Introduction to Aerospace Propulsion

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Module No. # 01

Lecture No. # 06

Specific heats at constant pressure and volume work and heat transfers

Hello and welcome to lecture 6 of this lecture series on introduction to aerospace propulsion. In the previous lectures, we have looked at different aspects of fundamental thermo dynamics like defining very basic terms which are to be used throughout this course of thermo dynamics.

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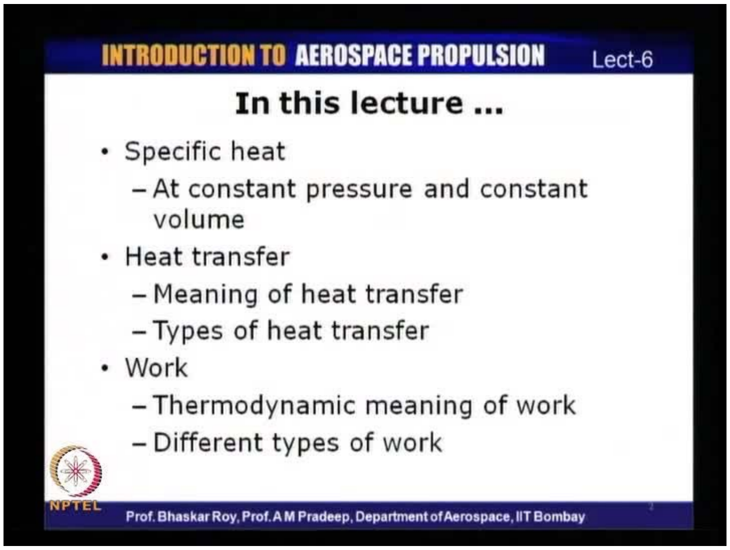

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

In this lecture ...

- Specific heat
  - At constant pressure and constant volume
- Heat transfer
  - Meaning of heat transfer
  - Types of heat transfer
- Work
  - Thermodynamic meaning of work
  - Different types of work

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In this particular lecture, we are going to take it forward and look at some more aspects of basic thermo dynamic interactions. Let us take a look at what we are going to get introduced to in this particular lecture. Now, in this lecture, what we going to look at are the following: we shall at the beginning understand what is meant by specific heat; we shall define specific heat and also define specific heat for two different cases or specific heat in two different forms known as specific heat at constant pressure and specific heat at constant volume.

Subsequently, we shall look at different forms or modes of energy interactions. One of them is heat transfer. We shall understand the thermo dynamic meaning of heat transfer and also look at the types of heat transfer and then we shall look at the other type of energy interaction that is known as work. We shall understand the basic meaning or thermo dynamic meaning of work and also look at different types of work interactions.

As we are already aware that it takes different amounts of heat or energy to raise the temperature of a given substance or identical masses of different substances.

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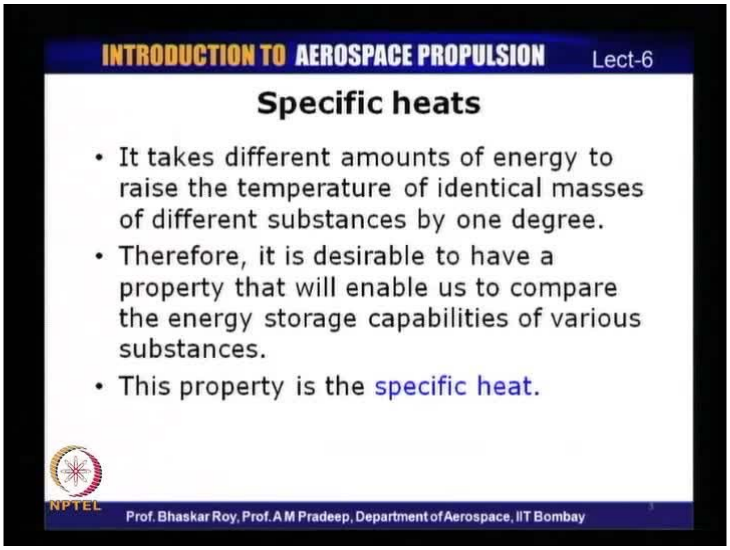

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Specific heats

- It takes different amounts of energy to raise the temperature of identical masses of different substances by one degree.
- Therefore, it is desirable to have a property that will enable us to compare the energy storage capabilities of various substances.
- This property is the specific heat.

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For example, if you would like to raise the heat of water by a particular temperature and if you would like the same amount of mass of iron to be heated to the same temperature then we know that it takes different amounts of heat. Based on this property, we shall define what is known as specific heat. Specific heat is a property that helps us in understanding how much is the amount of the temperature or energy required to raise the temperature of identical masses.

Therefore, it is desirable that we have a property that will enable us to compare the energy storage capabilities of different substances and this property is what we shall define as specific heat.

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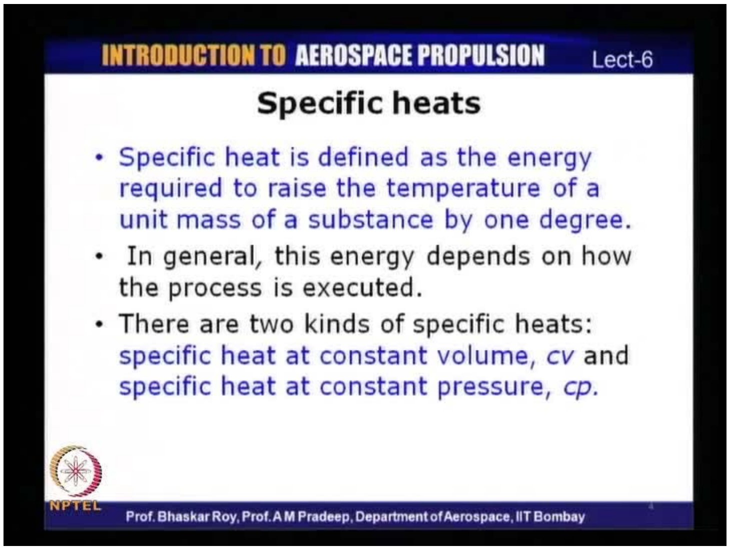

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Specific heats

- Specific heat is defined as the energy required to raise the temperature of a unit mass of a substance by one degree.
- In general, this energy depends on how the process is executed.
- There are two kinds of specific heats: specific heat at constant volume, *cv* and specific heat at constant pressure, *cp*.

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So, specific heat by definition is the energy required to raise the temperature of a unit mass of a substance by one degree. In general, this energy depends upon how this process is executed. Based on this, we can define two kinds of specific heat. One is known as specific heat at constant volume and the other is known as specific heat at constant pressure. If you were to look at specific heat as a property, which we shall see very shortly that specific heat is basically a property of a system. As we have already seen, properties are certain characteristics that define the state of a particular system.

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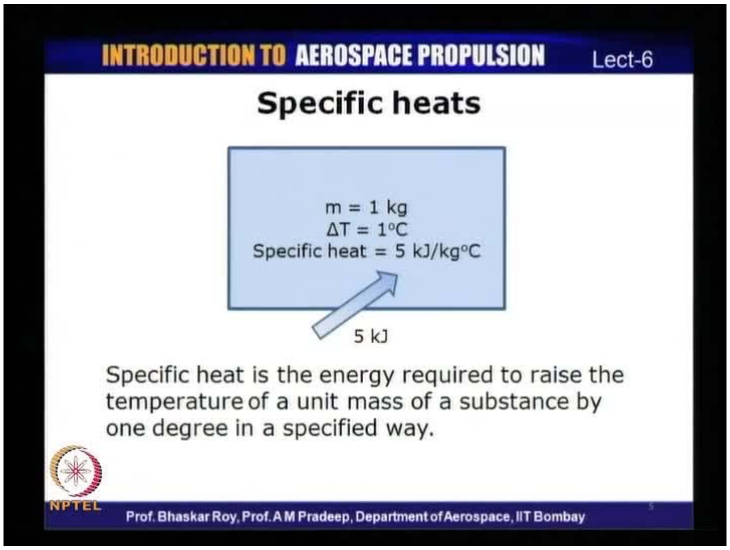

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Specific heats

Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

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Now, let us look at an example of how we can define specific heat for a particular substance for a particular process. Now, what is shown here is a particular mass which is let us say 1 kg and we have to increase its temperature by delta T which is equal to 1 degree celsius. If this is the case, then we will need 5 kilo joules of energy to accomplish this - that is to raise the mass of 1 kg by 1 degree celsius.

Therefore, specific heat would be the amount of energy required to raise the temperature of a unit mass which is 1 kg by 1 degree celsius in a specific way. Therefore, the specific heat for this particular process will be 5 kilo joules per kilo gram degree celsius. This is how one would define specific heat for a particular process.

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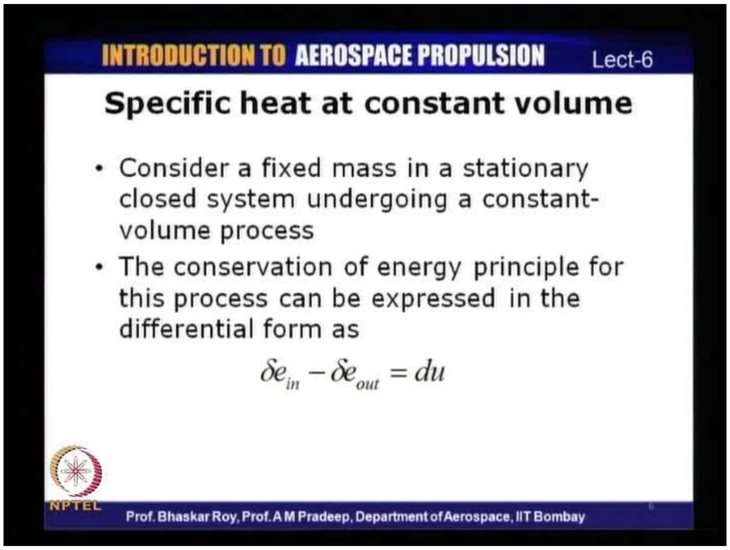

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Specific heat at constant volume

- Consider a fixed mass in a stationary closed system undergoing a constant-volume process
- The conservation of energy principle for this process can be expressed in the differential form as

$$\delta e_{in} - \delta e_{out} = du$$

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Now, let us now consider a fixed stationary mass of a closed system undergoing constant volume process. As I had already mentioned that specific heat can be defined in two different ways depending upon how the process is carried out. One of them is known as specific heat at constant volume and the other is known as specific heat at constant pressure. Let us now define specific heat at constant volume and also find specific heat at constant volume in terms of known properties.

Now, for this purpose, let us now consider a stationary mass of a particular closed system which is at constant volume. We are perhaps aware of the conservation of energy principle.

Now, if you were to apply conservation of energy principle which we shall see in much detail little later, as well, then conservation of energy principle for this process is expressed in a differential form as shown here. Now, this differential form of expressing the conservation of energy principle leads us to this equation, which is delta e in minus delta e out is equal to du. As we have seen earlier that for a stationary system, the net change in energy for the system because it is stationary will be equal to the change in its internal energy because kinetic energy and potential energy changes are 0.

Therefore, as we had seen in the previous lecture, delta e will be equal to delta u. This is the same equation that we have expressed in a slightly different form.

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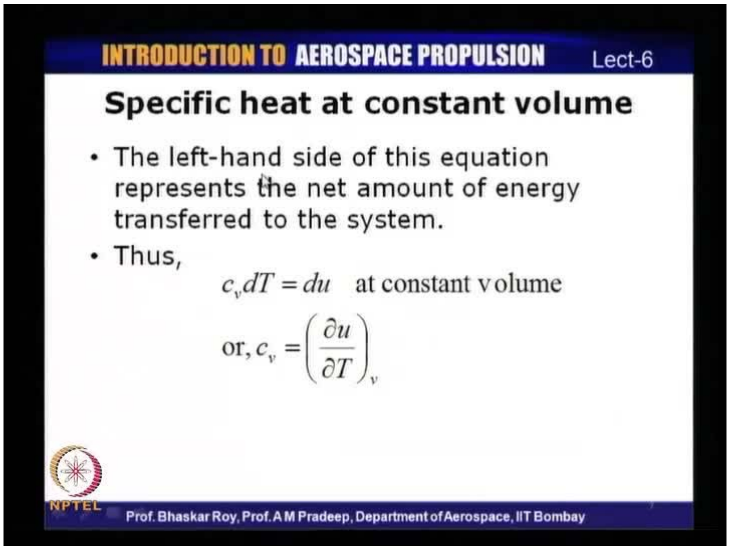

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Specific heat at constant volume

- The left-hand side of this equation represents the net amount of energy transferred to the system.
- Thus,

$$c_v dT = du \quad \text{at constant volume}$$

$$\text{or, } c_v = \left(\frac{\partial u}{\partial T}\right)_v$$

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Now, let us look at this equation once again, de in minus de out is equal to du. Now, this left hand side of this equation, as I was just mentioning represents the net amount of energy transfer to the system because it is delta e in minus delta e in out, which is essentially the net amount of energy which is transferred to the system.

Therefore, the left hand side is actually equal to c V times dT, because c V is specific heat at constant volume and as per the definition of specific heat, it is the amount of energy required to raise the temperature of a unit mass of substance by unit degree raise.

Therefore, left hand side of the equation is equal to c V times dT, which is equal to du. Therefore, specific heat at constant volume, which is denoted by c subscript V is equal to del u by del T at constant v.

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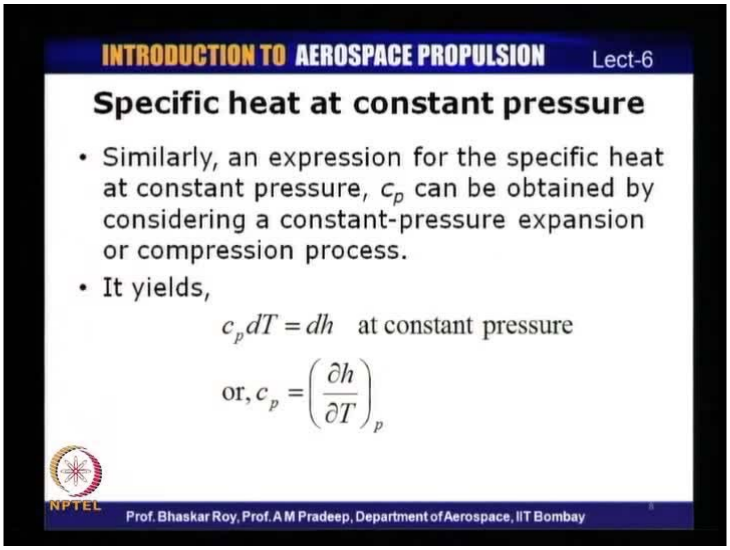

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Specific heat at constant pressure

- Similarly, an expression for the specific heat at constant pressure, c_p can be obtained by considering a constant-pressure expansion or compression process.
- It yields,

$$c_p dT = dh \quad \text{at constant pressure}$$

$$\text{or, } c_p = \left(\frac{\partial h}{\partial T}\right)_p$$

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Specific heat at constant volume is defined in terms of two properties of a system, which is internal energy and temperature and del u by del T at constant volume gives us specific heat at constant volume - that is c v.

Now, the other property which I had mentioned as specific heat at constant pressure can also be derived in a very similar fashion. So, for deriving c p, we would be considering a constant pressure process; it could be either an expansion process or it could be a compression process.

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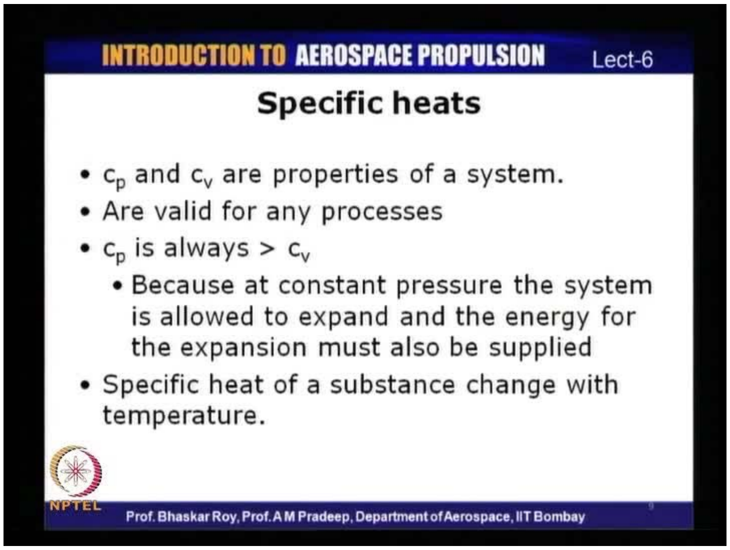

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Specific heats

- c_p and c_v are properties of a system.
- Are valid for any processes
- c_p is always > c_v
  - Because at constant pressure the system is allowed to expand and the energy for the expansion must also be supplied
- Specific heat of a substance change with temperature.

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So, if you were to do a similar exercise as we did for c V, then we get c p dT is equal to dh or c p is equal to del h by del T at constant p. As you can see here, specific heat at constant pressure is a function of two properties of a system that is enthalpy and temperature defined at constant pressure. Specific heat at constant volume is a function of two other properties of a system, the internal energy u and the temperature t. Since both of these depend on properties of system, it is obvious that c p and c V have to be properties of a system, because they depend on different properties of a particular system. For example, c p depends upon the enthalpy and temperature and c V depends upon the internal energy and temperature, which means that both c p and c V are properties of a system.

Both c p and c V definitions - though we have used or we had defined these properties for constant pressure and constant volume, these are valid for any other process. It can be shown that c p and c V would be valid for any other process and it is also a fact that specific heat at constant pressure c p is always greater in terms of its magnitude than specific heat at constant volume c V. Basically the reason for this is that, if you were to carry out process at constant pressure, we have to allow the system to expand which means that you have to spend additional energy for this particular expansion of a system which is not there in the case of a constant volume process.

So, if the volume got to be constant, then there is no more expansion or compression of a system. So, the system does not require additional energy for expanding against the atmosphere, because in a c p process, that is constant pressure process, you will need additional energy to keep the pressure a constant to allow for the system to expand.

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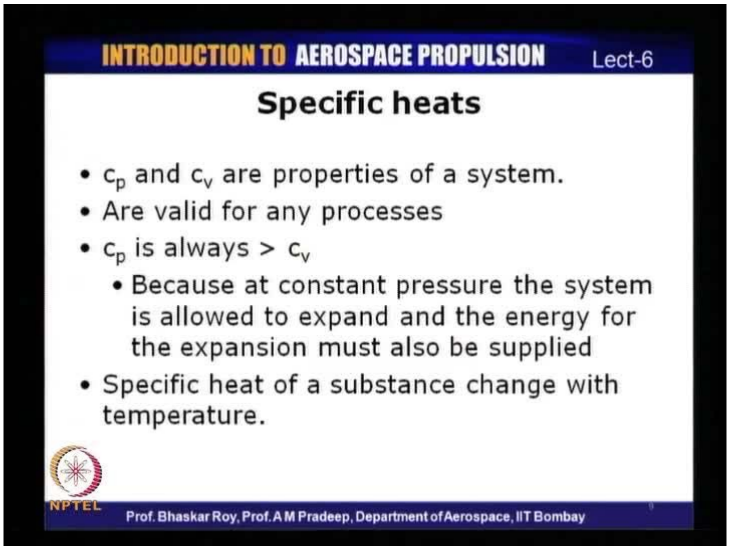

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Specific heats

- c_p and c_v are properties of a system.
- Are valid for any processes
- c_p is always > c_v
  - Because at constant pressure the system is allowed to expand and the energy for the expansion must also be supplied
- Specific heat of a substance change with temperature.

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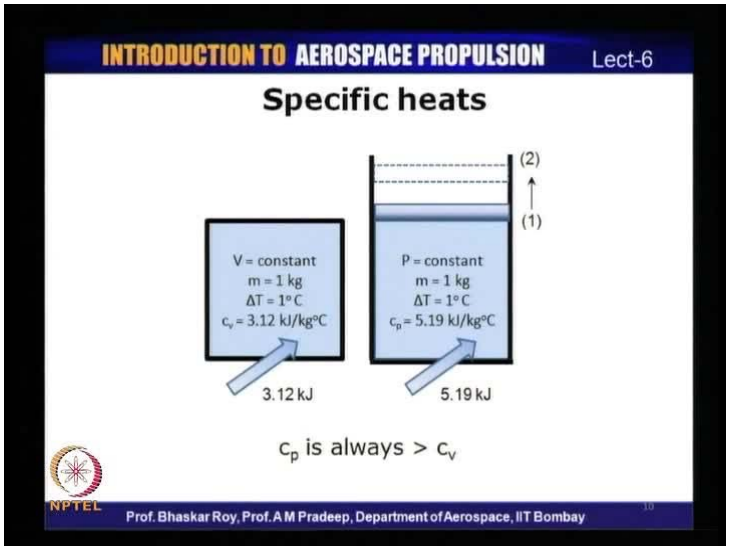

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Specific heats

c_p is always > c_v

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Therefore, c p is always greater than c V and specific heat of a substance will change with temperature which also will be cleared in one of the examples which we actually show little later.

Now, as I was mentioning c p is always greater than c V, let us look at why is that so. On the left hand side, you can see a system which is enclosed in a chamber and therefore, its volume is constant. Let us say its mass is 1 kg and we have to raise the temperature by 1 degree celsius and for that to happen, we have to supply, for example, an energy equivalent to 3.12 kilo joules.

Therefore, the c V would be 3.12 kilo joules per kilo grams degree celsius. If the same system, one of the boundaries let us say, the upper boundary were to be movable that can convert the system into a moving boundary closed system, and if this were to be the case, as you transfer the energy to the system, the system will expand, which means that its volume will keep increasing but the pressure would remain the same. We can keep the pressure a constant.

In this case, in addition to transferring energy to raise the temperature by 1 degree celsius, we need additional energy to account for this expansion process and therefore, that is reflected in the additional energy, which you can see here, in this example, we have an energy of 5.19 kilo joules. Therefore, c p would be 5.19 kilo joules per kilo gram degree celsius.

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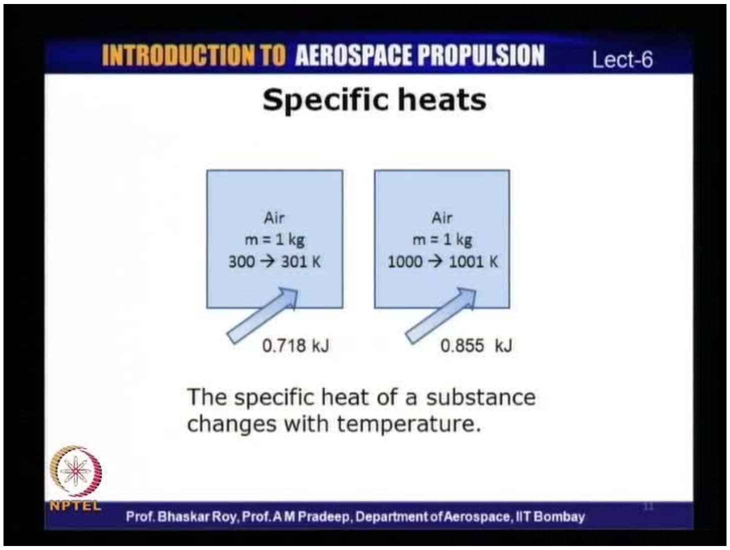

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Specific heats

The specific heat of a substance changes with temperature.

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This is why specific heat at constant pressure will always be greater than specific heat at constant volume. Now, the other point I was mentioning was that specific heat of a substance will change with temperature. To illustrate this, let us look at another example.

Let us consider air, which is enclosed in a closed volume has a mass of 1 kg. Let us say, we have to raise the temperature of air from 300 kelvin to 301 kelvin, so, for this process, we would probably require energy of about 0.718 kilo joules. Now, if we were to consider the same system which is initially at a higher temperature of 1000 kelvin and we have to raise it to 1001 kelvin, we will need additional amount of energy - that is amount of energy required to raise this unit mass of 1 kg by 1 kelvin which was initially at a higher temperature than the previous case will require - more energy. That means the specific heat in the second case will be greater than the specific heat in the previous case.

Therefore, specific heat of a substance will always change with temperature. Specific heat is a function; a strong function of temperature. In many of the practical engineering calculations, this has to be taken into account, because for simplistic calculations, we normally assume that specific heat does not change with temperature, but that is restricted to very simple calculations. As we go towards more and more complex calculations which are actually required in engineering applications, we have to take this variation of specific heat with temperature into account.

Perhaps in later lectures, we would take a look at some examples where we shall see how much difference we get by assuming specific heat to remain the same for different temperatures and also look at how specific heat changes with temperature for different cases. We shall compare the difference between the results we get from these two calculations and we shall see that for practical applications, it does make a lot of difference.

What we have defined now are two different properties of a system, specific heat at constant pressure and specific heat at constant volume. We shall see little later that these are very important properties of a system which have a lot of practical significance. We shall be using both these properties very frequently when we do engineering analysis of different systems.

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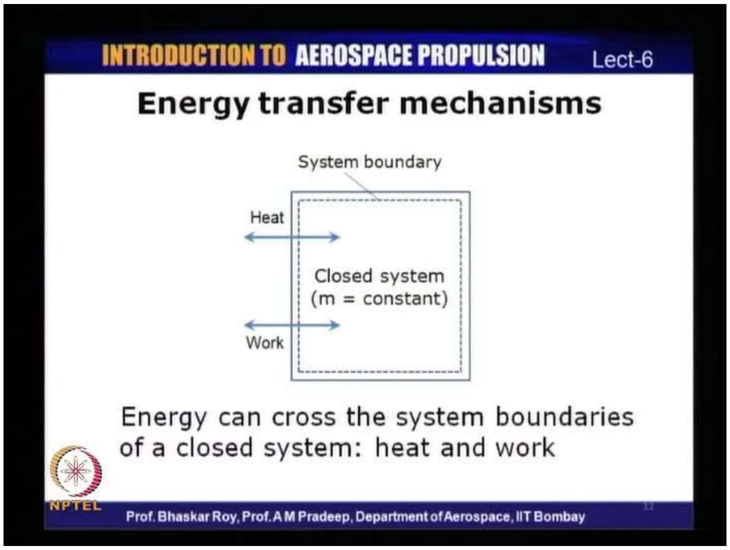

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Energy transfer mechanisms

System boundary

Heat

Closed system
(m = constant)

Work

Energy can cross the system boundaries of a closed system: heat and work

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What we shall see next is two different energy transfer mechanisms; one of them is known as heat and the other is known as work. Energy can cross the system boundaries of a closed system in two modes. One mode is known as heat and the other mode is known as work. What is shown here as an illustration is a system; a closed system, which has mass equal to constant. There can be two modes of energy transfer or energy interaction across the system boundaries.

Both of them are as we shall see little later, known as path functions. We will define path functions little later. So, there are two different energy interactions possible; one is known as heat and the other is known as work. We shall see in the next lecture that for an open system, there is one more form of energy interaction - that is through mass flow rate.

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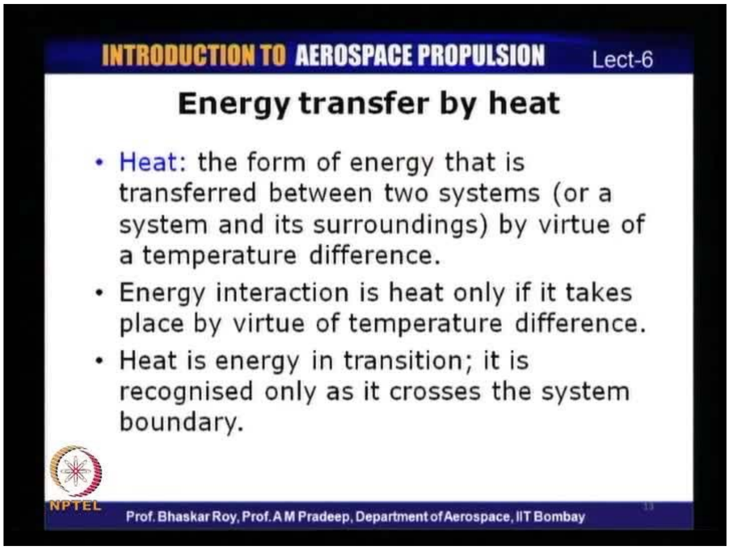

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Energy transfer by heat

- **Heat**: the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.
- Energy interaction is heat only if it takes place by virtue of temperature difference.
- Heat is energy in transition; it is recognised only as it crosses the system boundary.

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So, for a closed system, there are two forms of energy interactions. Let us look at one of the forms of energy interaction known as heat. As you are probably aware or we refer to heat on a day to day basis, for example, we say on a particular day, if it is hot humid day, we say the heat is very high and so on. So, heat is a term which is very commonly used in our day to day lives but thermo dynamically it might mean slightly different. It might be used in slightly different context.

Heat is - if we were to define thermo dynamically is a form of energy that is transferred between two systems or a system and its surroundings by virtue of a temperature difference. So, the energy interaction that takes place between either two systems or between a system and its surroundings by virtue of a temperature difference is known as heat. Therefore, energy interaction is classified as heat or is qualified as heat only if it takes pace by virtue of its temperature difference and therefore, it is obvious to state that heat is energy in transition.

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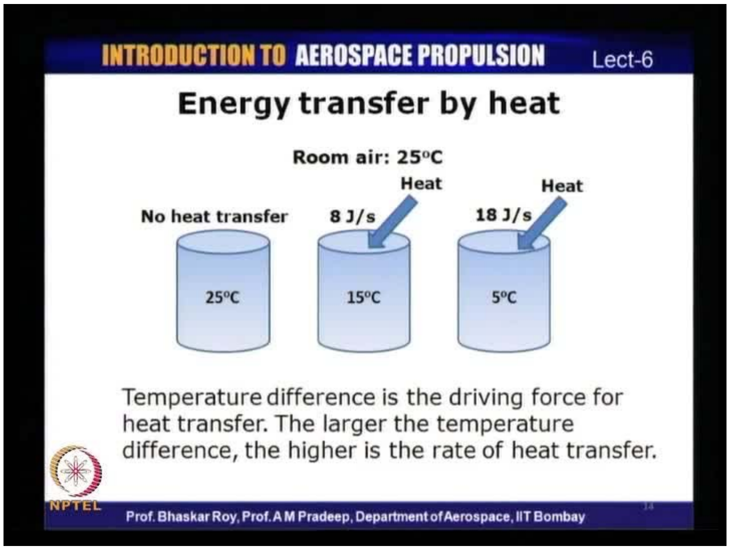

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Energy transfer by heat

Temperature difference is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.

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Heat is recognized only as it crosses a system boundary. So, thermo dynamically heat is a form of energy which gets transferred between two systems or between a system and its surroundings by virtue of a temperature difference and therefore, that is the thermo dynamics definition of heat.

Now, let us look at an example here. We have three different systems. It is the same system at three different temperatures. In the first case, we have the system at 25 degree celsius; we may consider this system as a cup of cold coffee or a can of cold drink or something like that. In the first case, let us say the system has the same temperature as the ambient. Let us say the ambient air or the room air is also at 25 degree celsius. If the system is also at the same temperature as that of the room, then there is no heat transfer between the system and the surroundings. If the system were at a lower temperature, let us say 15 degree celsius then there is definitely a heat transfer from the surroundings to the system because the surrounding air temperature is higher than the system temperature and therefore, there is a heat transfer from the surroundings to the system.

If the temperature of the system were even lower, let us say 5 degree celsius. There will still be heat transfer from the surroundings to the system. You might notice here that I have written 8 joules per second in the first case and 18 joules per second in the second case. These are just examples; but the point I wanted to state here is that because heat is recognized as an energy interaction by virtue of temperature difference. Temperature difference is the driving force for heat transfer which means that larger the temperature difference, the more is the rate of heat transfer.

So, larger the temperature difference between a system and its surroundings, higher is the temperature, well, higher is the heat transfer and which is why in the first case, where the system was at 15 degree celsius and the surroundings was at 25 degree celsius, we had the heat transfer of let us say 8 joules per second, whereas in the second case, because of the higher temperature differential between the systems and the surroundings, the rate of heat transfer is higher in the second case as compared to the first.

The point here is the rate of heat transfer is a very strong function of the temperature difference; the primary reason being heat transfer is basically by virtue of a temperature differential between system and its surroundings or between two different systems. Therefore, higher the temperature difference or higher the temperature gradient between a system and its surroundings, greater or higher would be the rate of heat transfer. In thermo dynamics, we would always refer to heat basically meaning heat transfer; so, whenever we refer to the term heat, it actually means heat transfer. As we have seen earlier, heat transfer is energy in transit by virtue of a temperature difference.

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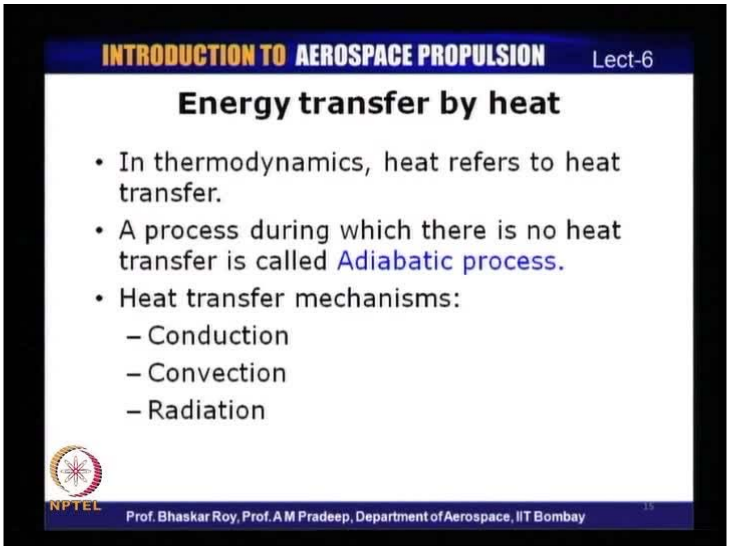

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Energy transfer by heat

- In thermodynamics, heat refers to heat transfer.
- A process during which there is no heat transfer is called Adiabatic process.
- Heat transfer mechanisms:
  - Conduction
  - Convection
  - Radiation

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If in a process that is there is no heat transfer across the system boundaries then that particular process is known as an adiabatic process. There are different modes of heat transfer or different mechanisms of heat transfer; we shall not go into the details of these modes of heat transfer in this particular course as it is out of scope of the syllabus. But I guess you would have already heard about these terms; heat transfer mechanisms. There are basically three mechanisms of heat transfer; one is known as conduction, the other is convection and the third is radiation.

Heat transfer can take place through three different mechanisms: conduction, convection and radiation. We shall not discuss details of these mechanisms of heat transfer. You may refer to any text book on heat transfer for more information on these mechanisms of heat transfer. Now, heat transfer as I mentioned earlier is recognized as an energy interaction between a system and its surroundings only as it crosses the system boundaries; that is a system may possess as we commonly refer to a system may have particular amount of heat, but thermo dynamically - a system is supposed to have had an energy interaction with the surroundings only has the heat that crosses the system boundaries.

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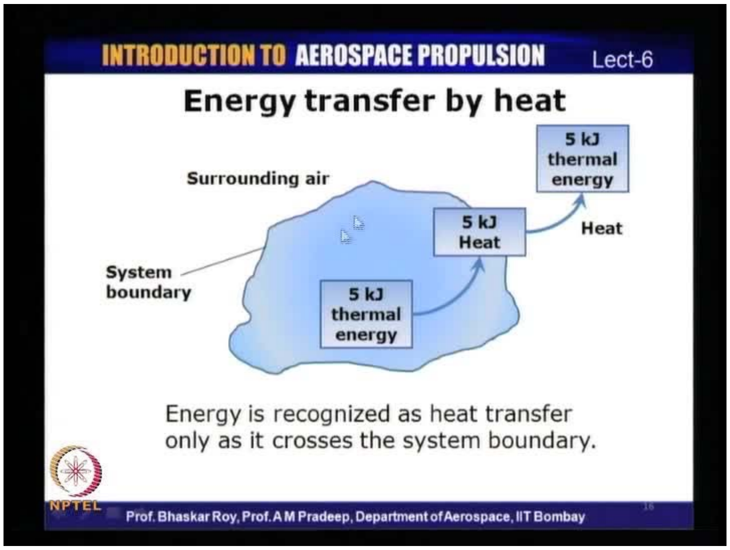

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Energy transfer by heat

Energy is recognized as heat transfer only as it crosses the system boundary.

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So, let us look at an example where I shall illustrate this point in little more detail. Now, the system that we are referring to here in this example, let us say has thermal energy of about 5 kilo joules. This is the system boundary as you can see and it is surrounded by surrounding air. If the energy that is contained within the system crosses the system boundary then that particular energy interaction which the system has had with the surroundings is referred to as heat. As long as the system does not transfer energy with the surroundings that is not thermo dynamically referred to as heat. So, heat transfer is recognized as an energy interaction only as it crosses the system boundary.

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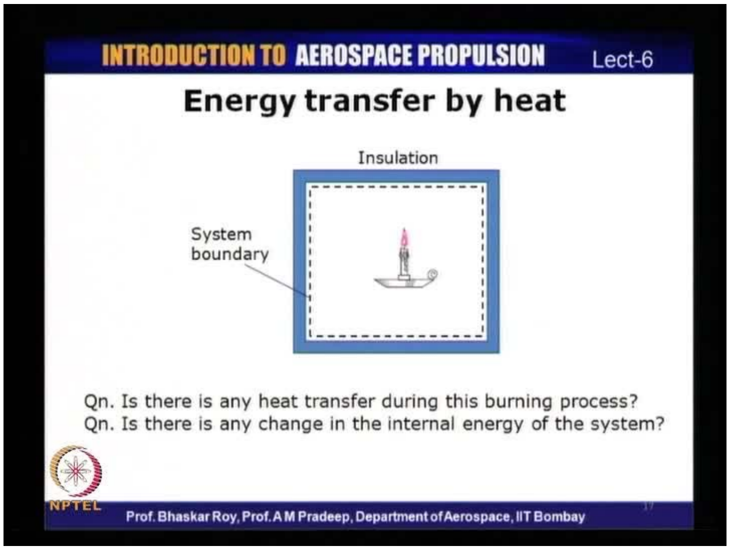

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Energy transfer by heat

Qn. Is there is any heat transfer during this burning process?
Qn. Is there is any change in the internal energy of the system?

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Now, if you were to look at this one small example which I would like to illustrate that we have a system here which is bounded by insulation. There is an insulation which is bounding a system and what is contained inside the system, let us say, a candle which is burning. So, a candle is contained within the system boundaries and the system is insulated which means that there cannot be any energy interaction between the system and the surroundings. For this particular system in question, is there any heat transfer which takes place during this burning process?

That is one of the question that you may have and the other question is that - is there any change in the internal energy of the system? Now, let us try to analyze these questions little deeper. We have here a candle, which is burning within a system volume and the system is insulated. Because the system is insulated, there is no energy interaction which is possible between the system and the surroundings. Therefore, obviously there cannot be any heat transfer which can take place between the system and surrounding.

So, thermo dynamically there is no heat transfer taking place in this process. The second question was, is there any change in internal energy? Well, you may wonder that because the candle is burning, there should be a change in internal energy of the system.

Well, the answer to that question is that there is no change in the internal energy as well. The reason is that as we have seen earlier, that for a system and the surroundings, the net change in energy of that particular process, if it is stationary will be equal to the change in internal energy because kinetic energy and potential energy are zero. So, in this case we have a system where in delta e is equal to delta u. Now, the question was, is there any change in delta u?

Well, there could be a change in delta u only if there is a change in delta e. The first question which we answered was - there is no heat transfer taking place between the system and surroundings. So, there is no net change in energy of this system and the surroundings which means that delta e is equal to 0. Therefore, delta u, that is internal energy change will also be equal to 0, which means that for adiabatic process, there is no change in the internal energy of the system as well as there is no heat transfer taking place between the system and surroundings.

Now, let us define the other mode of energy interaction which we had classified or qualified as work. Work is an energy interaction which takes place between the system and surroundings other than temperature difference. So, any energy interaction which takes place between the system and surroundings by virtue of something which is other than temperature difference is classified as work.

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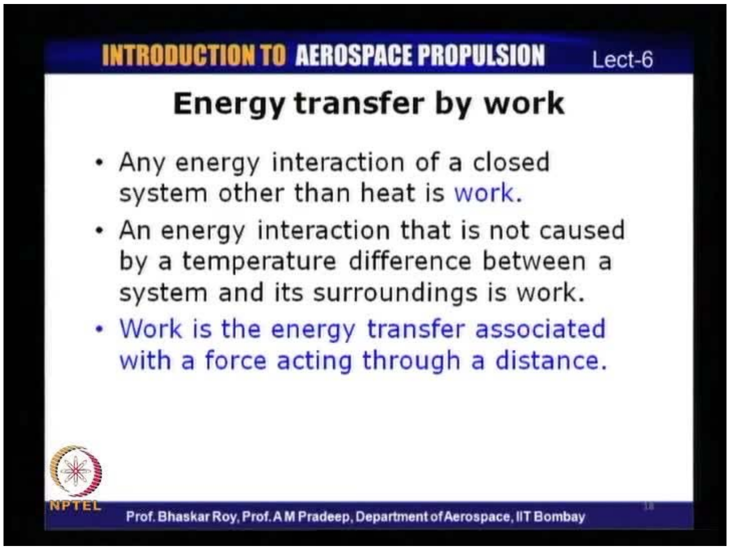

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Energy transfer by work

- Any energy interaction of a closed system other than heat is work.
- An energy interaction that is not caused by a temperature difference between a system and its surroundings is work.
- Work is the energy transfer associated with a force acting through a distance.

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Any energy interaction which takes place between a system and its surroundings by virtue of any other property which is not associated with temperature difference is known as work. Thermo dynamically, we shall define the work in the next slide. Work is basically the energy transfer associated with force acting through a certain distance. So, if we were to look at work and heat transfer, there is a certain sign convention that we follow for heat transfer processes as well as for work. In thermo dynamics, heat transfer to a system and work done by a system are usually taken as positive.

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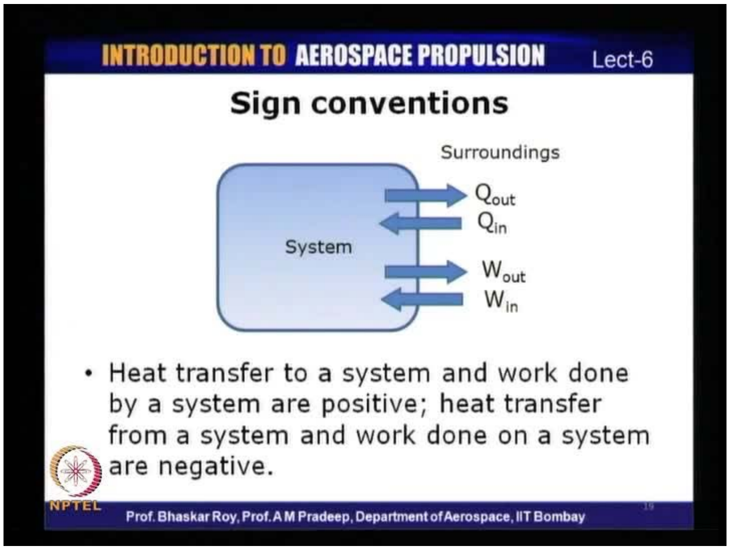

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Sign conventions

- Heat transfer to a system and work done by a system are positive; heat transfer from a system and work done on a system are negative.

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We attach a sign to heat transfer and work done; heat transfer to a system and work done by a system are taken as positive. Therefore, heat transfer from a system and work done on a system are negative. So, the interaction between the system and the surrounding is illustrated here; the two modes for a closed system are heat and work.

Heat transfer to a system, let us say, Q in and work done by a system that is W out - these two are usually taken as positive. Heat transfer from a system and work done on a system that is Q out and W in are usually taken as negative.

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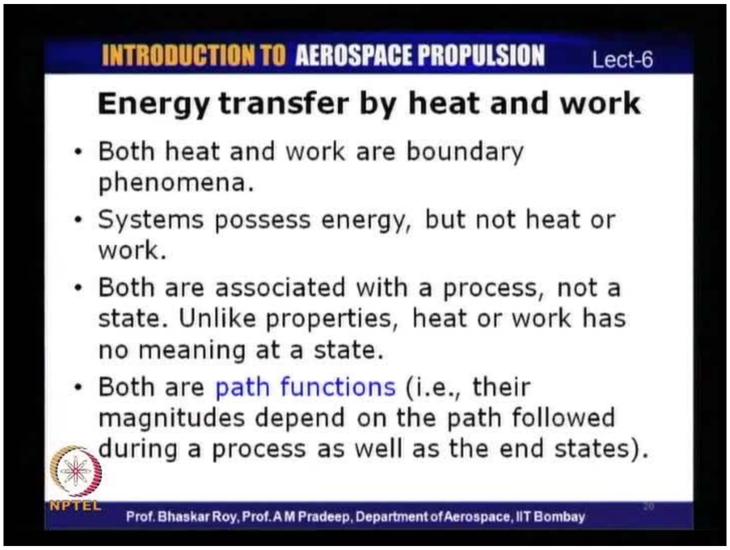

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Energy transfer by heat and work

- Both heat and work are boundary phenomena.
- Systems possess energy, but not heat or work.
- Both are associated with a process, not a state. Unlike properties, heat or work has no meaning at a state.
- Both are path functions (i.e., their magnitudes depend on the path followed during a process as well as the end states).

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So, this is a sign convention which we normally follow in thermo dynamics. Let us look at both heat and work interactions in little more detail. Both heat and work, as we know now are both energy interaction between the system and the surroundings. Both are usually referred to as boundary phenomenon; because, these are both energy interaction which take place across the system boundary. Therefore, they are referred to as boundary phenomenon.

A system can possess energy but it cannot possess heat or work. As we have seen heat or work are energy interactions between system and surroundings and they are also referred to as boundary phenomenon. Therefore, a system cannot essentially possess or contain heat or work; they can contain energy but not heat or work.

Both heat and work are associated with a process and it is not associated with the state. Unlike properties, heat and work do not have any meaning at a particular state and therefore, both of these are also known as path functions, that is, their magnitudes depend upon the path followed during a process and also depends upon the end states. Unlike properties which are point functions, both heat and work depend on the path taken during the process as well as the end states.

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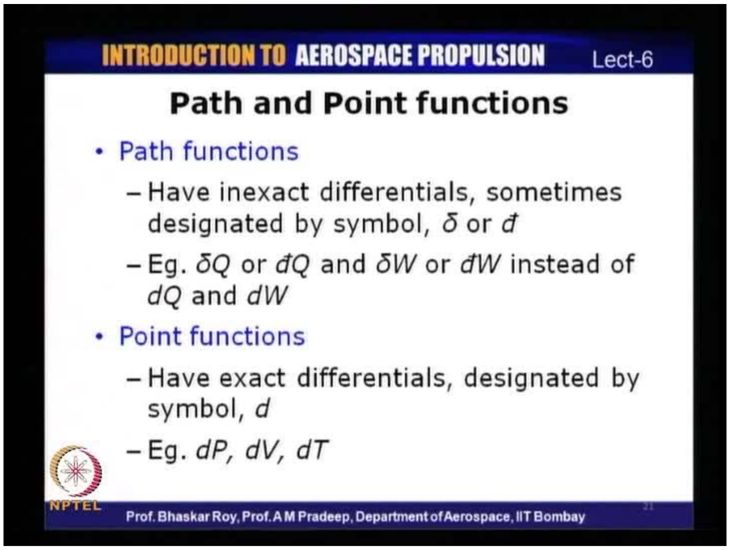

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Path and Point functions

- Path functions
  - Have inexact differentials, sometimes designated by symbol, δ or $đ$
  - Eg. δQ or $đQ$ and δW or $đW$ instead of dQ and dW
- Point functions
  - Have exact differentials, designated by symbol, d
  - Eg. dP, dV, dT

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You might wonder what are path and point functions. Let us look at what are path and point functions. Path functions are those functions which depend upon the path of the system as the name suggest and all path functions have in exact differentials. These are sometimes designated in different text books in different ways. It sometimes designated by symbols, delta Greek symbol delta or d with a cross; examples are, delta Q or d cross Q.

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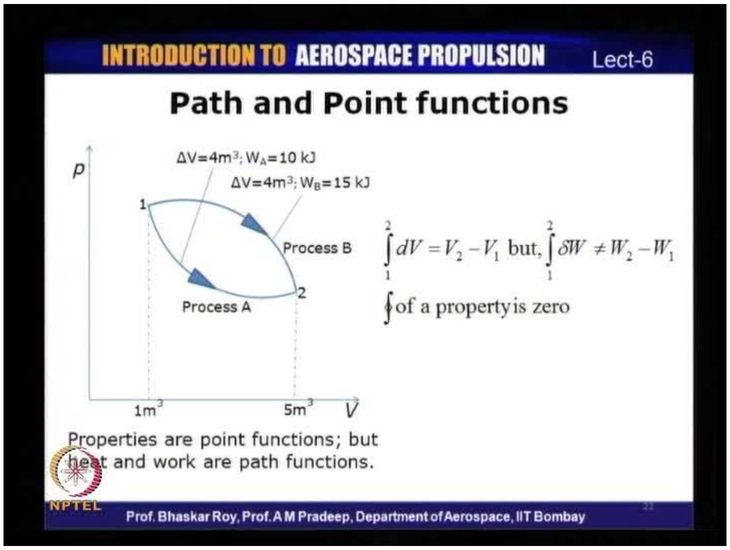

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Path and Point functions

$$\int_1^2 dV = V_2 - V_1 \text{ but, } \int_1^2 \delta W \neq W_2 - W_1$$

$\oint$ of a property is zero

Properties are point functions; but heat and work are path functions.

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In the case of work, it could be delta W or d cross W instead of dQ and dW. But, you might also come across some text books where it is also referred to as just dQ and dW. I think it is already implicit that these are path functions and point functions, on the other hand, like properties of a system, these are exact differentials and they are designated by symbol d. Therefore, differential change in pressure is denoted by dP, differential change in volume by dV and dT and so on. So, these are properties of a system and therefore, also referred to as point functions.

Now, let us look at an example to explain the properties which are point functions and path functions. In this pressure and volume diagram, P V diagram, we can see two processes process A and process B taking place between states 1 and 2. In the first process, that is process A, we have change in volume delta V because the end states are the same in both the processes. The change in volume, delta V is equal to 4 meter cube. As the initial volume was 1 meter cube and the final volume was 5 meter cube, the delta V, change volume is 4 meter cube for both the processes. If you look at the work which has occurred during process A and the process B, it will be different basically because from the P V diagram, work done during any process will be the area under the curve in a P V diagram.

For the first process, that is process A, W A will be area under this process A and for the second process, W B will be the area under process B. As you can see, W B should be greater than W A. Work is a path function; that is, it depends upon how the process is carried out or the path taken by the process; unlike properties like volume, it does not matter how the process was carried out; it depends only on the end states.

If you were to integrate volume between states 1 and 2, integral 1 to 2 dV is equal to V 2 minus V 1 because it is an exact differential. Whereas, you cannot integrate 1 to 2 dW, because it is not equal to W 2 minus W 1. The other aspect of property is that if you have a cyclic integral of a property, it will be equal to zero. Therefore, all properties of a system like volume, temperature, pressure etcetera are point functions, whereas, heat and work are the path functions.

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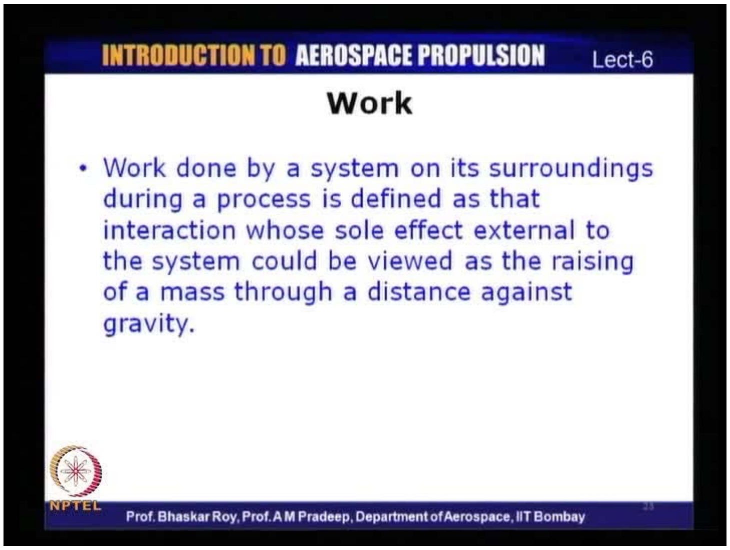

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Work

- Work done by a system on its surroundings during a process is defined as that interaction whose sole effect external to the system could be viewed as the raising of a mass through a distance against gravity.

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Now, let us define what is meant by work. Thermo dynamically, work done by a system and its surroundings is basically referred to as a work interaction; if there is the sole effect of this interaction can be viewed as raising of a mass through a distance against gravity. That is, work is set to be done by a system on its surroundings or vice versa, if the net effect can be considered to be raising of a particular mass through a certain distance against gravity. This is the thermo dynamic definition of work.

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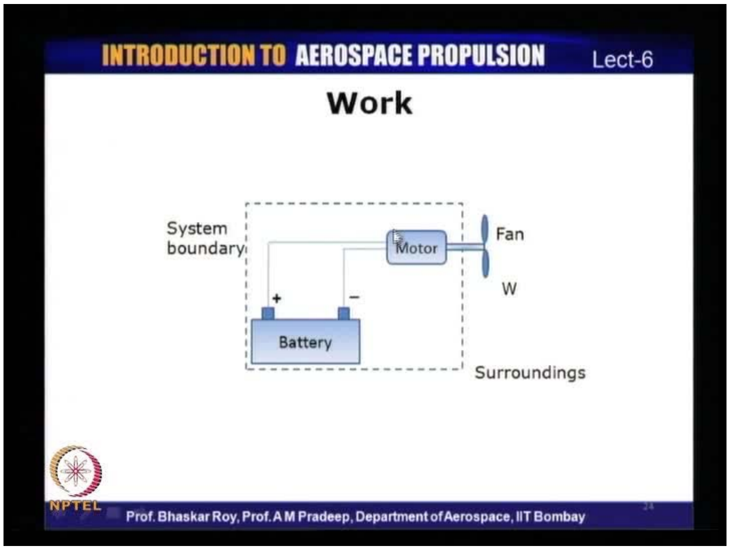

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Work

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We look at an example to understand what this definition basically means. In this example that I am going to show you, we shall consider that a system is having certain interaction with its surroundings. We shall see how we can understand work interaction for this particular system with its surroundings. We have here a system which is bounded within a system boundary. We have an electric motor which is driving a fan. Does the system do any work on the surroundings? The motor is driven by a battery which supplies the required power for the motor and it is driving a fan.

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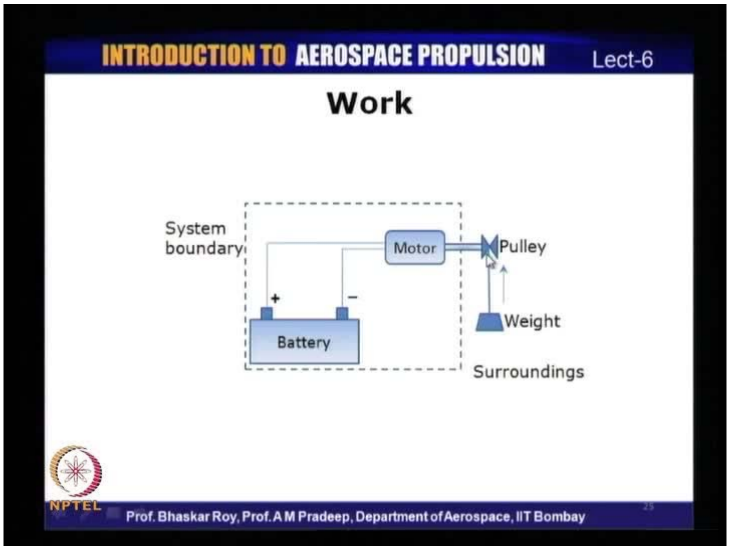

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If you were to consider that this system is doing work on the surroundings, as per thermo dynamic definition, this should reduce to this. That is, if we can replace the fan with a pulley, it means that we can attach a pulley instead of a fan to the motor and as the motor rotates this would raise a weight against gravity. Therefore, it satisfies the condition-thermo dynamic definition of work - that the net effect can be considered as raising of a weight against gravity.

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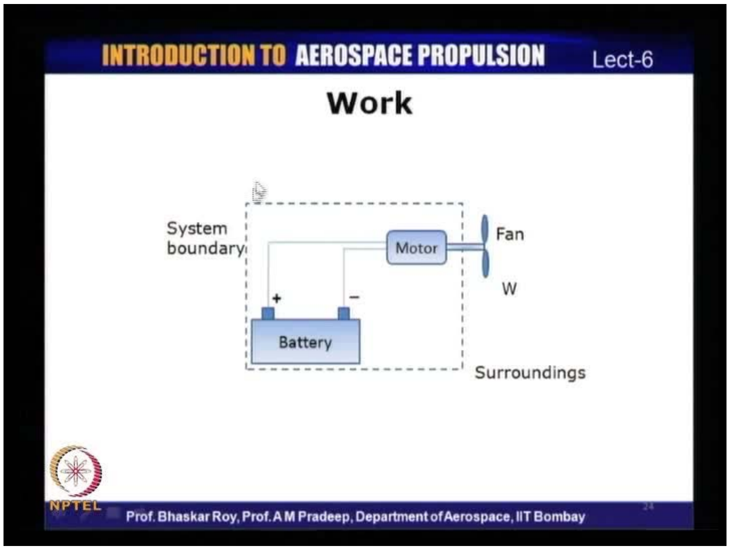

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Therefore, this example which has a system driving a fan definitely does work on the surroundings; because, we can always replace this fan with a pulley and therefore, raise any weight against gravity. This system does work on the surroundings as per the thermo dynamics definition of work.

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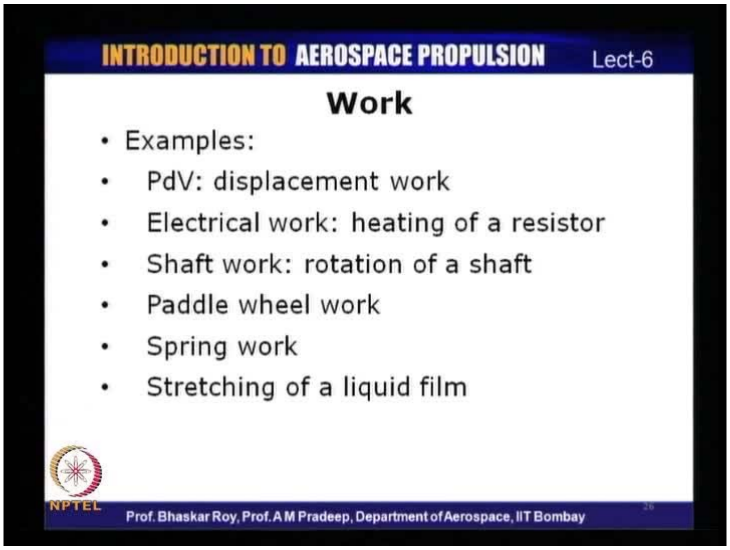

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Work

- Examples:
  - PdV: displacement work
  - Electrical work: heating of a resistor
  - Shaft work: rotation of a shaft
  - Paddle wheel work
  - Spring work
  - Stretching of a liquid film

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Now, we shall look at some examples of different work interactions. What are the different types of work interactions that are possible between the system and its surrounding? There are different ways in which work interactions can be carried out between a system and its surroundings. We shall look at one of these particular work interactions which is of interest to aerospace engineers and that is known as the displacement work. We will look at displacement work in lot more detail than the other types of work interactions.

Displacement work is one of the forms or modes of work interaction between the system and the surroundings. The other types of work interactions are for example, electrical work; that is, if you were to heat a resistor, then that is known as electrical work, because you can always replace the resistor with a motor and therefore, drive a pulley and raise a weight, as we have seen in the previous example.

Besides this, the other type of work interactions are shaft work; that its rotation of a shaft to generate output or it could be paddle wheel work or spring work or stretching of a liquid film etcetera. There are different modes of work interaction which can take place between a system and the surroundings and one of them as I have mentioned earlier, that is displacement work is what we shall be interested in analysis little more.

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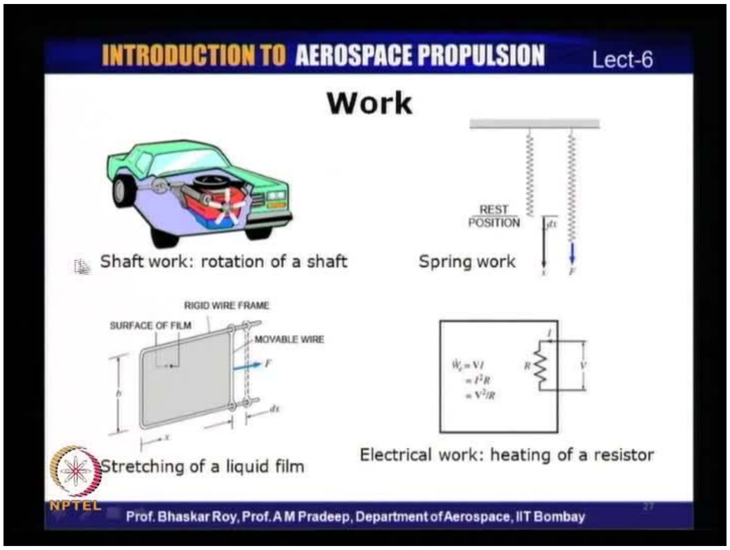

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Work

Shaft work: rotation of a shaft

Spring work

Stretching of a liquid film

Electrical work: heating of a resistor

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Now, let us illustrate these different modes of work interactions through these examples. Shaft work - that is rotation of a shaft to generate work output. As we have shown in this example, it is a motor car, an automobile which has an engine which generates a shaft work output and it is that shaft which drives the car or the automobile forward and therefore, it generates a work output.

The other possible mode of energy interaction or work interaction is spring work. An example shown here. We have a spring which is at rest and in a particular position and if you exert a force on the spring, then it expands and then gets displaced by a certain distance. The work done during this process is referred to as spring work. Stretching of a liquid film, that is, if you were to have a liquid film which is held between the rigid wire frame and a movable wire, there is a surface of film which is formed in between the rigid wire frame and the movable wire. As you move the wire, it causes stretching of the liquid film here. So, the work done during this process is also another mode of work interaction.

Electrical work would involve heating of a resistor; that is, if you have a system which houses a resistor, you supply a certain electrical power to the resistor; it causes heating of a resistor. There is work interaction between the system and its surroundings because of heating of this particular resistor. These are some examples of different modes of work interaction other than the main form or main mode of work interaction which we would be interested in; that is known as the displacement work.

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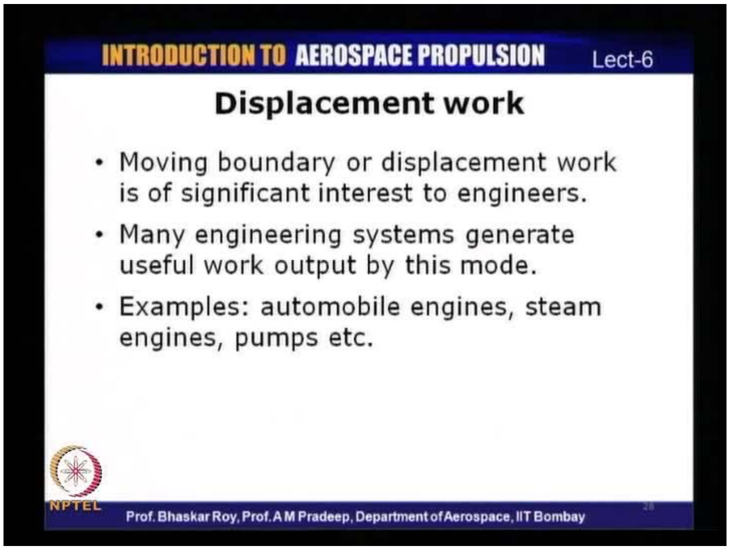

Displacement work

- Moving boundary or displacement work is of significant interest to engineers.
- Many engineering systems generate useful work output by this mode.
- Examples: automobile engines, steam engines, pumps etc.

Displacement work or moving boundary as it is also referred to is of significant interest to engineers. There are several engineering systems which can be approximated to be operating in the displacement work mode; that is they generate work output through the displacement mode. For example, if you were to look at the engine of a automobile, it generates work output because of the movement of the piston during the power stroke of the engine. That is displacement work. If you look at steam engines, different pumps, many of these pumps and steam engines all operate in the displacement mode, that is P times dV mode. As I mentioned, there are so many engineering applications for displacement work. We shall analyze displacement work in little more detail for different types of processes.

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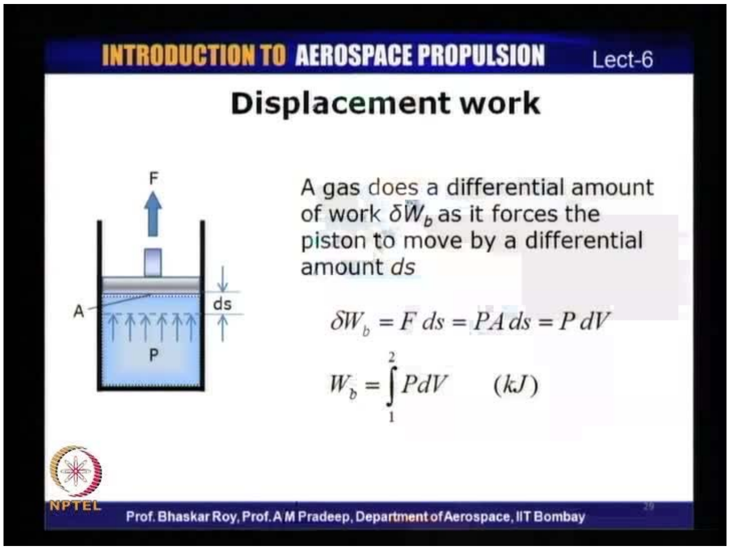

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Displacement work

A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount *ds*

$$\delta W_b = F\,ds = PA\,ds = P\,dV$$

$$W_b = \int_1^2 P dV \qquad (kJ)$$

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Let us look at what we actually meant by displacement work. In this example I am showing here, we have the piston and cylinder arrangement. There is a certain amount of gas which is housed within this cylinder volume. If we were to supply heat to this gas, as we know, it would expand. During expansion, the piston moves against the atmospheric pressure and therefore, it exerts a certain force. Therefore, the gas does a differential amount of work, which is delta W b, where subscript b denotes boundary work. As it does a work, it does a work is equal to delta W b, because, it forces the piston to move by a differential amount ds.

Therefore, delta W b, which is the differential work done during this process will be equal to force times the distance. As we know, force is pressure times area; because pressure is by definition, force per unit area. Therefore, force can be expressed as pressure into area. We are also aware that area times distance will be the volume that the piston has moved or displaced during this process. Therefore, we can replace A times ds by dV.

Therefore, delta W b, that is delta work done during this process is equal to P times dV or if you were looking at work done from state 1 to state 2, W b will be integral of P times dV. So, this is why displacement work is also referred to as PdV work, that is pressure times differential volume work.

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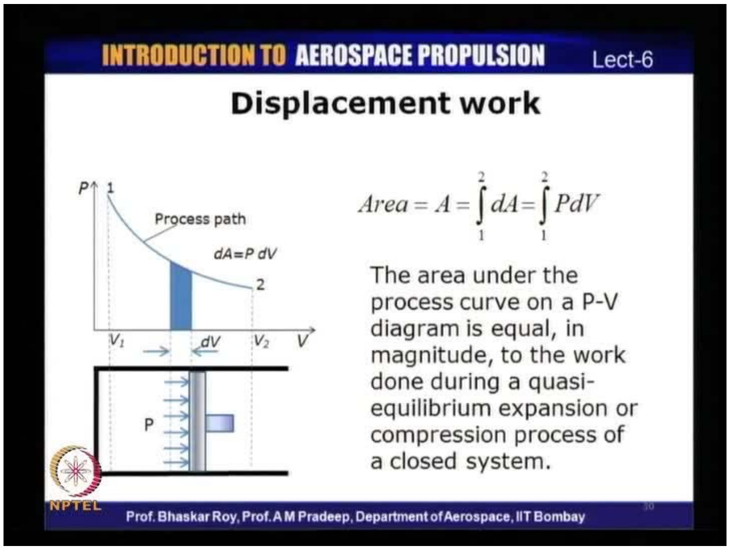
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Displacement work

$$Area = A = \int_1^2 dA = \int_1^2 PdV$$

The area under the process curve on a P-V diagram is equal, in magnitude, to the work done during a quasi-equilibrium expansion or compression process of a closed system.

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Now, the same process we can explain in terms of the P V diagram as well. In this P V diagram, we have the same piston cylinder arrangement here. As we supply energy to the cylinder, the piston moves generating work output. That is, the process would take place between states 1 and 2. This is an expansion process and so the process path is indicated here. This is the process path for this particular process.

If we were to look at one small differential strip on the process path, then the area of that differential strips will be equal to pressure average pressure during this process times d V. Therefore, area is equal to integral d A, which is integral PdV. Area under the curve on a P V diagram will be equal in magnitude to the work done during this quasi static or quasi equilibrium process which could be either a compression process or it could be an expansion process and it is basically for a closed system.

Therefore, area under the curve in a P V diagram should be equal to the work done during this process which obviously is quasi equilibrium or quasi static. The process may be either compression process or it could be an expansion process. If we can plot the pressure versus volume diagram for a particular process, we can actually calculate or determine the work done during the process simply by measuring the area under the P V diagram.

Therefore, for any work interaction process, a P V diagram plays a very significant role in analysis of work interaction during a particular process. We shall be using PV diagram very often in thermo dynamics analysis. Similar to P V diagram, we also have what is known as temperature entropy diagram which we shall see in detail later on; that is t s diagram. The t s diagram also plays significant role in thermo dynamic analysis of engineering systems.

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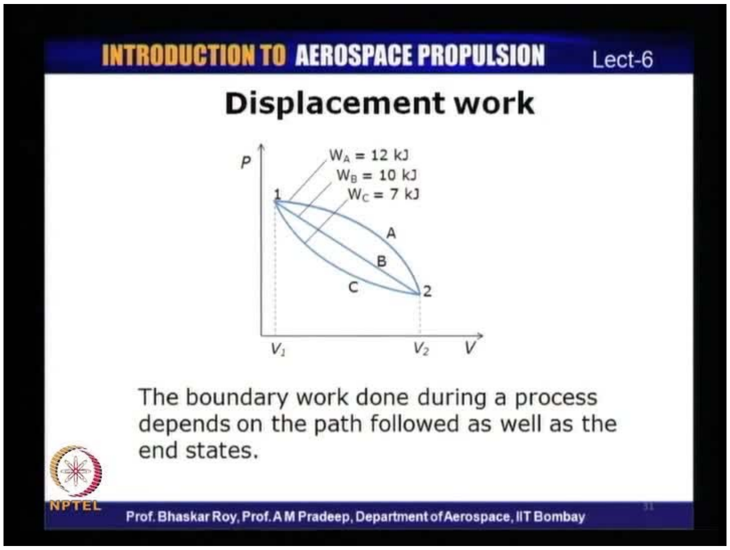

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Displacement work

The boundary work done during a process depends on the path followed as well as the end states.

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Displacement work as I mentioned, because work is a path function; it depends upon the path taken by the process and not just the end state. It depends on the end state but also it depends upon the path taken. Therefore, if we were to look at states 1 and 2, the infinite number of possibilities of carrying out a process between states 1 and 2, the properties at states 1 and 2 remain unchanged. You could do the process in different ways and depending upon how you do the process, the work done during the process will change. That is, if you can do this process by A B and C, the work done during each of these processes will be different. As we know, the work done is the area under the curve and therefore, work done during process C will be the least because the area under this curve is the lowest; followed by B and the highest work done would be done during process A, because area under this particular process is the highest. Just an example showed here - W A could be let us say 12 kilo joules, W B 10, W C is 7 kilo joules and so on.

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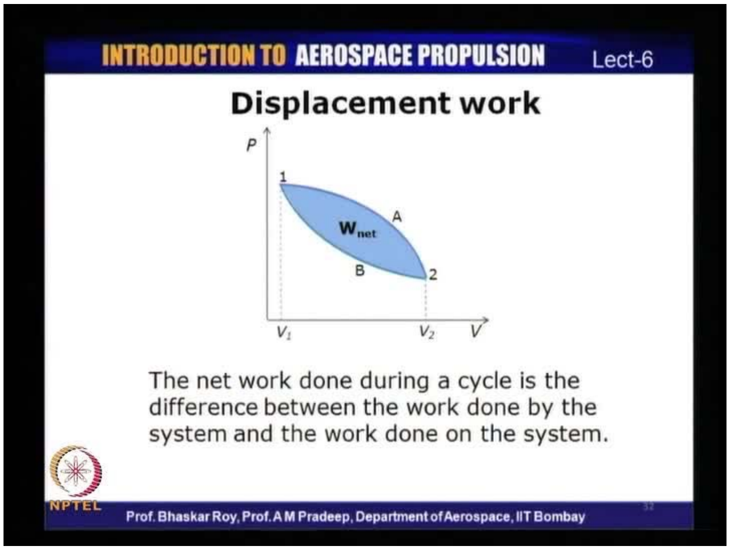

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Displacement work

The net work done during a cycle is the difference between the work done by the system and the work done on the system.

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Therefore, the work done during a process depends upon the path as well as the end states. The net work during a cycle is basically the difference between the work done by the system and work done on the system. If you were to consider this as a cycle, that is, the process starts at let us say, state 1 and takes path A and reaches state 2 and then takes path B to come back to state 1 again. The net work done during this process will be area between the curve, that is W net will be equal to area under A which is work done by the system minus area under B. That is work done on the system which is equal to W net. W net will be equal to W A minus W B - that is the net work done during this particular cycle. So, net work done during a cycle will be the difference between work done by the system and the work done on the system.

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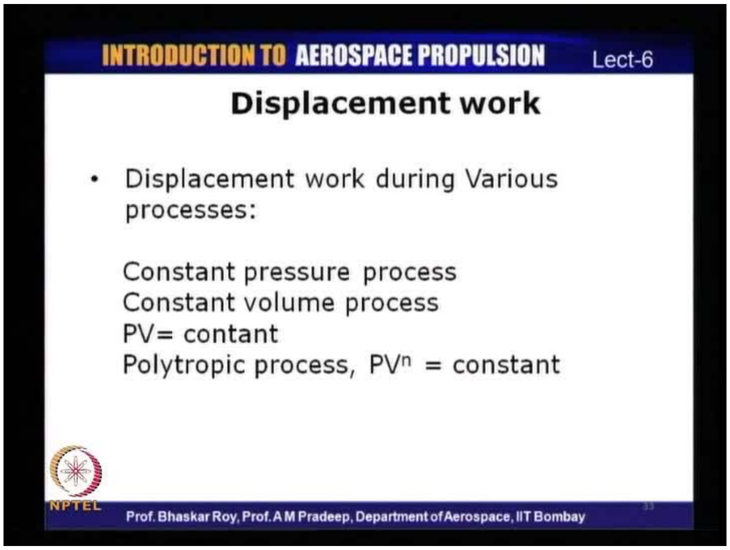

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Displacement work

- Displacement work during Various processes:

Constant pressure process
Constant volume process
PV= contant
Polytropic process, PV^n = constant

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We shall now analyze displacement work done during different processes. You can carry out the process in different ways; it could be either a constant pressure process, or it could be a constant volume process, or it could be a process wherein PV, product PV is a constant, which happens to be an iso-thermal process. Because, as per state equation, PV is equal to m r t. Therefore, if PV is constant, it means that temperature is a constant. So, an isothermal process wherein PV is a constant or it could be what is known as a polytrophic process, wherein, we have product P times V raised to n is a constant, where n is a number which can depend upon the type of process. That is known as a polytrophic process.

We shall now calculate the work done during these different processes: a constant pressure process, a constant volume process and then we shall consider a polytrophic process. PV is equal to constant is a subset of the polytrophic process.

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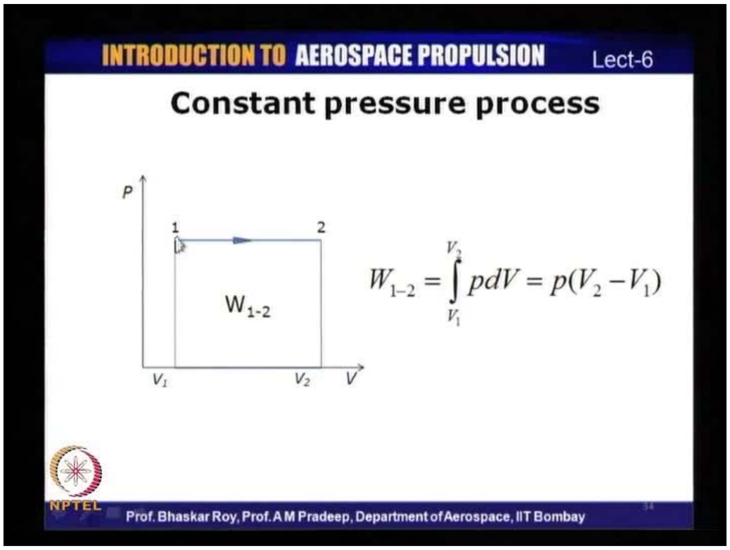

Constant pressure process

$$W_{1-2} = \int_{V_1}^{V_2} pdV = p(V_2 - V_1)$$

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Let us first look at a constant pressure process wherein the pressure remains constant; the volume keeps changing during the process. So, if you were to look at the PV diagram for such a process, wherein pressure is constant, this process takes place between states 1 and 2; since pressure is a constant, you can see that P 1 is equal to P 2.

What is the net work done during this process? It is basically the area under this curve. It is very easy to find the area under this curve because, the pressure as it is constant, p times V 2 minus V 1, which also comes from integral V 1 to V 2 pdV.

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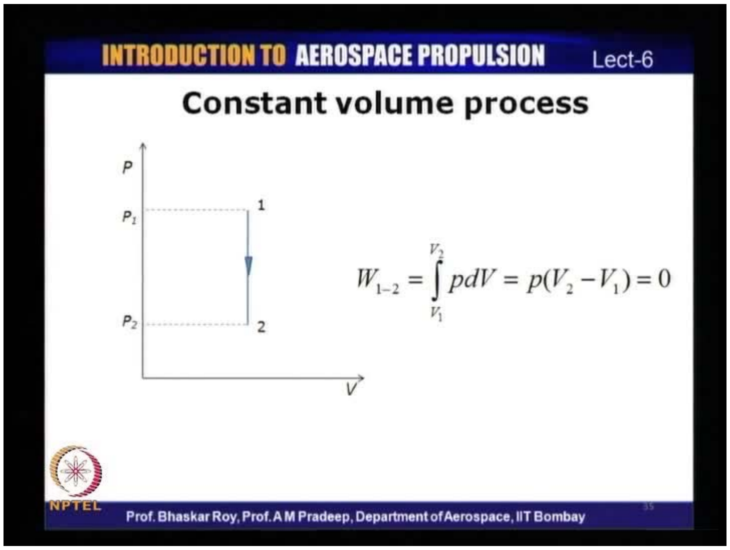

Constant volume process

$$W_{1-2} = \int_{V_1}^{V_2} pdV = p(V_2 - V_1) = 0$$

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So, if you were to integrate pdV between the states V 1 and V 2, you get p times V 2 minus V 1. Work done during a constant pressure process is the product of the pressure times the difference in the volume during the process. So, p times V 2 minus V 1 will be the net work done during the particular process.

What happens if the volume was constant? If you have a process where the volume is constant - that is, it is a closed system and the volume is also constant but the pressure can change. Is there any work done during this process? Since V is equal to zero, if you were to integrate p d V between the states V 1 and V 2, since V 1 and V 2 are the same in this particular process, the work done will be zero because there is no change in volume of the system.

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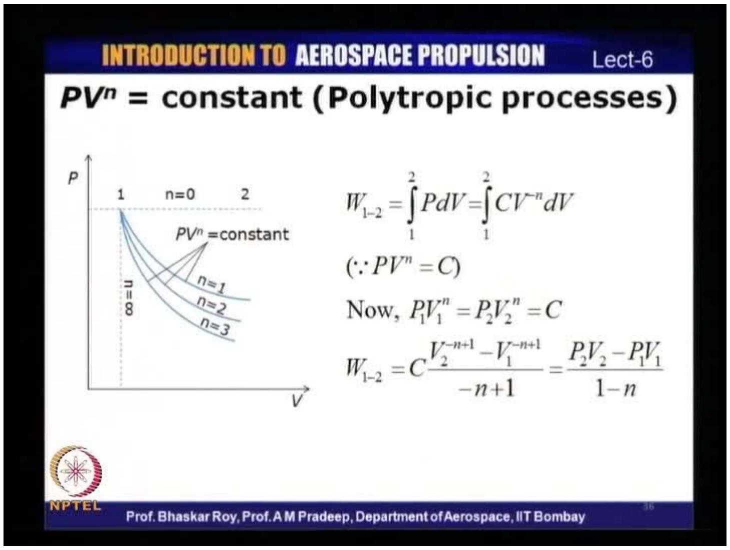

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

PV^n = constant (Polytropic processes)

$$W_{1-2} = \int_1^2 PdV = \int_1^2 CV^{-n}dV$$

$$(\because PV^n = C)$$

$$\text{Now, } P_1V_1^n = P_2V_2^n = C$$

$$W_{1-2} = C\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2V_2 - P_1V_1}{1-n}$$

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For a constant volume process, the net work done will be equal to zero. So, there is no work during a constant volume process. Let us look at a polytrophic process - that is a process in which p times V raise to n is a constant, where n can take different values 0, 1, 2, 3 or anything. We have here on a PV diagram, different processes are shown here; n equal to 1, n equal to 2, n equal to 3 and the limits of this particular process are n equal to 0. When n equal to 0, what happens is that you will have a constant pressure process. We have already seen what is work done for a constant pressure process, which is equal to pressure times the difference in the volumes.

If n was equal to infinity, then you get volume is equal to constant wherein the work done will be equal to zero, because area under the curve is zero. Now, for PV raise to n process, work done is integral 1 to 2 P dV which is equal to C times V raise to minus n times dV. Because PV raise to n is constant, let us say the constant is C. So, PV raise to n is equal to C. So, we can replace P by C times V raise to minus n.

Now, we also know that since PV raise to n is constant, P 1 V 1 raise to n is equal to P 2 V 2 raise to n is equal to C. If we were to substitute these values into the work equation here, that is, if we were to replace V in terms of the pressures, what we would get is work done from state 1 to 2. It will be C times V 2 raise to minus n plus 1 minus V 1 raise to minus n plus 1 divided by minus n plus 1. Since we know that p one V raise to n is equal to p 2 V 2 raise to n is a constant, this expression reduces to p 2 V 2 minus p 1 V 1 by 1 minus n.

Therefore, work done during polytrophic process is basically equal to the product of P 2 V 2 minus P 1 V 1 divided by 1 minus n. Suppose n was equal to 2, then the work done during this particular polytrophic process will be equal to- basically it depends upon the properties at the end states- P 2 V 2 minus P 1 V by 1 minus 2 and so on. So, you can actually calculate the work done during a polytrophic process, if you know the end states as well as the exponent of the polytrophic process.

We shall see later on that when n is equal to 1.4, where 1.4 for normal temperatures is also equal to the ratio of the specific heats. In such a process, we usually refer to this process as PV raise to gamma is equal to a constant, where gamma is the ratio of the specific heat CP divided by CV. So, this process we shall see in detail in later lectures.

Now, from this particular polytrophic process, if we were to assign different values of n, you can calculate the work done during these different processes and as a subset of this process would be n equal to 1 wherein PV is a constant. So, for PV is equal to constant, you need to integrate PdV between states 1 and 2. If you look at this particular equation, if you substitute n equal to 1, then that is not the right way to do it. You will still have to go back and integrate for the work equation substituting in the same way as we did for this case, where PV is equal to C and so on.

The work equation will come out to be P 1 V 1 log V 2 by V 1.I leave that as an exercise for you to calculate the work done during P V is equal to constant process. Let me now recap what we have discussed during this particular lecture. We started the lecture by defining what is known as specific heat for a process.

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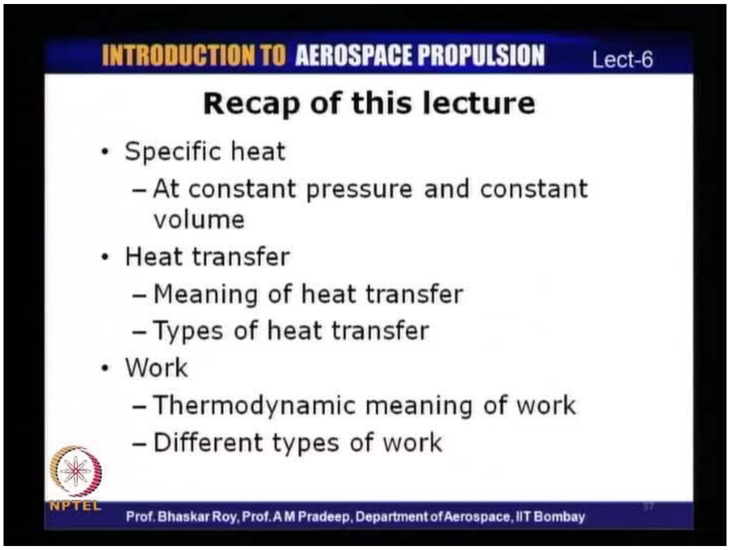

INTRODUCTION TO AEROSPACE PROPULSION Lect-6

Recap of this lecture

- Specific heat
  - At constant pressure and constant volume
- Heat transfer
  - Meaning of heat transfer
  - Types of heat transfer
- Work
  - Thermodynamic meaning of work
  - Different types of work

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We saw that specific heat is basically, the energy required to raise the temperature of a unit mass of a substance by unit degree rise in temperature. There are two different types: specific heat at constant pressure and specific heat at constant volume. Subsequently, we discussed about energy interaction modes between a system and its surroundings for a closed system.

For a closed system, there are two modes of energy interaction: heat transfer and work. We discussed about heat transfer, the meaning of heat transfer basically the thermo dynamic meaning of heat transfer and also mentioned about different modes of heat transfers. We discussed about work in lot more detail. We defined thermo dynamic definition of work and also the different types of work interactions possible between a system and surroundings.

Then, we also discussed the displacement work, PdV work in lot more detail. We also calculated work required for different displacement processes: a constant pressure process, constant volume process and a polytrophic process and somewhere in between the lecture we also discussed about path and point functions.

Basically path functions are those which depend upon the path of a particular process as well as the end state. Point functions depend only on the end states. All properties of a system are point functions. Heat and work are path functions. This is what we discussed in today's lecture and in the next lecture what we shall do is to solve some problems based on what we have discussed during lectures 4, 5 and 6.

Primarily we shall solve some problems related to calculation of work done during different types of processes. We shall solve these problems during the next lecture.