heat transfer into the system and W dot would refer to the net work transfer from the system.

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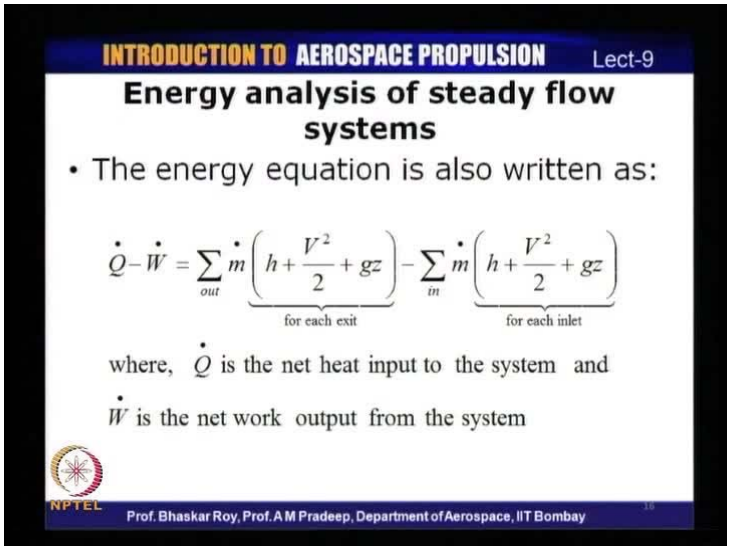


Q dot minus W dot is equal to sigma out m dot times the flow energy term. Energy flow term is is h plus V square by 2 plus gz for each exit minus sigma in into m dot times h plus V square by 2 plus gz for each inlet. Here, Q dot refers to the net heat input into the system, W dot is the net work output of the system and this again is an assumption. As I mentioned in the last lecture, we normally assume that for a given process, there is heat input into the system and work output from the system.

After any of the calculations that you are carrying out, if these numbers come out to be negative, it just means that the net heat was not input, but there was a net heat output from a system. If W comes out to be negative, it means that there was net work done on the system because we normally have systems, which generate work and requires heat input. This is why, as a common practice, we assume net heat input to the system and net work output from the system.

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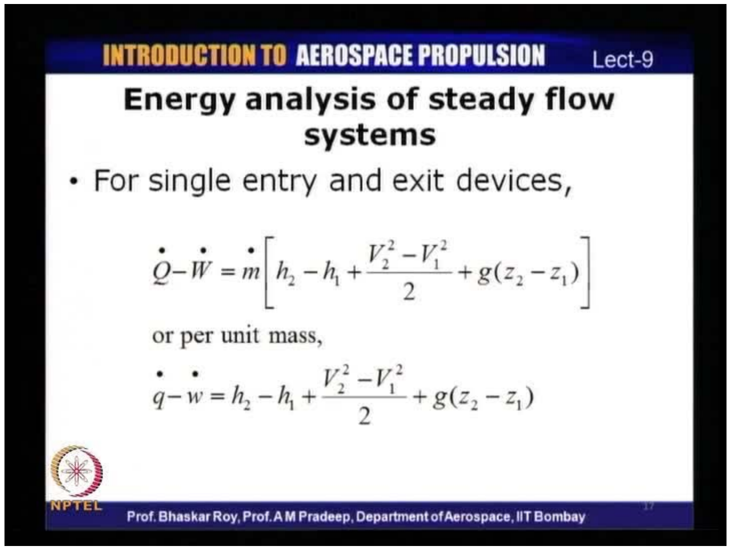


Now, if we look at this particular equation for a single entry system, which is how most of the engineering devices would be. For example, a turbine or a compressor or nozzle and diffusers, all these are all devices, which have single entry and single exit. The energy equation becomes simpler; you have only one particular term for the flow work. The energy equation is modified as Q minus W is equal to the difference in the enthalpies at the exit and the entry plus the difference in the kinetic energies plus the difference in potential energies at the inlet and exit.

If you were to write down the steady-flow energy equation for single entry device, then the equation would look like Q dot minus W dot is equal to m dot times h 2 minus h 1 plus V 2 square minus V 1 square by 2 plus g times z 2 minus z 1. This h 2 minus h 1 is the net enthalpy, V 2 square minus V 1 square by 2 is a net kinetic energy, g times z 2 minus z 1 is the net potential energy.

The same equation per unit mass would be Q dot minus W dot is equal to h 2 minus h 1 plus V 2 square minus V 1 square by 2 plus g times z 2 minus z 1. This is the general energy equation for steady-flow processes. In some textbooks, you might see that this equation is referred to as the steady-flow energy equation. So, steady-flow energy equation for single entry and single exit devices is Q dot minus W dot is delta h plus delta ke plus delta pe.

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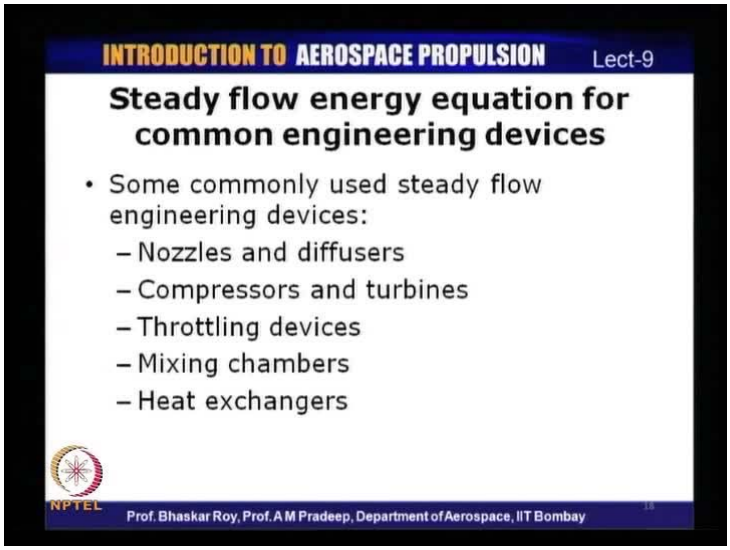


We shall now discuss about some common steady-flow devices, which we see in daily life. Some of these commonly used steady-flow energy devices are nozzles and diffusers, compressors and turbines, throttling devices, mixing chambers, heat exchangers etc. We shall now derive the steady-flow energy equation for some of these engineering devices, which are commonly used. We shall see how the general form of steady-flow energy equation can be used by applying appropriate boundary conditions for these devices like nozzles and diffusers, compressors, turbines or certain mixing chambers, throttling devices etc.

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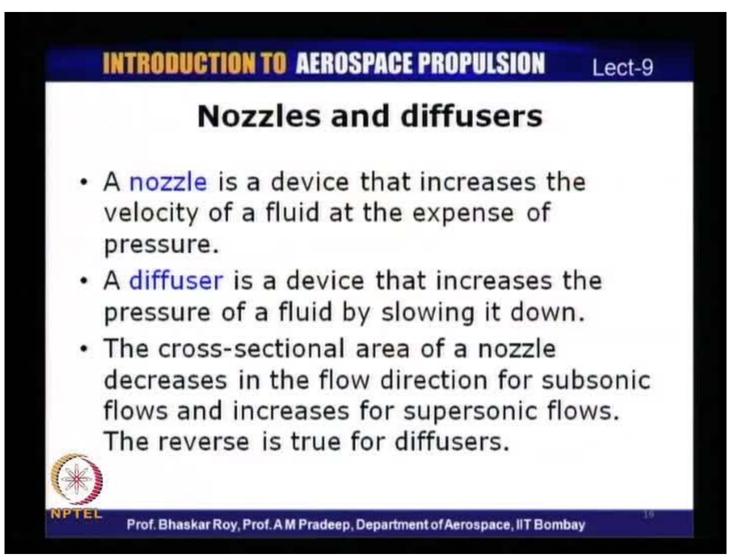

The first such device, which we shall discuss are nozzles and diffusers. A nozzle is a device, which increases the velocity of a fluid at the expense of pressure. Diffuser on the other hand is a device, which increases the pressure of a fluid by slowing it down. A nozzle and a diffuser in some sense are devices, which are opposite to that of each other in terms of their basic function.

The cross-sectional area of a nozzle decreases in the flow direction for subsonic flows and it increases for supersonic flows. Well, you might wonder what subsonic and supersonic flows are. At the moment, we will just define them as those flows, which have a mach number less than 1 are known as subsonic flows and those flows, which have a mach number greater than 1 are known as supersonic flows. I think we will define this little later in the course, when we discuss about compressible flows. A nozzle in a subsonic flow has decreasing area in the direction of the flow and increasing area in direction of flow in supersonic flows. Reverse of this is true for diffuser, because I mentioned that nozzles and diffusers are 2 devices, which have opposite functions. So, their geometry also in some sense will be opposite to that of each other.

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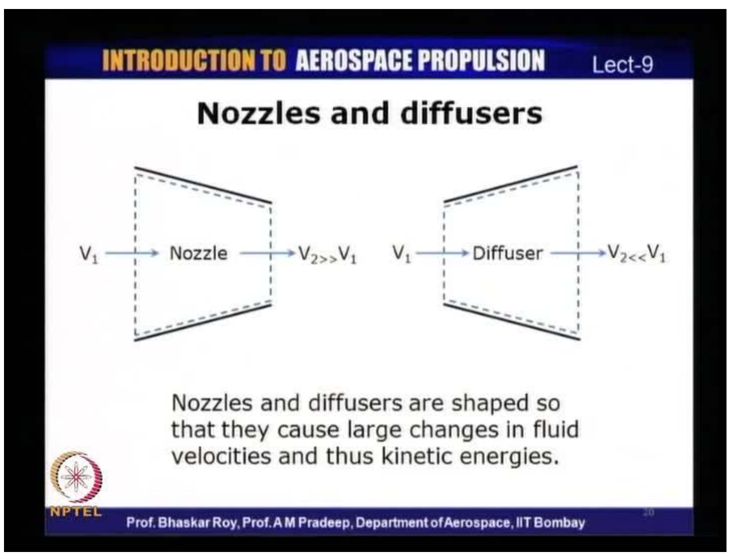


We will derive the energy equation or we will simplify the basic energy equation. Let us say, a nozzle will be very similar to that for a diffuser with appropriate boundary conditions applied. Now, we know that in the case of an energy equation, we have 3 different terms - the heat transfer, work and the mass on the flow energy terms. Some of these terms will become 0 as you apply it for different engineering devices.

In this particular example, we are discussing for nozzle and diffuser. I mentioned that a nozzle is a device, which has increase in velocity along the flow direction for subsonic flows. Let us say V 1 is the velocity at the inlet and V 2 is velocity at outlet. So, nozzle increases the velocity at the expense of pressure and therefore V 2 is usually greater than V 1.

For a diffuser, it is the opposite. If V 1 is the inlet velocity, V 2 is the exit velocity. V 2 will be less than V 1. You can also notice that a nozzle and diffuser have opposite shapes. A nozzle in the reverse way would look like a diffuser. So, nozzles and diffusers are those devices, which can cause large changes in fluid velocities. Therefore, there is a large change in the kinetic energy of the fluid as they pass through a nozzle and a diffuser.

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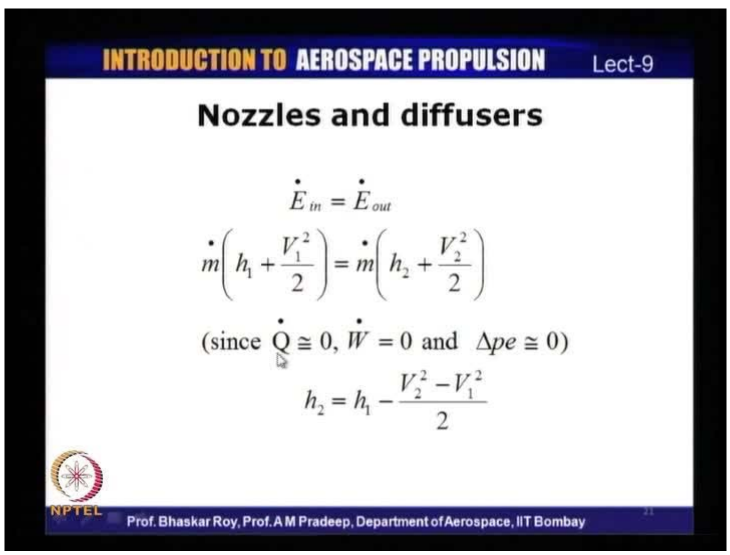


The general form of energy equation was E in is equal to E out for steady-flow systems. In the case of nozzle and diffuser, there is no net change in heat transfer. Therefore, Q dot can be approximated to be 0. There is no work done by a nozzle or a diffuser and therefore W dot is 0. We can also approximate the change in potential energy to be 0 as long as the nozzle is horizontal or the diffuser is horizontal. Even, if nozzles and diffusers do not have a long length, the net change in potential energy across the nozzle or diffuser can also be assumed to be 0.

If you apply all these boundary conditions on the energy equation, net heat transfer as 0, work done as 0 and delta pe is equal to 0. The energy equation reduces to m dot into h 1 plus V 1 square by 2 is equal to m dot times h 2 plus V 2 square by 2. Mass entering in and mass leaving the system are the same, m dot will get canceled out. Therefore, the energy equation for a nozzle or a diffuser would be h 2 is equal to h 1 minus V 2 square by minus V 1 square by 2.

You could also write it as delta h is equal to the delta k E across the system. The net change in the enthalpy is equal to the net change in kinetic energy. There is no net change in potential energy, heat transfer is 0, work done is also 0. This would be the basic energy equation for nozzles and diffusers.

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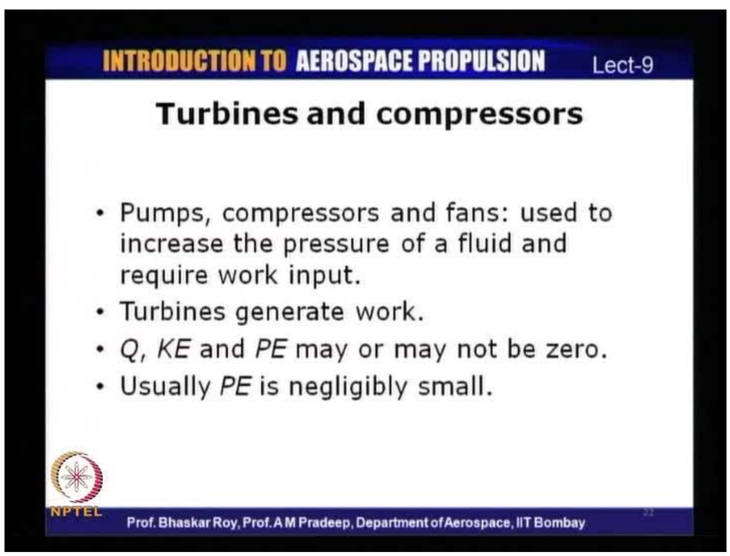


Let us now look at the second set of devices, turbines and compressors. I think you are already aware that pumps compressors and fans are devices, which are used to increase the pressure of a fluid. Therefore, they require work input. Turbines on the other hand, generate work. So, pumps and turbines in some sense are like nozzles and diffusers. They are opposite in function in some way or the other.

In the case of the energy equation, the heat transfer, kinetic energy and potential energy may or may not be 0. It depends upon the type of device that you are looking at. Usually, it is practice to assume heat transfer across the system boundary to be 0. If we consider that the turbine boundaries or casing is well insulated or compressor boundaries are insulated, then the process can be considered as adiabatic. So, heat transfer is 0, kinetic energy and potential energy may or may not be 0. Kinetic energy is usually not really assumed to be 0 because there is a change in velocities across the system boundaries. They may or may not be 0 and potential energy depending upon the type of system, we may assume it to be 0 and sometimes it is not taken as 0. In fact, when we solve some example problems later on in a lecture, we will see how much is the error introduced, if you were to neglect kinetic energies and potential energies for such systems.

If you look at the energy equation, for turbine and which is what we are going to derive today. In the case of turbine, we are going to assume that the changes in kinetic energy and potential energy are close to 0. So, Q is equal to 0 because we are going to assume that the process is adiabatic in some sense.

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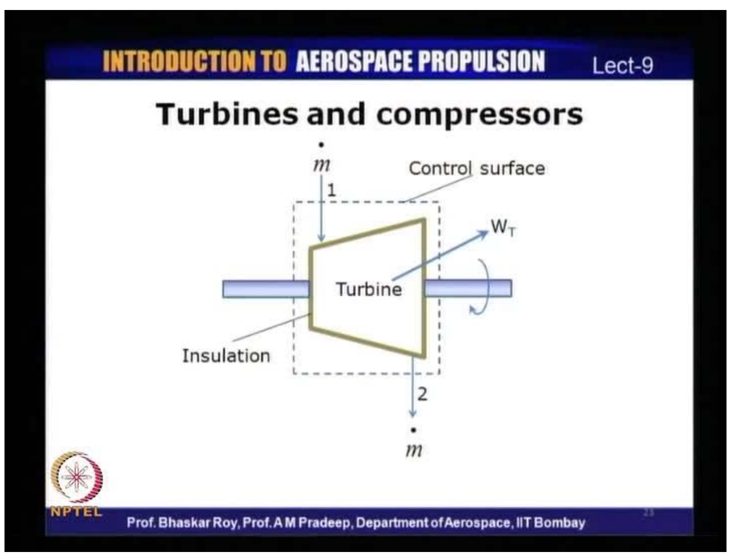


Let us look at a schematic diagram of a turbine here. What you see here is a turbine, which has a certain insulation. It means that there is no heat transfer across the system boundaries, across the control surface. The turbine generates a net work output and there is a certain mass flow entering the system and mass flow leaving the system. So, the turbine generates a net work across the system boundaries.

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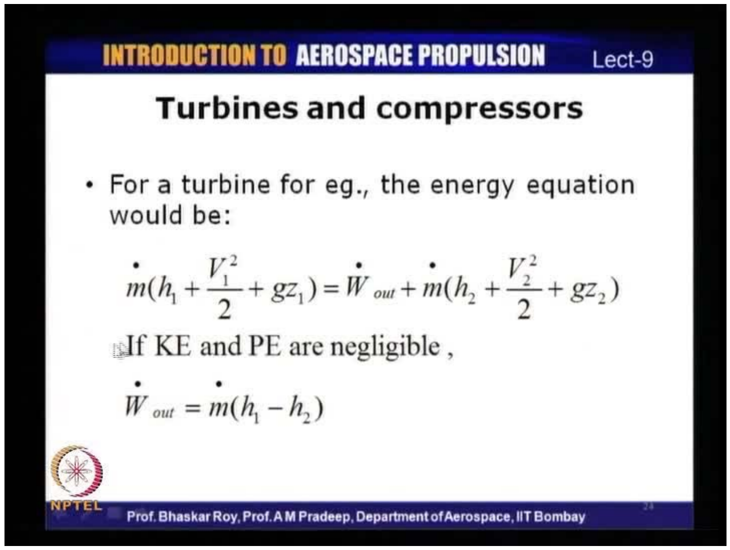


If you look at the energy equation for a turbine, since Q dot is 0, we get m dot multiplied by h 1 plus V 1square by 2 plus gz 1. It is equal to m dot is equal to work output that is W dot out plus m dot times h 2 plus V 2 square by 2 plus gz 2. If you assume kinetic energy and potential energy to be negligible, then the net work output is equal to m dot times h 1 minus h 2 that is work output from the turbine is mass flow times the difference in enthalpies.

So, difference between the enthalpy times the mass flow will give you, what is the work output that this particular turbine is giving. You can modify the same equation; the general energy equation for a compressor. Depending upon whether you neglect kinetic energy and potential energy, you can derive a very similar expression of work input required for compressors or pumps or fans. The equation will be similar to this, but just that the signs of h 1 and h 2 would be different because enthalpy leaving a compressor or a fan or a pump would be higher than the enthalpy coming in because there is work done on the system. You can modify the equation appropriately for the compressors or pumps. The equation for compressor and pump will be the same because they are thermodynamically same devices.

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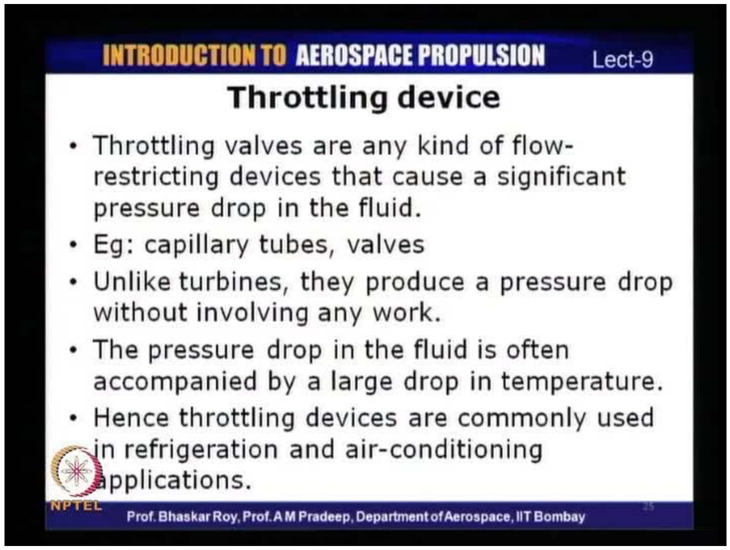


The next device that we are going to discuss is a throttling device. Well, a throttling device is a one, which basically cause flow restrictions leading to significant pressure drop in the fluid. Some examples are capillary tubes, valves or porous plug etc. Unlike turbine, where there is pressure drop across the turbine and a work output. In the case of throttling devices, they produce a pressure drop without involving any work. A large drop in temperature often accompanies this pressure drop. This is the reason why throttling devices are very commonly used in refrigeration and air-conditioning systems. Throttling device forms one of the components of a refrigeration cycle. So, throttling devices do not generate any work output. They obviously do not have any heat transfer and we will derive the energy equation for throttling devices.

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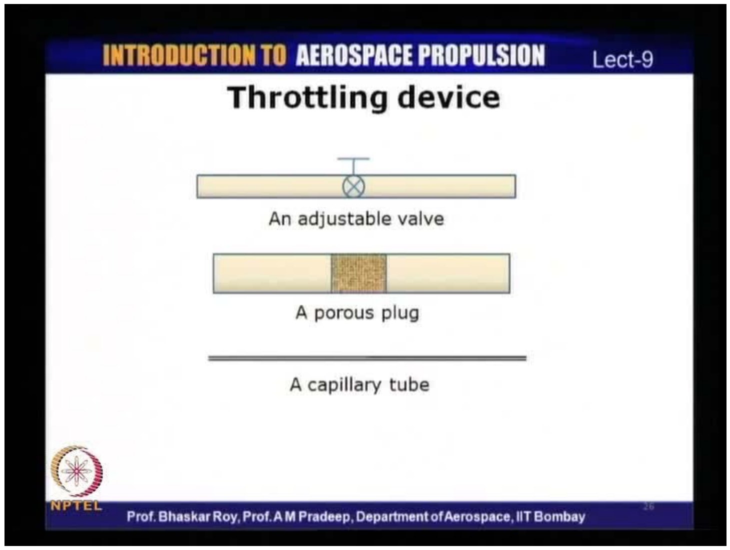


Some example of throttling devices are shown here, one example is a valve. As you adjust the valve, there is a large change in pressure across the valve. It is considered to be a throttling device. A porous plug have a porous substance within a pipe and as mass flow flows through the porous plug, it leads to significant drop in pressure. Capillary tube is another example of a throttling device. Thermodynamically all the 3 devices are the same.

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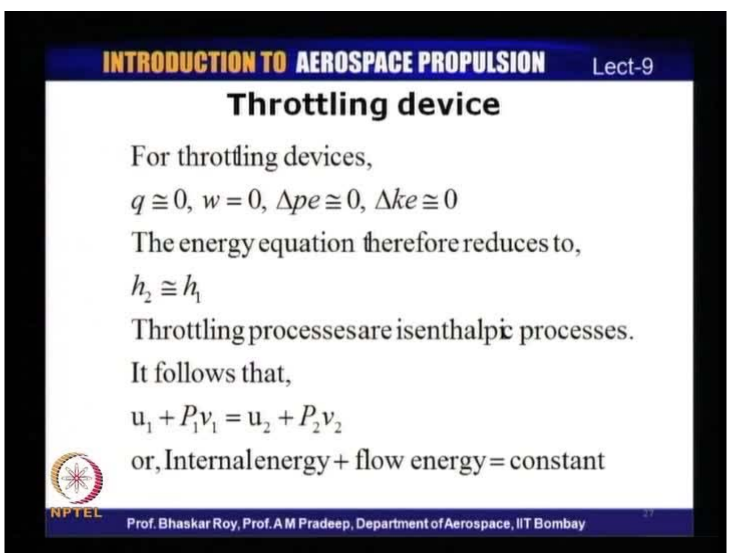

For throttling devices, the net heat transfer is 0. It can be assumed to be 0, there is no work output. Therefore w is 0, kinetic energy and potential energy can again be assumed to close to 0. Therefore, the energy equation will basically reduce to h 2 is equal to h 1 that is the enthalpy across throttling device is the same. This means that throttling processes are isenthalpic processes that is these are processes where enthalpy is a constant. Since, h 2 is equal to h 1, we can also write them in terms of their components that is internal energy and flow energy. Therefore, u 1 plus P 1v 1 is equal to u 2 plus P 2 v 2 that is the sum of internal energy plus the flow energy is a constant across a throttling device.

Now, this means that you can have different values of internal energy at the inlet and exit. That is compensated by a corresponding change in the flow energy. Let us say, you have a drop in internal energy across the throttling device. This has to be compensated by increase in the flow energy term across the throttling device. This is required because the net change in enthalpy across the throttling device will be the same and that is h 2 will be equal to h 1. Therefore, the total of u 1 plus v 1 should be conserved. Across a throttling device, the change in internal energy plus P 1v 1 should be compensated by corresponding changes in internal energy and the flow energy after the throttling device.

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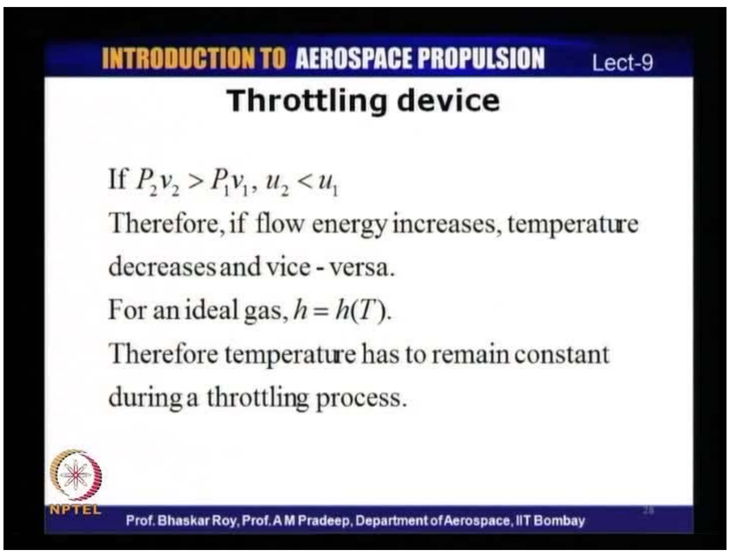


To illustrate it, if you look at one case, where P 2v 2 is greater than P 1v 1. This has to mean that u 2 should be less than u 1, so that there is h 1 equal to h 2 conserved.

Therefore, this also means that if flow energy increases, the temperature has to decrease because u is a function of temperature and the reverse is also true. If flow energy decreases, you may also have increase in internal energy and temperature.

Now, for an ideal gas, enthalpy is only a function of temperature. Therefore, for an ideal gas or for a system, which involves only ideal gases, the enthalpy and the temperature have to remain a constant during a throttling process. For an ideal gas, enthalpy is only a function of temperature. For ideal gases, enthalpy is only a function of temperature, which means that enthalpy has to be a constant and therefore temperature also has to remain a constant across a throttling device.

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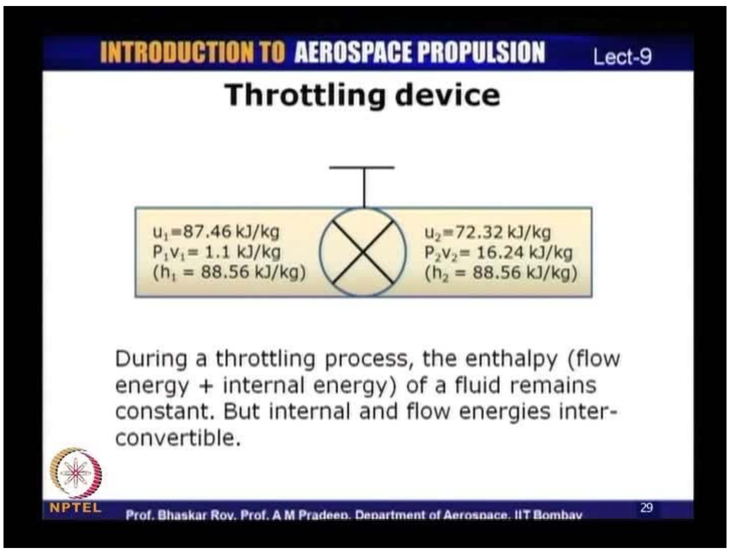


Just an example, as I mentioned, if across this device, at the inlet, you had u 1 is equal to 87 point some kilo joules. P 1v 1 as something else and total enthalpy is 88.56. After the throttling device, let us say, u 1 has reduced and P 1v 1 and therefore, it has to correspondingly increase, so that the net enthalpy is the same. During a throttling process, enthalpy of a fluid has to remain constant, but internal energy and flow energies are inter-convertible. So, you can covert internal energy into flow energy partially and so on and vice versa across a throttling device.

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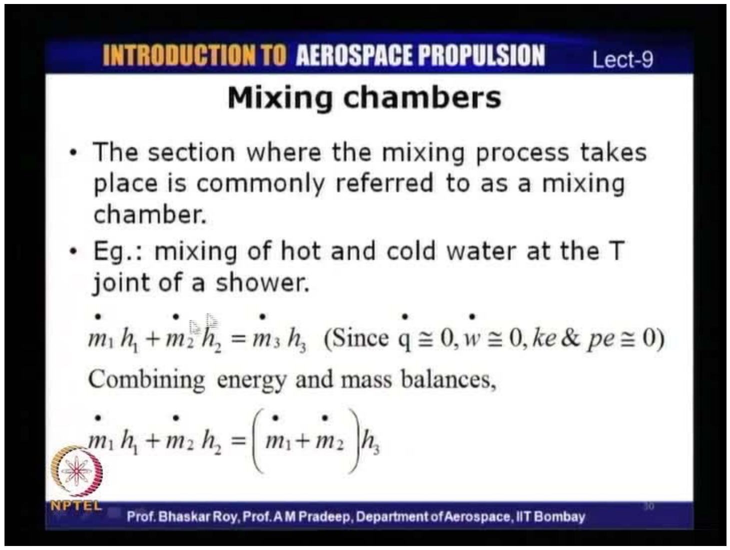


The last device that we are going to discuss is a mixing chamber. Mixing chamber is a section, where there is a mixing process taking place. Some examples are the mixing of hot and cold water at a T junction of a shower. For example, you have 2 different masses coming in m 1 and m 2, leaving out as m 3 for energy equation. Therefore, it will reduce to m 1 h 1 plus m 2 h 2 and it is equal to m 3 h 3. Since we assume again that net heat transfer is 0, work is 0, changes in kinetic energy and potential energy are 0.

You combine the energy and mass balances because m 3 is equal to m 1 plus m 2. Energy equation reduces to m 1 dot h 1 plus m 2 dot h 2 is equal m 1 plus m 2 dot times h 3. This would be the energy equation for a mixing chamber process that is the net enthalpy leaving the system is equal to sum of the enthalpies entering the system.

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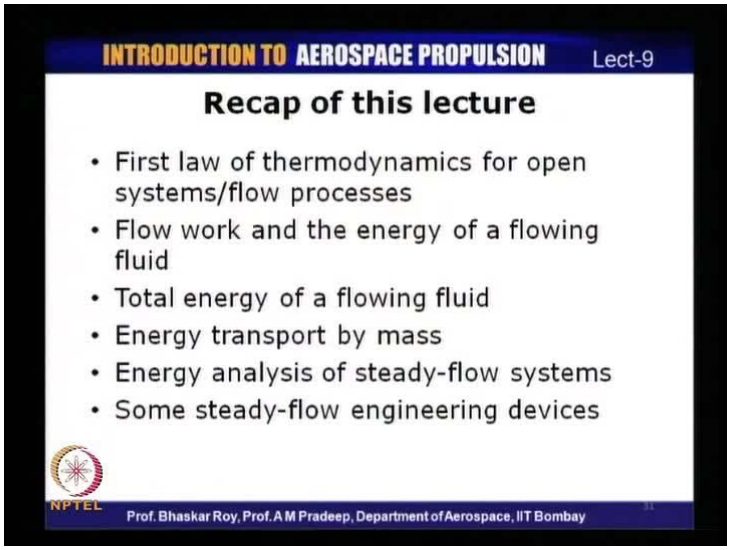


Now, that brings us to the end of this lecture. We have discussed about the first law as applied to flow processes. Let us take a look at what we had discussed during this lecture. We discussed about the first law of thermodynamics applied for open systems or flow processes. We then discussed about flow work and the energy associated with a flowing fluid. Then, what is the total energy that is available for a flowing fluid. As a consequence of mass flow rate what is the energy associated with mass flow process. We then discussed the energy equation for steady-flow processes. We derived the energy equation for the steady-flow processes and also we discussed about application of these energy equation. The basic energy equation for certain steady-flow devices like nozzles and diffusers, turbines, compressors, mixing chambers or heat exchangers. We also discussed about how we can apply energy equation for throttling processes.

The idea was to help you in understanding what is a process involved in making certain justifiable assumptions and applying first law thermodynamics for different flow processes. If you come across a different type of flow processes based on what we had discussed here, you could probably be able to extend or simplify the general energy equation to any other open system or any other flow processes.

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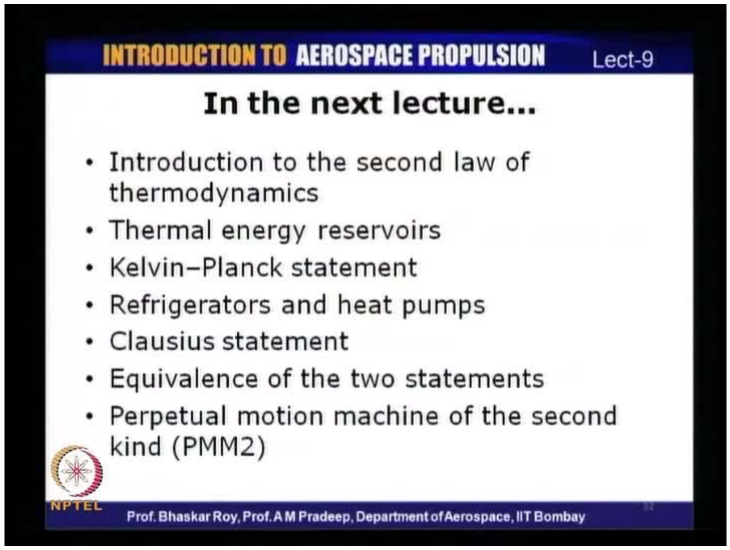


Now, in the next lecture, what we are going to discuss? Second law of thermodynamics, we shall define what is known as thermal energy reservoirs. We shall then state the Kelvin-Planck statement of the second law of thermodynamics. We shall subsequently discuss about refrigerators and heat pumps. As a consequence, what is the Clausius statement of second law of thermodynamics? We shall then prove that the Kelvin-Planck statement of second law and the Clausius statement of second law are equivalent. Towards the end of the next lecture, we shall again discuss about certain devices, which violate the second law of thermodynamics. They are known as perpetual motion machines of the second kind. We had already discussed this for the first law, which were known as perpetual motion machines of the first kind. Those devices, which violate second law, are known as perpetual motion machines of the second kind. So that is something we shall discuss during the next lecture.