Introduction to Aerospace Propulsion

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Module No. # 01

Lecture No. # 13

Tutorial

Hello and welcome to lecture 13. This is lecture 13 of the lecture series on introduction to aerospace propulsion. Last few lectures, we have covered a lot of ground in terms of understanding basic thermodynamics. We have covered the zeroth law, first law, second law and also the third law of thermodynamics which means that we have actually covered all the laws of thermodynamics, the fundamental laws of thermodynamics. In today's lecture, what we shall do is to try and solve some problems and this is the second tutorial we are conducting in this course.

So, we shall be solving some problems from the first law of thermodynamics applied to closed systems and open systems. We shall also solve some problems related to heat engines, efficiency of heat engines and so on and also certain problems associated with refrigerators and heat pumps, which means that we shall be covering the first law of thermodynamics as well as the second in some sense.

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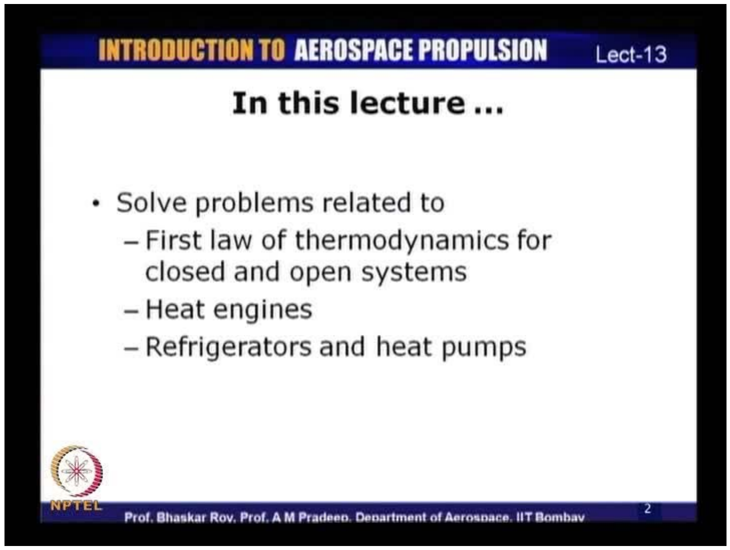

So in today's lecture, we shall basically solve problems which are related to the first law of thermodynamics applied to closed systems and open systems, heat engines, refrigerators and heat pumps.

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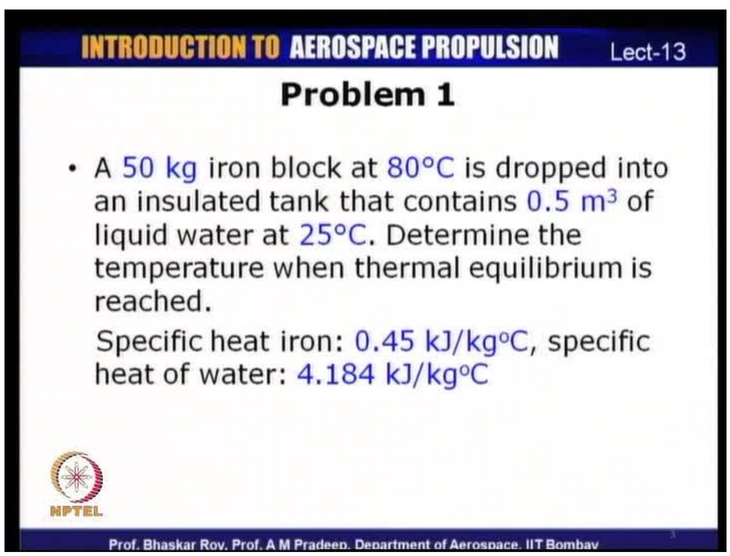

Let us look at the first problem that we have at hand. So problem 1; statement is a 50 kilogram iron block at 80 degree celsius is dropped into an insulated tank that contains a volume of 0.5 meter cube of liquid water which is at 25 degree celsius. Determine the temperature when the thermal equilibrium is reached. It is also given that the specific heat for iron is 0.45 kilojoules per kilogram degree celsius; specific heat of water is 4.184 kilojoules per kilogram degree celsius.

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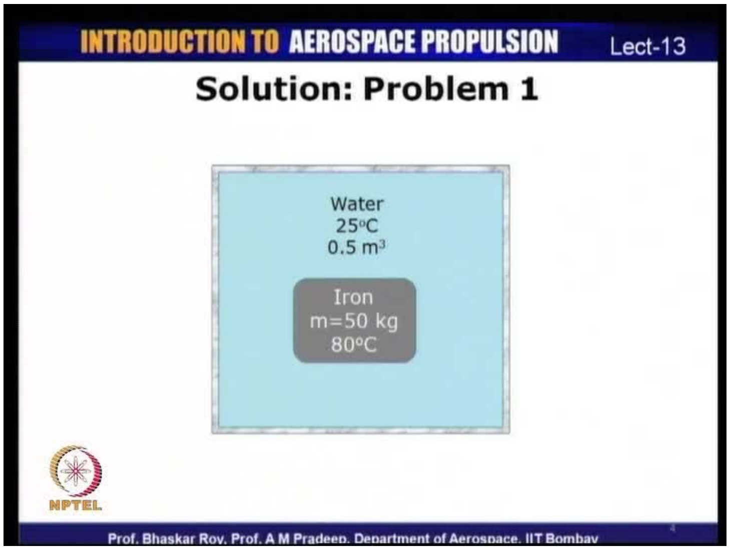

Illustration for this particular problem at hand is that, you have an iron block which has a certain mass; in this case, it is 50 kilograms and it is at a temperature of 80 degree celsius. So, if you drop this mass of iron which is at a higher temperature than the water system which is at 25 degree celsius and containing a certain volume. Then, what is the final temperature after thermal equilibrium is reached? So after the system reaches the thermal equilibrium, which is when both water and iron will be at the same temperature. What is the final temperature? So, we have been given the specific heats for water as well as that for iron.

Now, this is basically a problem which involves the first law of thermodynamics because what we shall consider is that the system is isolated in the sense that it is enclosed with in an adiabatic wall. So between the water and iron system, which constitutes the whole system there is no heat transfer between that system and the surroundings. So, within the closed system there is a certain energy interaction between the iron block and water which can be governed by basically the first law of thermodynamics. That is whatever energy iron had because of by virtue of its higher temperature will be transferred to water and finally, both the systems - will both these constituents of the systems - will come to thermal equilibrium.

Now, let us look at what are the assumptions which are implicit in solving such a problem. So basically, the assumptions will involve that both water and iron are incompressible which means that we can assume one particular value of specific heat; there is nothing like specific heat at constant volume and specific heat at constant pressure and so on.

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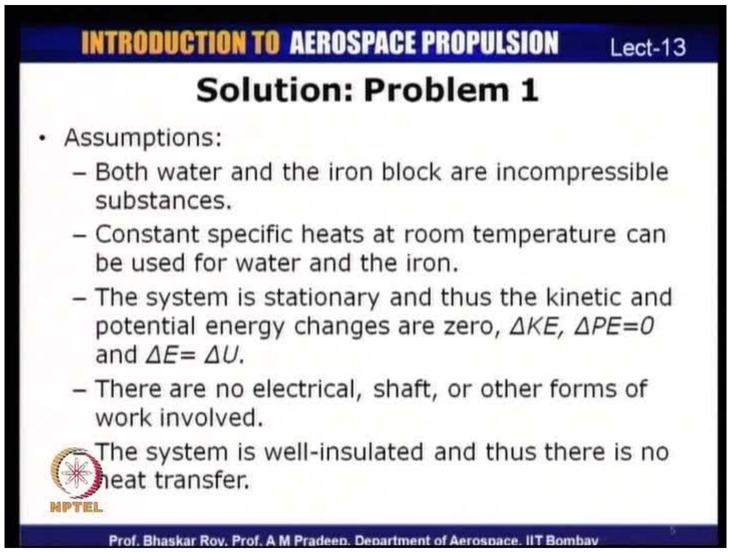

Then we shall assume that specific heat is a constant for this particular temperature which we are looking at then the system is stationary, there is no movement of the system. Therefore, kinetic energy and potential energy are 0, the changes in kinetic energy and potential energy will be 0. Therefore, the delta E which is change in energy of the system will be equal to the change in internal energy of the system.

Obviously, there are no other forms of energy interaction like electrical shaft or other forms of work and also that the system is well insulated; there is no heat transfer between the system and the surroundings. These are some assumptions which some of them are obvious and some of them are not; so it is important for us to state the assumptions if there are any.

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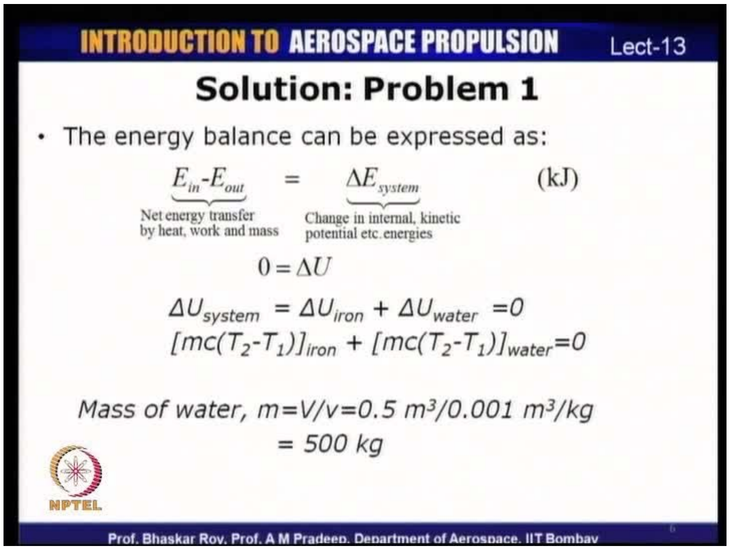

We have already looked at the energy balance which is again a consequence of the first law of thermodynamics. So energy balance can basically be expressed as the change in energy, net energy transfer basically by heat, mass or work interaction will be equal to change in internal kinetic and potential energies of the system. That is E in minus E out is equal to delta E of the system. Since this is a closed system, there is no energy transfer across the system boundaries either by heat, work or mass; so E in minus E out will be equal to 0.

Therefore, you have delta E of the system will be equal to 0 and we have also made an assumption that there are no changes in kinetic and potential energies, therefore it leads us to delta U is equal to 0. Delta U of the system is basically the sum of delta U of iron plus delta U of water. So, delta U iron plus delta U water should be equal to 0 and for an incompressible substance like liquids and solids, delta U is equal to the product of mass, specific heat and change in temperature. So, mc T 2 minus T 1 for iron, plus mc T 2 minus T 1 plus of water is equal to 0.

Now in this problem, we have been given the volume of water. So it is given that volume is housed in 0.5 meter cubes of the system boundaries. To find the mass, we have to take the ratio of volume and the specific volume which is basically the inverse of density.

So, density for water as we know is 1000 meter cube kilogram per meter cube. Therefore, specific volume is 1 by 1000 that is 0.001 meter cube per kg, so ratio of volume to specific volume gives us the mass.

So, 0.5 meter cube is the volume of water and divided by 0.001 meter cube per kg is the specific volume of water. This gives us a mass of water which is equal to 500 kgs. The mass of water corresponding to 0.5 meter cube is equal to 500 kgs, so we have calculated the mass of water. We know the mass of iron, specific heat is known for both water as well as for iron and we know the initial temperature of water and initial temperature of iron. So, if we substitute for these values in the equation which we derived from the first law, we should be able to find out the final temperature.

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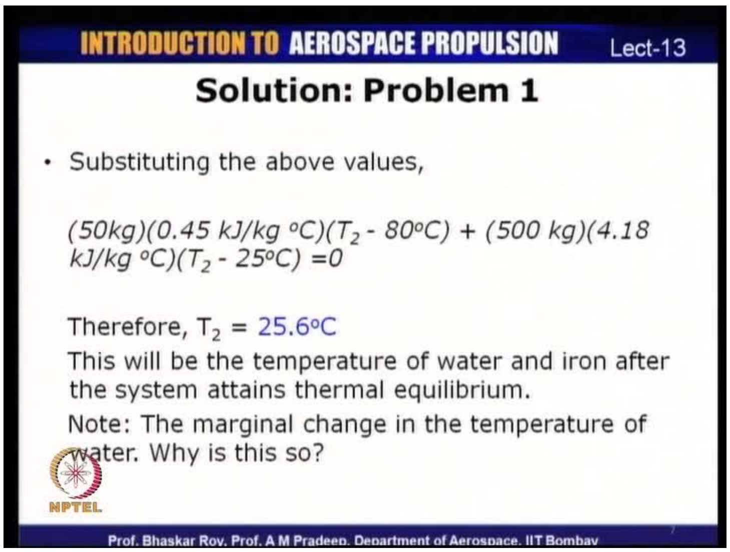

Let us do that now, if we substitute these values for iron block which is 50 kgs mass, 0.45 kilojoules per kilogram degree celsius is the specific heat of iron multiplied by T 2 minus - T 2 is the final temperature minus - initial temperature is 80 degree celsius; this plus 500 kgs of water multiplied by 4.18 kilojoules per kilogram degree celsius is the specific heat for water multiplied by T 2 which is final temperature for water minus 25 degree celsius, so this is equal to 0. If we solve for this, we can find out T 2 which is the final temperature, so T 2 comes out to be 25.6 degree celsius. This will be the temperature of water and iron after the system reaches thermal equilibrium; so after the system reaches thermal equilibrium both iron and water will have a temperature of 25.6.

You may wonder that even though your iron block was at 80 degree celsius which is much higher than 25 degree celsius of water, the final temperature of both iron as well as water is only 25.6. So, there is a very marginal change in the temperature of water.

You may wonder why is it that you have a very small change in temperature of water, whereas there is a very drastic reduction in the temperature of iron. There are 2 reasons for this; one is of course, that mass of water is 10 times that of mass of iron here; mass of water we calculated as 500 kgs, mass of the iron blocks is only 50 kgs, so that is one of the reasons.

The other reason is the change difference in the specific heats of water and iron, so specific heat of iron in this problem it was given as 0.45 kilojoules per kilogram degree celsius whereas, for water it is one order magnitude higher it is 4.18 kilojoules per kilogram degree celsius. This means that to raise the temperature of water, unit mass of water by 1 degree celsius you need 4.18 kilojoules whereas, for iron you only need 0.45 kilojoules.

So, specific heat of water being so high at the same time, the mass of water in this case is also much higher than that of iron; there is a very small change, very marginal change in the temperature of water as compared to that of iron.

This is the first problem, we have solved for which basically uses the first law of thermodynamics for closed systems. We have used the specific heats of these two different substances to calculate the temperature, which the system will have after it attains a thermal equilibrium. Now, let us look at the second problem that we have for today’s lecture.

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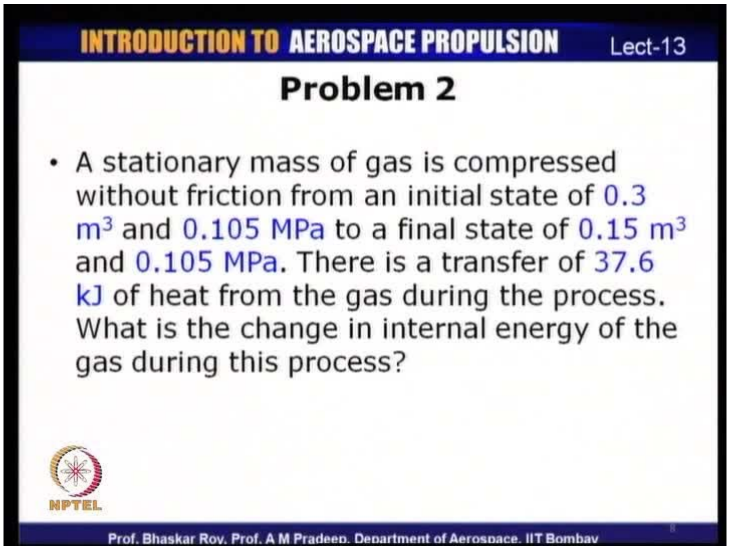

The second problem is looking at a stationary mass of gas is compressed without friction from an initial state of 0.3 meter cube and 0.105 mega pascal to a final state of 0.15 meter cube and 0.105 mega pascal. There is a transfer of 37.6 kilojoules of heat from the gas during the process, what is the change in internal energy of the gas during this process?

So, we have here a process which is basically an isobaric process that is the pressure is a constant; the volume has changed from 0.3 meter cube to 0.1 meter cube which means that it is isobaric process with a change in the volume. There is also a heat transfer during this process. So, what happens to the internal energy of the system during this process?

What is basically mentioned here is that when this process is occurring, there is only a change in the specific volume well just the volume but, there is no change in the pressure and there is a certain amount of heat transfer into this process. This is again a problem which will involve the first law of thermodynamics. So, if we apply the first law of thermodynamics for a stationary system, because it is given as the stationary system a closed system.

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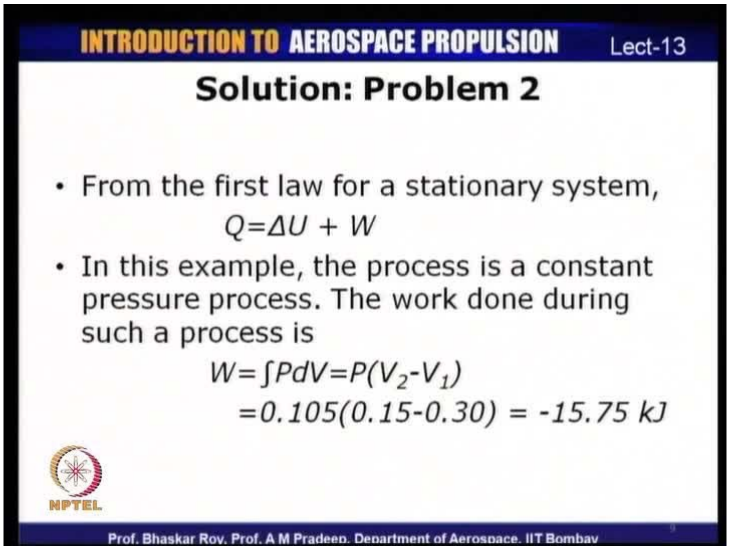

We have from the first law; Q is equal to delta U plus W. Now, in this example we have been given Q, Q is given as 37.6 kilojoules and since this process is a constant pressure process, work done during this process is something we had derived in a few lectures earlier. Work done will be equal to integral P d V which is equal to P times V 2 minus V 1 and here P is given as 0.105 mega pascal this multiplied by the change in volume will give us the work done during this process. So, 0.105 multiplied by 0.15 minus 0.3 which is equal to minus 15.75 kilojoules; we get a negative sign here because there is work done on the system and so it leads us to negative sign for the work done.

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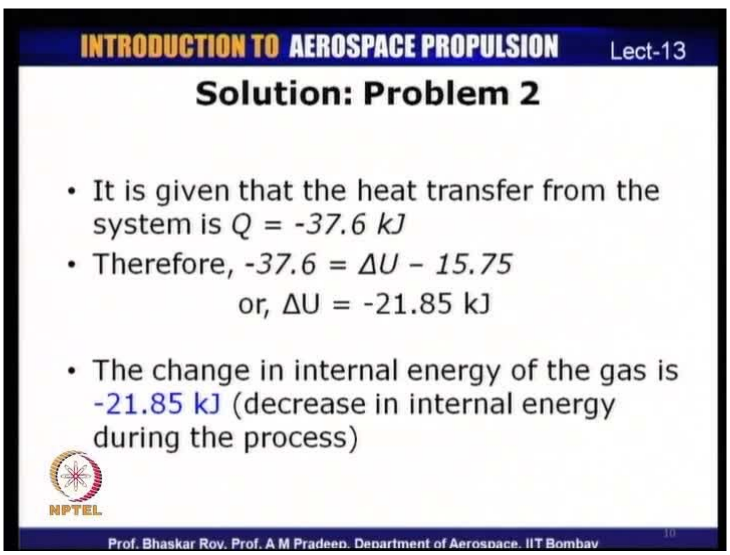

Now it is already mentioned that, heat transfer from the system is minus 37.6 kilojoules. We now have the work done during the process, which is a constant pressure process; work done during such a process is just the product of pressure multiplied by the change in volumes. So p times V 2 minus V 1 is the work done and heat transfer is already given to us. We just simply apply these two to the first law equation, we had stated earlier. So, Q is equal to delta U plus W and therefore, delta U can be calculated from the heat transfer and the work done which we have just now calculated.

Therefore minus 37.6 is equal to delta U minus 15.75 or delta U is equal to minus 21.85 kilojoules. Then total change or net change in internal energy of the gas is minus 21.85 kilojoules, this means that there is a decrease in internal energy of the process.

These are two problems that we have solved, where we have applied the first law for closed systems. We shall now solve a problem, which involves in open system and we shall use this steady flow energy equation to solve that problem.

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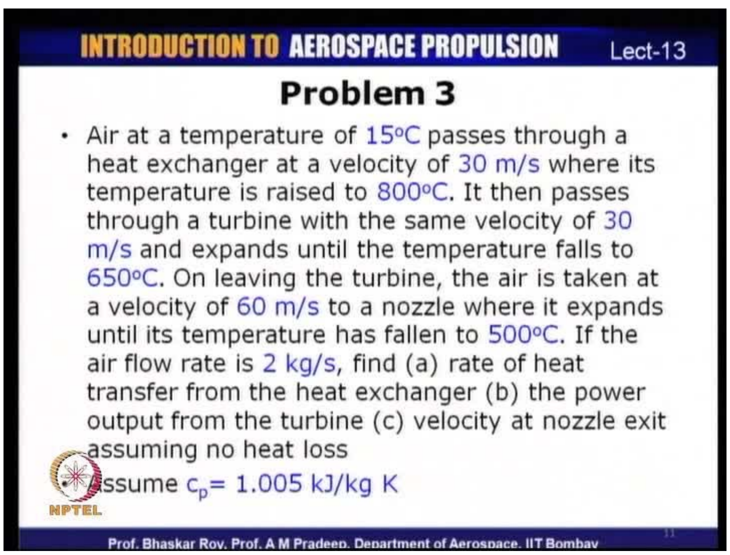

The third problem that we have today is involving a steady flow process. The problem statement is air at a temperature of 15 degree celsius passes through a heat exchanger at a velocity of 30 meter per second, where its temperature is raised to 800 degree celsius. It then passes through a turbine with the same velocity of 30 meters per second and expands until the temperature falls to 650 degree celsius.

On leaving the turbine, the air is taken at a velocity of 60 meters per second to a nozzle where it expands until its temperature has fallen to 500 celsius. If the air flow rate is 2 kilograms per second, find part a: rate of heat transfer from the heat exchanger, part b: the power output from the turbine and part c: velocity at the nozzle exit, assuming no heat loss or heat transfer. It is also given to assume c p for air as 1.005 kilojoules per kilogram kelvin.

Here is a problem, which consists of multiple components we have a heat exchanger where air is taken from an initial temperature of 15 degree celsius to a high temperature of 800 degree celsius and it is at a certain velocity. From the heat exchanger, air goes to a turbine where its temperature falls and there is an increase in its velocity. From the turbine exit it goes through a nozzle where again there is a drop in temperature and correspondingly, there is also an increase in its velocity.

So there are 3 distinct components and we are required to find the heat transfer in the heat exchanger, then the work done by the turbine and velocity at the exit of the nozzle. So before we start to solve this problem, let us make an illustration of these different components and also mark salient points on this combined system which involves three different components.

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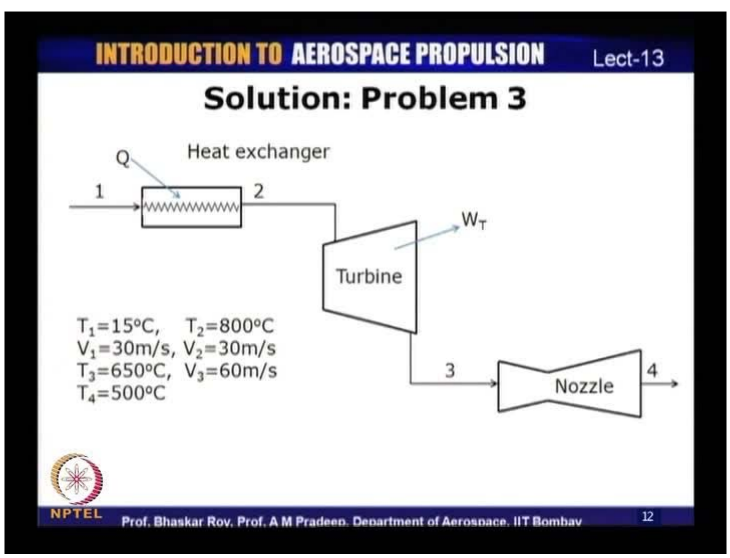

If we were to illustrate this on a sketch, we have a heat exchanger which is operating between states 1 and 2 and there is a heat transfer into the heat exchanger at a rate of Q and between states 2 and 3 there is a turbine which generates a net work output W t. The turbine exhaust at state 3 goes through a nozzle and comes out at state 4.

Now, in the problem it is given that T 1 is 15 degree celsius, T 2 is 800 degree celsius, V 1 30 meters per second, V 2 is again 30 meters per second, T 2 is 650 meters per second, V 2 is 30 meters per second, T 3 is 650 degree celsius, V 3 is 60 meters per second and T 4 is 500 degree celsius. So, temperature at the inlet of the heat exchanger and exit are given, temperature at the turbine inlet and turbine exit are given, and temperature at the nozzle entry and exit are also given.

So what is required to be calculated is firstly, the heat transfer at the heat exchanger end work done by the turbine and also velocity at state flow that is V 4. What we will do to solve this problem is to take up each of these components one by one. Now you can easily see that all these components are steady flow components, we have already derived equations for steady flow components for heat exchanger turbine as well as for nozzle. So, these 3 components that we have are steady flow components and so we can use the steady flow energy equation for solving this problem.

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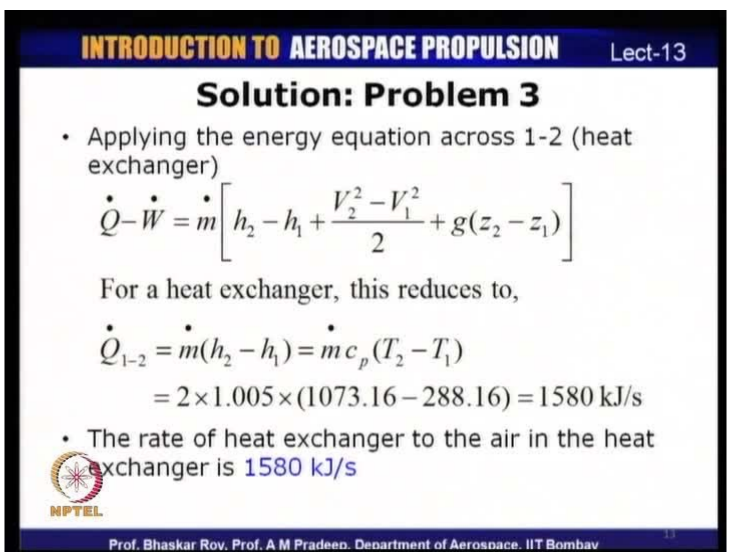

We will take up the heat exchanger first and we apply the energy equation across states 1-2 which is the heat exchanger. As per the steady flow energy equation, which was stated as Q dot minus W dot is equal to m dot multiplied by h 2 minus h 1 plus V 2 squared minus V 1 squared by 2 plus g times z 2 minus z 1. So this is the steady flow energy equation for a single entry system.

Now for a heat exchanger, we know that there is no work done by the heat exchanger and since velocity inlet and velocity outlet are the same, V 2 squared minus V 1 squared by 2 will become 0 and also there is no net change in the potential energy of the system.

Therefore, for a heat exchanger this energy equation will reduce to Q dot is equal to m dot times h 2 minus h 1. Now, this is equal to m dot times c p multiplied by T 2 minus T 1 and so for this system the mass flow rate is specified as 2 kilograms per second, specific heat is given at constant pressure 1.005 kilojoules per kilogram kelvin and temperatures are also given. The exit temperature from the heat exchanger is given as 800 celsius and the inlet temperature is given as 15 degree celsius.

Since we have to be consistent in terms of the units, we have converted the temperatures from celsius scale to the kelvin scale. So 800 degree celsius becomes 800 plus 273.16 which is 1073.16 kelvin. Similarly, T 1 is 15 degree celsius which is in kelvin scale would be 273.16 plus 15 and that is 288.16 kelvin.

So, substituting all these values we have mass flow rate 2 kgs per second multiplied by specific heat which is 1.005 multiplied by the temperature difference that is the 1073.16 minus 288.16; so this comes out to be 1580 kilojoules per second. The rate of heat transfer is at the rate of 1580 kilojoules per second; so heat transfer is receiving heat at a rate of 1580 kilojoules per second which is also kilowatts in that sense.

Now the next component we have, it is again a steady flow component that is a turbine. We have also derived expression for a turbine earlier, we again would apply the steady flow energy equation for the turbine which is Q dot minus W dot is equal to m dot into h 2 minus h 1 plus V 2 squared minus V 1 squared by 2 plus g times z 2 minus z 1.

For a turbine, we will assume that there is no heat transfer across the turbine boundaries Q dot for the turbine is equal to 0. Also there is no change in potential energy across the system boundaries and so g times z 2 minus z 1 will also be equal to 0.

If you were to make these assumptions, then we shall be getting an expression in terms of the enthalpy and also the velocities. In this case, we also have been given the velocities and they are not equal and so you cannot assume that the change in kinetic energy across the turbine is equal to 0. So, if you were to substitute these assumptions in the energy equation, we get W dot is equal to m dot times h 2 minus h 3 plus V 2 squared minus V 3 squared by 2.

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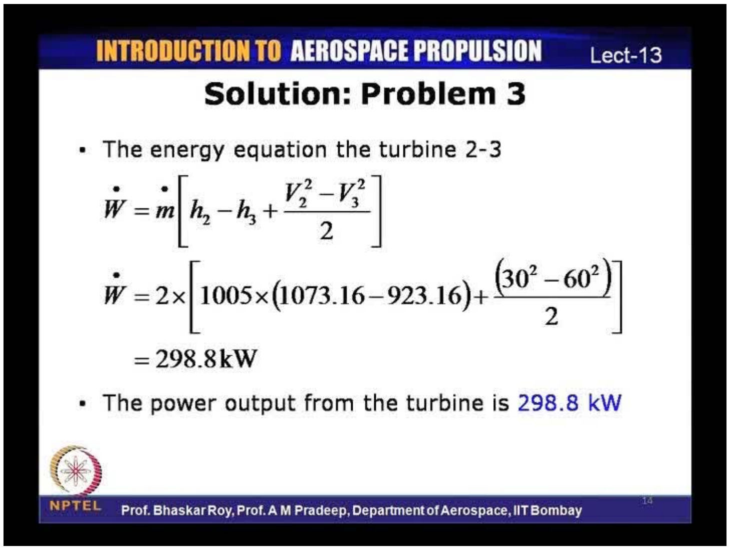

We have all these values given in the problem, we have the mass flow rate to calculate h 2 and h 3, it is basically c p times T 2 minus T 3 and T 2 is already known is 1073.16 kelvin and T 3 is also given as 650 degree celsius.

So, 650 plus 273.16 is 923.16 kelvin. So W dot is equal to 2 into 1005 into delta T which is 1073.16 minus 923.16 plus the change in velocities - the inlet velocity is 30 meters per second, exit velocity is 60 meters per second, so that would be plus 30 squared minus 60 squared by 2. So this comes out to be 298.8 kilowatts. Therefore, the power output from the turbine is 298.8 kilowatts; so this is the power output or work done by the turbine.

Now, the third component that we have to solve for is the nozzle. Nozzle again is a steady flow component, we shall again apply the steady flow energy equation for the nozzle as well and for a nozzle we know that there is no work done by the nozzle, also the heat transfer across the nozzle boundaries can be neglected.

If you assume these assumptions and also that there is no change in potential energy across the system boundaries, we basically would have an expression for the velocities in terms of the enthalpies. What we will have is that, if you apply the energy equation for a nozzle, we will get V 3 squared by 2 plus h 3 is equal to V 4 squared by 2 plus h 4.

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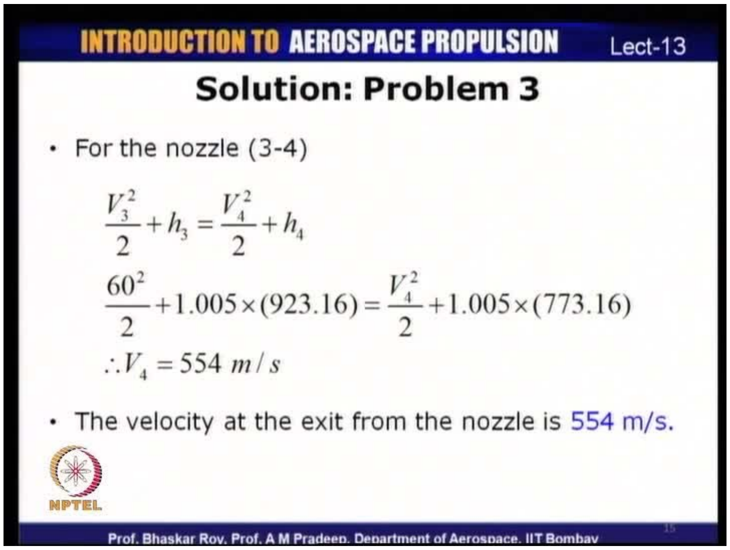

So, we have already being given V 3 which is the turbine exit velocity that is 60 meters per second and h 3 is 1.005 times the temperature, c p times t that is 1.005 into 923.16 kelvin plus V 4 squared by 2 plus the change in enthalpy at state 4 that is 1.005 and its temperature that was 500 degree celsius, 500 plus 273.16 that is 773.16.

So from this, we can calculate velocity at the exit of the nozzle; velocity at the exit of the nozzle comes out to be 554 meter per second. Here, we can calculate and see that the velocity at the exit of the nozzle is 554 meters per second. You can see that from an inlet velocity of 60 meter per second, it has increased by almost more than a factor of almost a factor of 10 and it has gone to a velocity of 554 meters per second which is one of the functions of the nozzle. As I had mentioned earlier, nozzle is a component which increases the kinetic energy at the expense of pressure.

So there is a decrease in pressure and also temperature and there is an increase in the kinetic energy of the system. In this problem what we have solved is basically applying the energy equation which is again the first law applied to open systems to 3 different components. One was a heat exchanger, a turbine and a nozzle.

So what we have to understand here is that depending up on the particular problem at hand, we may have to simplify the basic energy equation depending up on what component it is. For example, in the case of the heat exchanger we had assumed that there is no net work done by the system which is true and also that the change in potential energy is 0. In this particular problem, it was given that the inlet and exit velocities are the same. So basically, the heat transfer was just mass times mass flow rate multiplied by change in enthalpy.

For the second case that is the turbine, we have assumed that there is no heat transfer across the turbine walls and also there is no change in potential energy. So work done was equal to change in enthalpy plus change in the kinetic energy. For the third component that is the nozzle, work done is 0, heat transfer is 0 and also the potential energy change is 0; so, sum of enthalpy plus velocity squared by 2 at inlet of the nozzle will be equal to enthalpy plus velocity squared by 2 at the exit of the nozzle.

So, from that you can calculate the velocity at the exit of the nozzle. We have just used the same equation for all the three components but, we have applied appropriate boundary conditions for these equations and simplified the equations depending up on what component we are trying to analyze. So, this is one of the applications of the steady flow energy equation which is consequence of the first law of thermodynamics for open systems.

Now what we shall try to solve next would be a problem from a heat engine; we shall solve a problem from heat engine and find out the efficiency associated with that.

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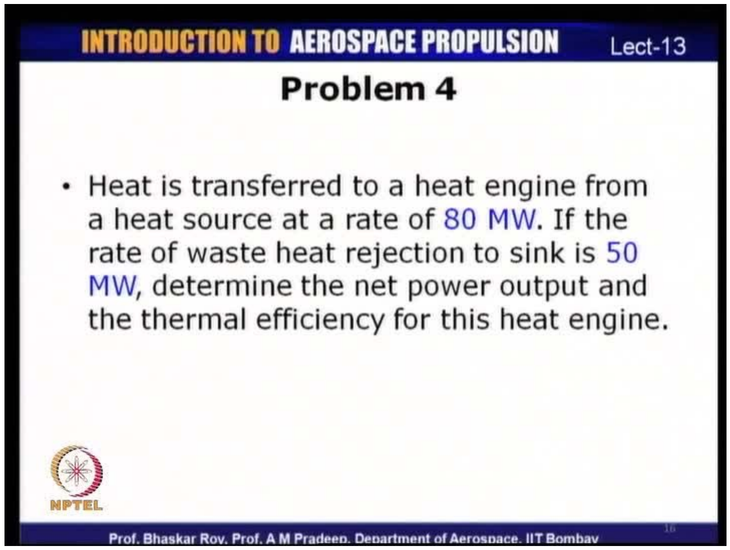

So, let us look at the fourth problem we have at hand today. Problem 4 we have is heat is transferred to a heat engine from a heat source at a rate of 80 megawatts. If the rate of heat rejection to the sink is 50 megawatts, determine the net power output and the thermal efficiency of the heat engine.

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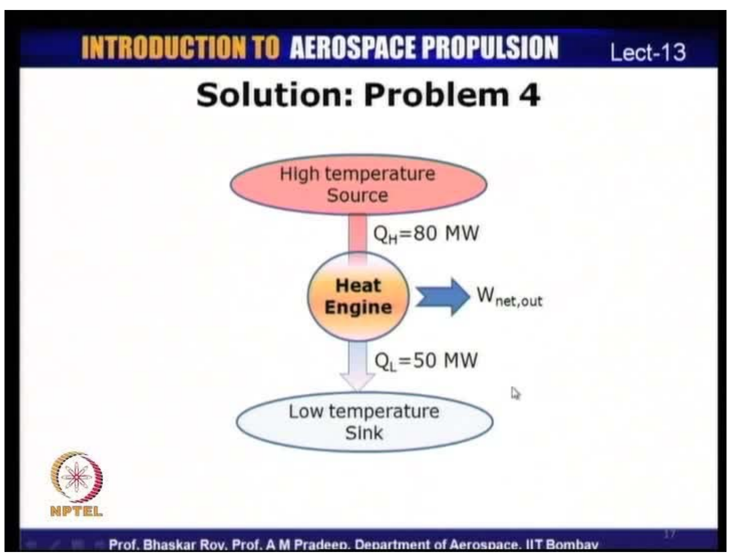

In this problem if I were to illustrate it here, there is a heat engine which is operating between a high temperature source and a low temperature sink. So, rate of heat transfer from the high temperature source to the heat engine is 80 megawatts and then the heat engine rejects some amount of heat to the sink at a rate of 50 megawatts. We need to find what are the net work output and the efficiency of this heat engine.

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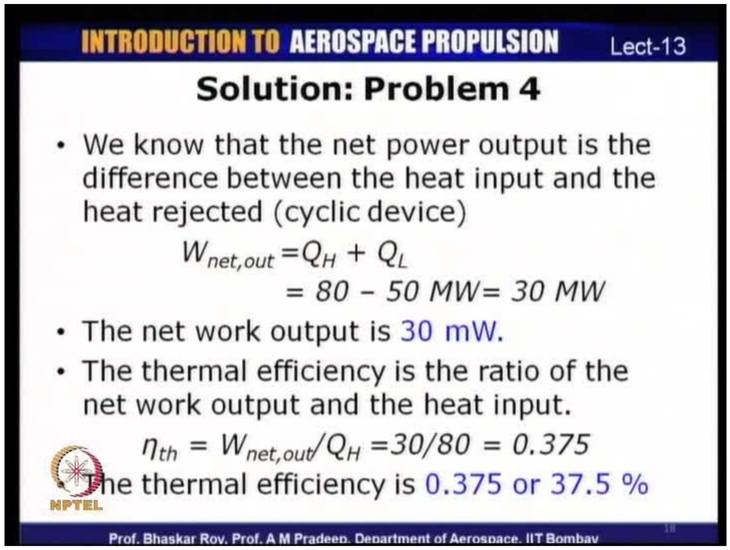

Now the net work output basically is equal to the net heat transfer or heat input and heat rejected difference because it is a cyclic device, from first law, delta W is equal to delta Q. So net work input will be equal to Q h minus Q l and so in this case we have Q h is equal to 80 megawatts and Q l is equal to 50 megawatts; so Q h minus Q l will be 80 minus 50 megawatts that is 30 megawatts, so the net work output of this cycle is 30 megawatts.

Now to find out the thermal efficiency of this particular system, thermal efficiency is the ratio of the net work output and the heat input. So, we have just now calculated the net work output, so thermal efficiency is W net out divided by Q h that is 30 divided by 80 which is equal to 0.375, so thermal efficiency for this particular heat engine comes out to be 0.375 or 37.5 percent.

So, this was a very simple problem on trying to find out the net work output and efficiency of a heat engine. The net work output for any heat engine will be equal to the difference between the heat input to the system and the heat output or heat rejected by the system.

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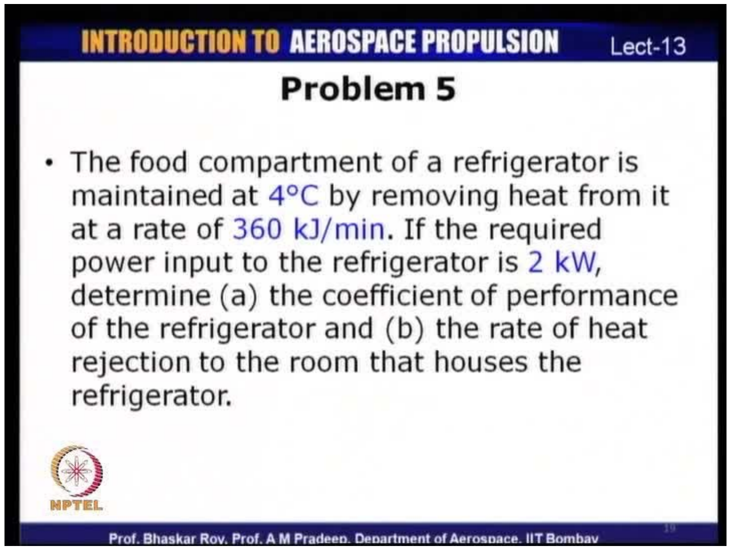

So, w net out was Q h minus Q in and efficiency is the ratio of the net work output to the heat input. Here it was W net out divided by Q h and so you can actually calculate the efficiency associated with this particular heat engine. Now let us look at a problem, were we have a refrigeration system and we shall try and solve a problem which involves a refrigerator as well as a combination of refrigerator and a heat engine.

In the first problem that we will solve for a refrigerator, we will just consider a refrigerator which is operating between a low temperature sink and high temperature surrounding. So the problem statement is the food compartment of a refrigerator is maintained at 4 degree celsius by removing heat from it at the rate of 360 kilojoules per minute. If the required power input to the refrigerator is 2 kilowatts, determine part a: the coefficient of the performance of the refrigerator and part b: the rate of heat rejection to the room that houses the refrigerator.

So this question is on a refrigeration system; we have a refrigerator which is maintaining a certain temperature by removing heat from it at a certain rate and the power input for the refrigerator is also given. We need to find out the coefficient of performance and the rate of heat rejection to the room where the refrigerator is kept.

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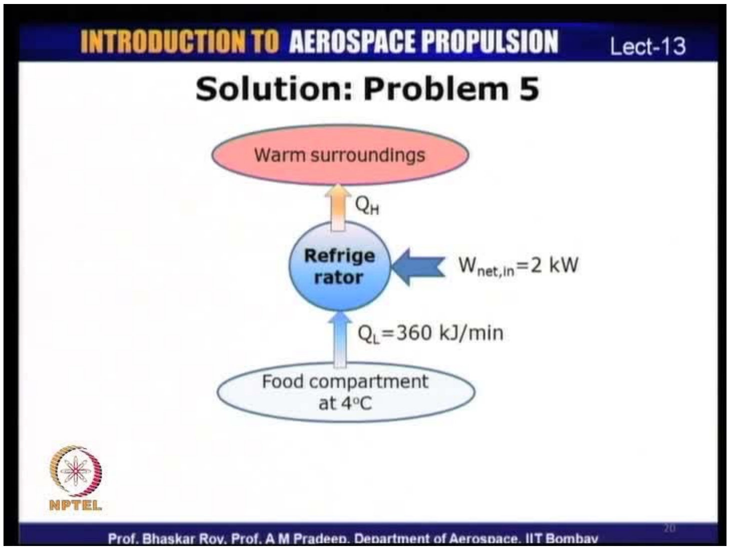

So, the problem statement would look something like this (Refer Slide Time: 33:06). We have a refrigerator which is maintaining a temperature of 4 degree celsius in the food compartment; it is transferring heat at a rate of 360 kilojoules per minute from the refrigerator and the required work input for maintaining this temperature is 2 kilowatts. We need to find out the coefficient of performance and Q h.

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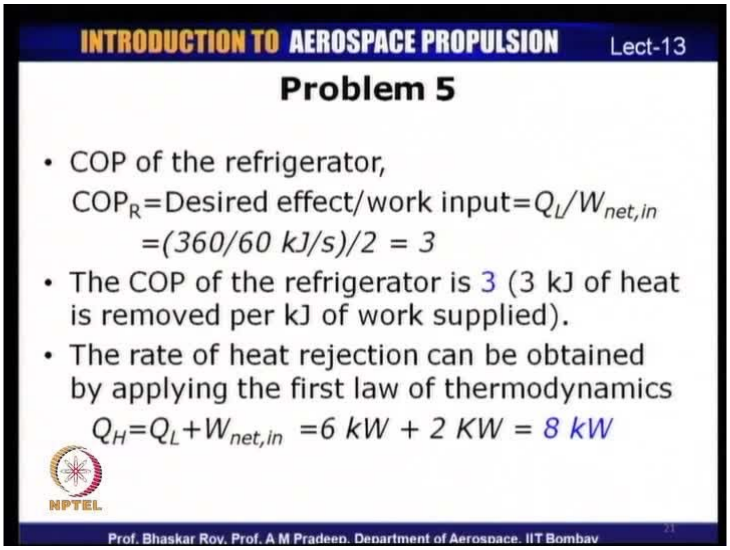

So COP of this refrigerator, as we have defined earlier is the ratio of desired effect divided by the work input. In the case of a refrigerator, the desired effect is Q l because you would desire to maintain the temperature of the food compartment at a lower temperature and so that requires a Q l of 360 kilojoules per minute. Here the desired effect for the refrigerator is Q l and therefore, COP of the refrigerator is Q l divided by W net,in and so here Q l is given as 360 kilojoules per minute. So, we have to convert this to kilojoules per second and therefore, 360 divided by 60 is in kilojoules per second and therefore, that is 6 divided by 2 and so the COP of this refrigerator is 3.

So, what it means is that in this refrigerator, 3 kilojoules of heat is removed per kilo joule of work supplied. In this refrigerator that we have, the COP comes out to be 3 which mean that this refrigerator will be removing heat at the rate of 3 kilojoules per kilo joule of work that is supplied.

The second part of the question was to find out the rate of heat rejection from the refrigerator and this again we can find from the first law of thermodynamics. So, Q h which was the rate of heat rejection minus Q l will be equal to W net,in. So Q h is equal to the heat rejection from the food compartment to the refrigerator plus the work input; so sum of these two will give you Q h from the system.

So, Q l is given as 6 kilowatts that is 360 kilojoules per minute and that is 360 divided by 60 kilojoules per second, that is 6 kilojoules per second which is kilowatts and so 6 plus the work input was 2 kilowatts that is equal to 8 kilowatts. So, the heat input from or well heat rejection rate from the refrigerator would be equal to sum of work input plus the heat rejected by the food compartment. That is equal to 6 plus 2 that is 8 kilojoules per second which is kilowatts.

So that is the net rate of heat rejection from the refrigerator to the surroundings in which the refrigerator is placed. In this problem, what we have solved is a system which is consisted of a refrigerator which is continuously transferring heat from low temperatures, food compartment maintaining it at a low temperature of 4 degree celsius and rejecting heat to the surroundings at certain rate.

So what we have found is the COP, which is the coefficient of the performance rate of which is basically the ratio of desired effect to the work input and for a refrigerator the desired effect is Q l. So Q l by work input is COP and in this case, we calculated that to be 3 which is 360 by 60, which is 6 kilowatts of desired effect divided by 2 which is the work input, so 6 by 2 is equal to 3.

In the second part of the question, was to find out the rate of heat rejection from the refrigerator to the surroundings which is Q h is equal to Q l plus W net,in and that is equal to 6 kilowatts plus 2 kilowatts that is 8 kilowatts.

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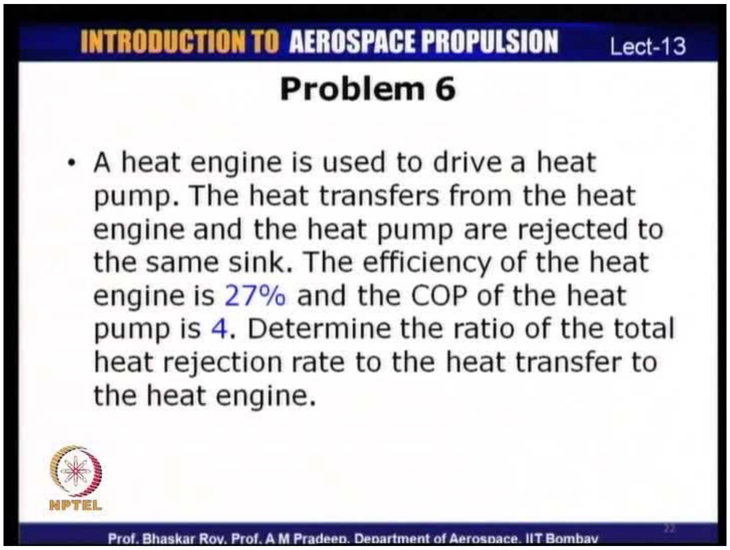

Now this problem that we have, that is problem number 6 is a problem which combines a heat engine and a heat pump. A heat engine is used to drive a heat pump, the heat transfers from the heat engine and the heat pump are rejected to the same sink that is both the heat engine and heat pump are rejecting heat to the same sink, efficiency of the heat engine is 27 percent and COP of the heat pump is 4. Determine the ratio of the total heat rejection rate to the heat transfer to the heat engine, so here we have a system which consists of a heat engine as well as a heat pump.

So heat engine is basically being used to drive a heat pump and both the heat pump and the heat engine are rejecting heat to the same sink. We have been given the efficiency of the heat engine is 27 percent, COP of the heat pump as 4. Based on this data, we need to find out the ratio of total heat rejection rate to the heat input to the heat engine.

We will first illustrate this problem in terms of sketch and we will find out what are the different heat rejection and heat input rates to these two different components. Then, we shall try and solve this problem based on this illustration.

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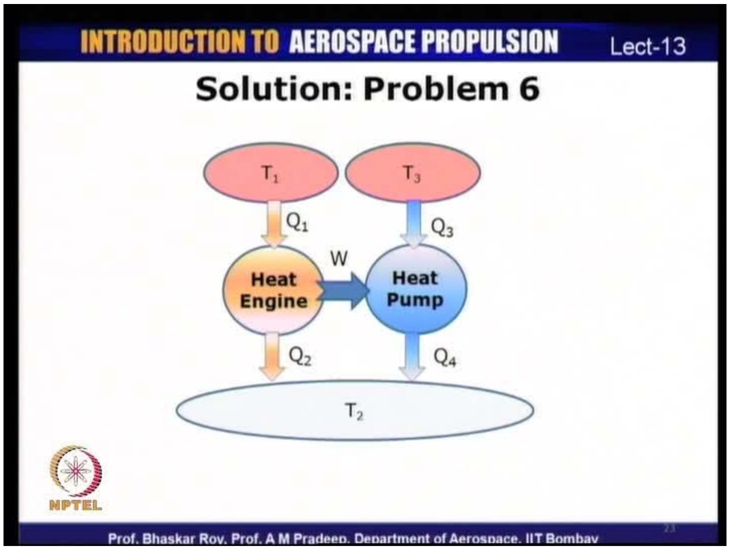

What I have shown here is a combination of heat engine and heat pump; so we have a heat engine here and then a heat pump. This heat engine is driving the heat pump through a work in work of W, heat engine rejects a heat of Q 2 to the sink, and heat pump rejects a heat of Q 4 to this heat sink. The heat engine operates between a source of T 1 and transfers heat at a rate of Q 1 to the heat engine and heat pump on the other hand transfers heat from T 3 at a rate of Q 3 and rejects heat to the sink at Q 4 and this heat pump is getting its work input from the heat engine.

So there are 2 different cyclic devices here; one is a heat engine and other is a heat pump. Work output of the heat engine is used to drive the heat pump and both the heat engine and heat pump reject heat to the same sink that is at temperature T 2. What we are required to find is the ratio of the total heat rejection that is Q 2 plus Q 4 to the heat input to the heat engine that is Q 1. So what we need to find out is Q 2 plus Q 4 divided by Q 1.

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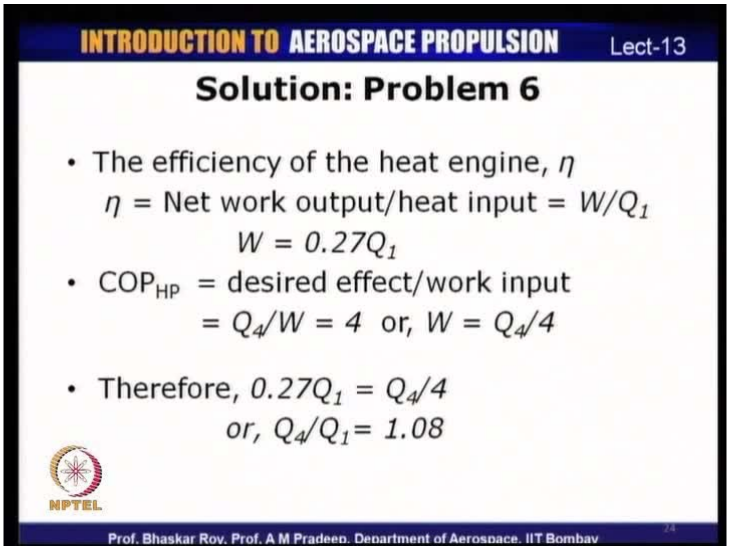

For doing this, we have been given the efficiency of heat engine and COP of the heat pump. Now efficiency of heat engine is already known to us, the definition is net work output divided by heat input. So, W net or just W here divided by Q 1 is the efficiency of the heat engine and efficiency is given as 0.27. Therefore, W is equal to 0.27 times Q 1. Similarly, we have been given the COP of the heat pump, COP is the desired effect by work input and for a heat pump the desired effect is Q 4.

So, Q 4 divided by W is equal to COP which is 4 in this case; so w is also equal to Q 4 divided by 4. If you equate these 2 equations in terms of W, you get 0.27 Q 1 is equal to Q 4 divided by 4 or Q 4 by Q 1 is equal to 1.08.

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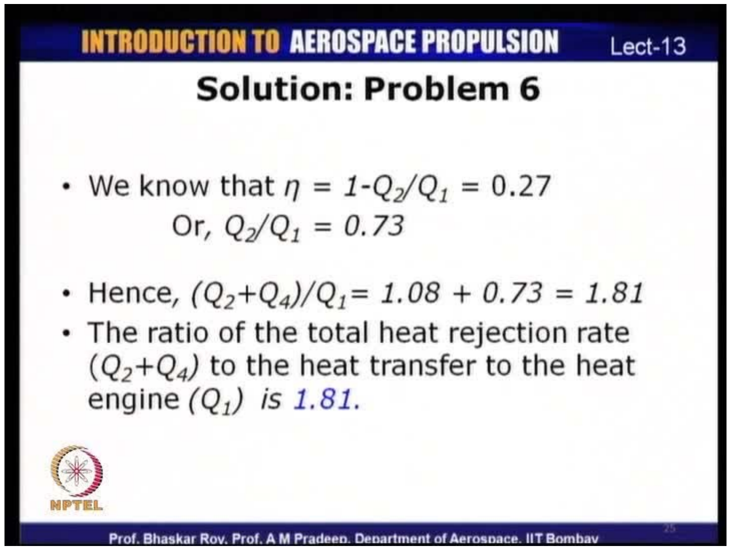

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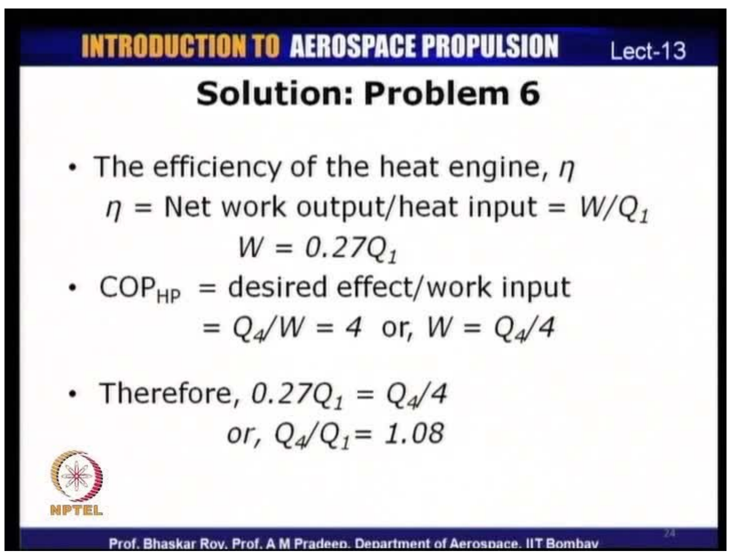

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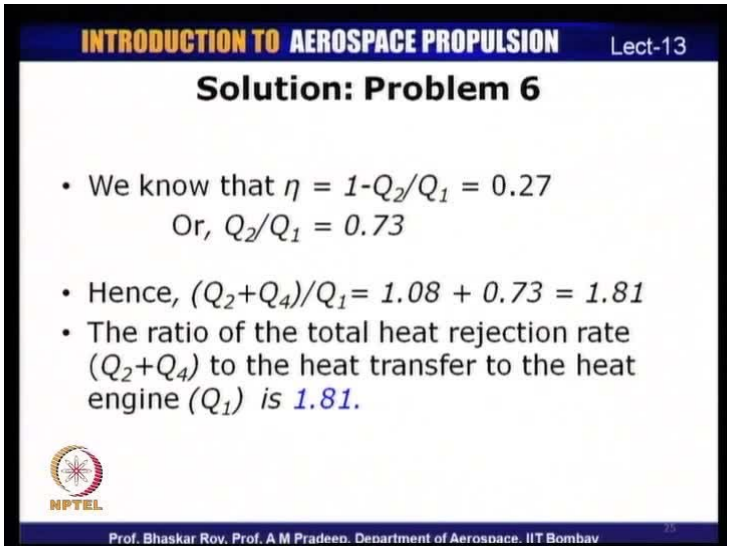

So ratio of heat rejection by the heat pump to the heat transfer to the heat engine which is Q 1 is 1.08. We also know that efficiency is also equal to 1 minus Q 2 by Q 1 and that is basically because efficiency of the heat engine is W by Q 1 and W is equal to Q 2 minus Q 1. We get efficiency as Q 2 minus Q 2 divided by Q 1 which is equal to 1 minus Q 2 by Q 1 and this is given as 0.27. We have an expression for the ratio Q 2 by Q 1; so Q 2 by Q 1 will come out to be 0.73 because that will be 1 minus 0.27 and therefore, that is 0.73.

We have an expression for Q 4 by Q 1 which is equal to 1.08 and we have another expression for Q 2 by Q 1 which is 0.73 and what we are required to find is the ratio of heat rejection rate, total heat rejection rate which is heat rejection from heat pump as well as the heat engine divided by heat input to the heat engine. So, we are required to find out Q 2 plus Q 4 divided by Q 1. We have calculated Q 2 by Q 1 and Q 4 by Q 1 separately, which means that the desired ratio can be found out just by adding up these two individual ratios.

So, Q 2 plus Q 4divided by Q 1 will be 1.08 plus 0.73 that is 1.81. So the total the ratio of total heat rejection rate which is Q 2 plus Q 4 to the heat transfer to the heat engine which is Q 1 is basically 1.81. In this problem that we have solved right now is a combination of 2 devices, 2 cyclic devices, one of them is the heat pump and other is a heat engine. Heat engine is driving the heat pump and then there is a certain efficiency given for the heat engine and a COP given for the heat pump.

So based on these parameters, it is possible for us to find out the different rates of heat rejection from the heat engine and heat pump separately as compared to the heat input to these systems. What we did was to calculate the rate of heat rejection Q 4 by Q 1 which comes by equating efficiency of the heat engine as W net divided by Q 1 is equal to 0.27 the efficiency here, so W is equal to 0.27 Q 1.

Similarly for the heat pump, the COP is equal to desired effect which is Q 4 divided by W which is equal to 4, W is equal to Q 4 by 4 and so you can find out the ratio Q 4 by Q 1 from that. Similarly, efficiency is also equal to 1 minus Q 2 by Q 1 because efficiency is W by Q 1 and W is Q 1 minus Q 2 divided by Q 1; therefore, that is 1 minus Q 2 by Q 1.

You can also calculate the ratio Q 2 by Q 1 from there and combining these two different expression or ratios, we can find out the total ratio of heat rejection rate and ratio of that as compared to the heat input to the heat engine. So sum of 1.08 plus 0.73 is 1.81, so that is the desired ratio of total heat rejection rate from heat engine heat pump combination as compared to the heat engine input to the heat engine.

We have solved a few problems on the first law of thermodynamics as applied to closed systems and also applied first law of thermodynamics to open system which was basically using the steady flow equations for a system comprising of different components. Then we have also calculated efficiency and work output of a heat engine and then we looked at a system which consisted of a combination of 2 cyclic devices a heat engine and a heat pump. So, I have a few exercise problems for you to solve.

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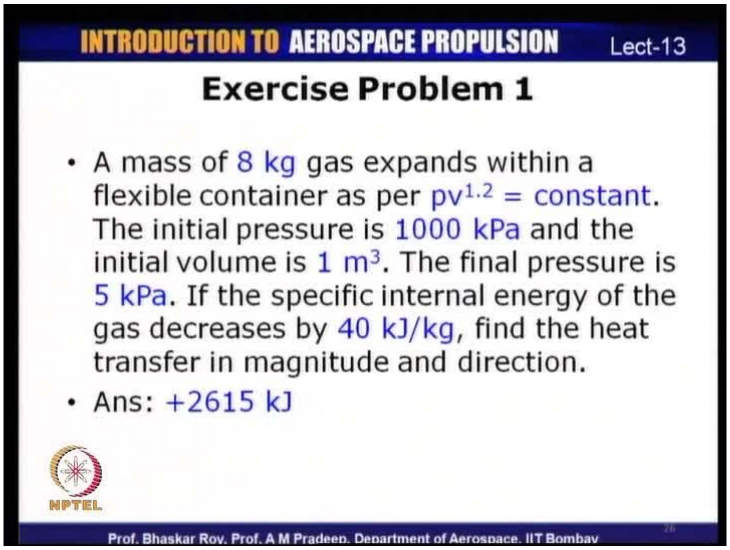

The first exercise problem that is stated as a mass of 8 kilogram gas expands within a flexible container as per the law p v raised to 1.2 is a constant. The initial pressure is 1000 kilopascal and the initial volume is 1 meter cube, the final pressure is 5 kilo pascal. If the specific internal energy of the gas decreases by 40 kilojoules per kilogram, find the heat transfer in magnitude and direction.

So this is a problem, which is again requires application of the first law and there is a certain process given here which means that you can calculate the pdv work for pv raised to n is equal to constant. We have already calculated work associated with pv raised to n equal to constant processes. So pressure is given, initial pressure and final pressure is given, initial volume is given and mass of the gas is also given based on that one should be able to find the final volume.

Therefore, we can find out the work done for this process and since specific internal energy change is given so applying first law one should be easily able to find out Q minus from Q minus W is equal to delta U. You can find out what is the heat transfer associated with this particular process. Net heat transfer can be found in both magnitude and direction and the final answer that I have given here is plus 2615 kilojoules.

This is the magnitude of the heat transfer during this process which consisted of a pv raised to n equal to constant process and certain pressures and volume is given, mass of the gas is given, so you should be able to find out work done for this pv process. The heat transfer can be found out because the change in the internal energy is also specified.

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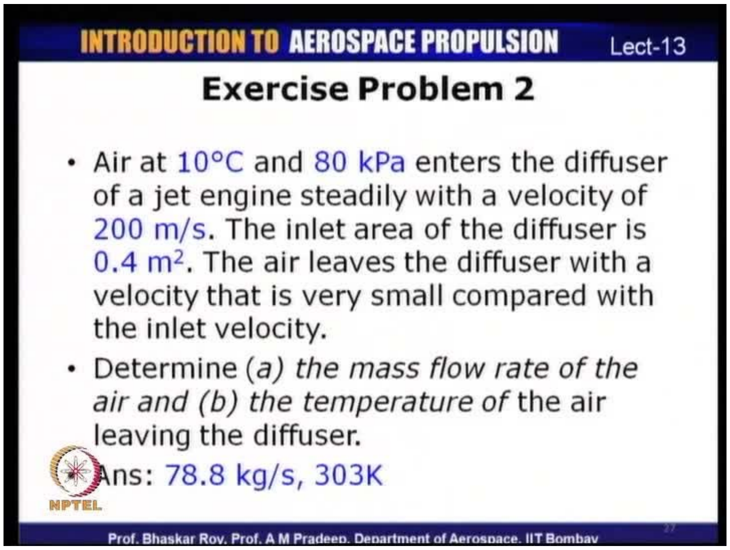

The second exercise problem is on a diffuser, it is again a steady flow process. Air at 10 degree celsius and 80 kilopascals enters the diffuser of a jet engine steadily with a velocity of 200 meters per second. Inlet area of a diffuser is 4 meter squared, air leave the diffuser with the velocity that is very small compared with the inlet velocity. Determine part a: mass flow rate of the air and part b: temperature of the air leaving the diffuser.

So, this is an open system where you would have to apply the steady flow energy equation for a diffuser. It is mentioned that the exit velocity from the diffuser is negligible as compared to the inlet velocity but, it still means that the inlet velocity needs to be considered and based on this you need to calculate the mass flow rate.

Well, to calculate mass flow rate basically you have area which has been specified, pressure and temperature is given. So, you can calculate density as well and from area velocity and density you can calculate mass flow rate. To calculate temperature of air leaving the diffuser you would need to use the energy equation.

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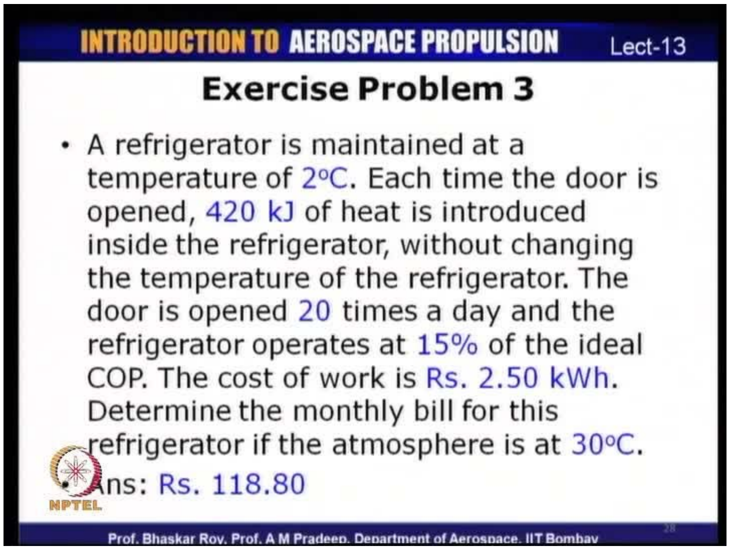

The third exercise problem is of a refrigerator; a refrigerator is maintained at a temperature of 2 degree celsius and each time the door is opened 420 kilojoules of heat is introduced inside the refrigerator, without changing the temperature of the refrigerator. The door is opened 20 times a day and the refrigerator operates at 15 percent of the ideal COP. The cost of work is rupees 2.5 kilowatt hour and if this is the cost, determine the monthly bill for this refrigerator, if the atmosphere is at 30 degree celsius.

So in this problem, there is a refrigerator which is maintained at a temperature, the rate of heat into the refrigerator is given as 420 kilojoules and the number of times the refrigerator is opened or operated is also given. The refrigerator is operating at 15 percent of the ideal COP and given these conditions, we need to calculate the monthly cost of the refrigerator and the ambient temperature is also given as 30 degree celsius. So the answer for this is rupees 118.8, if you assume a cost of work as rupees 2.5 kilowatt hour.

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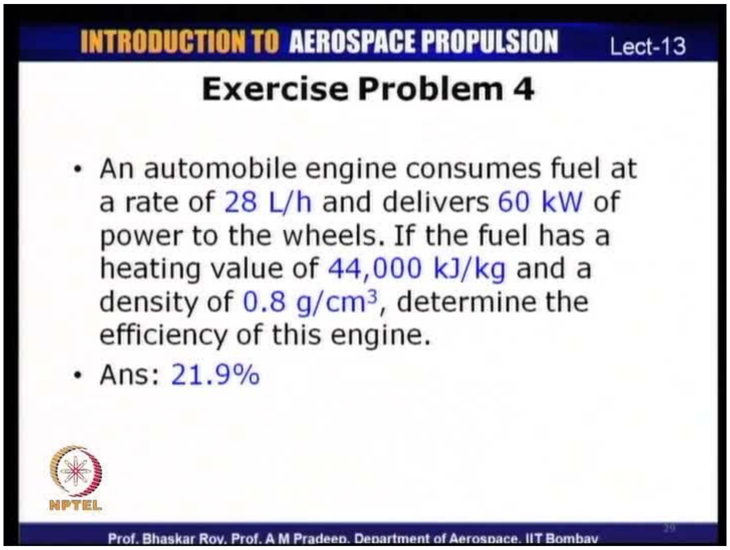

The last problem, the fourth exercise problem we have is that of a heat engine. An automobile engine consumes fuel at a rate of 28 liters per hour and delivers 60 kilowatts of power to the wheels. If the fuel has the heating value of 44,000 kilojoules per kilogram and a density of 0.8 grams per centimeter cube, determine the efficiency of the engine. So here we have, the rate of heat input in terms of heating value and work output is also specified and density is specified, the rate of consumption of fuel is also given. So based on this, we are required to find the efficiency of the engine and the answer to this question is 21.9 percent.

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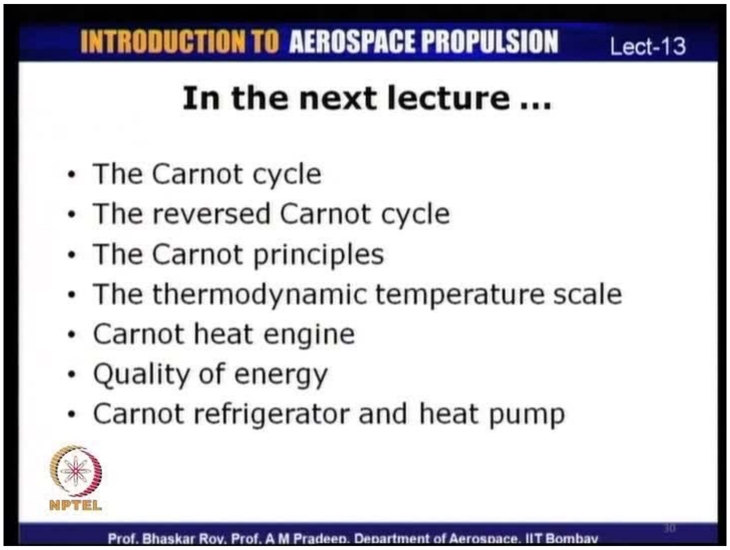

In today's lecture we had solved certain problems associated with heat engines which are basically based on the principle of second law of thermodynamics as well as some problems on refrigerators and heat pumps. So what we shall do in the next class, in the next lecture we shall look at some more aspects of certain special types of heat engines. In the next class, we shall be discussing about the Carnot cycle which forms a very fundamental cycles of the reversed heat engine.

We shall also talk about reversed Carnot cycle subsequently, we shall define what are known as the Carnot principles and based on this we shall define thermodynamic temperature scale. Once we have understood what a Carnot cycle is, we shall then define or understand what is meant by Carnot heat engine. What we shall also study in the next lecture is that heat engines are in fact energy associates itself with a certain quality; there is a quantity associated with energy, there is also a certain amount of quality associated with energy. Towards the end of the next lecture, we shall be discussing about Carnot refrigerators and heat pumps.

So these are some of the aspects which we shall be discussing in the next lecture, were we shall understand some of the very important aspects of thermodynamics which is basically the Carnot cycle, the Carnot principles and also the associated quality of energy.

So we shall take up these topics during our discussion in the next lecture.