**Introduction to Aerospace Propulsion**

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**Module No. # 01**

**Lecture No. # 11**

# Reversible and irreversible processes concept of entropy

Hello and welcome to lecture 11 of this lecture series on introduction to aerospace propulsion. In the last few lectures, we have been discussing about some of the very basic fundamental concepts of thermodynamics. As we continue our journey on understanding thermodynamic concepts and aspects, we shall unravel many more terms that you probably have not been really aware of or you may have heard of them but, you would not probably be aware of the thermodynamic meaning of some of these terms.

In the previous lecture, we were discussing about the second law of thermodynamics and while discussing about the second law, we discovered that there are two different statements for the second law of thermodynamics. One of them is called the Kelvin-Planck statement of thermodynamics, which basically states that it is impossible for a cyclic device to continuously generate work by interacting with just one reservoir.

As a consequence of the second law of thermodynamics, it means that no heat engine can have an efficiency of 100 percent. Even that is applicable for an ideal engine that it really cannot have an efficiency of 100 percent, which would mean that it is just generating work by interacting with one reservoir and it is not rejecting any heat to a second reservoir and its efficiency will be 100 percent.

So, such a device cannot exist because it violates the second law of thermodynamics. Mind you, it is not really a limitation of real processes in terms of frictional losses and other irreversibilities but it is also valid for an ideal process; so that was the Kelvin-Planck statement.

We also discussed about refrigerators, heat pumps and subsequently the Clausius statement of the second law of thermodynamics. The Clausius statement was basically stating that, you cannot have a heat engine or a cyclic device, which will continuously transfer heat from a low temperature reservoir to a high temperature reservoir, which means that there is a certain work input required for any transfer of heat from a low temperature reservoir to a high temperature reservoir.

Eventually, we also proved that the Kelvin-Plank and the Clausius statements are equivalent in some sense or the other. At least, they are thermodynamically equivalent that means that if there is device which violates the Kelvin-Plank statement, it will also be violating the Clausius statement in some sense or the other and vice versa. So, the Kelvin-Plank and the Clausius statements are basically equivalence statements and these both are statements of the second law of thermodynamics.

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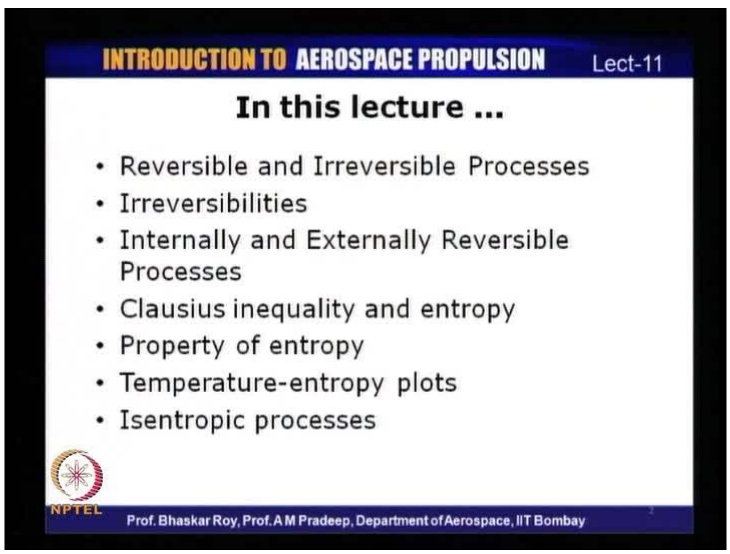


Towards the end of the last lecture, we also discussed about certain devices which seem to violate or which apparently seem to be very efficient and very attractive actually violate the second law of thermodynamics and these devices were termed as the perpetual motion machines of the second kind. So, this is what we had discussed in the last lecture.

What we are going to discuss in today's lecture are the following. We will be talking about reversible and irreversible processes and also we will look at what are the causes of irreversibilities, we shall then discuss about internally and externally reversible processes, we will then discuss about the Clausius inequality and entropy. So, entropy is basically a consequence of the Clausius inequality and then we will discuss in little more detail about entropy, which we will also discuss in subsequent lectures.

Then we shall be talking about temperature-entropy plots, we have already discussed about pressure and volume plots similarly, we also have temperature-entropy plots which are of significant in thermodynamics analysis. Towards the end of the lecture, we shall be talking about isentropic processes. We shall just get introduced to isentropic processes now. Few lectures later, we shall be discussing isentropic processes in more detail in later lectures.

As I mentioned few minutes ago that as a consequence of the second law basically the Kelvin-Plank statement, what we have is a statement which states that no heat engine can have an efficiency of 100 percent, which is also valid for ideal cycles. You might wonder then, how do we find the highest efficiency that any particular engine can have? What is the highest efficiency that a heat engine can basically have?

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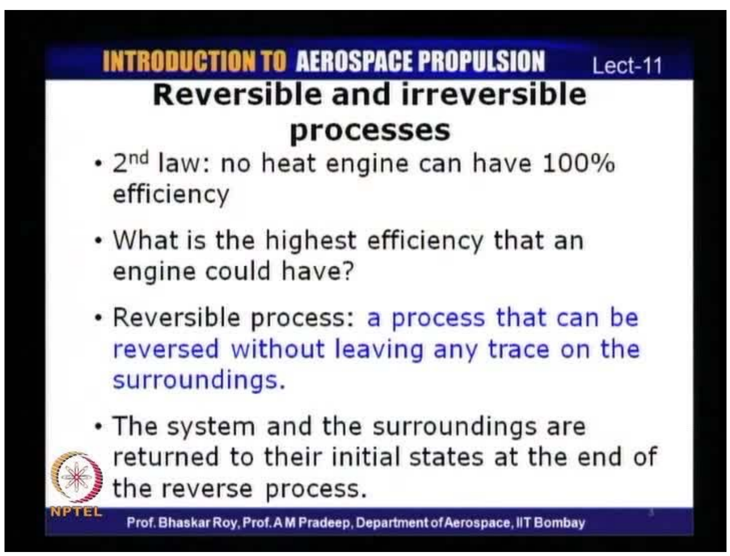


So, if we have to find out the highest efficiency possible for a given cyclic device or a heat engine we need define what are known as reversible processes. So, reversible process is one which can be reversed without basically leaving any trace on the surroundings. So, reversible processes are those processes where at the end of the process you can actually come back to its initial state and reversible process does not leave any trace of its occurrence on the surroundings, which also means that the system and the surroundings are returned to their initial states at the end of the reverse process. In reversible process it is possible to completely restore the initial states and it will appear as though such a process has never taken place because this process does not leave any trace on the surroundings.

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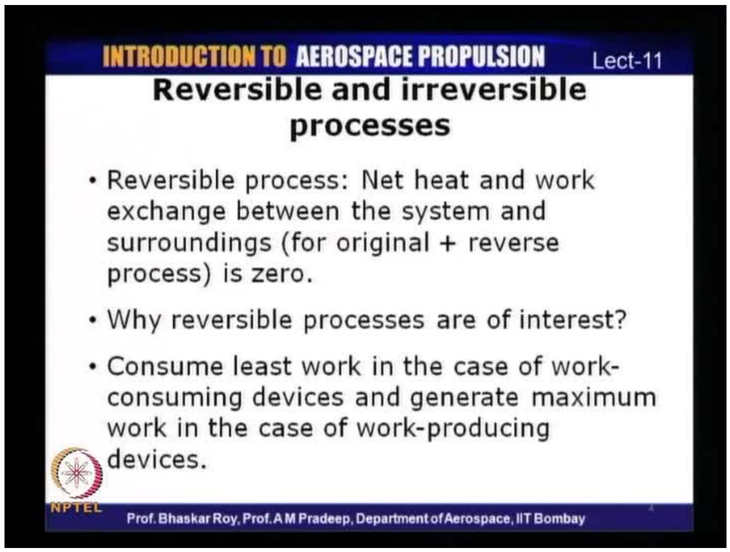


To define highest efficiency associated with any cyclic device or heat engine we will need to define basically reversible processes. In a reversible process the net work and heat exchange between the system and the surroundings which includes both the original and the reverse process will be 0. In a reversible process since the net heat and work exchange between system surroundings are 0.

Basically, you might wonder then what is it that makes reversible processes of interest? Why should one be interested in a reversible process? Well, reversible processes are a significant interest because these are devices which will consume the least work. If you were to consider a work requiring device like a pump or a compressor or a fan or so on, these are devices which require work input.

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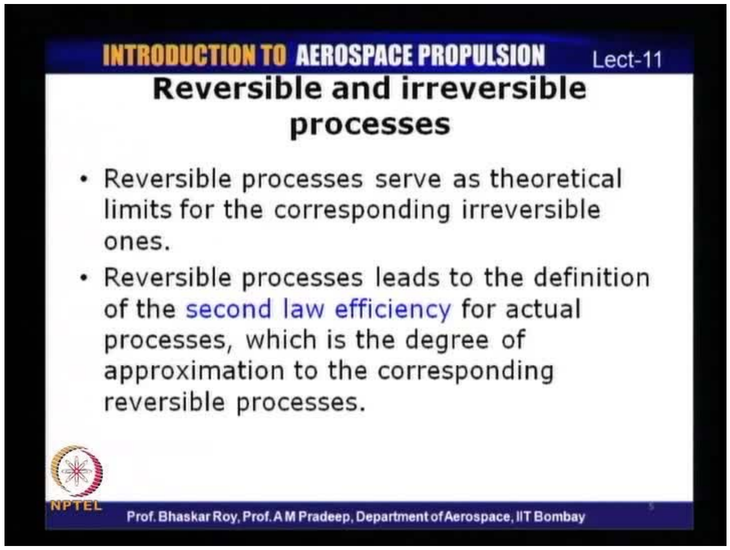


If this particular process was to be reversible these devices will require the least work and if you also consider those devices, which generate work like a turbine. Then in a reversible process or if the turbine is undergoing a reversible process then the turbine would be generating the maximum amount of work. So, this takes us closer to our question earlier on that why it is that efficiency cannot be 100 percent and therefore, what is the efficiency maximum efficiency that you can get? Because that is of interest to all designers and engineers that you would like to obviously maximize the efficiency of any particular process. So, the key to this maximizing the efficiency is to make the processes reversible.

As I just mentioned now that if you look at work producing device like a turbine a reversible process would give you the highest work and consequently you would have the highest efficiently possible if the process that is being undergone is reversible process. So that is why reversible processes are of interest to us, at least for in the thermo dynamics aspect of the process.

In this sense, the reversible processes will also serve as theoretical limits for the corresponding irreversible ones, which mean that if the irreversible cycle has some efficiency - thermal efficiency of let us say 30 or 40 percent. If the same process was to be carried out in a reversible manner then that efficiency that you get from the reversible process will be the maximum efficiency that you can get for the corresponding irreversible process. So, which means that you will obviously, not be able to get an efficiency which is higher than that what you get from a reversible process. Reversible processes also often lead to the definition of what is known as second law efficiency for actual processes.

Second law efficiency is basically a degree of approximation of the corresponding reversible process. We shall be discussing a lot more details of second law efficiency in subsequent lectures and we shall actually define second law efficiencies for different processes. Second law efficiency will basically tell us, what is the maximum efficiency that this particular process can get, if the processes were reversible.

Let us take an example; if you consider a turbine, usually turbines as a component have very high efficiencies because they are work producing devices and turbine efficiency is about 85 percent usually you would have slightly higher efficiencies as well. Defining a second law efficiency, you can actually get an idea of what is the maximum efficiency that you can get, if you were to try and make the processes reversible.

So, if you calculate second law efficiency, you may get something like 92 percent, 93 percent or may be little higher but, definitely not 100 percent because that is an infeasible process. Second law efficiency will basically set the theoretical limit for an actual process which could be irreversible process.

Let us also understand now, what are the causes of irreversibility? Why does basically a process or all processes, actual process, why is it said that they are irreversible? To understand the causes of irreversibility we need to understand, where does this irreversibility originate? One of the most common sources of irreversibility is friction and I am sure, you would also know that frictional losses are irreversible.

Now, to understand why it is that friction is irreversible? Let us take an example of a piston and cylinder assembly. Now, you know that as the piston moves within the cylinder assembly there is going to be a certain frictional loss between the friction, between the piston and the cylinder in a reverse. As a result of that there is a certain amount of energy which is lost in the friction and this is an irreversible process because it is not possible to get back that energy by providing the same amount of heat and that makes friction or frictional losses an irreversible process.

So, there are many other types or forms of irreversibilities as well besides friction; friction is one of the most common sources of irreversibility.

The other sources of irreversibilities are temperature or heat transfer across the finite temperature difference that is if you consider a heat transfer across temperatures, which are finite numbers then that makes the process irreversible. We will explore some example of this as well to understand, why they are irreversible. The other source of irreversibility could be frictional losses then finite temperature difference mixing of two fluids, for example, if you mix two fluids let us say, two different oils or water and alcohol the mixing process causes them to be irreversible because how do you retrieve the two fluids back and so mixing of two fluids is also an irreversible process.

Then electrical resistance, it is very similar to that of frictional losses electrical resistance is again an irreversible process basically because if you pass electricity through a resistor it causes heating up of the resistor but, if you transfer heat to the resistor obviously you do not get any electricity out of this resistor. So, electrical resistance or electricity passing through a resistor is basically an irreversible process.

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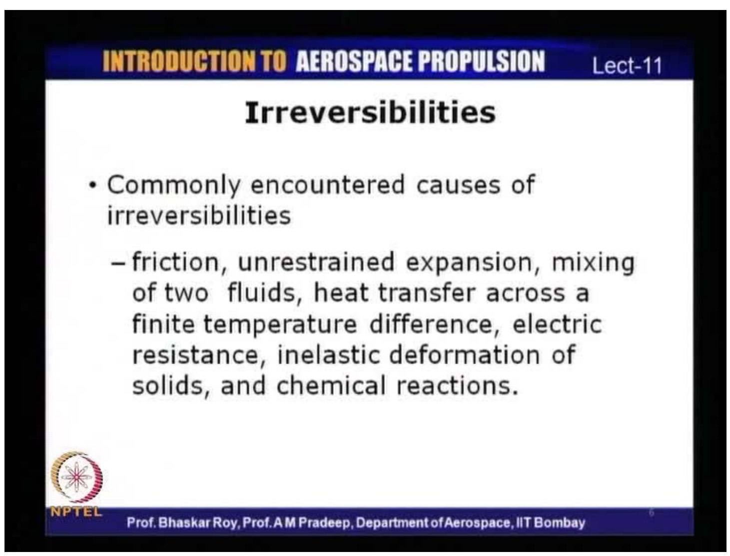


The other form of irreversibility is basically chemical reactions, if you consider reaction between two different chemicals after the reaction is over, you get a different chemical composition and it is not really possible to achieve the original products in the same way and that is why it makes it an irreversible process. Then inelastic deformation of solids let us say, if you were stretch a piece of iron rod and it causes an inelastic deformation - it extends and then that makes the process irreversible process.

Just go through the different types of irreversible processes I was mentioning about friction; friction is one of the forms of irreversible process then, unrestrained expansion unrestrained expansion is basically an expansion across a very high temperature of pressure difference, mixing of 2 fluids, heat transfer across finite temperature difference, electrical resistance, then inelastic deformation of solids and chemical reactions. So, these are some common sources or common causes of irreversibility. Of course, there are many more which can be defined but, there are obviously not very commonly observed. These are certain processes or irreversibilities or sources of irreversibilities in most of the today life.

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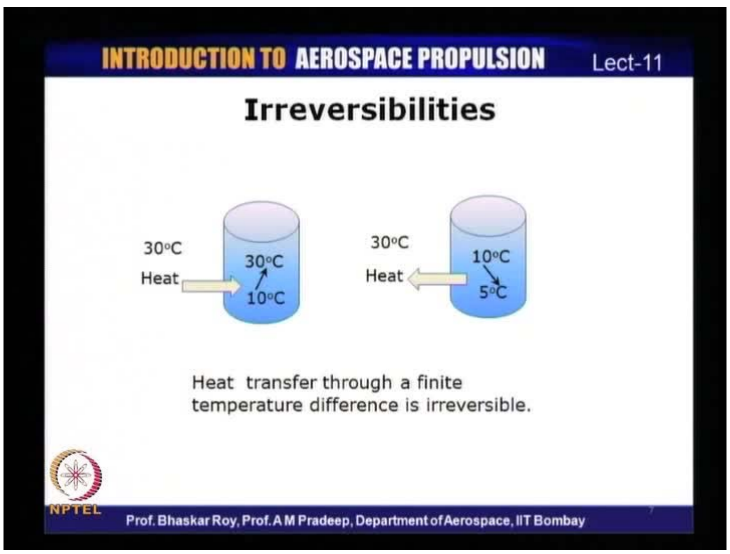


Now, I mentioned about heat transfer through a finite temperature difference. Let us consider a system here which is indicated by this can and the system was initially at a temperature of 10 degree celsius, the ambient is at 30 degree celsius. If the system was not to be insulated then we know that there is obviously going to be a heat transfer from the surroundings to the system and eventually the system will have a temperature rise from 10 degree celsius to 30 degree celsius. Now, if this process were to be reversible then it should be so possible that you can transfer heat from this 30 degree celsius back to the atmosphere and bring back the temperature to 10 degree celsius. We know that this is not possible because it violates the Clausius statement. So that is not possible without any influence of work or without any work done on the system.

Now that is what is shown on the right hand side that if you were to cool a system, which was originally at 10 degree celsius to 5 degree celsius, this is an impossible process as it has to transfer to heat from a low temperature medium to a high temperature medium. So, which is impossible naturally; it can occur only if you use a certain devices like refrigerator or a heat pump, so you can definitely reduce the temperature but, that requires a work input. So, such a process does not occur naturally. Therefore, heat transfer through a finite temperature difference is definitely an irreversible process.

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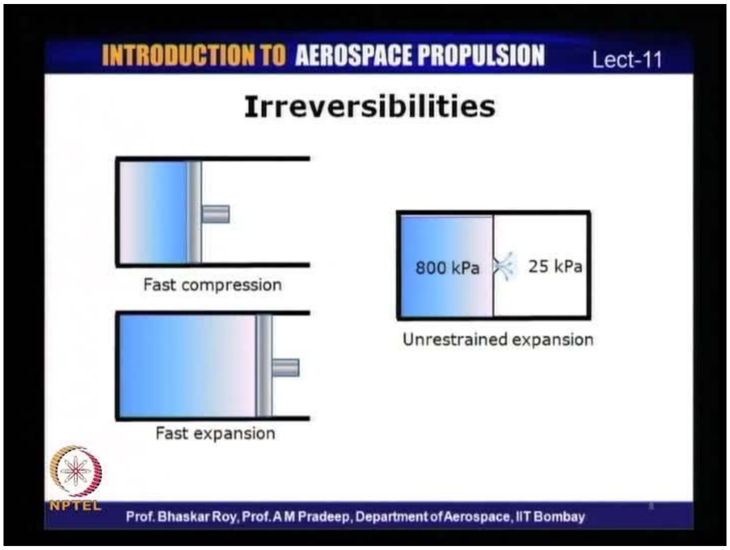


Other forms of irreversibilities I mentioned, fast compression that is if you consider a piston moving into the cylinder, at a very fast rate, at a finite rate that is definitely a source of irreversibility because the system will not be in pressure equilibrium at all instances of time. Similarly, fast expansion is also not a reversible process it is also a source of irreversibility and both these processes are basically not quasi static processes. Now, you might recall that in the beginning of the lecture series I mentioned that in thermodynamics we normally assume different processes to be quasi static or in quasi equilibrium, so both of these processes definitely are not in quasi static processes or they are definitely not in quasi equilibrium and therefore, obviously they are irreversible processes.

The other source of irreversibility is unrestrained expansion. Let us consider a system here which has a certain partitions at the center. On one side of the partitions you have a very high pressure for example, 800 kilo pascals. On the other side of the system we have a pressure of around 25 kilo pascal relatively low pressure.

Now, if this diaphragm was to be ruptured at the center or anywhere else if it is to be ruptured then, there is going to be a sudden expansion from this very high pressure to a very low pressure. So that eventually there is a pressure equilibrium or mechanical equilibrium which is maintained within the system boundaries. Therefore, unrestrained expansion is an irreversible process because it is not possible to obtain the original state by a natural process; that is you cannot restore the system to its initial state which had 800 kilo pascal on one side and 25 kilo pascal on the other side naturally.

You can obviously use special devices like a vacuum pump etcetera, to bring back to the system to the original state but that requires a certain work input. So, unrestrained expansion also is source of irreversibility. These are some examples of different sources of irreversibility friction being the most common source of a irreversibility, electrical resistance, heat transfer to a temperature difference which is finite, then fast compression fast expansion or unrestrained expansion chemical reactions and so on.

All these sources of irreversibilities causes real life processes to be irreversible, most of the real life in fact, all the real life process are irreversible. Though there are certain process which can be assume to be or approximated to be a irreversible process but in general, all real life processes are irreversible and that is why real life cycles or real life engines or processes do not attain the efficiency that is dictated by the second law, which is obviously less than 100 percent but, still that will be the maximum efficiency that you could obtain; because of these irreversibilities it is not possible to attain or achieve an efficiency equivalent to that of the highest efficiency possible.

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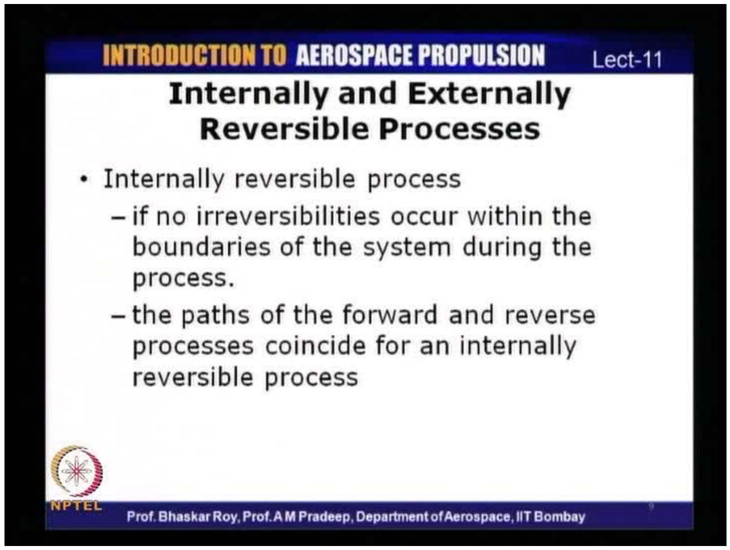


Now, we have looked at the different sources of irreversibilities. Let us also look at what are the types of reversible processes that are feasible. There are 2 types of reversible processes that are possible: internally reversible processes and externally reversible processes. An internally reversible process is one in which no reversibilities occur within the boundaries of the system during the process. So if there are no irreversibilities which occur within the system boundaries that make it an internally reversible process because it is only within the system boundaries that you have no irreversibilities.

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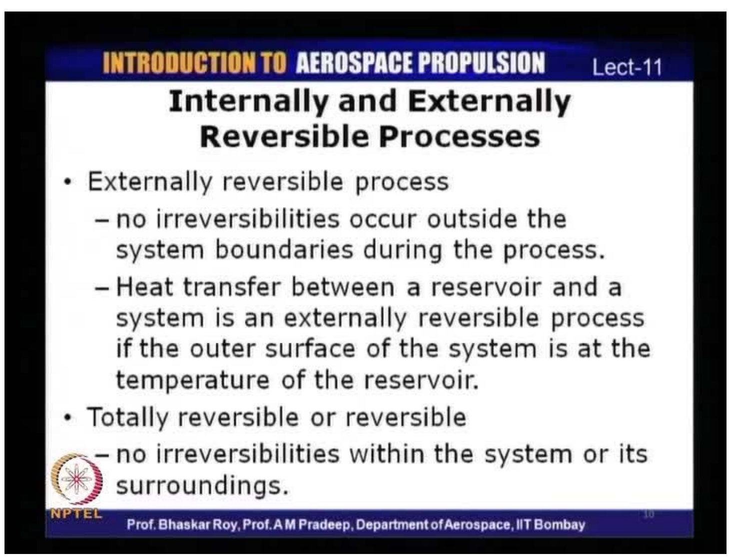

In this case, the paths of the forward and the reverse processes will coincide and this is true for an internally reversible process. The other type of process is an external reversible process. Externally irreversible process or externally reversible process rather is one in which no irreversibilities occur outside the system boundaries of the process; so outside the system boundaries you do not have any irreversibilities.

Now, heat transfer between a reservoir and a system is an externally reversible process if the outer surface of the system is at the same temperature of that of the reservoir; that is if the system outer surface has the same temperature as that of the reservoir even though there is a temperature heat transfer across finite temperatures it makes it externally reversible because the reservoir is basically having a constant temperature.

An externally reversible process means that the boundaries or across the system boundaries or outside the system boundaries the surroundings are basically do not have any irreversibilities. Like in a reservoir, you do not have any source of irreversibilities there. So a process which satisfies both these criteria that are externally reversible at the same time it is also internally reversible. Such a process is known as totally reversible or just reversible process.

So, when we talk about reversible process it is implicit that such processes are already internally reversible and also externally reversible. Those processes which satisfy both these criteria are basically known as totally reversible or sometimes just reversible process. So, when we refer to the term reversible we imply that it is internally as well as externally reversible process.

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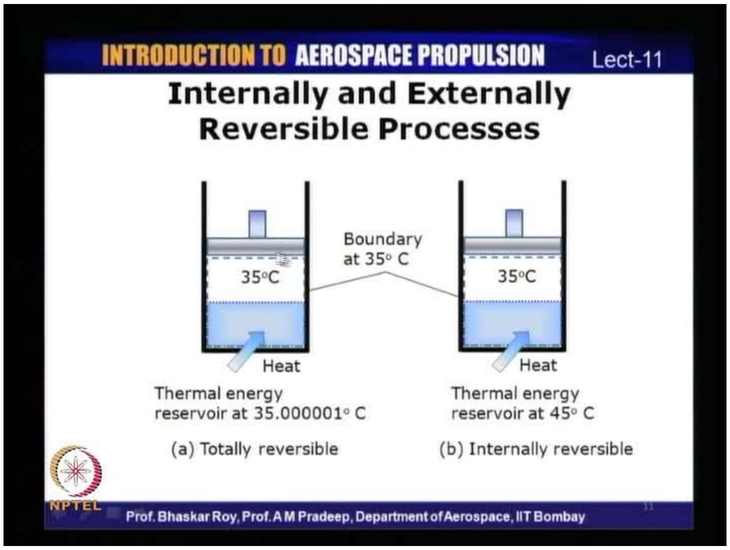


Now, we will just look at one example of system which can be in both these modes of operation. On the left hand side we have a system basically it is a 2 phase system. Let us say, water and steam, well not really steam because temperatures are pretty low but, it could be some other system which has a two phase - a liquid phase and gaseous phase. There is a heat transfer across the system boundaries making this process a constant pressure process and consequently, it is also an isothermal process. As this pressure is a constant of course, we allow the piston to change its position and that is why we can maintain the pressure as a constant.

In this case, the reservoir is at a temperature which is infinitesimally higher than the temperature of the system itself, so there is a heat transfer which is not exactly finite. Temperature difference, heat transfer is taking place through two different systems which infinitesimally close to each other in terms of temperature. So, thermal energy reservoir here is at a temperature of 35 point many 0s 1s, so it is a very infinitesimally higher temperature than that of the system.

Therefore, the boundaries can be assumed to be at 35 degrees because heat transfer is taking place across the boundaries. In this case, there are no irreversibilities occurring within the system boundaries because it is a constant pressure process, which means that it is in mechanical equilibrium, it is also at constant temperature and so it is in phase equilibrium the mass of both the phases eventually are same and there are no chemical reactions occurring.

So, this is basically a system in thermodynamic equilibrium that no irreversibilities within the system and there are also no irreversibilities outside the system. Therefore, this process or a system which is an internally reversible as well as externally reversible process and therefore, this is a totally reversible process. On the right hand side, on the other hand we have the system is at the same conditions as it was in the previous case that is on the left hand side; but now the thermal energy reservoir is at a higher temperature of around 45 degree celsius.

Now, if heat transfer was to take place across the system boundaries obviously that makes it externally irreversible because the temperature difference or the heat transfer is taking place across a finite temperature difference, which makes it externally irreversible. But, since the system has constant because the system is following a constant pressure process and it is at same temperature of 35 degree celsius it is in thermodynamic equilibrium and also there are no irreversibilities occurring within the system boundaries. So, this is basically a system which is internally reversible but not necessarily externally reversible.

Out of these two processes it is the first process which is a totally reversible or just a reversible process. The system that is shown on the left hand side corresponds to a reversible process. So, this is just to illustrate how we can have internal and external reversible process or what are the two different types of reversible processes that are possible? One of them is internally reversible that has that is there are no irreversibilities occurring within the system boundaries. The other is externally reversible which means there are no irreversibilities outside the system boundaries; a system which has both internal as well as externally reversible is known as a totally reversible or just reversible process.

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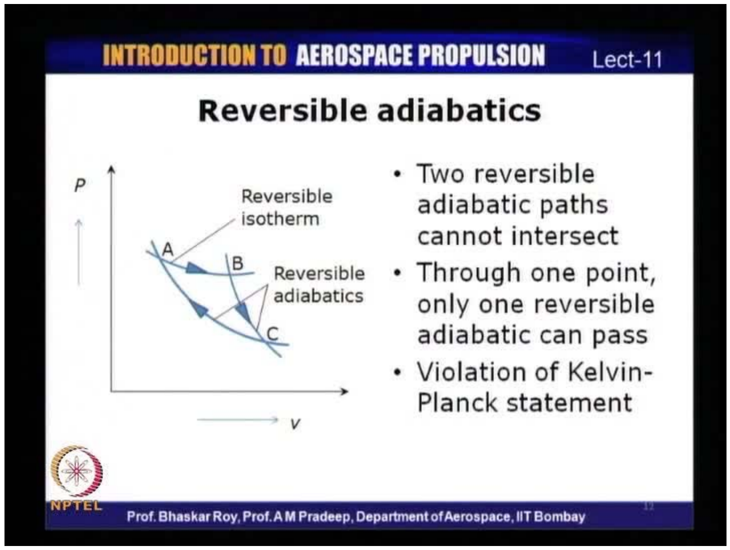


Let us look at one of the properties of reversible adiabatic processes. Now, what we shall look at is that what we see here is two reversible adiabatic processes and let us say, a reversible isotherm.

What we shall see is that by virtue of the second law of thermodynamics no two reversible adiabatic paths and intersect; that is reversible adiabatic paths cannot intersect. A reversible isotherm can intersect a reversible adiabatic but; reversible adiabatic cannot intersect that is through one point only one reversible adiabatic process can pass. Now, if you look at this process closely, now in this example, I have shown on the P V diagram we have shown two reversible adiabatic processes which are crossing at point C and of course, there is a reversible isotherm which crosses these reversible adiabatic at A and B.

Now, together these three different processes form a cycle and you can see that together they can form a cycle but, there is a net area under this curve it means that there is a net work output by this particular set of processes. But, it is transferring heat with only one reservoir that is basically the isothermal process. So it is during this process, you would transfer heat to this cycle.

Here, we have a cyclic device which is generating a network output but, transferring heat with a single reservoir. This is a clear violation of the Kelvin-Plank statement and so it means that or it proves that reversible adiabatic processes cannot intersect. On the other hand, if you had a reversible adiabatic which was parallel to the first let us say, the B C process you would need to have a reversible isothermal which can cross the reversible adiabatics and we shall see little later that this is basically corresponding to a Carno cycle. Carno cycle is the cycle which consists of two reversible adiabatics and two reversible isotherms. So, this is one process or property that you need to keep in mind that reversible adiabatic process cannot intersect.

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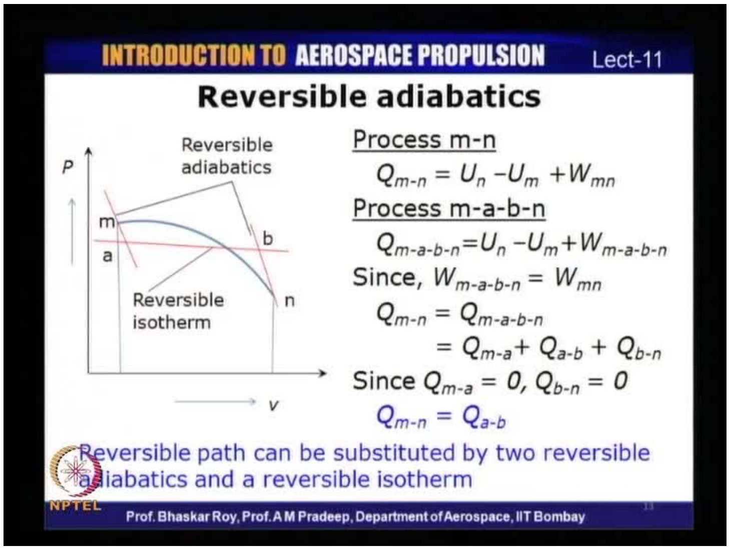


What we shall now look at is that reversible adiabatic, if you were to carryout thermodynamic analysis of a system which has reversible adiabatic processes and isotherms you may have to at times do some manipulation to be able to analyze the whole process in a better way.

So, one of the process one of the properties that we shall probably be using some time little later is that a reversible adiabatic can be substituted by two reversible isotherms and one reversible adiabatic. So, if you look at this particular process, the reversible isotherm is shown by the path or the red line between a and b. We have reversible adiabatics which are shown by this parallel lines m a and n b and this blue line here is the reversible path. So, what we are going to prove is that any reversible path can be substituted or replaced by two reversible adiabatics and one reversible isotherm.

As we have already seen reversible adiabatics cannot intersect and therefore, these two lines have to be or these two reversible adiabatic paths have to be parallel. You can also have a reversible isotherm which can obviously intersect these two reversible adiabatics.

For the reversible process which was for the process m n, from the first law we have Q m-n which is heat transfer during the process m n is equal to U n minus U m plus W m-n. Now, U n and U m are the final and initial internal energies of this particular process, W m-n is the net work done by this process. So, this is as per the first law.

Since, we are saying that we can replace it by two adiabatic: reversible adiabatics and reversible isotherm. Let us look at the path m a b n. For this path if you were to apply the first law of thermodynamics. Before that let me mention that when we create this replacements for the reversible path we make sure that the net area under the reversible path which is known already is also equal to the area under this path here. So, the net area under the reversible path will be the same as area under m-a-b-n.

As per first law Q m-a-b-n is equal to again U n minus U m plus W m-a-b-n. The change in internal energy is the same because internal energy is a property of a system it is not a path function and does not depend upon how a process is carried out. But, heat transfer and work both are path functions; they depend upon the path taken by the process.

Since, I mentioned that the work done by the both the processes are same W m-a-b-n is equal to W m-n and therefore, Q m n is equal to Q m-a-b-n, which is also equal to Q m-a plus Q a-b plus Q b-n or heat transfer during m-a, heat transfer during a-b and heat transfer during b-n. Now, Q m-a is basically a reversible adiabatic process and since it is adiabatic Q m-a is equal to 0 that is also true for Q-b and which is also a reversible adiabatic that is equal to 0. Therefore, Q m-n is equal to Q a-b.

Basically, what does means is that any reversible path can be substituted by two reversible adiabatics and one reversible isotherm, so this is another property of a reversible process that you can substitute a reversible process using three processes two of them are reversible adiabatics and one is a reversible isotherm.

What we shall understand or look at next is what is known as the Clausius inequality. Now, as a consequence of Clausius inequality we shall come across a very important term in thermodynamics which is known as entropy. Entropy is a certain property of a system which we shall understand in very much detail in today's lecture as well as subsequent lectures. To define or understand the Clausius inequality let us take a look at a system which is receiving heat from a cyclic device - a reversible cyclic device, which intern is receiving heat from a thermal energy reservoir.

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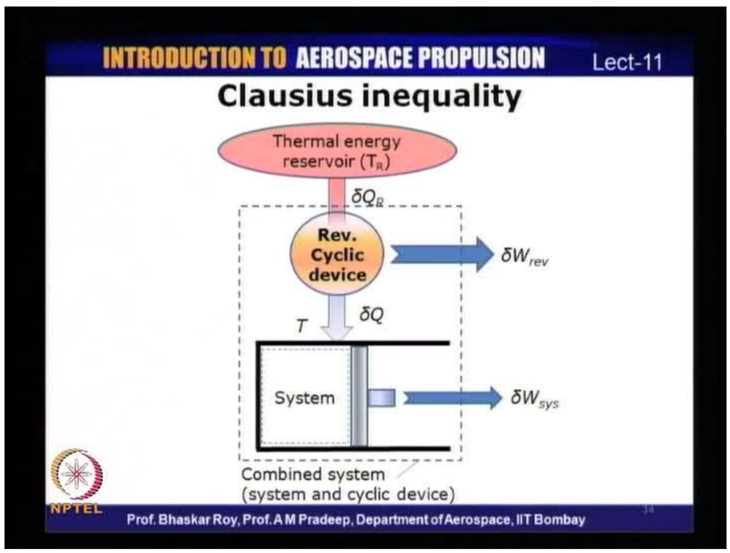


Here we have a thermal energy reservoir, which is at a temperature of T R which is transferring heat to the reversible cyclic device at delta Q R. The system which we are looking at is basically receiving heat from the reversible cyclic device at delta Q and the system is at a temperature of T. So, the system because it is receiving heat from a cyclic device it is doing certain work which is given by delta W sys or W system. Reversible cyclic device also does a certain work output which is delta W reversible.

Now, both this cyclic device as well as the system together constitutes a combined system which consists of the system which is of interest to us as well as, the cyclic device which is the reversible cyclic device, it could be a heat engine or it could be any other cyclic device. The combined system is enclosed in these dotted lines as shown.

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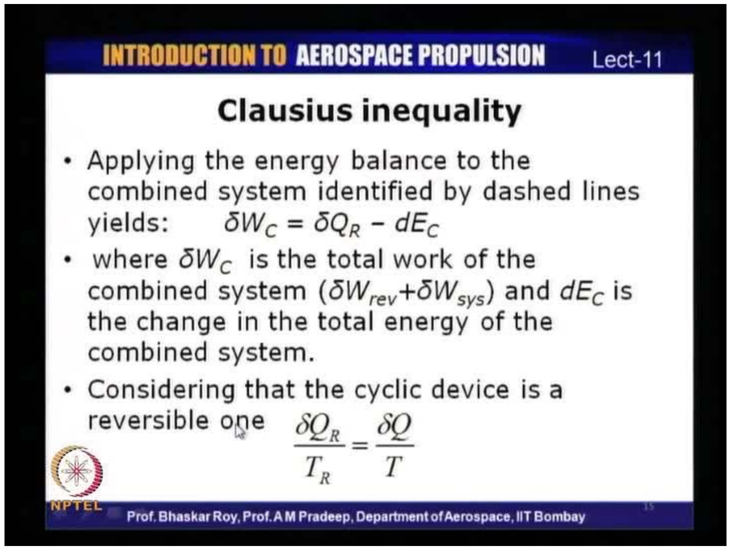


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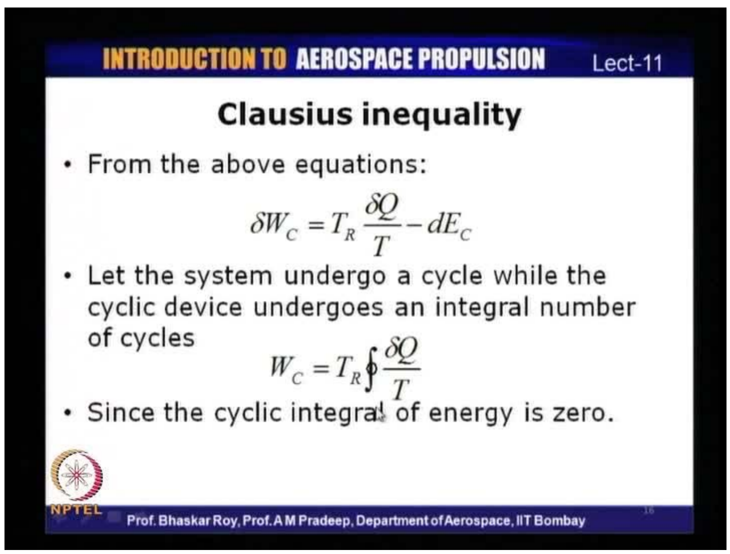


If you were to apply the energy balance to the combine system that we have seen which consist of the system as well as the cyclic device, the network output delta W C is equal to delta Q R minus d E C. Now, delta W C is the total work of the combined system which consists of the work done by the reversible cycle as well as the work done by the system. So, delta W C is equal to delta W reversible plus delta W system and d E C is the change in total energy of the combined system.

For a cyclic device we already know that because it is reversible delta Q R by T R is equal to delta Q by T, because for a cyclic device which is reversible these already known that delta Q R by T R is equal to delta Q by T. So, if you go to substitute for delta Q R in the work equation that we had written first, then that equation reduces to delta W C is equal to T R delta Q by T minus d E C. Let the system undergo a cycle and the cyclic device undergoes an integral number of cycles, so the system that we discussed earlier.

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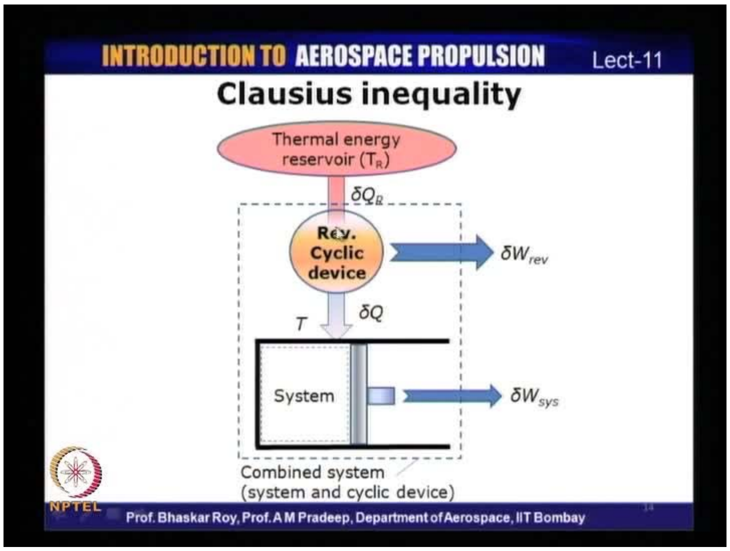


Let us say, it is undergoing a cyclic in the meantime this is the cyclic device obviously undergoes an integral number of cycles. If that were to be the case, because both of them are undergoing cyclic process d E C will be equal to 0, because for a cyclic process the net change in any property will be equal to 0. Therefore, W C net work done will be equal to T R cyclic integral delta Q by T that is because d E C is basically equal to 0.

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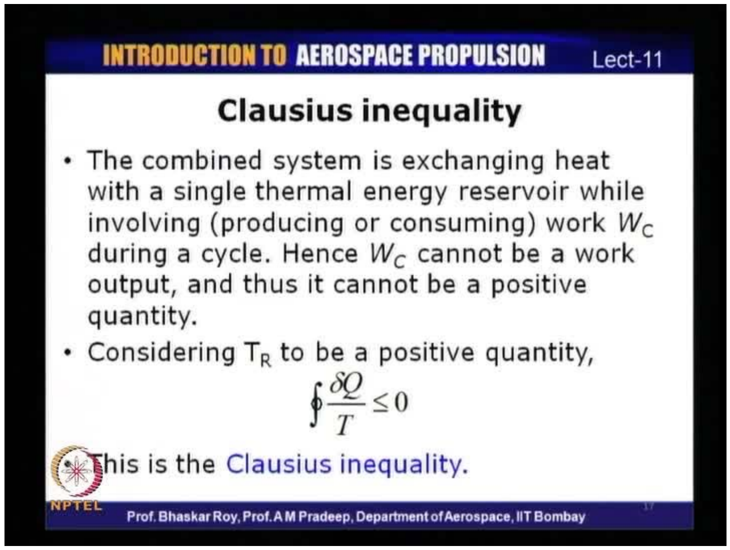


Now, what we see is that the combined system is basically exchanging heat with a single thermal energy reservoir and it is generating a network output of W C, which we have seen if this was to be true then it clearly violates second law of thermodynamics, because you now have a system which in combination with the cyclic device, the combined system is generating a network output equal to W C. It is interacting with just one reservoir so, obviously that will be a violation of the second law of thermodynamic; so it means that W C cannot be a network output.

If second law of thermodynamics was not to be violated and also if we consider T R the reservoir temperature to be a positive quantity, which is true because T R is a thermodynamic temperature in kelvin, it cannot be negative. So, if T R verse to be positive quantity this would mean that if W C was not to be the work output, then cyclic integral d Q by T should be less than or equal to 0. This property of cyclic integral delta Q or d Q by T less than or equal to 0 is known as the Clausius inequality.

There is a lot of significance to the Clausius inequality which we shall explore shortly so, cyclic integral d Q by T less than or equal to 0 is known as Clausius inequality. So, what is the consequence of the Clausius inequality?

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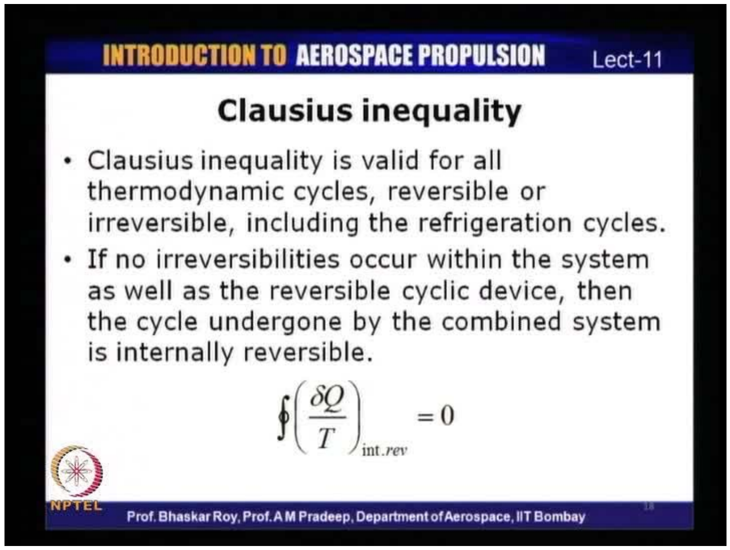


Basically, what we have seen is that the cyclic integral d Q by T less than or equal to 0 means that for a combined system example that we are looking at the net work output obviously cannot be positive, because it is exchanging heat with just one reservoir and which is as a consequence of the second law. We had to state that cyclic integral of d Q by T should be less than or equal to 0.

If you look at the Clausius inequality its basically valid for all thermodynamic cycles whether it is reversible or irreversible or if it is a refrigeration cycle, it is true for all these processes; but if no reversibilities, irreversibilities occur within the system as well as within the cyclic device, then the cycle undergone by the combined system is basically internally reversible. For an internally reversible process cyclic integral d Q by T will be equal to 0. So, the equality in the Clausius inequality is valid only for an internally reversible process.

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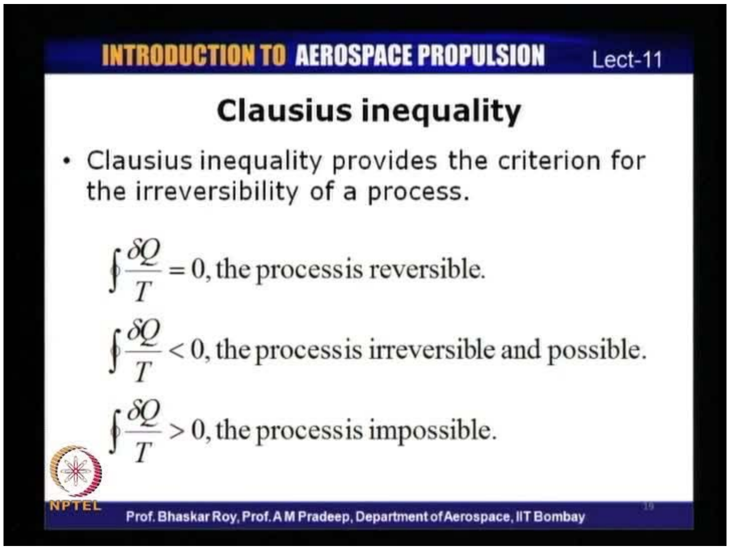


Clausius inequality provides the criterion for the irreversibility of a process; you can basically define the irreversibility of a process using the Clausius inequality. So, Cyclic integral d Q by T equal to 0 means that the process is reversible, cyclic integral d Q by T is less than 0 means the process is irreversible and it is a possible process or a feasible process, but cyclic integral d Q by T greater than 0 is impossibility, so such a process is impossible.

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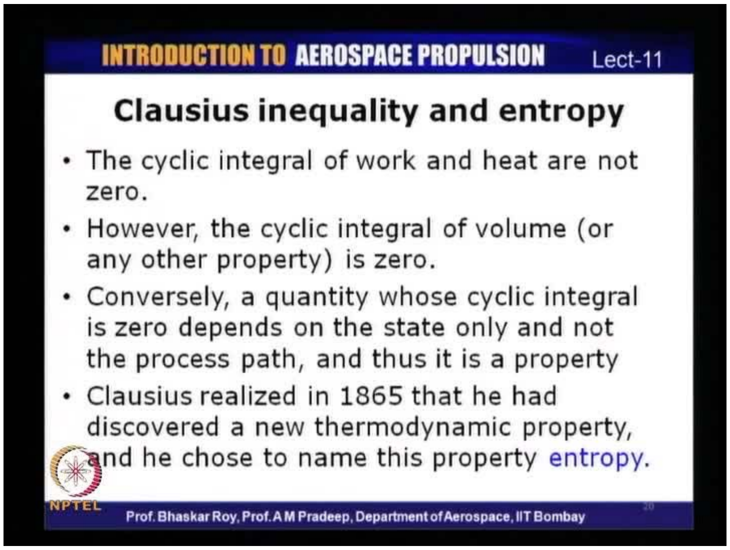

Now, we already have seen that cyclic integral of work and heat are not 0, but cyclic integral of a property like a volume or pressure etc is 0. Therefore, a quantity whose cyclic integral is 0 it basically depends only on the state and not on the process path and thus it should be a property. So, Clausius in late 1860s realize that if that was to be the case we have a new property here, because cyclic integral of d Q by T is equal to 0 for a reversible process, which means that there is cyclic integral d Q by T has to be a property of a system and Clausius shows to name this property as entropy.

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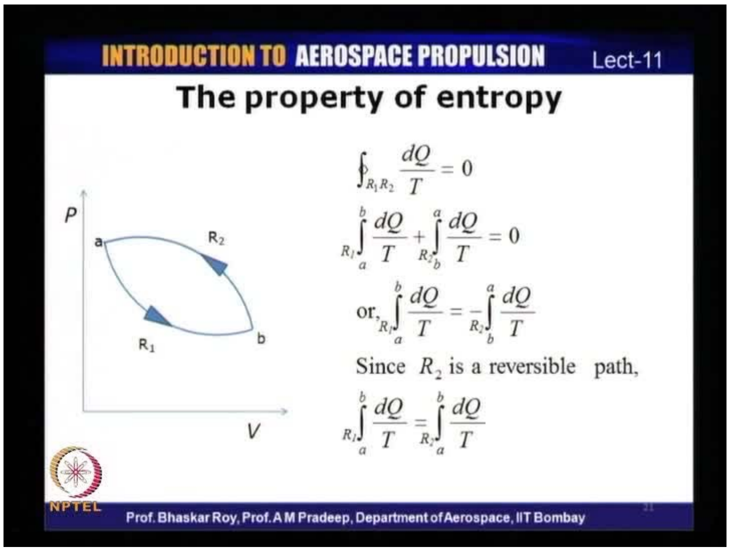


This cyclic integral d Q by T was named as entropy by Clausius in 1865. Let us look at the property of entropy a little carefully, here we have 2 processes given by R 1 and R 2 occurring between states a and b. So, cyclic integral R 1 R 2 that is for both the reversible processes both R 1 and R 2 are reversible process, d Q by T should be equal to 0 or cyclic integral from a to b for R 1 d Q by T plus cyclic integral from b to a for R 2 d Q by T is equal to 0 which is cyclic integral a; well not cyclic, it is just cyclic integral a to b R 1 d Q by T is equal to minus b to a R 2 d Q by T. Since, R 1 and R 2 both are reversible paths or reversible processes integral a to b R 1 d Q by T is equal to integral a to b R 2 d Q by T.

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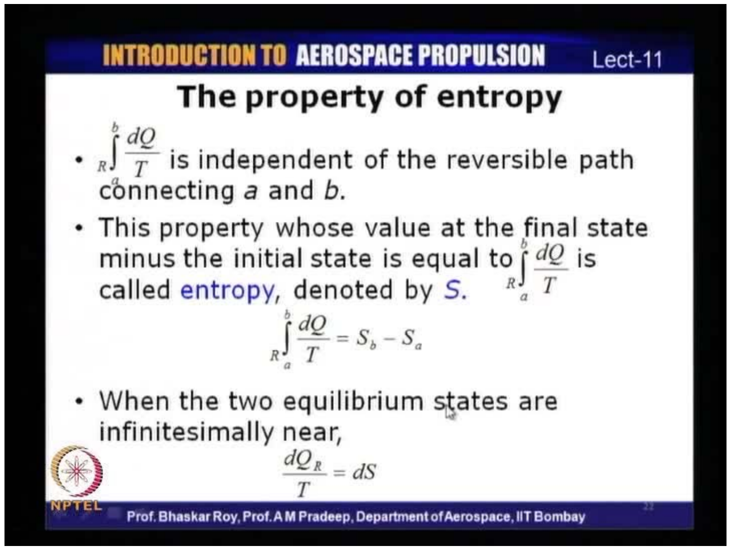


This means that integral a to b d Q by T is independent of the reversible path connecting a and b. It does not depend upon how the processes carried out, it just depends upon the end states a and b. This property that whose value basically depends upon the final state minus the initial state and is equal to integral d Q by T is called entropy as we have just now defined and it is denoted by the symbol S. So, integral a to b for reversible process d Q by T is equal to S b minus S a. If the 2 equilibrium states are infinitesimally near, then d Q R by T is basically equal to d S.

So, entropy is basically equal to the integral between the initial and final states of d Q by T applied for a reversible process. For a reversible process it is possible to equate integral d Q by T as the difference in the entropies or difference delta S. This particular property that is entropy is basically equal to the integral of d Q by T applied for a reversible process between the initial and the final states.

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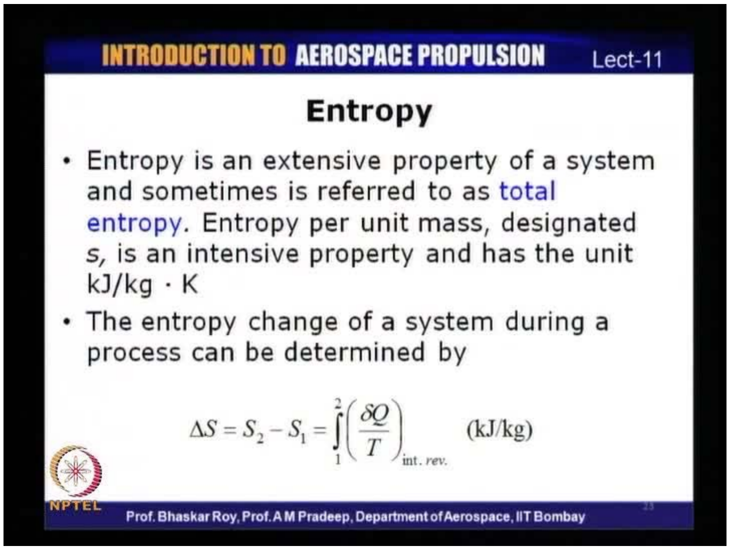


Entropy is basically an extensive property, we have denoted entropy by capital S; capital S would be entropy because it is extensive entropy, it is also referring to as the total entropy. Entropy per unit mass which is small s is basically an intensive property and it has units of kilo joules per kilogram Kelvin. So, entropy change of any of a system during a process can be determine by delta S is basically equal to S 2 minus S 1, which is integral 1 to 2 d Q by T if the process is internally reversible.

So, this equality of S 2 minus S 1 is equal to integral d Q by T is applicable for reversible process. We shall see later on that for actual processes or irreversible processes, we shall have an inequality here that is entropy will be always greater than integral d Q by T. We shall look at that in detail in next lecture.

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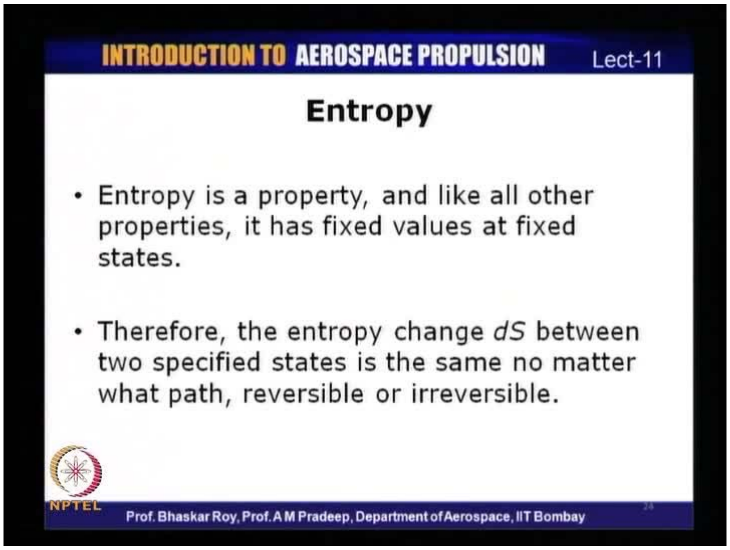


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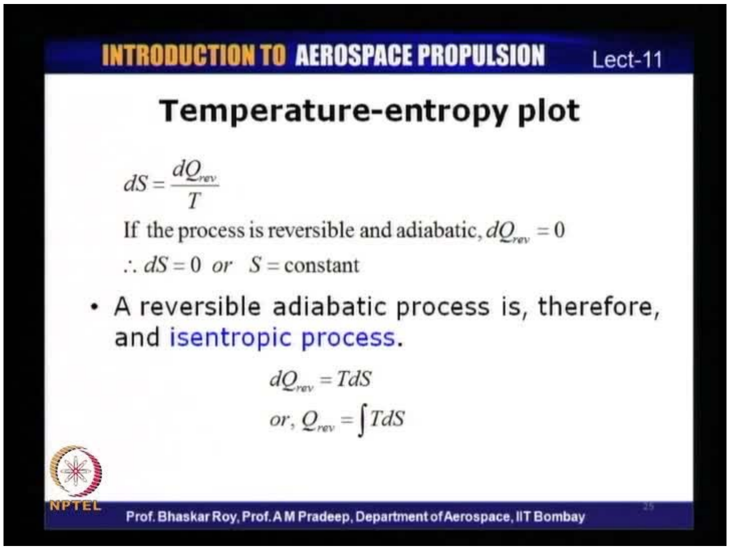


Now, entropy as we have already seen is a property; like all other properties it has fixed values at fixed states. Therefore, entropy change between 2 specified states is the same irrespective of what path is taken weather it is reversible or irreversible and so on. So, entropy basically depends upon the end states because it is a property of the system. We have already seen that for a reversible process d S that is change in entropy is equal to d Q for a reversible process by T.

If the process was adiabatic in addition to being reversible, then d Q will be equal to 0. If d Q is equal to 0 it would mean that d S is also equal to 0 or S will be equal to constant that is a reversible adiabatic process will therefore, be an isentropic process. That is if the process is reversible as well as it is adiabatic, then such a process will be also isentropic, because we have seen that d S is d Q reversible by T. In addition to being reversible if it was also adiabatic, then d Q will also be equal to 0 which means, the d S is 0 or entropy S will be a constant. So, a process in which entropy is a constant is known as an isentropic process.

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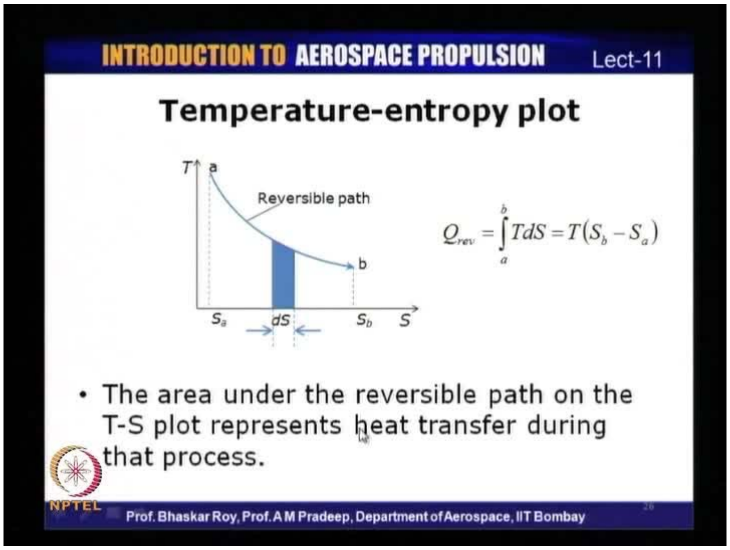


So, d Q reversible is also expressed in as T integral of T times d S integral T d S is equal to heat transfer Q d reversible so, heat transfer Q reversible is integral T d S. Now, what is the significance of this is what we shall see in this slide that if we look at a plot of temperature verses entropy, on the y axis we have temperature; on the x axis we have entropy. Let us consider a reversible path between a and b, states a and b. So, Q reversible is integral a to b T d S or if it is an isothermal process we have T times S b minus S a which means that area under the curve in a T-S plot or a T-S diagram represents the heat transfer during this process. You might recall that in the case of a P V diagram the net area under the curve was equal to the net work done during the process.

If the coordinates of or if the process is expressed in terms of temperature and entropy or in a T S diagram, then the area under a reversible path will basically represent the heat transfer that has taken place during this process. If we also look at let us say differential area as I showed here as d s and this is a reversible path between states a and b. Therefore, the entropy at state a is S subscript a, entropy at state b is S b. If you were to find out the heat transfer, which has taken place during this process a b which is a reversible path, then Q reversible is simply equal to integral of a to b T d S which basically comes from our expression for entropy where d S was equal to d Q by T for a reversible process.

Therefore, Q reversible is integral a to b T d s, which is equal to T times S b minus S a. Integral the area under the path for a reversible path basically on a T-S plot represents the heat transfer during that process. We shall see during analysis of different cycles later on that we shall be using both the P V diagram as well as the T S diagram very frequently.

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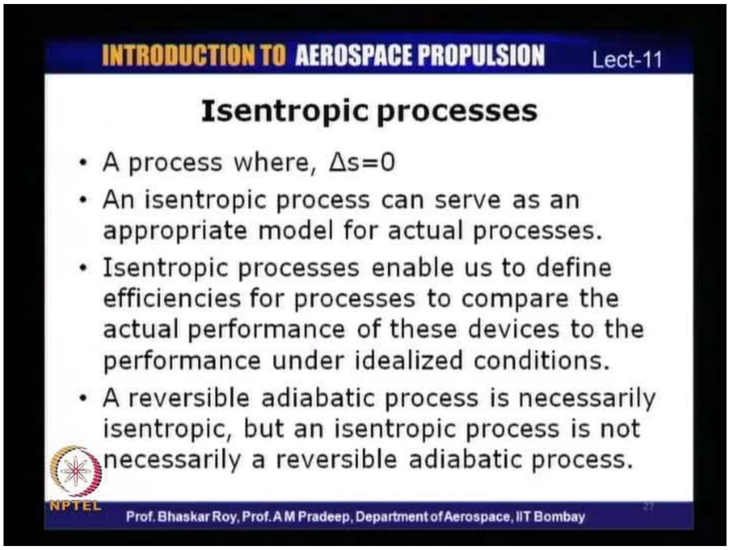


I already mentioned that a process in which the net entropy is equal to 0 or if delta s is equal to 0, then that is an isentropic process. So, what is a significance of an isentropic process? An isentropic process can basically serve as an approximate or an appropriate model for an actual process.

From an isentropic process, we can get an idea of what the actual well; we can approximate the actual process to that of an ideal process if we know the corresponding isentropic process. Isentropic processes basically help us in defining certain efficiencies associated with a process, which basically compares what the performance of a process in practice is as compared to if the process was to be isentropic. You can basically define efficiencies or isentropic efficiencies as they are called of different components like compressors and turbine etc.

Another property that we need to know is that we already know that a reversible adiabatic process is isentropic. If a process is reversible and if it is also adiabatic, then it qualifies to be an isentropic process, but an isentropic process need not be reversible or adiabatic. So, a process which is reversible and adiabatic will always be isotropic, but an isentropic process need not necessarily mean that it is reversible or adiabatic.

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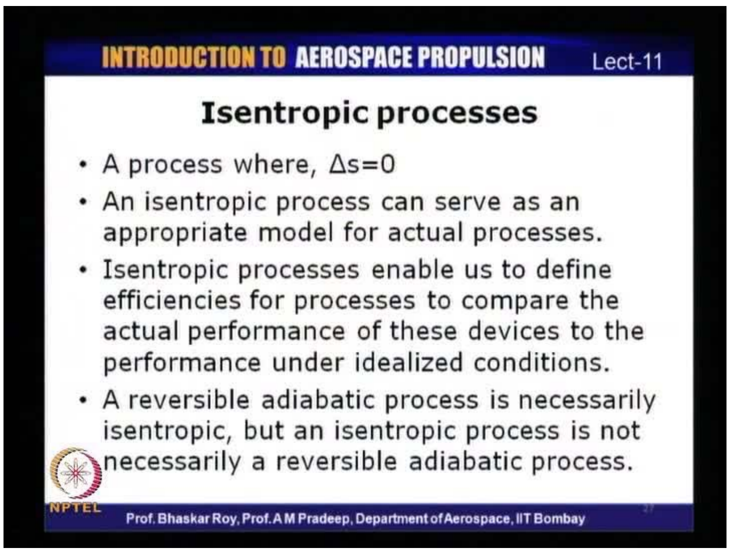


Because an isentropic process may also be true if you have net increase in entropy during some parts of the process, which is compensated by decrease entropy during other parts of the process. This may occur through heat transfer, through finite temperature difference which will make it an irreversible process even though the entropy is a constant. Net entropy delta s will be equal to 0, which means it is an isentropic process, but it need not necessarily mean it is reversible and adiabatic, but a reversible and adiabatic process is necessarily an isentropic process.

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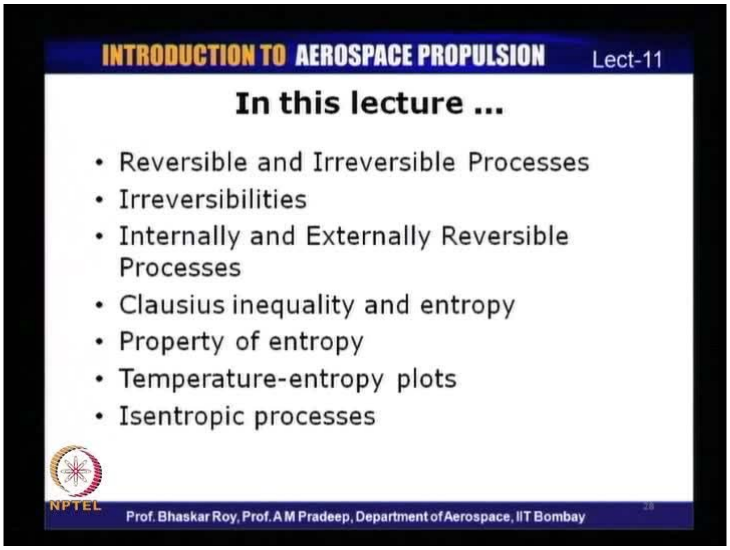


So that brings us to the end of this lecture. Let us quickly recap what we had discussed during this lecture. In this lecture, we were discussing about reversible and irreversible processes and we also discussed about the sources of different irreversibilities in a process. We then discussed about the types of reversible processes, internally as well as externally reversible processes. Then we looked at Clausius inequality and entropy as consequence of the Clausius inequality. Clausius inequality is basically stating that cyclic integral d Q by T is less than or equal to 0. That is applicable for all processes whether they are reversible or irreversible.

Entropy is a consequence of the Clausius inequality that is integral d Q by T will be equal to a property known as entropy for a reversible process. We also discussed about the property of entropy that it is a property of a system. Therefore, it does not depend upon the path taken by the system depends only on the end states.

Then we discussed about temperature and entropy plot basically for reversible process or reversible path area under the T-S diagram or temperature entropy plot gives you the heat transfer during that particular process. Towards the end of the lecture, we were discussing about isentropic processes which are processes where net entropy or net change in entropy is equal to 0.

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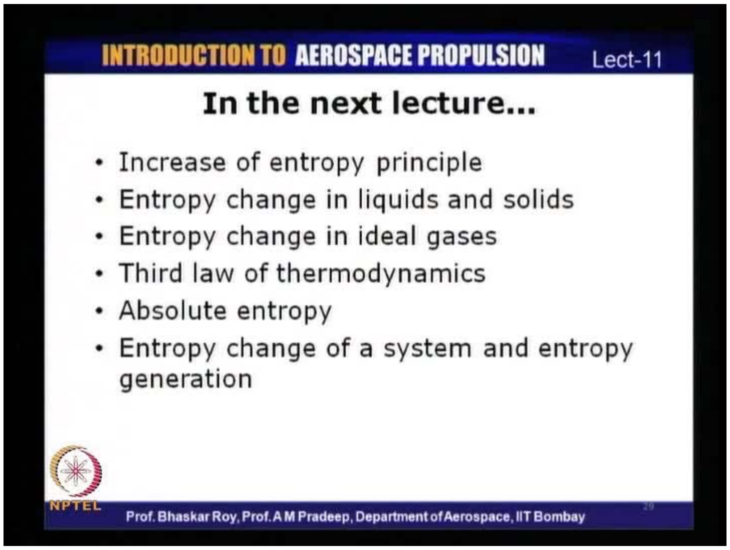


In the next lecture, what we shall discuss about the increase of entropy principle. We shall look at what is known as increase of entropy principle that entropy of the universe is increasing we will discuss that in the next class. We shall derive expressions for entropy change in liquids and solids and also entropy change in ideal gases.

We shall then talk about type third law of thermodynamics and absolute entropy as a consequence of the third law of thermodynamics. Then in the next lecture we shall also discuss entropy change of a system and also what is known as entropy generation for a process. So, all real processes will have a certain amount of entropy generation associated with them and that we shall take up during the next lecture.