Introduction to Aerospace Propulsion
Prof. Bhaskar Roy
Prof. A. M. Pradeep
Department of Aerospace Engineering
Indian Institute of Technology, Bombay

Module No. #01
Lecture No. # 16
Tutorial

Hello and welcome to lecture 16 of this lecture series on introduction to aerospace propulsion. In our journey so far on understanding basic aspects of thermodynamics, we have understood quite a bit about the fundamental aspects of thermodynamics.

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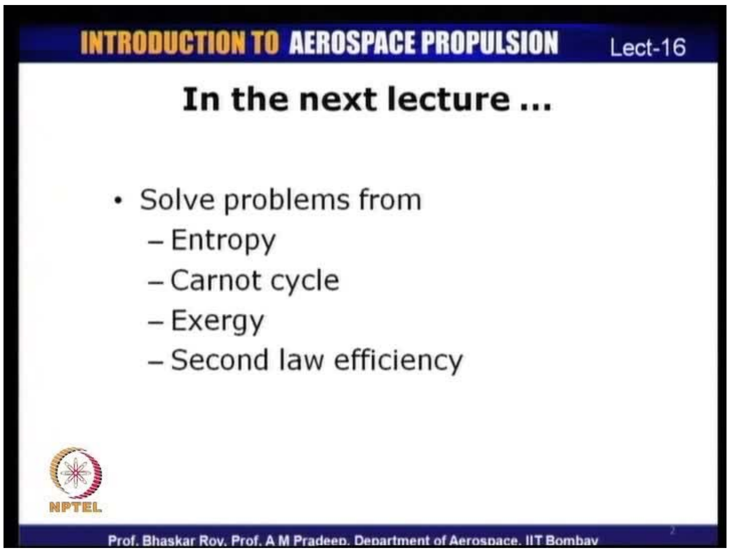

In the last several lectures, we have got introduced to the different laws of thermodynamics, different terms in thermodynamics like system property, some of the very important terms like entropy and rather recent terminology known as exergy. These are some of the aspects that we have been exposed to, over the last several lectures. What we are going to do today is to have a tutorial session, where we shall try to solve some numerical problems from some of the topics that we have covered during the last few lectures.

What we are going to do in today's lecture is the following: we will solve some problems based on entropy. We will solve problems from carnot cycle, then also solve couple of problems from exergy and on second law efficiency.

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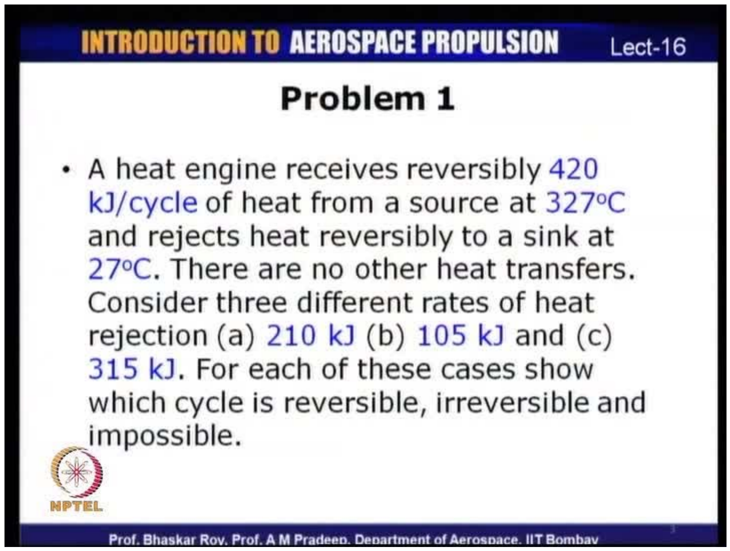

We shall try to pick up at least two problems from each of these topics. And towards the end of the lecture, I shall give some exercise problems which you can solve at your leisure time. Once you have understood the basic aspects, you can make an attempt to solve some of these exercise problems. The first problem that we shall try to solve today is the following: the problem statement for the problem number 1 is the following: a heat engine receives reversibly, 420 kilojoules per cycle of heat from a source at 327 degree Celsius and rejects heat reversibly to a sink at 27 degree Celsius. There are no other heat transfers.

Consider three different rates of heat rejection: part (a) 210 kilojoules, part (b) 105 kilojoules and part (c) 315 kilojoules.

For each of these cases, show which cycle is reversible, irreversible and impossible. This is the first question we have. The problem statement says that there is a heat engine which is receiving some heat from a source, which is at 327 degree Celsius. And the reversible heat transfer from the source is given as 420 kilojoules per cycle. This heat engine is rejecting heat to a sink which is at 27 degree Celsius. Now, what is given here is that if there are three different rates of heat rejection, one is 210 kilojoules, the second is 105 kilojoules and the third is 315 kilojoules, then in each of these cases, which cycle is reversible, which one is irreversible and which cycle is impossible? What we have here is heat engine which is operating between a source at a certain temperature and a sink which is at another temperature.

We have been given the rate of heat transfer to the heat engine from the source. There are - three cases - three different heat rejection rates which are given. We need to find out which of these three cases is possible heat engine, which of the cases is irreversible and which one is impossible.

What I have done is I have illustrated these heat engines. Let us assume that there are three different heat engines: heat engine 1, 2 and 3. Or it could be the same heat engine operating in three different modes, that is: heat engine 1 mode, 2 and 3.

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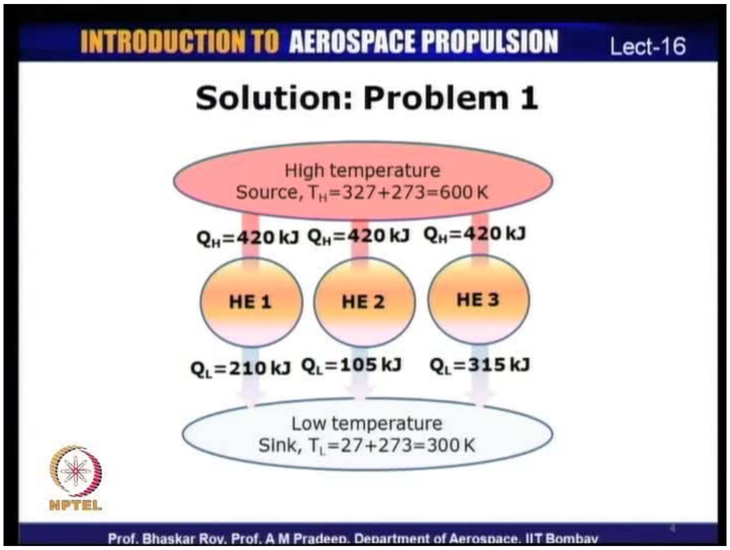

If you look at this illustration that is shown here, we have a high temperature source which is given as 327 degree Celsius. In kelvin scale it will be 327 plus 273, that is 600 kelvin. And the three different forms of the heat engine is given here as HE 1 which means heat engine 1, heat engine 2 or heat engine version 2 and heat engine version 3.

Heat transferred to the heat engine is the same for all these three different cases. It is QH is equal to 420 kilojoules. It is the same for all the three cases, but what is different is the rate of heat rejection. In one case, QL, that is rate of rejection from the heat engine to the sink is 210 kilojoules. In the second case, it is 105 kilojoules and in the third case, it is 315 kilojoules. All these heat rejections are going to a sink which is at a temperature of 27 degree Celsius or 300 kelvin.

The sink is at a fixed temperature of 300 kelvin. We need to find out which of these cycles are reversible, irreversible and impossible. Now there are two different ways of solving this problem. I shall be solving this problem in one way. And after the solution, I shall give a hint towards solving it in the second way.

I will leave it to you to solve the problem in the second format or second way in which you can solve the same problem, but in a slightly different way.

The way I am going to solve the problem today is by using the Clausius theorem, because we have been given the rates of heat rejection and heat absorption; we can use the Clausius theorem which says that cyclic integral of dq by t is less than or equal to 0 for all practical cycles.

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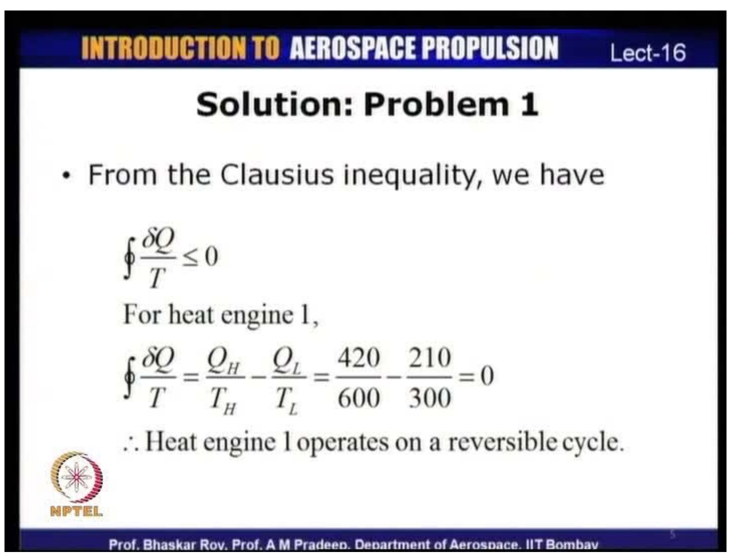

And the equality is valid for a reversible cycle. We shall use this property of Clausius theorem to try and solve this problem, because we have been given the rates of heat rejection and absorption as well as the temperature at which these heat interactions are taking place. As per the Clausius theorem, Clausius inequality states that cyclic integral dQ by T is less than or equal to 0. If you look at the first heat engine or first version of the heat engine, cyclic integral dQ by T reduces to QH by TH, minus QL by T L, where QH is the rate of heat transferred to the heat engine at a temperature of the source, which is TH; and QL is the rate of heat rejection to the sink, which is at a temperature of TL.

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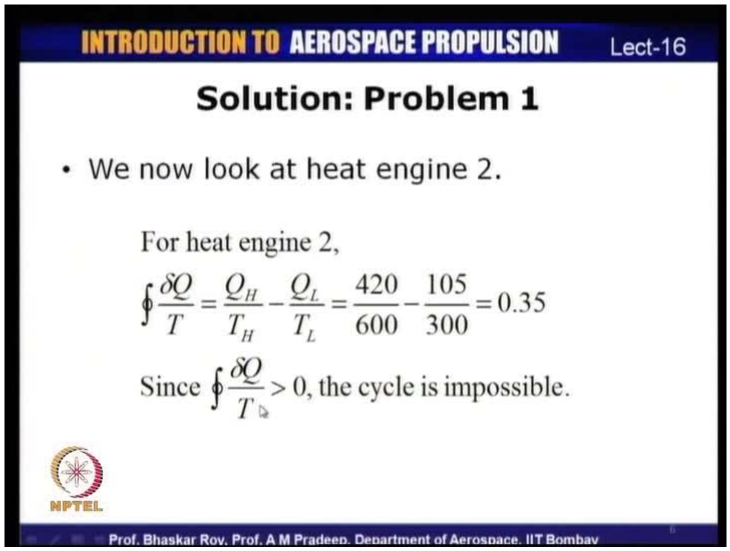

All these numbers are already known to us; QH is given as 420, TH is given as 600, QL is given as 210 and TL is 300. If you calculate this, the cyclic integral dQ by T will come out to be 0. As per the Clausius inequality, cyclic integral dQ by T equal to 0 corresponds to a heat engine which is operating on a reversible cycle. Heat engine 1 or the first version of the heat engine operates on a reversible cycle, because cyclic integral dQ by T comes out to be 0. Let us look at the second version or heat engine 2. For the second version of the heat engine, cyclic integral dQ by T is equal to again QH by TH minus QL by TL.

We substitute the values because all the numbers are known to us. Only difference in this case is that the QL is different from what we had calculated for heat engine 1. QL here is 105 kilojoules. If we calculate this, cyclic integral dQ by T will come out to be 0.35. Here we have a case where cyclic integral dQ by T is greater than 0. As per Clausius inequality, this should correspond to a cycle which is impossible. Such a cycle is not practically feasible because it will violate the second law of thermodynamics. So this is an impossible cycle. The second version of the heat engine is an impossible cycle.

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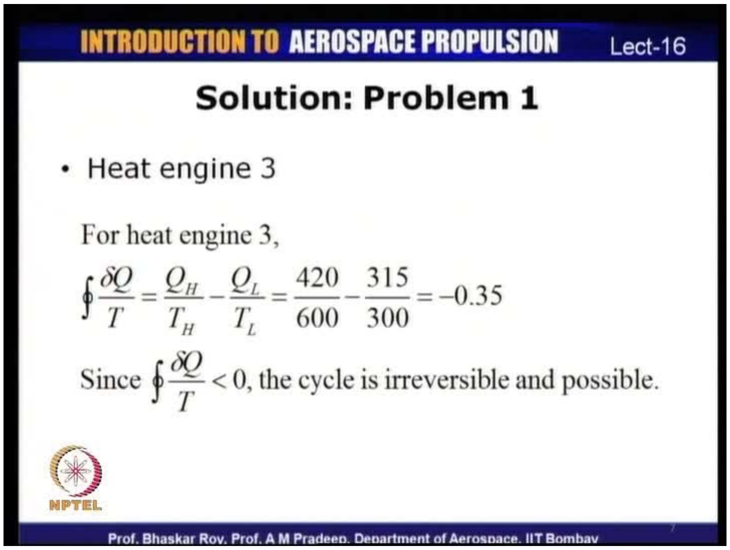

Let us look at the third heat engine or version 3 of heat engine. For this heat engine, QL is given as 315 kilojoules. If you substitute the values and calculate cyclic integral dQ by T, it will come out to be minus 0.35. Here cyclic integral dQ by T is less than 0 which means that such a cycle is irreversible; therefore, such a cycle is possible, because as we know, all practical cycles are irreversible because of the presence of irreversibilities in the system. What we have done now is that we have calculated the cyclic integral dQ by T. We have used the property of Clausius inequality which states that cyclic integral dQ by T less than 0 or less than or equal to 0 is valid for all cycles, which includes reversible cycles, wherein cyclic integral dQ by T is equal to 0. It is less than 0 for all real cycles or irreversible cycles and if it is greater than 0, it means that such a cycle is impossible.

We have seen that version one of the heat engine was a reversible engine or which was operating on a reversible cycle, because the cyclic integral dQ by T was coming out to be 0. The second version of the heat engine, that is, where we had cyclic integral greater than 0, which means that, such a cycle is impossible. Third version of the heat engine was when we had cyclic integral dQ by T less than 0; therefore, that cycle is irreversible and possible.

I mentioned in the beginning that this problem can be solved in a different way as well, by using a slightly different principle. Now let me give a hint here.

Right now what we have used is the Clausius inequality. We can also solve this problem using the Carnot principles or using the Carnot efficiencies. Let me explain how you can solve this problem in the second way. If you recall, please let us take a look at the illustration which we had shown in the beginning of the problem.

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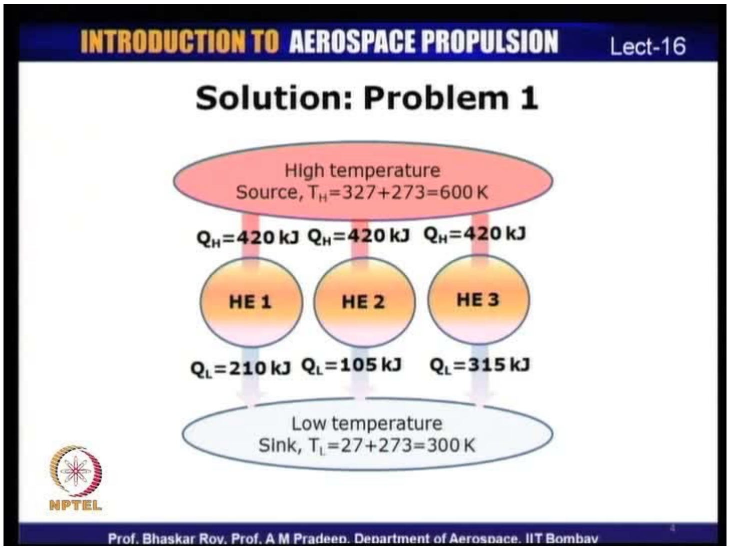

Now if you recall, all these cycles are supposed to be reversible or their heat transfer is taking place reversibly, which means that QH by QL is proportional to TH by TL. You can also find the efficiency of a Carnot cycle. The maximum efficiency which is possible in this particular problem would be 1 minus TH by TL or rather TL by TH. 1 minus TL by TH is 1 minus 300 by 600 which is equal to 0.5. This is the maximum efficiency that a cycle can have, which can be only for a cycle which is reversible. Let us calculate it for each of these heat engines. If you calculate it for heat engine 1, 1 minus QL by QH will be 1 minus 210 by 420 which is 0.5, which means that heat engine 1 is a cycle which is reversible, because its efficiency is equal to the Carnot efficiency. Heat engine 1 is reversible cycle as its efficiency is equal to the Carnot cycle. Now if you calculate the same for the second heat engine, 1 minus QL by QH, that is 1 minus 105 by 420, you will get a number of the efficiency which is greater than that of the Carnot cycle. Such a heat engine is obviously not possible, because the Carnot efficiency is supposed to be the highest efficiency of a heat engine which is operating between a source and a sink. In the second problem or second heat engine, you would get an efficiency which is greater than the Carnot efficiency, which means that such a heat engine is not possible, because its efficiency is exceeding the Carnot efficiency. For the third version of the heat engine, you calculate the efficiency based on 1 minus QL by QH, you would get an efficiency which is less than that of Carnot efficiency. Therefore, such a heat engine is possible and irreversible, because its efficiency is less than Carnot efficiency. This problem, as I mentioned can be solved in both these ways. One of the ways which we used for solving was using the Clausius inequality.

You can also solve the same problem using the Carnot efficiency or the Carnot principle. I will leave it to you as an exercise to solve the same problem using second method; that is using the Carnot efficiency. I have already given you the hint on how to solve the problem using the Carnot efficiencies.

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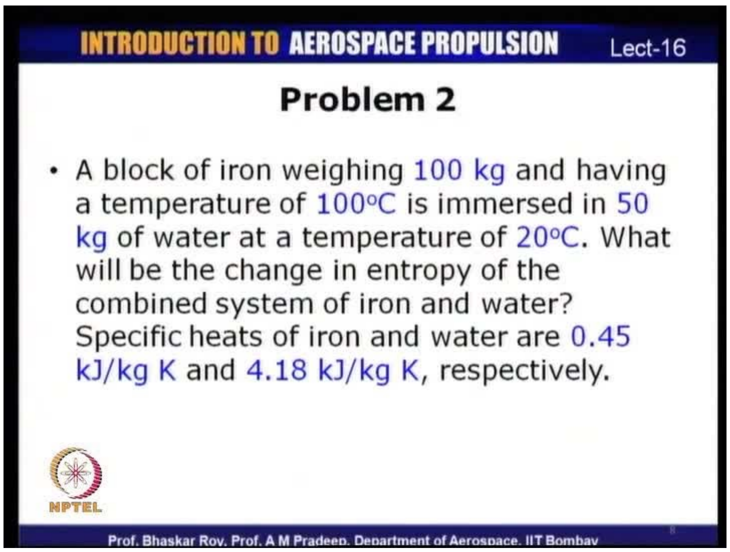

Now let us move on to the second problem. The problem statement for problem number 2 is: a block of iron weighing 100 kg and having a temperature of 100 degree Celsius is immersed in 50 kilograms of water at a temperature of 20 degree Celsius.

What will be the change in entropy of the combined system of iron and water? Specific heats of iron and water are 0.45 kilojoules per kilogram kelvin and 4.18 kilojoules per kilogram kelvin respectively.

In this problem, we have a block of iron of a given mass and a certain temperature, which is immersed in water, which is also having a certain mass and a temperature. We are required to find out, what is the change in entropy of the combined system of iron and water.

We had solved the same problem for a different context on finding out the final temperature, when we were solving the same problem using the first law of thermodynamics.

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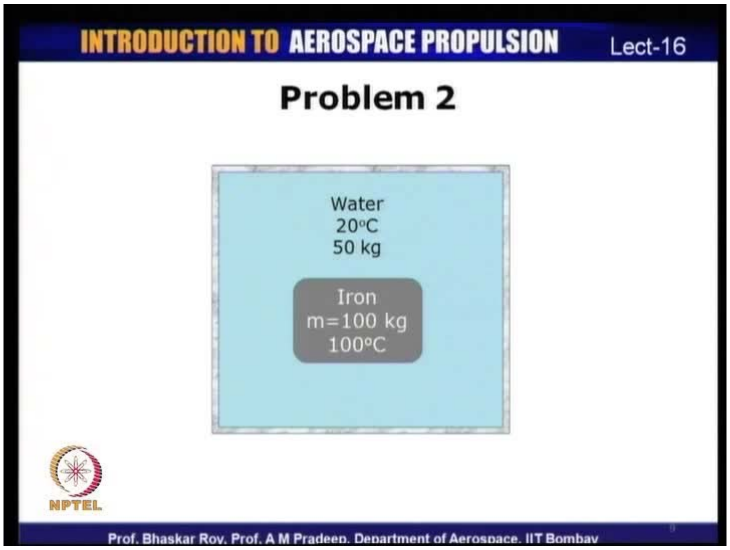

We are using the same problem, but to calculate entropy in this case. This is what the problem states: block of iron which is weighing 100 kgs and 100 degree Celsius is immersed in water which is at 20 degree Celsius and has a weight of mass of 50 kgs. We need to find the change in entropy of the combined system of water and iron.

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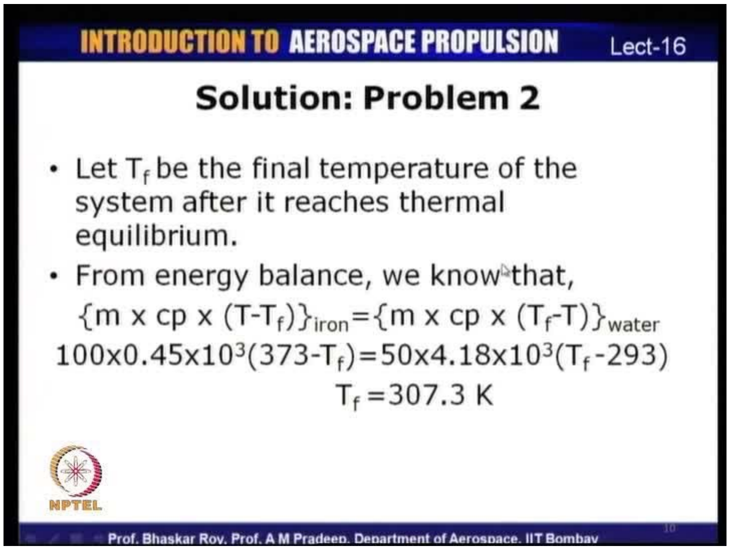

Now in order to find the entropy, we need to know the temperatures. We know the initial temperatures of water and iron. We need to know the final temperature as well.

When we were solving this problem using the first law, that is, using the energy balance, we had found the final temperature in a very similar manner. Let us assume that tf is the final temperature of the system after it reaches thermal equilibrium.

From the first law and from the energy balance, we know that the product of mass, the specific heat and the temperature difference for iron should be equal to the product of mass times specific heat times the temperature difference. So m times c, that is the specific heat multiplied by T minus Tf for iron should be equal to m - which is mass - times c - which is specific heat - times Tf minus T for water. Mass of iron is given as 100 kilograms. We substitute for mass as 100, c is given as 0.45 kilojoules per kilogram kelvin. This is 0.45 into 10 raised to 3. And initial temperature is 100 degree Celsius. It is 373 kelvin minus Tf is equal to mass, which is of water which is 50 kgs multiplied by 4.18 into 10 raised to 3. The specific heat multiplied by Tf, the final temperature minus 293 water temperature is 23 degree Celsius so that is 293 kelvin. If we substitute these value we can calculate the final temperature Tf as 307.3 kelvin.

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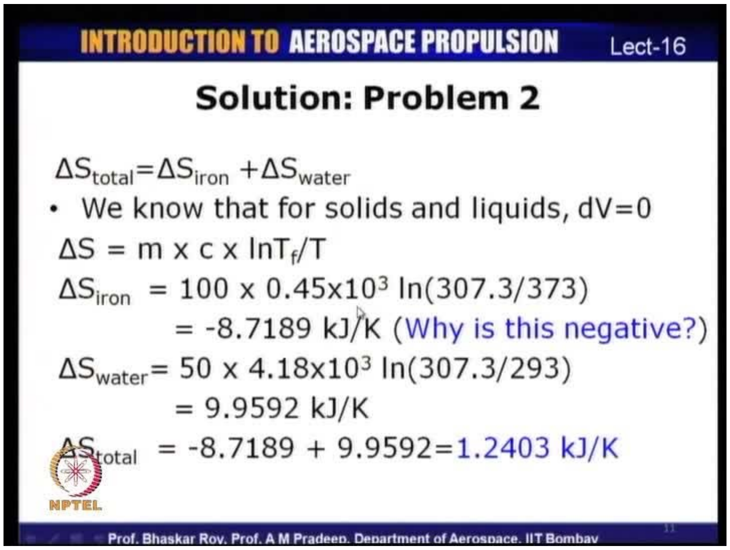

Now it is very important to remember here, that you need to be consistent with the units. Specific heats of iron and water are given in kilojoules per kilogram kelvin, whereas temperatures are given in degree Celsius. You need to make sure that you convert the temperatures to kelvin scale before calculating it; otherwise, you might make mistakes in calculating the final value of temperature. The final temperature of the water and iron system after it reaches thermal equilibrium is 307.3 kelvin. Now once we have calculated the final temperature, we need to now calculate the change in entropy.

The net change in entropy for the system, that is, including water and the iron, delta S total should be equal to delta S of iron plus delta S of water, where delta S of iron is change in entropy of iron, as its temperature drops from 100 degree Celsius to - that is 373 kelvin to - 307.3 kelvin. Delta S of water is the change in entropy of water as its temperature rises from 293 to 307 kelvin.

Now for solids and liquids, we have already derived expressions for change in entropy. As we know that for solids and liquids, we can assume that change in volume would be equal to 0.

In which case the net change in entropy delta S will be product of mass times specific heat times the logarithmic ratio of the temperatures, T final by initial temperature.

We can use this formulae for calculating the change in entropy for iron as well as for water. Delta S for solids and liquids is a function of the mass, specific heat, and initial and final temperatures.

Now that we have calculated the final temperature as 307.3 kelvin. We can use this temperature to calculate the change in entropy for iron as well as change in entropy for water.

And the sum of these two will give us the net change in entropy of the system, after the system reaches thermal equilibrium.

When we calculate delta S for iron, delta S for iron would be mass of iron times specific heat of iron times log of T final by T initial. Mass of iron is given as 100, specific heat is given as 0.45 into 10 raised to 3 and log of temperature, that is, ln 307.3 which is a final temperature divided by 373. If you calculate this, we would get delta S of iron S minus 8.7189 kilojoules per kelvin.

Similarly, we can calculate delta S for water, that is, mass times specific heat times the log of temperature ratios. So, 50 into 4.18 into 10 raised to 3 log 307.3 divided by 293, that is, 9.9592 kilojoules per kelvin. Now, you might notice that, for iron, when we calculated the entropy, we got a negative value; that is, entropy is decreasing for iron.

You might also recall that we had discussed about increase in entropy of the universe. You probably might wonder, is this a violation of the entropy principle! It is negative primarily, because the temperature of iron is reducing and entropy is directly proportional to the temperature. As the temperature reduces, its entropy should also reduce and that is why we get a negative value for delta S for iron. On the other hand, for the water, since its temperature is rising during this process, this is a positive entropy, but it is does not mean, that decrease in entropy for iron is equal to the increase in entropy for water.

Entropy is one property which is not conserved during a process. During all real life processes, entropy will be greater than 0. Net change in entropy will be greater than 0.

The change in entropy for the combined system of water and iron, if you add up the two, the increase in entropy of water is greater than the decrease in entropy of iron. And therefore, the net change in entropy will always be positive for a real life process. For all irreversible processes, if you were to calculate delta S for the system, then we get delta S which was positive for water, but that increase in entropy for water is greater than the decrease in entropy of iron. Therefore, there is a net increase in entropy which we can calculate as around 1.24, that is, minus 8.7189 plus 9.95 which is 1.024 kilojoules per kelvin.

This is to illustrate how we can calculate the change in entropy for a particular system, as well as a combination of individual processes, like in this case, there is a cooling of iron and heating up of water. So, we can calculate the net change in entropy for this particular process. What we saw is that in one case, there was a decrease in entropy, but in the other system there was an increase in entropy, but the increase in entropy is greater than the decrease in entropy of the iron in this case.

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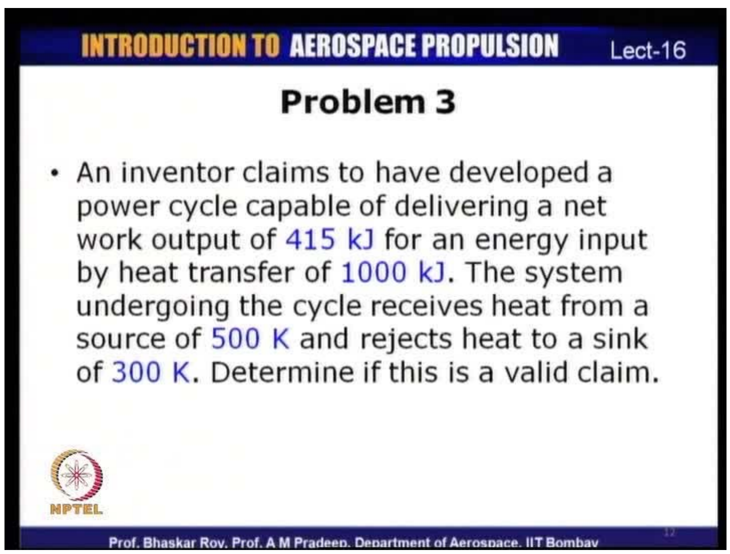

Therefore, there is a net increase in entropy of the system. This is very much consistent with the increase in entropy principle. Now, let us take up the third problem we have today. In this third problem, the statement is: an inventor claims to have developed a power cycle capable of delivering a net work output of 415 kilojoules, for an energy input by heat transfer of 1000 kilojoules. The system undergoing the cycle receives a heat from a source of 500 kelvin and rejects heat to a sink of 300 kelvin. Determine if this is a valid claim.

Now this is a problem wherein we have an inventor who claims that he has designed a power cycle which can deliver a net work output of 415 kilojoules, for an energy input of 1000 kilojoules, and this heat engine is operating between a source of 500 kelvin and a sink of 300 kelvin.

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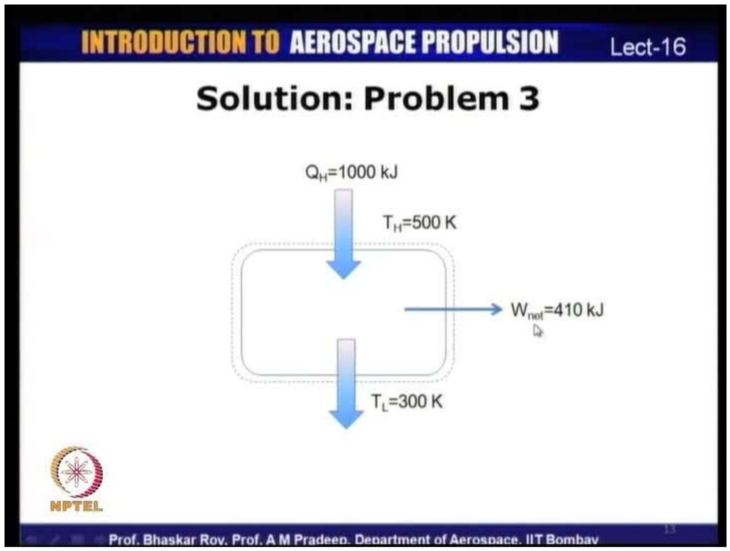

We need to find out if this claim makes sense, if this is a valid claim. This is what the so called inventor claims, that there is a heat engine which is generating a net work output of 410 kilojoules by receiving heat of 1000 kilojoules, and this is operating between a temperature source of 500 kelvin; that is TH is equal to 500 kelvin and TL is equal to 300 kelvin, that is the sink temperature.

Now, in order to solve this problem, what we shall do is, since the source and sink temperatures are given, we can easily calculate the Carnot efficiency for this heat engine, which is 1 minus TL by TH. This should be the maximum efficiency that any heat engine can achieve.

This would be achieved only if the heat engine is reversible. All actual heat engines - as we know - are irreversible and so actual heat engines can never achieve the Carnot efficiency. Once you calculate the Carnot efficiency, we know that this is the maximum efficiency that any heat engine can have. As per the claim of this inventor, we now have the work output as well as the heat input given to us. So, the thermal efficiency is also equal to - 1 minus or - ratio of work output by heat input; that is W net by Qin. Both of these are also given to us. If we can calculate the net work output divided by q, we get the thermal efficiency of this heat engine, which is the actual thermal efficiency. We compare the actual thermal efficiency with the Carnot efficiency and see that, if the actual thermal efficiency is greater than the Carnot efficiency, then this is an invalid heat engine, because it has efficiency exceeding the Carnot efficiency which is not possible without violating any of the laws of thermodynamics. Let us try to solve that by using this approach.

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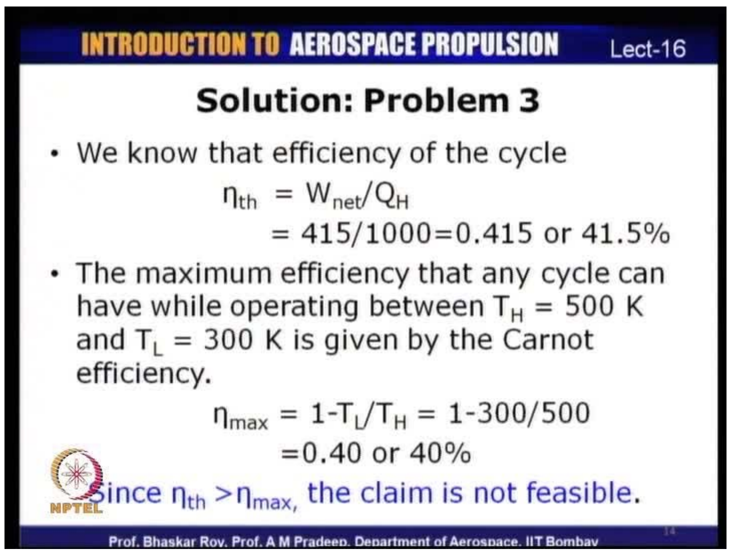

Efficiency of the cycle we can calculate by because we know that the net work outputand the heat input. Therefore, thermal efficiency is equal to W net by QH which is 415 by 1000 and therefore, that is equal to 0.415 or 41.5 percent, but we know that the maximum efficiency that any cycle can have while operating between a source of 500 kelvin and sink of 300 kelvin is defined or limited by the Carnot efficiency.

So eta max, that is, maximum thermal efficiency is equal to 1 minus TL by TH, which is 1 minus 300 by 500, which is 0.4 or 40 percent.

This is the maximum efficiency that any cycle can have and this can be achieved only if the actual cycle has reversible processes. In this case, we find that the thermal efficiency as per the claim of the inventor is 41.5. This is greater than the Carnot efficiency or the maximum efficiency, which means that, the claim of the inventor is not true and so, this not a feasible cycle, because it has efficiency exceeding the maximum efficiency.

Therefore, eta thermal greater than eta max means that the cycle is not feasible; it corresponds to a cycle which is impossible, because it will violate the second law of thermodynamics. In this manner, we have solved this problem. We can actually use the same approach if you are evaluating performances of actual heat engines. And we can see how efficient is the heat engine as compared to the Carnot efficiency or Carnot cycle, because we have defined - if you recall in the previous lecture - what is meant by second law efficiency, which was basically the ratio of the actual heat engine to the maximum efficiency given by the Carnot efficiency.

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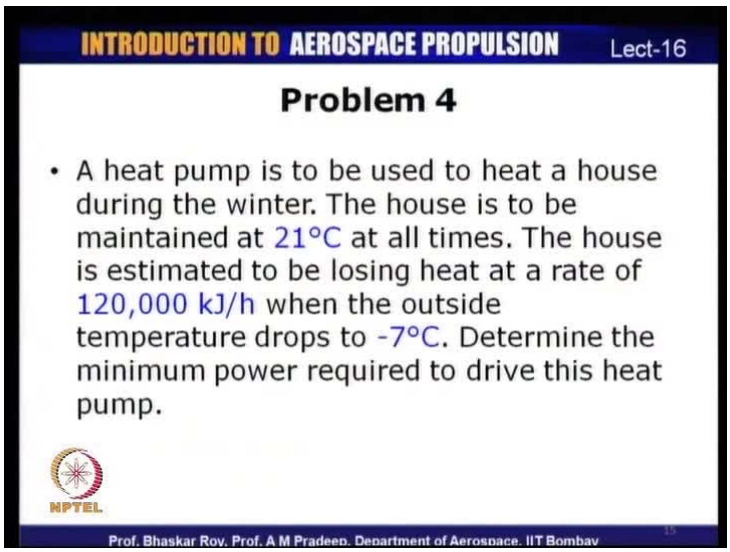

We can actually compare performances of actual heat engines if we know the source and sink temperature and also the net work output and heat input rates. We can compare the performance of different heat engines based on this approach.

Let us move on to the next problem we have. The statement for problem number four is: a heat pump is to be used to heat a house during winter. The house is to be maintained at 21 degree Celsius at all times and the house is estimated to be losing heat at a rate of 120000 kilojoules per hour, when the outside temperature drops to minus 7 degree Celsius.

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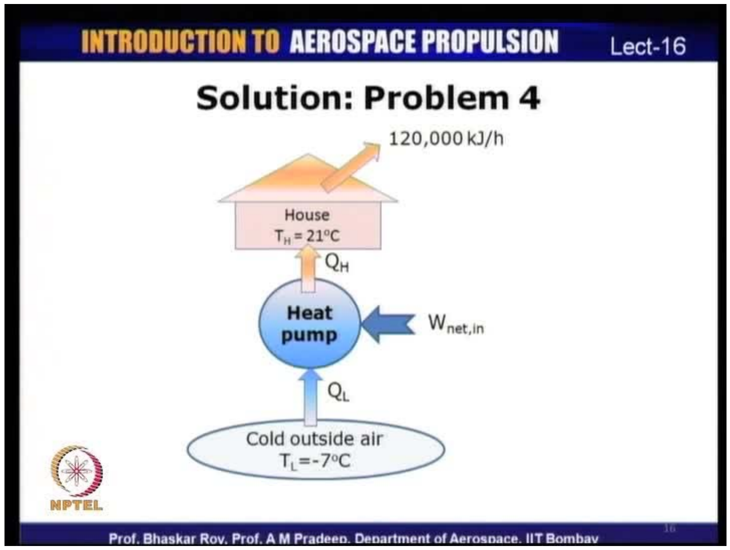

Determine the minimum power required to drive this heat pump. In this problem - we have so - this is the problem statement illustrated. There is a house which is supposed to be maintained at a temperature of 21 degree Celsius, but this house is continuously loosing heat to the surroundings at the rate of 120000 kilojoules per hour. We need to - design - develop a heat pump which can maintain the house at 21 degree Celsius, when the ambient temperature outside the house is minus 7 degree Celsius. We need to find out what will be the minimum power required or work required to drive this heat pump so that it can maintain the house at 21 degree Celsius, when the ambient temperature is minus 7 degree Celsius.

In order to solve this problem, we need to basically find out the Carnot COP given by the reversed Carnot cycle. A heat pump which is operating on a reversed Carnot cycle will have the maximum COP, as we have discussed in the earlier lectures that COP of a heat pump which operates on a reverse Carnot cycle has the maximum value.

Since we know the temperature between which this heat pump has to operate, we can calculate the maximum COP that the heat pump can have, operating between these two temperature limits. And from the maximum COP corresponds to our in the case The heat pump is operating on a reversed Carnot cycle. The required work input is the minimum, because with minimum work input, such a heat pump which is operating on a reversed cycle will be able to generate or will be able to maintain the temperatures of the source and sink as required.

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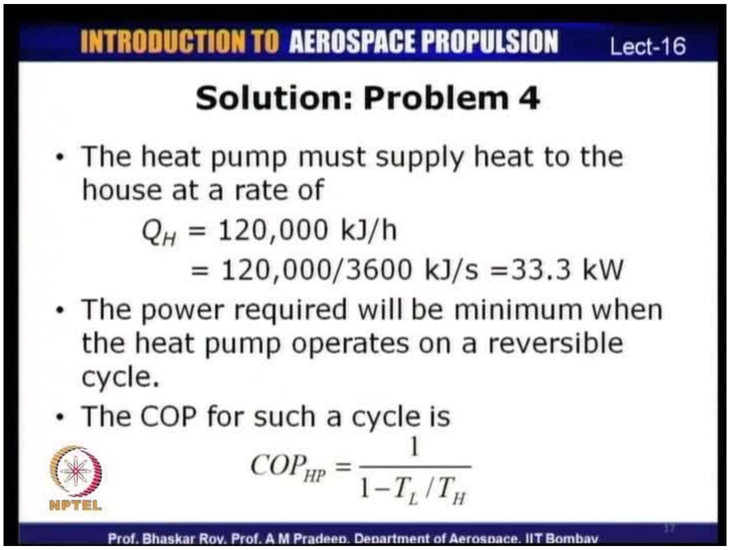

In this case, we know the temperature between which the heat pump is to operate. We can therefore calculate the COP max, which is possible if the heat pump was to be operating on a reversed Carnot cycle. We also know the rate at which the heat has to be supplied to the house, because heat loss is also known to us.

Heat pump is required to supply heat at a rate which is equal to the heat at which heat is lost from the house, which is given as 120 kilojoules per hour, which we shall convert to kilowatts as 120000 divided by 3600. That gives us 33.3 kilowatts. We have converted kilojoules per hour to kilojoules per second which is basically kilowatts.

The power required will be minimum when the heat pump operates on a reversible cycle.

If the seed pump is operating on a reverse cycle or a reverse Carnot cycle, then power required to drive such a heat pump will be minimum. So the COP in such a case will be 1 by 1 minus TL by TH.

We have already defined this in the earlier lectures. COP of a heat pump which is operating on a reversed Carnot cycle is 1 by 1 minus TL by TH.

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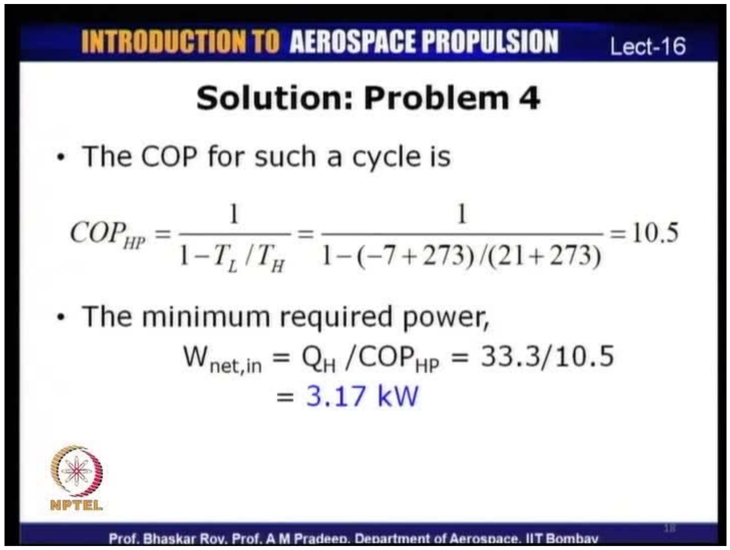

We already know TL and TH. TL is minus 7 degree Celsius, TH is 21 degree Celsius and so we convert them to the kelvin scale. Therefore, we have COP of the heat pump as 1 divided by 1 minus 7 plus 273 divided by 21 plus 273. So this comes out to be 10.5.

This is the maximum COP that such a heat pump would have, which is operating on a reversed Carnot cycle, and this maximum COP also corresponds to the case when the work required is minimum.

Hence we know, that by definition COP is the ratio of the desired effect to the work input. And we know that the desired effect in this case is to transfer heat at the rate of 33.3 kilowatts to the house.

Work input is what we need to calculate. Work minimum will now be equal to the rate at which heat has to be transferred to the house divided by the max COP. Max COP in this case we have calculated as 10.5.

Therefore, the minimum work required will be QH divided by COP of the heat pump. Therefore, that is 33.3 divided by 10.5, which is 3.17 kilowatts.

This is the minimum work that is required to transfer 33.3 kilowatts of heat into the system. Now this is using a heat pump. There are other ways of heating, maintaining the house at a given temperature.

If instead of a heat pump, we use electrical resistance heater - electrical resistance heater is one of the most efficient forms of heating and so in the case of an electrical resistance heater - if you were to transfer 33.3 kilowatts, it will convert that work into heat, electrical work of 33.3 kilowatts will be entirely converted into heat at the same rate of 33.3 kilowatts And you actually need much less power, if you were to use an electrical resistance heater to maintain the house at same temperature as compared to a heat pump, which requires far more work to maintain the same temperature as desired.

In this case, in this particular problem - that was problem 4 - what we did was to calculate the performance of a COP which is operating on a reversed Carnot cycle. We know that as it operates on a reversed Carnot cycle, the COP max will be a direct function of the temperature ratios; that is, 1 divided by 1 minus TL by TH. Temperatures are known. So, you can calculate the COP for this case and COP by definition is desired effect; that is QH divided by work input. Work input, you can calculate by the ratio of QH divided by COP and so this would be the minimum work that is required to maintain the house at 21 degree Celsius.

For actual engines, we know that we will never have a COP equal to that of the max COP. Therefore, net work input required will be higher than what we have calculated here, because COP will be less than COP max and it would be 33.3 divided by a COP, which is less than 10.5. And so, you would get a work input required which is greater than what we have calculated in this case.

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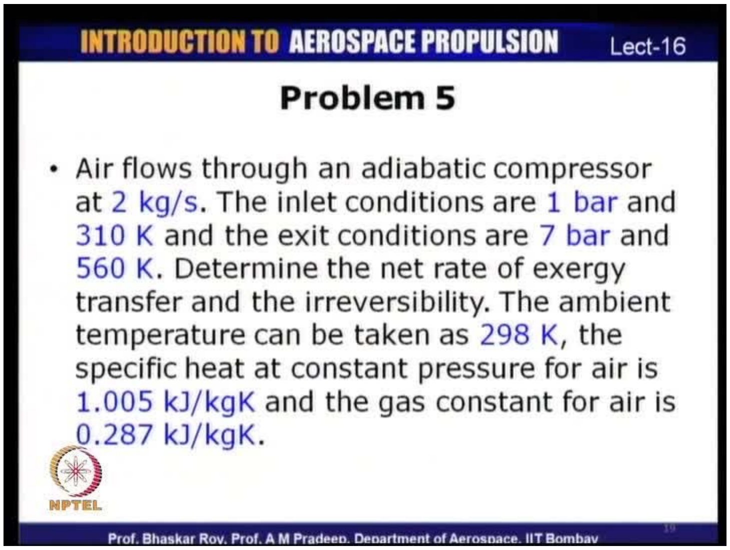

In this particular problem, we have calculated the work input which is the minimum work required to maintain the house at the desired temperature. Now let us take the problem number 5. In this case, the problem statement for this particular problem is that air flows through an adiabatic compressor at 2 kilograms per second and the inlet conditions are 1 bar and 310 kelvin, and exit conditions are 7 bar and 560 kelvin. Determine the net rate of exergy transfer and irreversibility. The ambient temperature can be taken as 298 kelvin, specific heat at constant pressure for air is 1.005 kilojoules per kilogram kelvin and the gas constant for air is 0.287 kilojoules per kilogram kelvin.

In this particular problem, we have a compressor for which certain properties are given like: inlet conditions in terms of temperature and pressure, exit conditions again in terms of temperature and pressure, the mass flow rate is given and We need to find the net rate of exergy transfer and also irreversibility associated with this process. We have been given the ambient temperature as 298 kelvin. The specific heat and gas constant for air are also been specified. We need to find the net rate of exergy transfer and irreversibility for this process.

Now, during the previous lecture we have discussed about exergy and net exergy transfer for closed systems as well as for open systems. For open systems, we have seen that exergy transfer is a function of the enthalpy and product of T naught times delta S, where delta S is the entropy, plus v square by 2 and gz, which corresponds to kinetic and potential energy. In this case, we are going to assume that the kinetic and potential energies are negligible and so those terms will become 0.

Kinetic energy and potential energy being 0, we can see that the net change in exergy will be only a function of net enthalpy and entropy multiplied by the ambient temperature.

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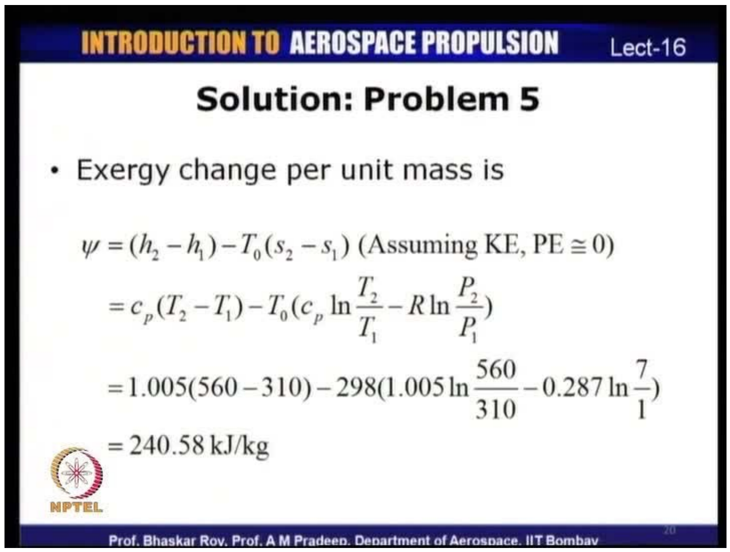

Therefore, exergy per unit mass is psi is equal to h2 minus h1, minus T naught into s2 minus s1, if we assume kinetic and potential energies to be 0. This can be again expressed as h2 minus h1 is cp times T2 minus T1, minus T naught into s2 minus s1; for an ideal gas, if you again assume air to be an ideal gas we get s2 minus s1 is equal to cp log T2 by T1 minus R times log of P2 by P1, where R is the gas constant, T1 and T2 are the initial and final temperatures or inlet and exit temperature, P1 and P2 are inlet and exit pressures.

If you substitute the values for these parameters: cp is given as 1.005, T2 is 560 kelvin, T1 is 310 kelvin, minus 298 is T naught the ambient temperature, multiplied by cp which is again 1.005 log of - T2 by T1 - 560 by 310, minus 0.287 which is the gas constant for air, log P2 by P1 that is 7 by 1 - 7 bar is exit pressure and 1 bar is the inlet pressure.

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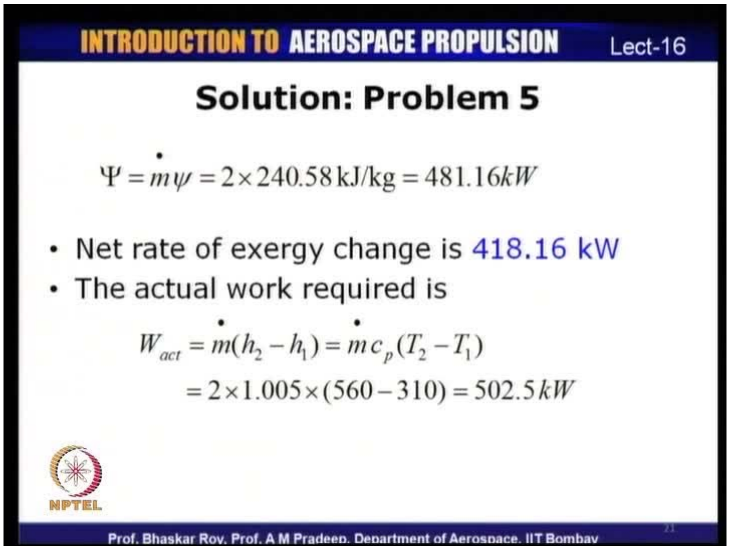

If you substitute these values, you can calculate the exergy change per unit mass as 240.58 kilojoules per kilogram.

This is exergy change per unit mass. Total exergy change would be equal to mass flow rate multiplied by exergy change per unit mass. Mass flow rate is given as 2 kilograms per second and therefore we get 2 kgs per second multiplied by 240.58 kilojoules per kilogram, that is 481.16 kilojoules per second, which is kilowatts. Therefore, the net rate of exergy change is 418.16 kilowatts.

Now, the second part of the question was to find out the irreversibility associated with the process. We know that irreversibility is the difference between the actual work output and the reversible work or the exergy. In this case, we have already calculated the exergy or the reversible work, which is the work potential of the system, and the actual work is what we need to find out if we have to calculate irreversibility.

How do we find out actual work? Actual work is the product of mass times the enthalpy. We have already derived this when we were discussing about the steady flow energy equation using the first law.

The actual work required is m dot into h2 minus h1, which is m dot into cp times T2 minus T1.

We already know cp, T2, T1 and also mass flow rate. Therefore, we can calculate actual work output as equal to m dot which is 2, into 1.005, into T2 minus T1 - that is 560 minus 310 - that is 502.5 kilowatts.

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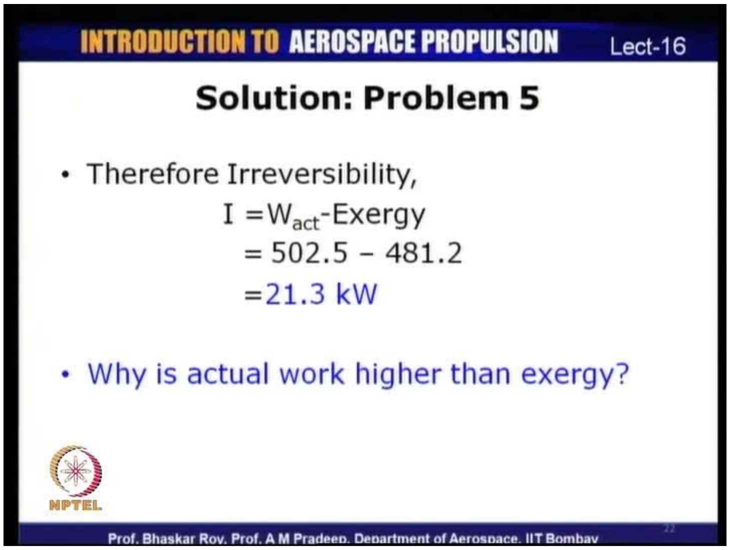

Therefore, irreversibility is equal to actual work minus exergy or the reversible work, that is 502.5 minus 481.2. Irreversibility is equal to 21.3 kilowatts.

Now, you might notice that you get a work output. The actual work output is higher than exergy. Well, in the case of a compressor as we know that compressor is a device which requires a work input for increasing the pressure. Therefore, the actual work required is greater than exergy. Exergy in this case corresponds to the reversible work, which means that reversible work is the minimum work that is required to increase the pressure from 1 bar to 7 bar and correspondingly there is also an increase in temperature.

The reversible work required for this process will be obviously the minimum and therefore the reversible work is less than the actual work. Therefore, for a compression process, we have the reversible work less than the actual work and therefore irreversibility is the difference between actual work and reversible work.

Now, for a turbine on the other hand, turbine is a device which is supposed to generate a work output. In the case of a turbine, actual work output will always be less than the reversible work output. Irreversibility, in the case of a turbine would therefore be the reversible work minus the actual work, because actual work output will always be less than the reversible work due to irreversibilities. In the case of compressor, like in this problem, the actual work required is higher than the reversible work, because of presence of irreversibilities like friction, heat transfer and so on. Therefore, we have an actual work input required which is greater than the reversible work input. This was a problem for finding out exergy change of a process. In this case it was a flow process. Exergy change, in this case is a function of the enthalpy difference and the entropy difference. And irreversibility is the difference between actual work and exergy change or the reversible work.

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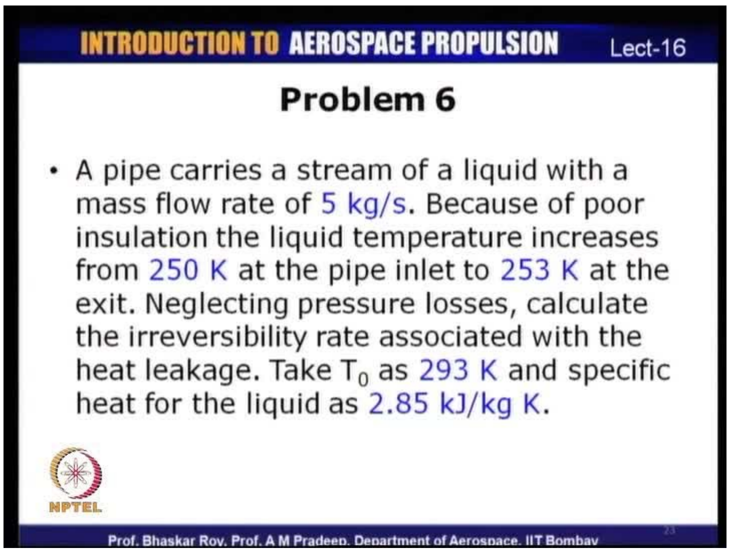

Now, the last problem that we shall solve in today's class will again be with reference to irreversibities. In the problem statement for problem number 6 is: a pipe carries a stream of a liquid with a mass flow rate of 5 kilograms per second; because of poor insulation, the liquid temperature increases from 250 kelvin at the pipe inlet to 253 kelvin at the exit. Neglecting pressure losses, calculate the irreversibility rate associated with the heat leakage. Take T naught as 293 kelvin and specific heat for the liquid as 2.85 kilojoules per kilogram Kelvin.

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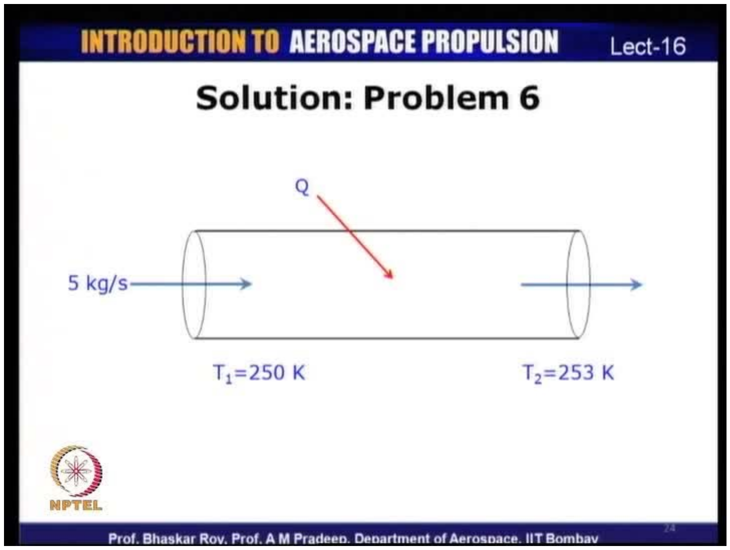

This is what the problem states that there is a pipe through which certain liquid is flowing at a rate of 5 kilograms per second. Now, because of heat transfer from the surroundings to the pipe, because the ambient temperature is given as 298 kelvin which is higher than that of the pipe which is because of a poor insulation on the pipe, there is a heat transfer into the pipe resulting in an increase in temperature from 250 kelvin at the inlet to 253 kelvin at the exit. We need to calculate what is the irreversibility associated with this particular process which involves a heat transfer across the system boundaries.

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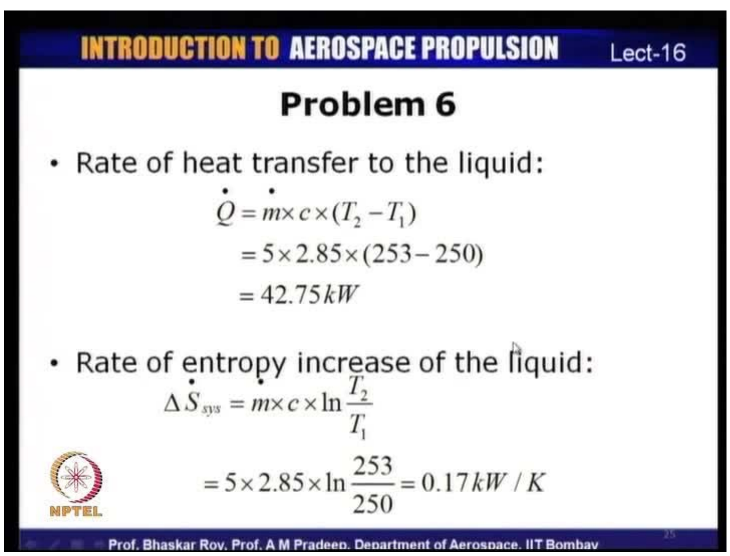

Let us first calculate what is the rate of heat transfer into the system. Now, from the first law we have seen, that for this particular process there is no work done by the system. So, heat transfer will be equal to change in internal energy itself - which is equal to - that is Q dot will be equal to u dot which is equal to m dot into c into delta T, which is m dot into c into T2 minus T1.

m dot is 5 kilograms per second, c is given as 2.85 kilojoules per kilogram kelvin and T2 is 253 kelvin T1 is 250 kelvin. So the rate of heat transferred to the liquid is 42.75 kilowatts.

We can also calculate the rate of entropy increase of the liquid, because for liquids net change in entropy will be equal to the product of mass times specific heat times the log ratio of the temperatures; because it is incompressible, we assume liquids to be incompressible. So, delta S of the system is equal to 5 into 2.85 into log of 253 by 250, which is 0.17 kilowatts per Kelvin. So, the net change in entropy of the system or rate of change of entropy of the system is 0.17 kilowatts per kelvin.

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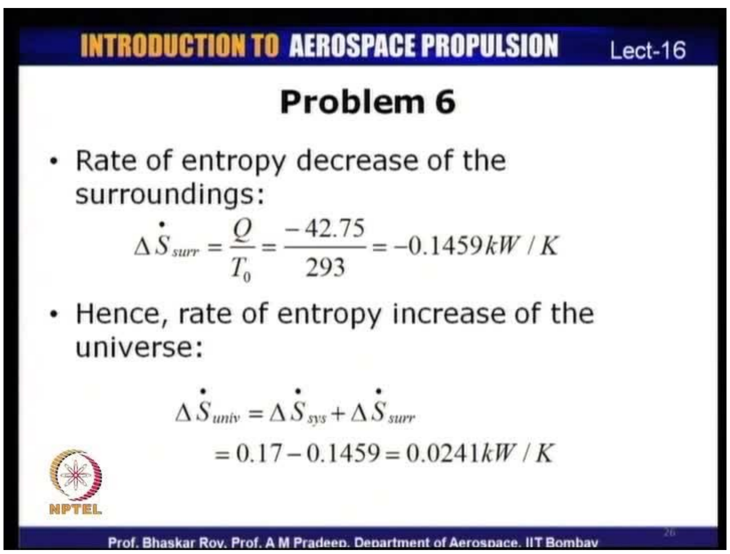

We can also calculate the entropy decrease of the surroundings, because there is a certain heat transfer into the system from the surroundings, which means that the immediate surroundings around the pipe will experience a decrease in its entropy. Entropy change of the surroundings, delta S surroundings is given by the rate of heat transfer and the temperature at which the heat transfer is taking place at the boundaries, which is 293 kelvin. And since heat is transferred to the system, it is denoted by a negative sign. As we have already discussed, the sign convention for heat transfer. So delta S of the surroundings is Q by T naught, which is minus 42.75 divided by 293, that is minus 0.1459 kilowatts per Kelvin. Therefore, the rate of entropy increase of the universe is equal to delta S of the system plus delta S of the surroundings. You have seen there is a decrease in entropy of surroundings, but there is also an increase in entropy of the surroundings of the system, which is greater than the decrease in entropy of the surroundings. So, delta S universe will be equal to 0.17 minus 0.1459 which is equal to 0.0241 kilowatts per kelvin. This is the net rate of entropy increase of the universe, which is system plus its immediate surroundings.

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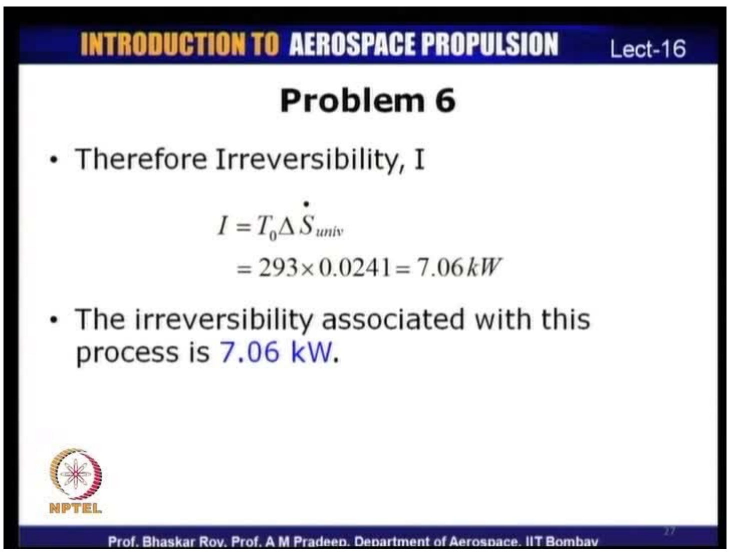

Therefore, we can now calculate irreversibility as irreversibility as, irreversibility is the product of the temperature times the delta S of the universe. Irreversibility I is equal to T naught into delta S universe, which is equal to 293 into 0.0241 which is 7.06 kilowatts. Irreversibility associated with this process is therefore 7.06 kilowatts.

That brings us the end of this tutorial. I shall now give a few exercise problems and I leave it to you to try and attempt to solve these problems based on what we have solved in today’s tutorial as well as based on our discussions during the last few lectures.

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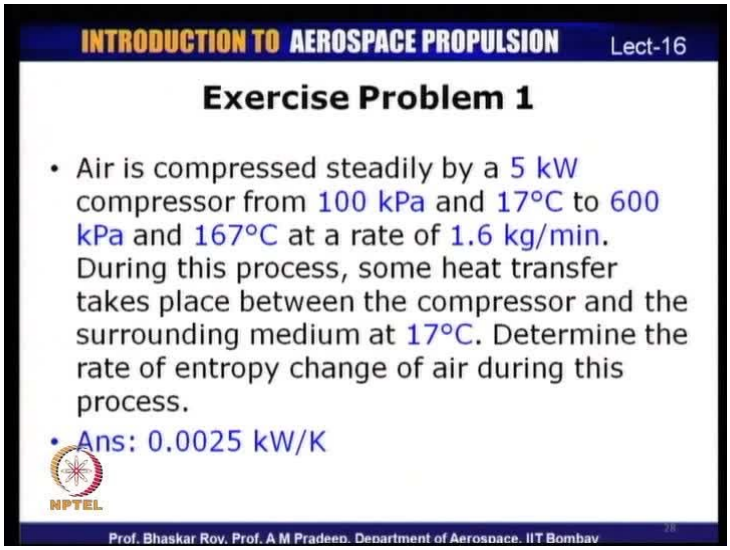

The first exercise problem we have is: air is compressed steadily by a 5 kilowatt compressor from 100 kilopascals and 17 degree Celsius to 600 kilopascals and 167 degree Celsius at a rate of 1.6 kilograms per minute. During this process, some heat transfer takes place between the compressor and the surroundings which is at 17 degree Celsius.

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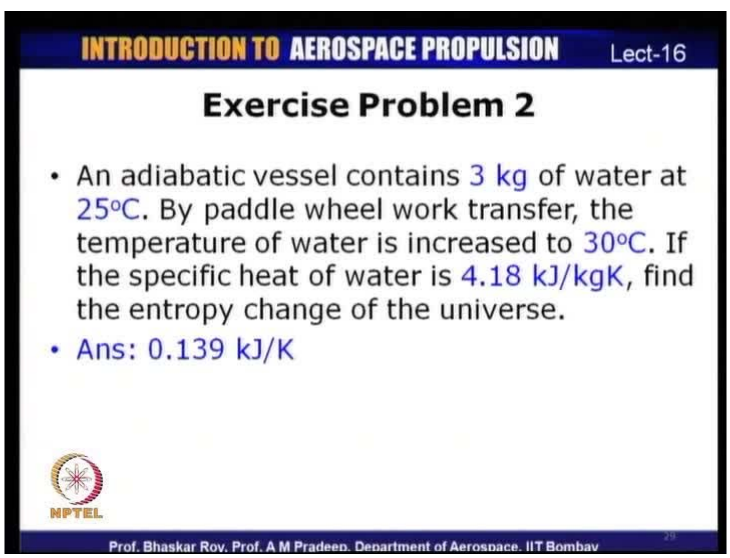

Determine the rate of entropy change of air during this process. We have seen how we can calculate rate of entropy of change for this particular process. It is a flow process and we have been the heat transfer, the power input is given, the pressure at the inlet and exit are given. Therefore we can find out the net rate of entropy change during this process.

Exercise problem number 2 is: an adiabatic vessel contains 3 kilograms of water at 25 degree Celsius. By paddle wheel work transfer, the temperature of water is increased to 30 degree Celsius.

If the specific heat of water is 4.18 kilojoules per kilogram Kelvin, find the entropy change of the universe. In this case, we have an adiabatic vessel which contains water at a certain mass and temperature. There is a paddle wheel work on the system which causes its temperature to increase. What is the entropy change of the universe? We have already solved one of the problems on finding out the entropy change of the system plus the surroundings and therefore that of the universe; that is entropy of the surroundings. If there is a decrease in the entropy of the surroundings and the increase in entropy of the system, increase in entropy will between greater than that of decreasing entropy in the surroundings.

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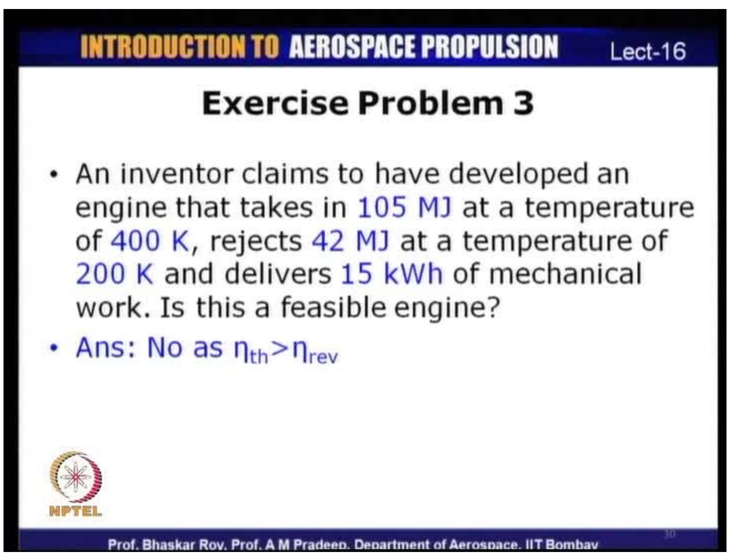

Third exercise problem is: an inventor claims to have developed an engine that takes in 105 mega joules at a temperature of 400 kelvin and rejects 42 mega joules at a temperature of 200 kelvin and delivers 15 kilowatt hours of mechanical work. Is this a feasible engine? Answer is no, because you can calculate thermal efficiency and the reversible efficiency. You will find that thermal efficiency is greater than reversible efficiency

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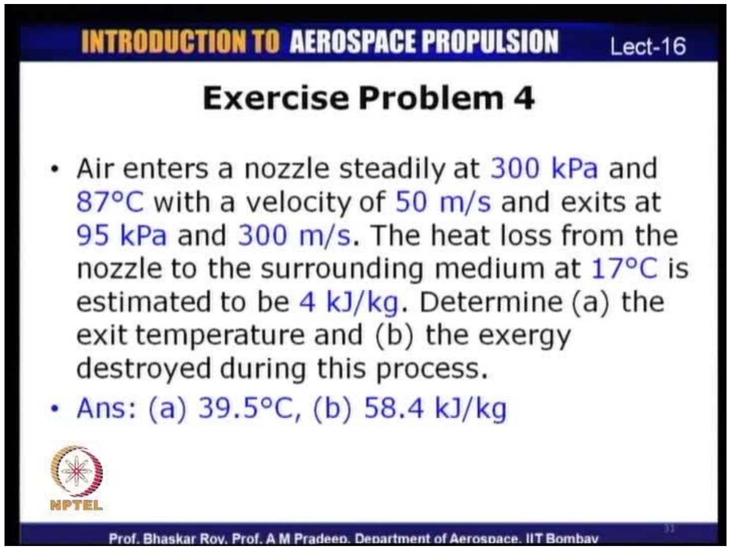

Problem number 4 is: air enters a nozzle steadily at 300 kilopascals and 87 degree celsius with a velocity of 50 meters per second, and exits at 95 kilopascals and 300 meters per second. Heat loss from the nozzle to the surrounding medium at 17 degree Celsius is estimated to be 4 kilojoules per kilogram. Determine part (a) the exit temperature and part (b) exergy destroyed during this process. We have calculated exergy calculation in this today's lecture, that was irreversibility. Exergy destroyed is basically irreversibility and we can calculate the exit temperature from the steady flow energy equation. The answer to this problem would be, 39.5 degree Celsius is the temperature and exergy destroyed is 58.4 kilojoules per kilogram and that was problem number 4.

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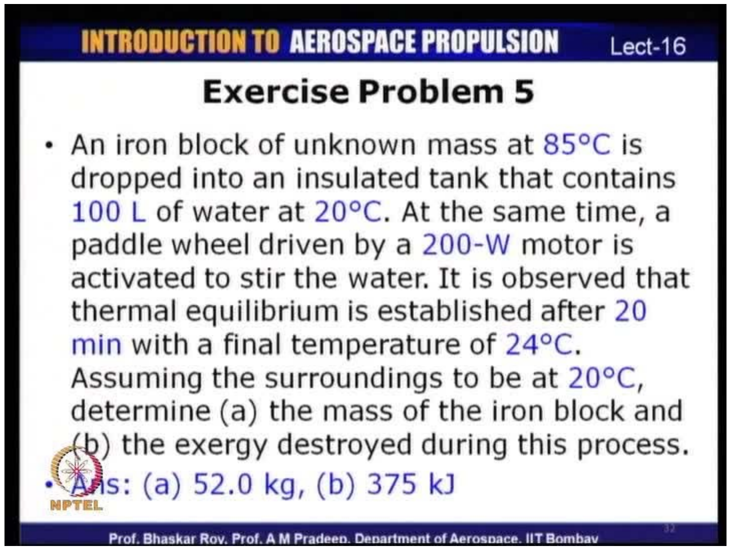

Problem number 5 is: an iron block of unknown mass at 85 degree Celsius is dropped into an insulated tank that contains 100 liters of water at 20 degree Celsius. At the same time, a paddle wheel driven by a 200 watt motor, is activated to stir the water. It is observed that the thermal equilibrium is established after 20 minutes with a final temperature of 24 degree Celsius.

Assuming this surrounding to be at 20 degree Celsius, determine mass of the iron block and exergy destroyed during this process. This is a slightly tricky problem. You would have to think a little deeper to find out the mass of the iron as well as exergy destroyed during the process. Basically, there is a work input at a certain rate given for a certain period of time. Therefore, from that you can calculate, what is the mass of iron from the energy balance as well as exergy destroyed from the formulae for exergy destruction which we have discussed.

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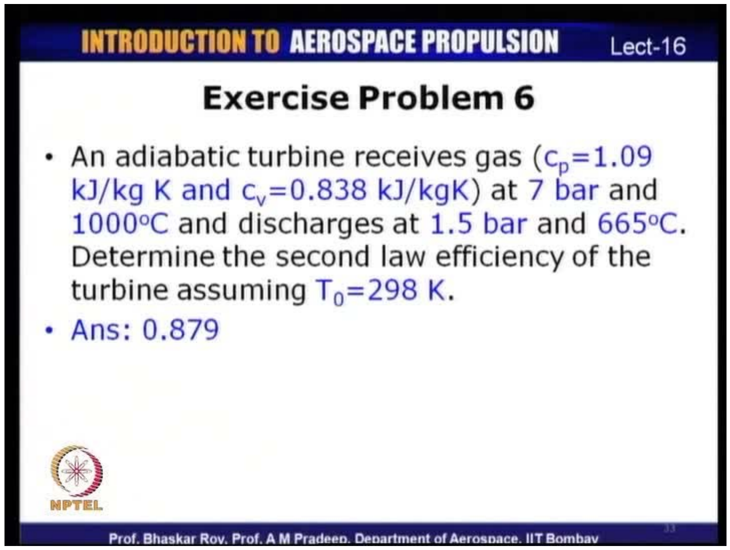

In the last exercise problem is: an adiabatic turbine receives gas which has a cp of 1.09 kilojoules per kilogram kelvin and cv which is 0.838 kilojoules per kilogram kelvin at 7 bar and 1000 degree Celsius and discharges at 1.5 bar and 665 degree Celsius. Determine the second law efficiency of the turbine assuming T naught is equal to 298 kelvin.

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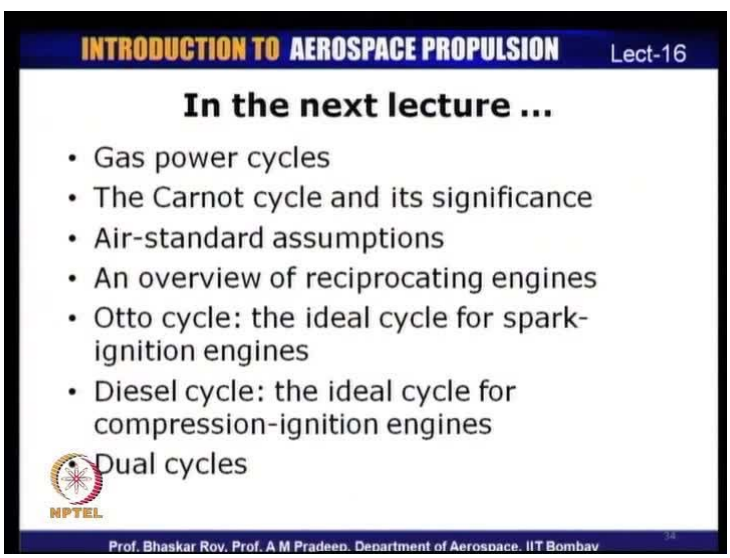

Second law efficiency, we have discussed for different work producing devices, how you find the second law efficiency and for work generating work requiring devices, how do you calculate second law efficiency. Based on that you can determine what is second law efficiency for this particular process.

Now, this brings us to the end of this tutorial. What we shall discuss in the next lecture are the following: we shall now be talking about applications of these thermodynamic principles.

We shall discuss about gas power cycles. We have already discussed about Carnot cycle. We shall discuss its significance in a little more detail. In the next lecture, we shall discuss about what are known as air standard assumptions and an overview of reciprocating engines. Then we shall discuss about three of the fundamental reciprocating engine cycles: the otto cycle which is the basic cycle for spark ignition engines, the diesel cycle which is the basic cycle for compression ignition engines and the dual cycle which is a combination of the otto cycle and the diesel cycle. We shall take up these topics during our discussion during the next lecture.