Introduction to Aerospace Propulsion

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

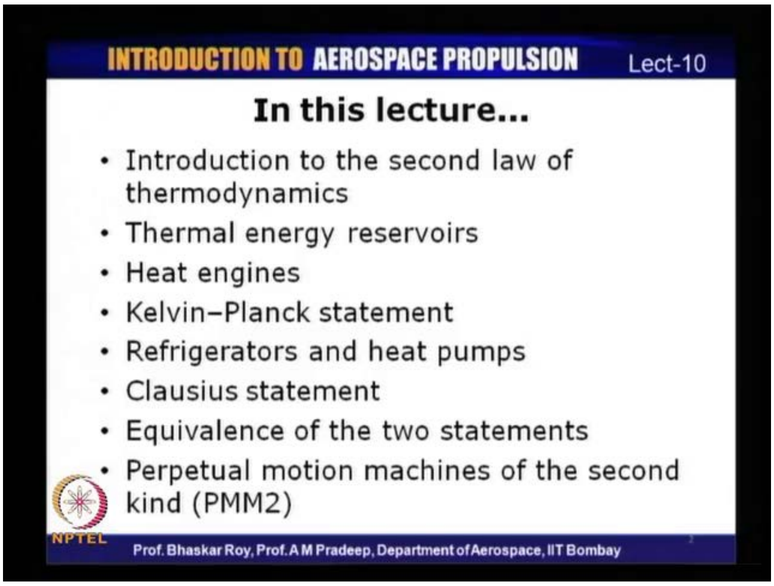
Module No. # 01
Lecture No. # 10

Second law of thermodynamics, heat engines, refrigerators and heat pumps, Kelvin-Planck and Clausius statement of second law of thermodynamics

Hello and welcome to lecture 10 of this lecture series on Introduction to Aerospace Propulsion. In the last lecture, we had discussed about the first law of thermodynamics applied to flow processes, and what we are going to discuss toady is about the second law of thermodynamics and some consequences of the second law of thermodynamics.

So, what we were discussing up to the last lecture was on different basic concepts of thermodynamics and the different laws of thermodynamics. The two laws that we have discussed were the zeroth law of thermodynamics and the consequence of temperature as result of the zeroth law of thermodynamics. Subsequently, we discussed about the first law of thermodynamics as applied to closed systems and then applied to open systems. Then we also derived energy equation - steady flow energy equation - for different steady flow engineering devices as examples.

(Refer Slide Time: 01:21)



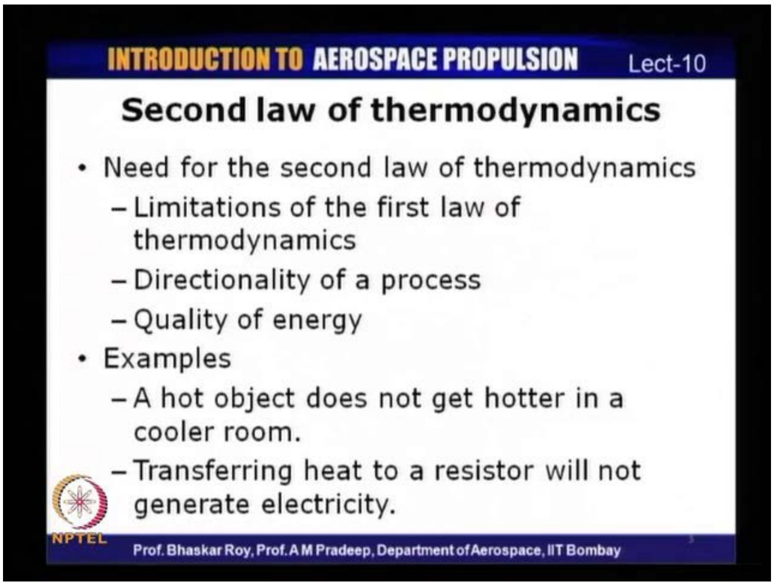
In today's lecture, what we are going to discuss is basically the second law of thermodynamics. We shall get introduced to the second law of thermodynamics and then we shall define what are known as thermal energy reservoirs, and we shall also discuss about heat engines, what are heat engines and why do you need heat engines.

We shall formally define the second law of thermodynamics in the form of Kelvin Planck's statement after we discuss about heat engines. We shall then discuss about refrigerators and heat pumps, and then, again, formally define the second law of thermodynamics in the form of the Clausius statements. So, Kelvin Planck and Clausius statements are two different statements of the second law of thermodynamics, but we shall also prove that these two statement are equivalent. So, equivalence of the two statements will also be discussed.

Towards the end of the lecture, we shall, we shall be discussing about some interesting devices which we also discussed for the first law of thermodynamics known as perpetual motion machines of the second kind. These are called devices of the second kind because these are devices which violate the second law of thermodynamics. So, perpetual motion machines of the second kind is what we shall discuss towards the end of this lecture.

Now, before we start looking at the second law of thermodynamics itself, we need to understand why do we need to basically define second law of thermodynamics.

(Refer Slide Time: 03:07)



We already have a first law of thermodynamics, which is basically the conservation of energy principle stated in a different way that energy can neither be created nor be destroyed, and so, we already have a a law which states that you can neither create energy nor destroy energy. So, what is the need for defining the second law of thermodynamics? We shall now very soon see that there are some limitations of the first law of thermodynamics.

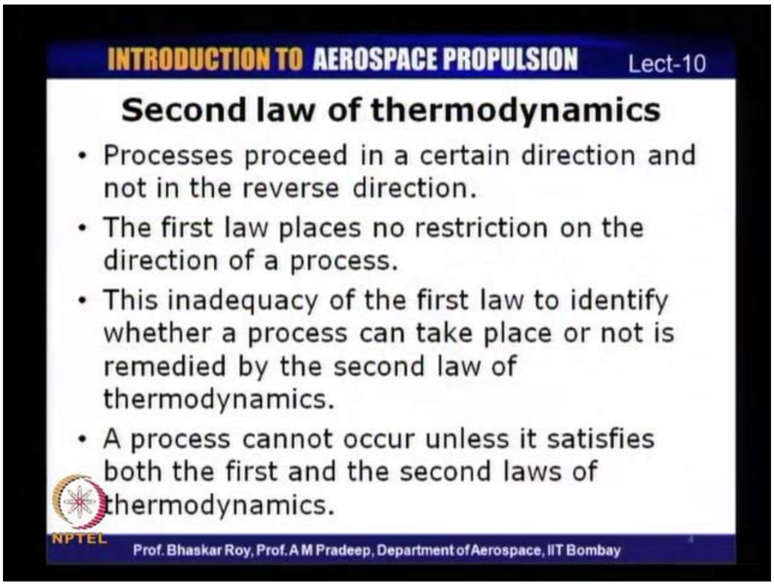
In the sense that first law of thermodynamic, thermodynamics does not give any indication of the directionality of a process nor does it give any indication of quality of energy, and so, we shall discuss those in little detail later on as well. So, we, there it was realised very soon that there are some limitations of the first law of thermodynamics, and as a result of this, there was a need to define a second law which would basically define that there is a certain direction in which a process can take place and processes cannot takes place in the reverse direction.

Let us see some examples. For example, if you look at a cup of coffee which is, let us say at 50 degree Celsius, now this cup of coffee if you keep it in a cold room, you know that with after a certain instance of time, the cup of coffee cools down, but you also know that if you keep a cup of coffee which is cold, it will not raise to a temperature which is higher than the ambient temperature. So, this is a common knowledge that you cannot obviously heat a cup of coffee by just keeping it and it will not heat up on its own to a temperature which is higher than the ambient temperature. First law of thermodynamics does not state that this cannot happen. All that first law states that, energy has to be conserved. In the sense that, you cannot create energy; you can always transfer energy from one, one, form to another.

Let us look at another example. We know that if you pass electric current through a resistor, it heats up, but we also know that if you simply heat up a resistor, you will not get electricity, and again as per first law, you, this is not something which the first law prohibits. First law does not state that this cannot occur. Only, it only states that you can only transfer energy from one form to another. Now, so, here we have certain processes. We can, in the same way, we can give numerous examples. Wherein, we can see that processes can occur only in a certain direction. You cannot have processes taking place naturally in the reverse direction, like you cannot heat up cold body beyond the ambient temperature on its own.

So, this means that all processes take place in a certain direction naturally. The reverse of that process cannot occur naturally, and so, there is a need to define this with a fundamental law of thermodynamics, and the second law of thermodynamics is one such law which places certain restrictions on what direction that a process can take and that reverse of this particular process cannot occur naturally. So, second law of thermodynamics is basically a fundamental law which places certain restrictions on a process being taking place.

(Refer Slide Time: 06:11)

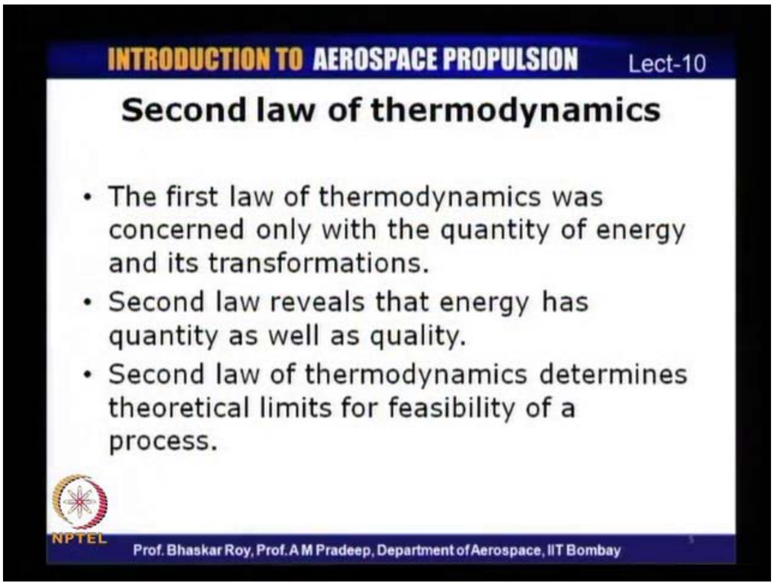


And therefore, a process cannot really take place if it does not satisfy both the first and the second law of thermodynamics. So, this means that processes always proceed in a certain direction and not in the reverse direction, and we have discussed that the first law of thermodynamics really does not place any restriction on what direction a particular process can take, and therefore, this is an adequacy of the first law that it cannot identify whether a process can take place or not. First law cannot identify whether a process is feasible or not, and so, this has to be remedied by defining the second law of thermodynamics.

Therefore, a process really cannot be considered to be feasible if it does not satisfy both the first and the second laws of thermodynamics. So, process can occur only if its satisfies the first law of thermodynamics as well as its satisfies the second law of thermodynamics because both of these are fundamental laws of thermodynamics. Now, the first law of thermodynamics was basically looking at the quantity of energy. It was saying that you can have only energy changes taking place between two systems or between the system and the surroundings, whereas, it was not defining quality associated with a particular energy interaction.

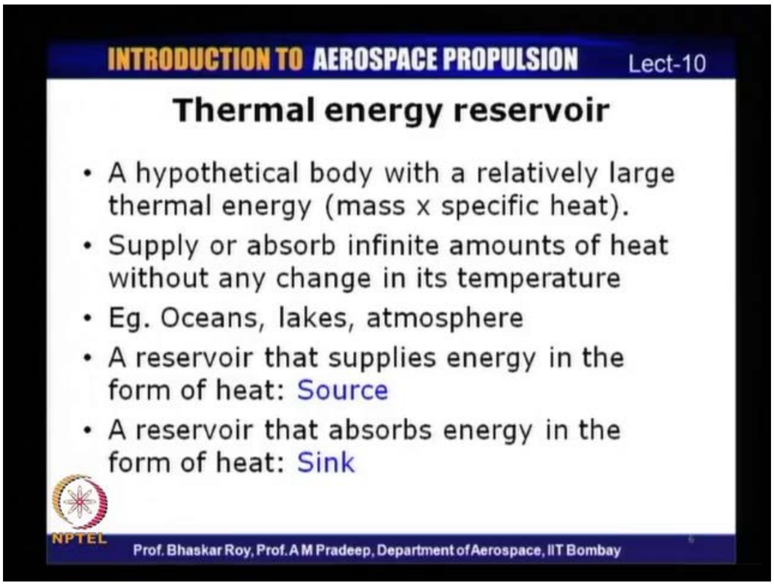
Second law of thermodynamics on the other hand also associates energy to be having a certain quality. we shall very soon see that heat and work are as we have seen earlier also, are two different interactions of energy. Both of these have different qualities of energy associated with them. So, second law of thermodynamics basically helps us in associating certain quality to energy as well. So, it states that energy has quantity; it also has a certain quality.

(Refer Slide Time: 08:08)



Second law of thermodynamics also gives us or helps us in defining theoretical limits for feasibility of a process. That second law of thermodynamics says that there is a certain limit - theoretical limit - for certain process to occur, which was obviously not defined by the first law of thermodynamics.

(Refer Slide Time: 08:22)

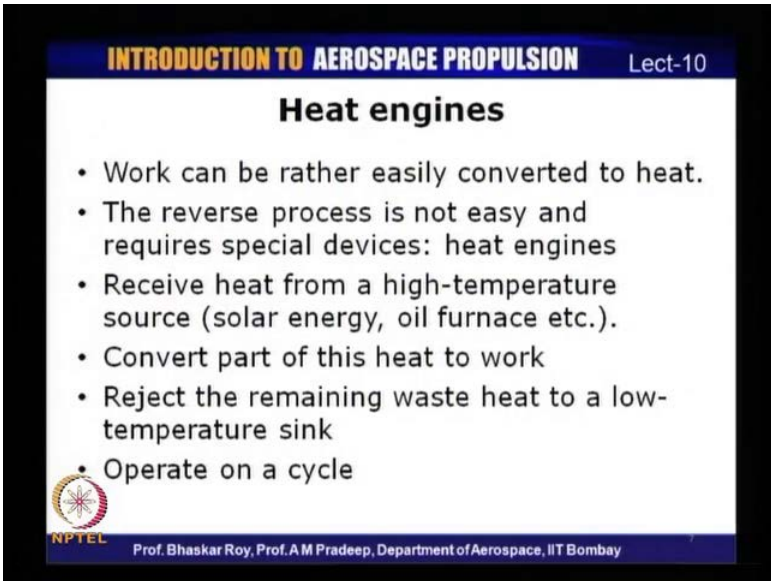


We shall now look at what is known as a thermal energy reservoir. You note that we discuss more about the second law of thermodynamics and different systems like heat engines, etcetera. We need to understand what is meant by a thermal energy reservoir. Thermal energy reservoir is a hypothetical body with a relatively large thermal energy. Thermal energy here means the mass multiplied by the specific heat of that particular body. So, by definition, a thermal energy reservoir should be able to supply or absorb infinite amounts of energy in the form of heat or work without any changes in its temperature.

So, some examples of thermal energy reservoirs are the atmosphere itself or ocean or large lakes, etcetera. These are considered to be devices or these are considered to be systems which can supply infinite amounts of, which can either supply or absorb infinite amounts of energy without any change in its temperature. Now, so, a reservoir which can supply infinite amounts of energy is known as a source. So, a source is a thermal energy reservoir which can supply infinite amounts of energy without any change in its own temperature or energy content, whereas, a sink on the other hand is a thermal energy reservoir, which can absorb infinite amounts of energy without any change in its own temperature.

So, a source can supply energy; a sink can absorb energy, and therefore, thermal energy reservoirs are part of what are known as heat engines and refrigerator and so on, which we will define shortly, because eventually these devices either receive heat from the atmosphere or the surroundings or reject heat to the atmosphere or its surroundings, and therefore, we need to consider what is the thermal energy reservoirs with which these systems interact with.

(Refer Slide Time: 10:34)



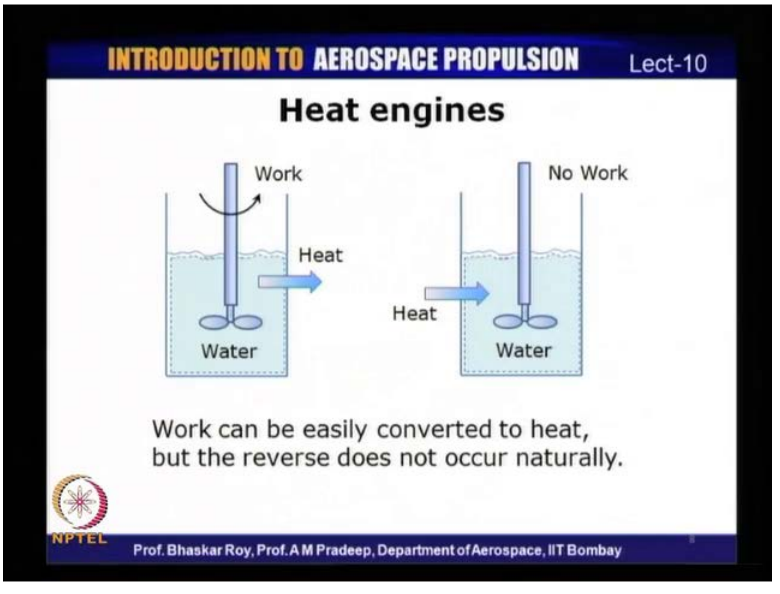
Now, we already know that work is something which you can rather easily generate or which you can convert to heat, but on the other hand, you cannot directly convert heat into work and it is rather not easy or it requires certain complicated devices which are, which we will refer to as heat engines. Heat engines are devices which can convert heat into work. Work can always be converted to heat. You do not really need a heat engine to convert work into heat, but if you have to generate work from certain heat, you need devices known as heat engines.

So, heat engines basically receive heat from a high temperature source which could be solar energy or an oil furnace or so on, and then, heat engines will convert part of this heat into work and then reject the remaining waste heat to a low temperature sink, which could be atmosphere or a lake or a condenser and so on.

So, and therefore, heat engines always operate in a cycle. So, heat engines will require a certain amount of heat supply of heat input through a certain source or a thermal energy reservoir like a furnace or solar energy and so on, and then what heat engines would do is convert part of this heat into work and then the remaining amount of heat which is the waste energy or waste heat is rejected to a low temperature sink and heat engines obviously operate in a certain in a cycle.

Now, you immediately notice that there is a certain component of waste energy that is involved here. Why do you have to waste energy? Why cannot you convert whatever energy is coming in to work output? It does not violate the first law of thermodynamics. Well, it does not violate first law, but definitely it does violate the second law of thermodynamics which we shall define very shortly, which is the reason why it is always required to reject a certain amount of heat to a low temperature sink. You cannot convert whatever energy is input to work output, and we shall very soon see that it is not a limitation because of frictional loses and so on or real effects or irreversibilities, but it is a basic restriction even for an ideal process that, when an ideal heat engine should be rejecting certain amount of heat to the surroundings or to a low temperature sink.

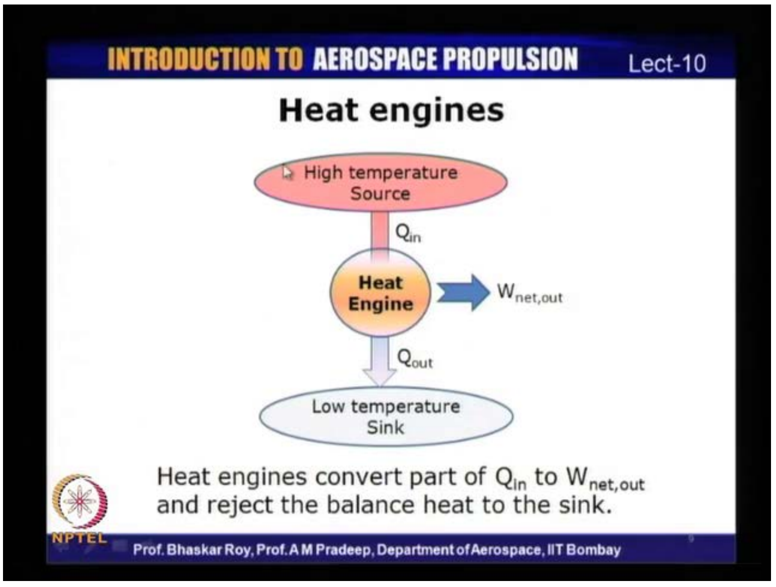
(Refer Slide Time: 13:14)



Now let us understand the concept or requirement of heat engines, why do you need heat engines in the first place. Now, one example I have shown here is that, if you supply certain amount of work to let us say water through a paddle wheel here, so you rotate the paddle wheel, and therefore, it does work on water, and so, water gets heated up, and this heat eventually if it is not an insulated surface, will get transferred to a sink.

So, on the other hand, if you were to transfer heat into a stationary paddle, let us say there is, this paddle is stationary, and if you were to heat up this or if you transfer heat in to this water, you know that that is not going to generate any work output. So, you can immediately see that work can be easily converted to heat, but to convert heat into work is something that does not happen naturally and which is the reason why you need a heat engine which basically does this it converts input heat partially into work and rejects the remaining heat to the ambient.

(Refer Slide Time: 14:12)



So, what is shown here is a schematic of a heat engine. So, heat engine is something which operates between a high temperature source which is a thermal energy reservoir, and it, the other end of the heat engine is a low temperature sink which is yet another thermal energy reservoir which is a sink.

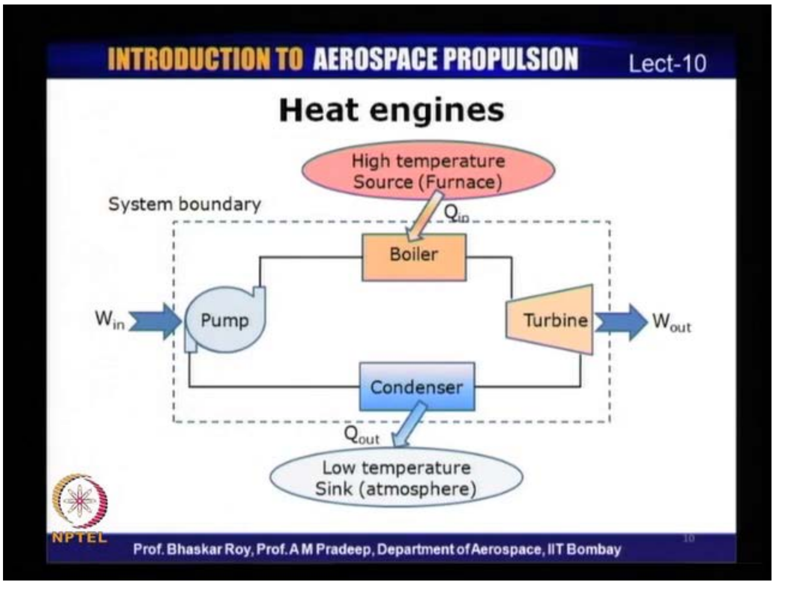
So, between the source and sink, the heat engine generates a work output. So, there is a heat transfer which is denoted by Q in from the high temperature source to the heat engine. The heat engine converts part of this Q in into net work output and it rejects the remaining heat which is Q out to a low temperature sink.

So, heat engine is a device which can convert a certain amount of heat or energy into net work output and rejects some amount, the remaining amount of heat back to a sink. So, this is how we would normally denote or illustrate a heat engine, and what can be, within this heat engine could be let us say an example is a steam turbine cycle which consist of several components. So, heat engine is not a single component device. It does not mean that though I have shown indicated by heat engine by just a single circle here.

What could be inside this circle which is denoted here could be multiple components? It could consist of pump and a turbine, condenser and a boiler. All these put together constitutes a steam turbine unit which generates a net work output, and so, heat engine can. So, all these components put together constitute the heat engine. So, it is not just the turbine which constitutes the heat engine there though that is one of the components of the heat engine cycle.

There are other components that could be involved like condenser. The turbine outlet goes into a condenser; then that condenser outlet goes into a pump, which then goes into a boiler which generates steam. So, all these four components put together constitutes a heat engine cycle, and in this case, it is just a steam turbine cycle.

(Refer Slide Time: 16:29)

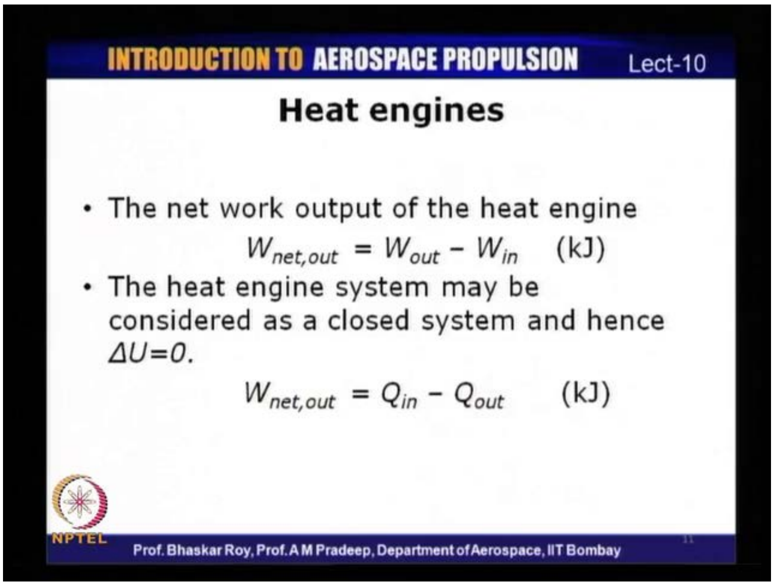


So, heat engine can be actually a multi component cycle. Now, I am explaining the same example here in the case of I mentioned about the steam turbine unit, which is illustrated here. So, what you see, what you saw here denoted by heat engine is shown in the form of is basically the system boundary here as indicated. It could consist of let us say in this example we have four components. There is a turbine; there is a condenser, a pump and a boiler.

So, heat is transferred into the system or across the system boundaries from a high temperature source which could be a furnace in this case, which transfers heat into the boiler and generates steam. So, Q in occurs here, that is, heat input. From the boiler, steam goes into the turbine which generates a work output, and then the turbine exhaust is going into a condenser through the condenser. Heat is rejected to the low temperature sink or the atmosphere which is how, which is why Q out is shown here, and as the steam condenses, water is then pumped again back into the boiler and pump obviously requires a work input.

So, through this steam turbine cycle, there is a net work output which will be the turbine work minus the pump input work. So, there is a net work output of the system besides that there is a Q in which occurs at the boiler end and there is a Q out, that is, heat is rejected at the condenser end. So, all these different components put together constitute the heat engine cycle which we mentioned earlier.

(Refer Slide Time: 18:07)



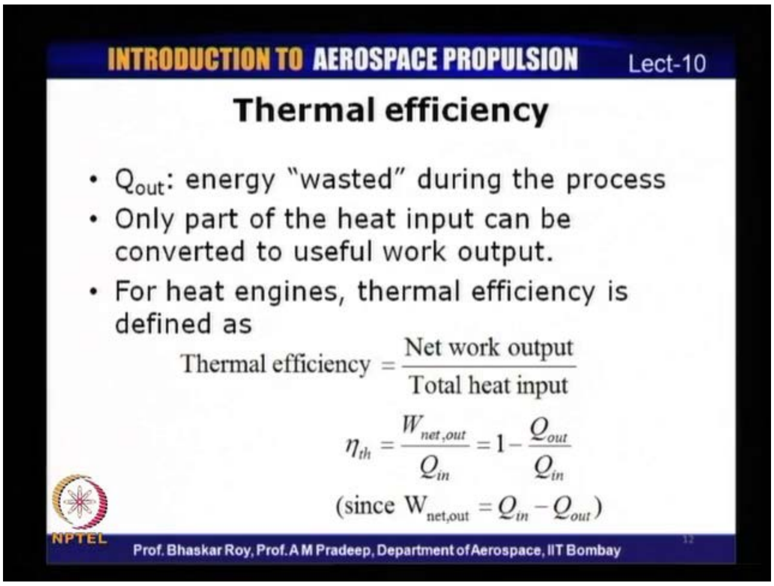
So, the net work output of this heat engine example we saw is equal to w out which is work output of the turbine minus W in which is a work required for the compressor in this case or the pump in this case. Now, as you can see the heat engine system which we discussed can be considered as a closed system, because it is the same fluid which is moving in and there is no net mass which is moving out of the system boundaries. The system boundary, so, the only energy interaction which was taking place across system boundary was the heat interaction Q out and Q in.

So, this whole heat engine cycle which we discuss can be considered as a closed system, and so for a closed system, we know that delta U net change in internal energy is 0. So, therefore, w net output should be equal to Q net. Therefore, net work output should be equal to the difference in the heat input and heat output of the system.

So, w net should be equal to Q in minus Q out because delta w is equal to delta Q for a closed cycle system which we discussed in a two lectures earlier that, for a cycle, delta w is equal to delta Q. So, if you apply the first law for a cycle, heat engine is basically a cycle. You get delta w is equal to delta Q. So, net work output is equal to Q in minus Q out.

Now, I mention that there is a certain restriction on why we need Q out from a system. Why is it that you cannot have Q out equal to 0. So, this heat energy which is wasted during a process means that there is a certain efficiency associated with all heat engines. So, all heat engines have a certain efficiency. It cannot convert the entire amount of energy input to work output, and therefore, this difference between the work output and the energy input is known as efficiency of a heat engine cycle.

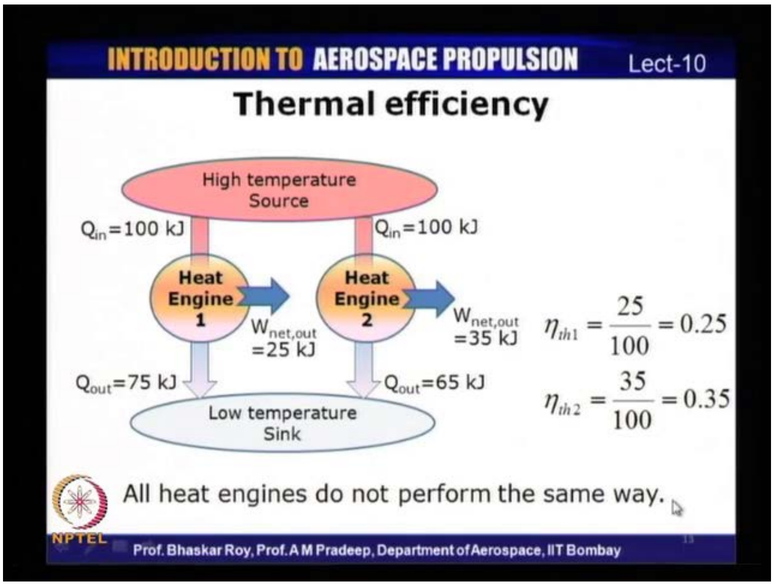
(Refer Slide Time: 20:11)



So, thermal efficiency as we will define is basically the ratio of the net work output to the total heat input, and this is because only part of the heat input can be converted to useful work output. So, for heat engines, we will define thermal efficiency as the net work output divided by total heat input, and therefore, which is also equal to w net out divided by Q in, and we normally denote efficiency with this Greek symbol eta and eta to the subscript T H which denotes thermal. So, eta thermal is equal to w net out divided by Q in.

We already saw that w net out is equal to Q in minus Q out, and therefore, eta thermal is one minus Q out by Q in. So, thermal efficiency is equal to the ratio of the heat out from the system and heat input from the system that subtracted from one will give you the thermal efficiency. You can immediately see that if Q out were to be 0, then thermal efficiency will become 1. That is because w net out will then be equal to Q in and then you get thermal efficiency which is equal to 1 or 100 percent efficiency of a system.

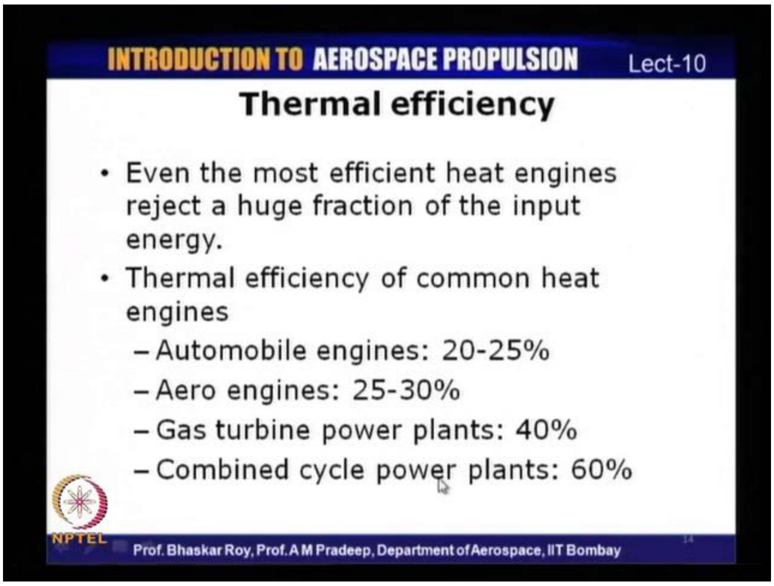
(Refer Slide Time: 21:35)



Now, to illustrate this example to this point of thermal efficiency, let us look at this example of two heat engines which are operating between the same temperature source and sink, but both of them generate different amounts of net work output. For the first heat engine, - heat engine one - it receives a let us say a heat input of 100 kilo joules. It generates a work net work output of a 25 kilo joules and rejects 75 kilo joules to the sink. Therefore, the, the thermal efficiency of this heat engine will be w net out divided by Q in, that is, 25 by 100, that is, 0.25

Now, you could also have a heat engine which is again operating between the same source and sink but it generates a different work output. In this example shown here, this generates a net work output of let us say 35 kilo joules. Thermal efficiency of this heat engine is 35 divided by 100, that is, 0.35. This means that all heat engines do not perform in the same way. Different heat engines can have different efficiencies even if they are operating between the same source and sink, and so, it is possible to have different types of heat engines. Some of them may be more efficient than other operating between the same source and the sink and generating different amounts of net work output.

(Refer Slide Time: 23:07)



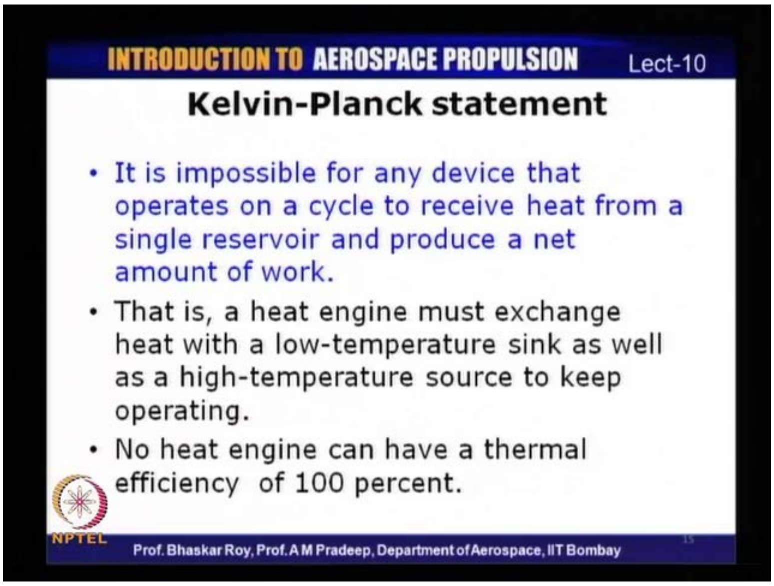
And so, even the most efficient heat engine that is known to have been built will reject a huge amount of heat input back to low temperature sink. Just to give some examples of thermal efficiency of some common heat engine cycles which you might be coming across. The range of efficiency causes only indicative; it may be slightly different for some engines which are little more efficient.

Typical examples, typical efficiencies of automobile engines, thermal efficiency of automobile engines could range from between 20 to 25 percent. There could be some engines which have slightly higher efficiencies but they are of the same order. Aero engines on the other hand slightly have slightly higher efficiencies of the order of 25 to

30 percent. Gas turbine based power plants which are land based power plants have efficiencies of the order of forty percent, and power plants operating in the combined cycle mode, that is, gas turbine and steam turbine together, put together in a cycle are known as combine cycle power plants. They have probably the highest efficiency of heat engines that are known close to about 60 percent, and so, that is like the highest amount of efficiency that is known, which means that there is still 40 percent of the heat input which is being rejected.

Even the most efficient cycle is rejecting close to 40 percent of the heat input. Now, this is something which we shall see soon is not really a limitation of the real effects like frictional losses and so on, but that is a limitation that is fundamentally imposed by the second law of thermodynamics itself, which is something we shall explain in the form of Kelvin Plancks statement very shortly.

(Refer Slide Time: 25:10)

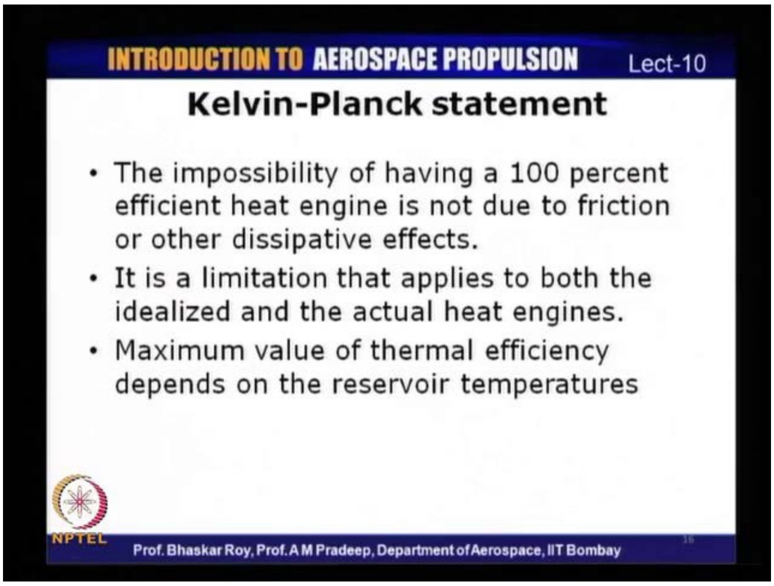


So, basically Kelvin Plancks statement of thermodynamics states that you cannot convert the entire amount of heat input to work output. So, in a statement, the Kelvin Plancks states that: the statement of the second law of thermodynamics is that it is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

So, this basically means that a heat engine must always exchange heat with a low temperature sink as well because it cannot just operate between a high temperatures, it cannot just operate from a high temperature source and generate a net work output. It has to interact with a low temperature sink as well.

So, this immediately means that there has to be a Q out from the system, that is, there has to be a heat rejection from the system, and therefore, no heat engine can have a thermal efficiency of 100. So, it is always possible that you may have efficiencies of the order of very high efficiencies like eighty percent and so on, but even an ideal cycle or an ideal heat engine can still cannot have an efficiency of 100 percent, because as per the Kelvin Plancks statement of the second law, it is impossible for a heat engine to interact with just one reservoir and generate a net work output, and so, it means that any heat engine has to interact with two different, at least two reservoirs - one where in the heat is input to the system and one from which the heat is rejected from the system, and then it can generate a net work output. So, that is the basic statement by Kelvin Planck.

(Refer Slide Time: 26:47)

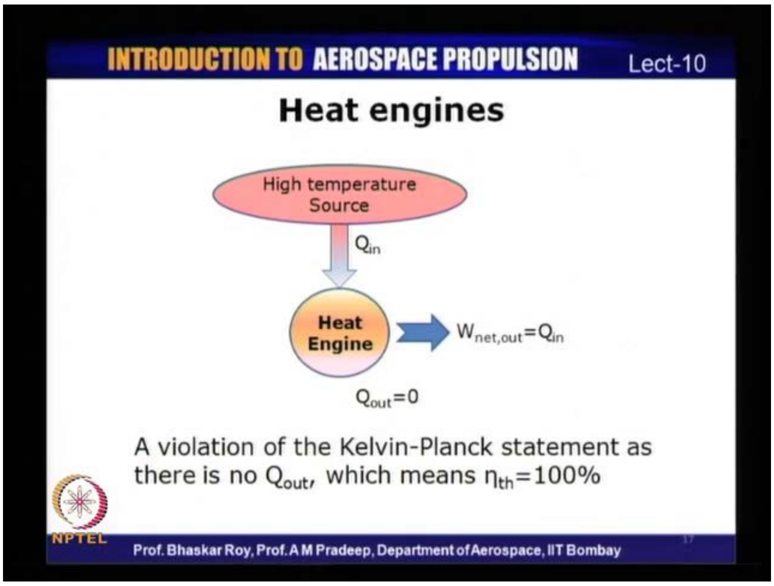


So, Kelvin Planck statement puts a limitation on the amount of efficiency then that a system can have, and therefore, this impossibility of having 100 percent efficient heat engine is not because of frictional or other dissipative effects or real life effects, but it is a limitation which is applicable for both idealized as well as actual engines.

And so, how much efficiency a system can gain will also depend upon the reservoir temperatures. So, higher the source temperature and lower the sink temperature naturally you will have a higher efficiency of the system, which means that some of the examples which we will see little later on in subsequent lectures is that, if a system or if a heat engine is operating between a relatively low temperature source and a sink, then the efficiency has to be naturally low and which is one of the reasons why some of the non conventional sources of energy like geothermal and so on have very poor efficiencies, because the source temperature itself is low.

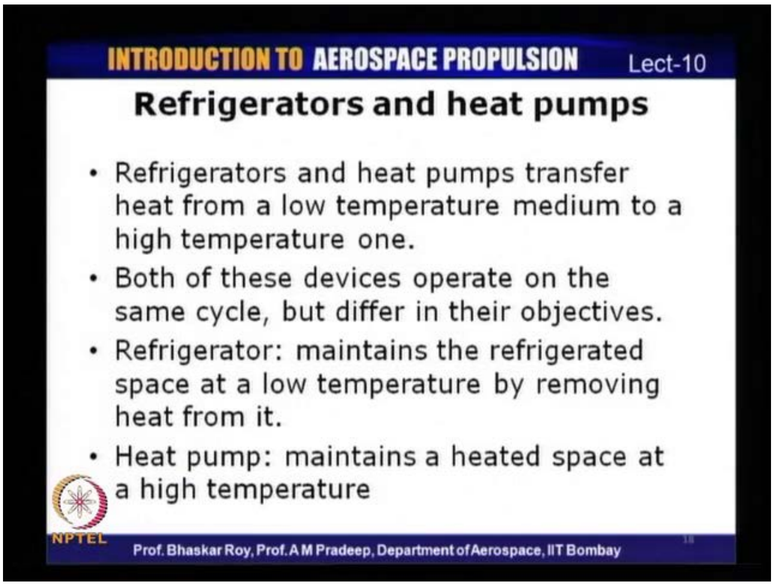
On the other hand, if you look at gas turbine engine, the source temperature is as compared to the sink temperature the differential is very high, and therefore, the efficiencies can be high. Whereas, if you look at solar devices or geothermal devices though they are renewable sources of energy, but because they are operating between a source and a sink were the differential in temperature is not very high. Their efficiencies are bound to be naturally very low. So, that is as a consequence of the Kelvin Planck statement of the second law.

(Refer Slide Time: 28:34)



Now, if you look at this example I am showing here of a heat engine, we have a high temperature source and which is providing a certain heat, that is, Q in to the heat engine and because Q out is equal to 0. The net work output is equal to Q in. Therefore, thermal efficiency of this particular system will be equal to 100 percent because Q out is 0, and this is clearly a violation of the Kelvin Planck statement that, such a heat engine is impossible because you should, you cannot have a device which continuously generates work output by; at the same time, it is interacting only with a single reservoir and it is not rejecting heat to a sink. So, this is something that we discussed about the heat engines.

(Refer Slide Time: 29:23)



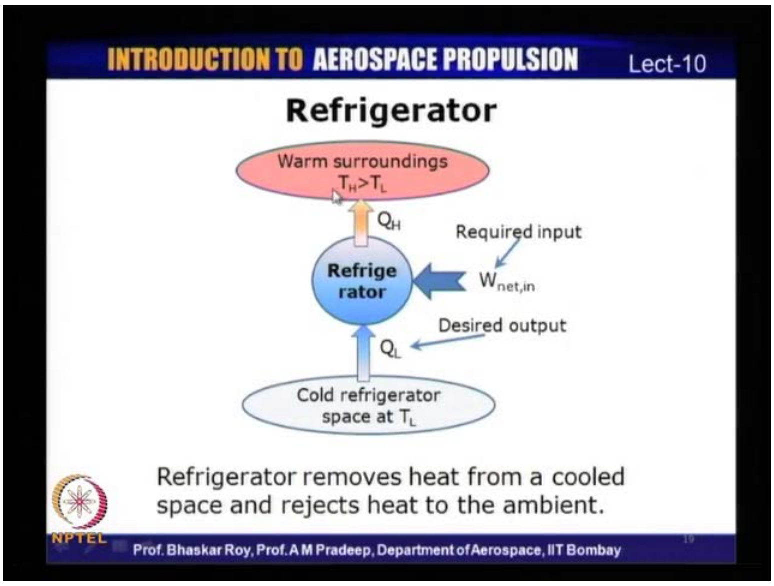
So, let us now discuss about two other devices which are of interest to us, which are refrigerators and heat pumps. These are devices which are in some sense opposite to that of a heat engine. Heat engine as we know operates between a high temperature source and a low temperature sink and generates a net work output.

Refrigerators and heat pumps on the other hand transfer heat from a low temperature medium to a high temperature one and this requires a work input. So, it is in some sense opposite to that of a heat engine. Refrigerators and heat pumps as we know, refrigerator for example, it maintains what is stored inside the refrigerator at a temperature which is lower than the surroundings, which means it is continuously transferring heat from a low temperature sink to a high temperature surroundings and this requires work input, which is why refrigerator consumes work. Heat pump is yet another device and an equivalent of refrigerator is an air conditioner, which is very similar to that of a refrigerator. Air condition maintains a room at a temperature which is lower than that of the ambient.

Heat pump on the other hand transfers heat again from low temperature surroundings to maintain a room at a temperature which is higher than the surroundings. So, a heat pump would be like ah an air conditioner put on the heating mode, that is, you would want to maintain a room which is at a temperature higher than the surroundings and this again requires a certain work input. So, refrigerators and heat pumps both transfer heat from low temperature medium to a high temperature one. Both of these devices operate on the same cycle but they differ in their objectives.

Refrigerator is a device which will maintain the refrigerated space at a low temperature by removing heat from it. A heat pump on the other hand will maintain a heated space at a temperature which is higher than the surroundings. So, both of these devices basically operate on the same cycle but have different objectives. Now, we will look at how a refrigerator functions in the form as we discussed for a heat engine. At least thermodynamically refrigerator for example, operates between a cold space and a warm surroundings, and so, it continuously transfers heat from, it is from cold space to the warm surroundings but requires a certain work input.

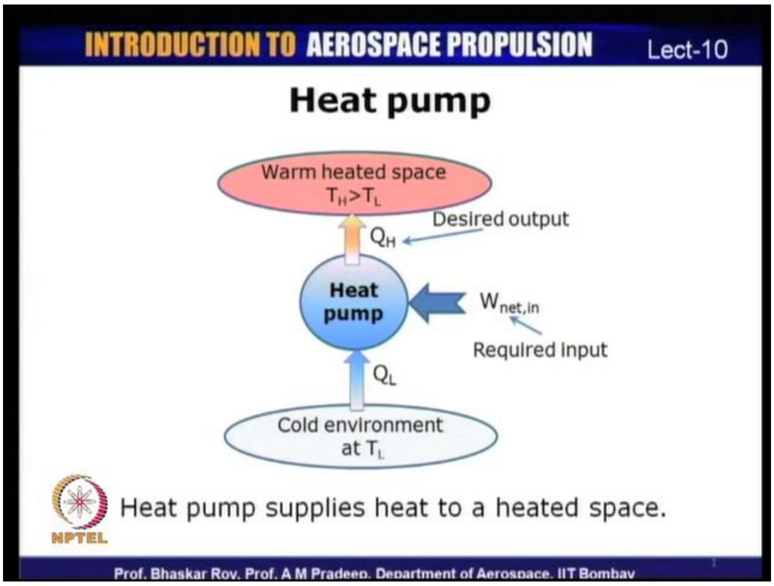
(Refer Slide Time: 31:59)



So, in the case of a refrigerator, a refrigerator removes heat from this cold space which is shown here which is at temperature, let us say at temperature of T L and it rejects a heat to warm surroundings which is at a temperature T H - where T H is greater than temperature T L. So, refrigerator continuously transfers heat from T L to T H, and so, we, have since we have to maintain this space at this temperature T L, we have to continuously transfer heat at a rate of let us say Q L.

And therefore, in the case of refrigerator the desired output is Q L. So, it is desired to maintain this at T L, and therefore, if you have to achieve that, you have to continuously transfer heat at a rate of Q l from the refrigerated space, and so, this is the desired output in the case of the refrigerator, and if this is to be carried out, there is a certain work input that is required. So, the required work input is the net work input, that is, w net in. The refrigerator rejects Q H from the refrigerator to the surroundings which is warm, which is warmer than the cold space which is having a temperature T H greater than T L.

(Refer Slide Time: 33:19)

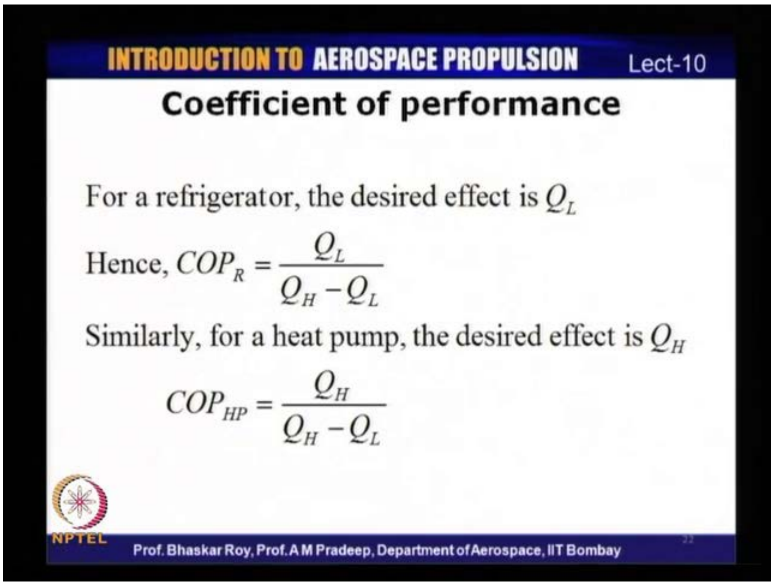


A heat pump on the other hand is very similar to that of a refrigerator. You can clearly see that it is also transferring heat from cold environment to warm heated space but the desired output is different. In the case of refrigerator, we had seen that it was transferring heat from a low temperature refrigerated space to the surroundings. In the case of heat pump, it is transferring heat from Q L to a warm heated space which is at T H again at a temperature greater than T L.

So, here, we see that the desired output is Q H, where as in the case of refrigerator, it was Q L. For heat pump, the desired output is Q H and work input remains the same. That is the required input. So, heat pump supplies heat to a heated space. They only differ in their desired outputs. In refrigerator, it is Q L; heat pump, it is Q H.

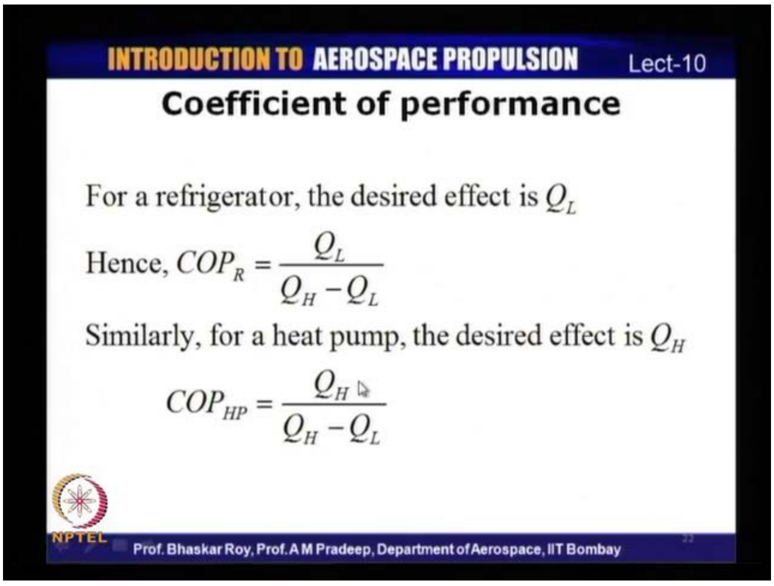
Now, one, now that we have understood what is a refrigerator and a heat pump. For heat engines, we had seen that we can assess the performance of heat engines by what is known as thermal efficiency. Now, how do we assess the performance of refrigerators and heat pumps? So, to assess the performance of these devices, we have a term known as coefficient of performance. So, we do not really have efficiency of these devices. We define their performance in the form of what is known as coefficient of performance or C O P.

(Refer Slide Time: 34:52)



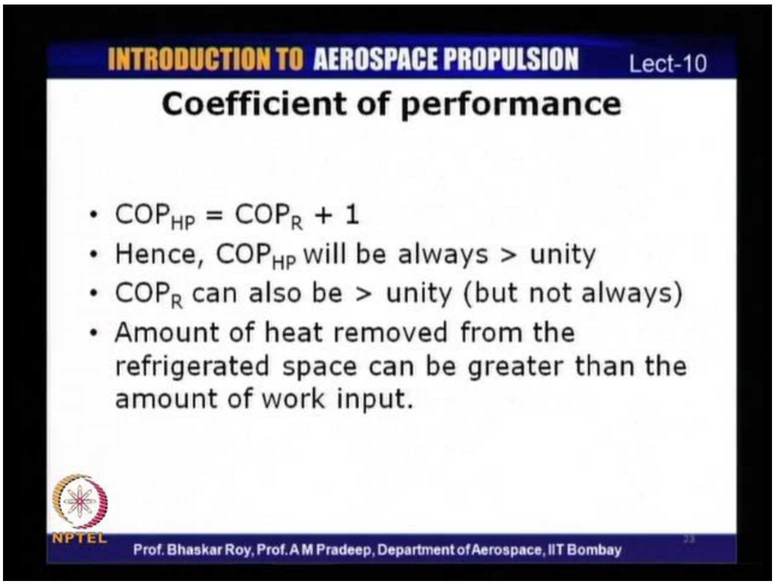
So, C O P is basically efficiency as characterized for a refrigerator or a heat pump. So, C O P is basically defined as the ratio of the desired effect to the required input, and we have seen the required input is w net in which is basically the difference between Q H and Q L. So, w net in is Q H minus Q L, and the desired effect changes if it a refrigerator or a heat pump.

(Refer Slide Time: 35:25)



So, for a refrigerator, we have seen that the desired effect is Q L, and therefore, the C O P of a refrigerator is Q L divided by Q H minus Q L. Similarly, for a heat pump, the desired effect is Q H, and therefore, C O P of a heat pump is Q H divided by Q H minus Q L, and so, the coefficient of performance of the refrigerator and heat pump differ by the desired effect. In one case, it is Q L, and in the other case, it is Q H.

(Refer Slide Time: 36:01)

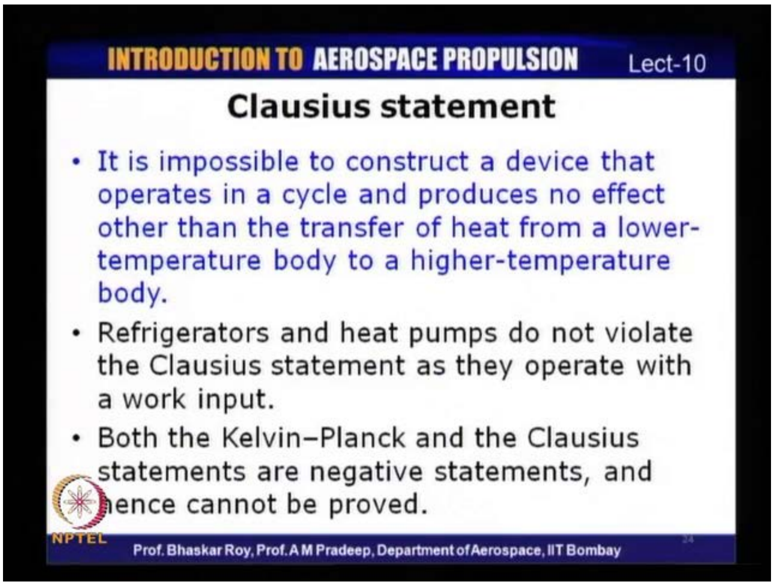


And so, we can, from these two equations, we can actually prove that C O P of a heat pump is equal to C O P of refrigerator plus 1. So, this means that C O P of a heat pump will always be greater than unity, and C O P of a refrigerator on the other hand can also be greater than unity but it is not always the case. In some cases, it can be greater than one; it may not be greater than one in some cases depending upon the design of the refrigerator itself.

But C O P of a, of a, heat pump on the other hand is always greater than 1 because C O P of heat pump is C O P refrigerator plus one, and this means that amount of heat that is removed from the refrigerated space can actually be greater than the work input, and so, you may wonder is there a violation of some law here because you are trying to remove more amount of heat than the work input itself.

Well, there is not really any violation of any of the thermodynamic laws, and you can actually see that unlike a device which is generating work output. We have discussed that converting heat into work is not always possible without having certain devices like heat engine, and therefore, you cannot have a heat engine which has 100 percent efficiency, but converting work into heat is always possible, and therefore, in this case, we have a work input, and so it is possible that your amount of heat that is removed from the refrigerated space can actually be greater than the work input itself, and which is why you have the C O P values which can exceed unity.

(Refer Slide Time: 37:51)



Now, we have already discussed the Kelvin Planck statement of the second law of thermodynamics, which was a limitation placed on heat engines that they cannot really have 100 percent efficiency. Now, the Clausius statement is coming from the discussion which we had on refrigerators and heat pumps.

Clausius statements states that it is impossible to construct a device that operates again in a cycle and produces no other effect other than transfer of heat from a low temperature body to a high temperature body. So, Clausius statement is stating that you cannot transfer energy from low temperature to high temperature without a work input, that is, if you have a cycle which is continuously transferring energy from low temperature to a high temperature without work input, that is an impossibility as per the clausius statement.

So, refrigerators and heat pumps you may wonder probably are they violating Clausius statement? Well, they are not violating because there is a work input required. So, they are not naturally trying to transfer heat from low temperature to a higher temperature. That is occurring because there is a certain work input in both these devices in refrigerators and heat pumps. So, refrigerators and heat pumps are not transferring energy naturally from low temperature to a high temperature but they do so with a certain work input.

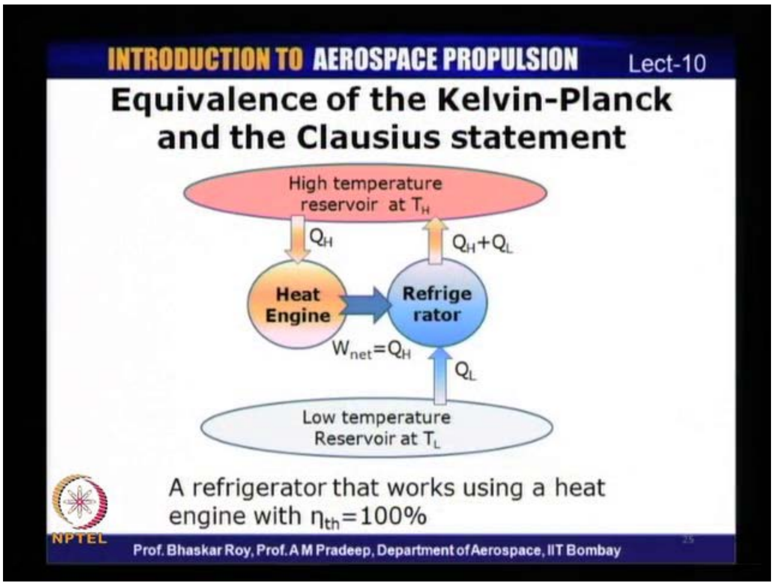
Clausius statement only states that it is impossible for a device to continuously transfer energy from low temperature to high temperature without any work input or without any other effect, and what we will see now is that though both these statements look to be very different - the Kelvin Planck statement and the Clausius statement, they are in fact not different. In some sense, thermodynamically it is possible to prove the equivalence of the Kelvin Planck statement and the Clausius statement.

So, remember, Kelvin Planck statement states that you cannot construct a device which can have, which can continuously generate a net work output by having simply a heat input, and Clausius statement states you cannot simply transfer energy from low temperature to high temperature without any work input. So, though on paper, they look to be entirely different statements. Well, that is not really the case. We are going to prove that both of these statements are equivalent thermodynamically equivalent in some sense.

So, to prove this equivalence of the Clausius and the Kelvin Planck statement, what we will do is to take a look at a system which consist of a refrigerator and a heat engine operating between the same source and sink, and one of these devices will be violating the Kelvin Planck statement, and in due course, we will prove that, if they violate Kelvin Planck statement, they also violate the Clausius statement, and please remember that both Kelvin Planck and the Clausius statements are negative statements, and by negative statement, we mean that it is impossible to construct at certain device or it is impossible for a certain process to occur. So, negative statements cannot be proved mathematically.

Well, what you can prove is that, since there have been no violation of these devices which have been proven or demonstrated, that is a sufficient proof that these statements are valid. So, negative statements cannot be proved and you can only show that there are no violations of these devices which have been demonstrated, and that is considered as a sufficient proof that these statement are still valid.

(Refer Slide Time: 41:44)



So, let us look at how we can prove the equivalence of the Kelvin Planck and the Clausius statement. So, here, we have a system which consists of two devices - a heat engine and a refrigerator operating between a high temperature reservoir, which is let us say at temperature T H and a low temperature reservoir which is at a temperature of T L. In this case, this heat engine is something which is violating the second law of thermodynamics as per Kelvin Planck statement because this heat engine is transferring heat at Q H and converting that entire amount of Q H into work output - w net.

So, w net here is equal to Q H. So, this is a heat engine which has an efficiency of 100 percent, and therefore, this clearly violates the Kelvin Planck statement of the second law, which states that you cannot have devices which converts whatever energy is input entirely into work output. So, this heat engine violates the Kelvin Planck statement.

Now, here, we have a refrigerator which is transferring heat at Q L from the low temperature reservoir, and using this net work output from the heat engine of Q H, it transfers Q H plus Q L to the high temperature reservoir which is at T H. So, this refrigerator is using the work input from the heat engine. So, heat engine generates a net work output of w net equal to a h, and this heat work input goes into the refrigerator.

So, at the first moment, we, if we look at it, it does not look like the refrigerator violates any law because you have that work input to the refrigerator and it is transferring heat from low temperature to a high temperature which is perfectly fine, but the refrigerator is actually getting work input from a heat engine which has 100 percent efficiency.

So, if you take a closer look at this refrigerator and heat engine combination, what we see is that this high temperature reservoir is receiving a net energy input which is equal to Q H plus Q L minus Q H, that is, the refrigerator receives energy at the rate of Q L, and therefore, if you take a closer look at the heat engine refrigerator combination, the high temperature reservoir is receiving heat at a net rate of Q H minus Q L which is the heat rejected by the refrigerator minus the work input, which is Q H. So, the net heat transferred to the high temperature reservoir is Q l.

So, this whole system now reduces to this what is shown here which is the equivalent refrigerator. So, this equivalent refrigerator continuously transfers energy at Q L from the low temperature reservoir and rejects Q L to the high temperature reservoir again at at the rate of Q l. Now, you can immediately see that there is a refrigerator here which does not require any work input but is continuously transferring heat at Q L from the low temperature reservoir to the high temperature reservoir.

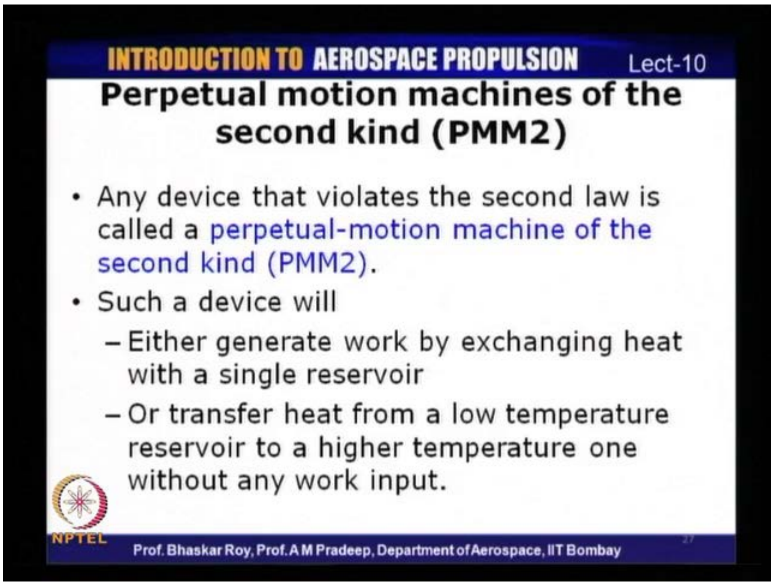
Now, this is a clear violation of the Clausius statement which states that you cannot have a refrigerator, which has a net effect of transferring energy from a low temperature reservoir to a high temperature reservoir without any work input. So, here is a refrigerator which does not require any work and is continuously transferring energy from low temperature to high temperature.

So, this system which consisted of a heat engine with a 100 percent efficiency, and therefore, clearly violating the Kelvin Planck statement in combination with a refrigerator becomes an equivalent refrigerator which violates the Clausius statement. So, what it means is that, if there is system which violates the Kelvin Planck statement of the second law of thermodynamics, it will also be violating the Clausius statement of the second law of thermodynamics, and therefore, it means that both of these, both the statement - the Kelvin Planck as well as the Clausius statements - are in some sense equivalent. Both of these statements of the second law of thermodynamics are equivalent and say the same thing, and though on paper, both of these statements look to be entirely different. It is possible to prove the equivalence of the Kelvin Planck as well as the Clausius statement.

So, both Kelvin Planck and the Clausius statement of the second law of thermodynamics are equivalent. One of the statements, that is, Kelvin Planck statement is basically stating that it is impossible for a devices to convert the entire heat input to work output and the Clausius statement states that it is impossible for a device to continuously transfer energy from low temperature to high temperature without a work input. So, it is possible to prove the equivalence of both of these statements. So, in this example, we saw of a heat engine and refrigerator combination. What we proved was violation of the Kelvin Planck statement leads to eventually a violation of the Clausius statement also.

It is also possible to prove the reverse that, if there is a device which violates the Clausius statement, we can prove that they will eventually also violate the Kelvin Planck statement, and so, it has been proved beyond doubt that Kelvin Planck as well as Clausius statement are both equivalent. In some sense of the other, both of these devices are equivalent and it is possible to prove the equivalence of the Kelvin Planck and the Clausius statement. Now, so, in spite of these laws which have been in existence for a very long time, there have been many so called inventers who have come with devices which clearly violate the either of these statements.

(Refer Slide Time: 48:04)

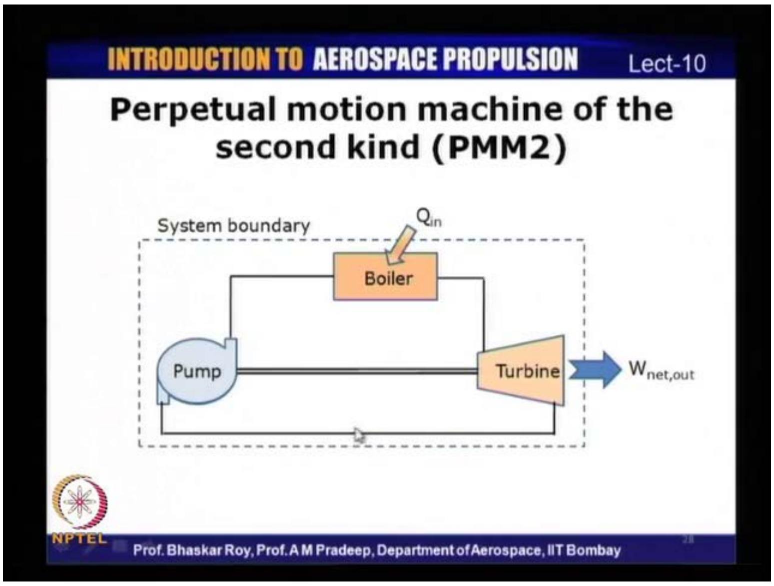


And therefore, these are devices which cannot really exist in nature; these are infeasible devices. We had discussed about a set of infeasible devices while we were discussing about first law of thermodynamics those who are termed as Perpetual Motion Machines of the first kind. Those are devices which violate the first law of thermodynamics, and therefore, they would create or destroy energy in some sense or the other, and there are yet another class or set of devices which violate the second law of thermodynamics and these devices are known as perpetual motion machines of the second kind.

Now, perpetual motion machine is any device which violates the second law of thermodynamics and these are referred to as perpetual motion machine of the second kind. So, it means that as per the Kelvin Planck statements such a device will either or Clausius statement, such a device will either generate work by exchanging heat with a single reservoir which is a violation of the second Kelvin Planck statement or it would transfer heat from a low temperature reservoir to a high temperature one without requiring any work input which is a violation of the Clausius statement.

So, a perpetual motion machine would end up doing either of this. It could be either generating work by exchanging heat with a single reservoir, and therefore, it will violate Kelvin Planck statement or it will just be transferring heat from low temperature to a high temperature without any work input, and therefore, it will violate the Clausius statement. So, we will look at one example of such a device - perpetual motion machine - which will basically be we will prove that it violates one of these laws of thermodynamics. If you recall during our discussion of perpetual motion machines of the first kind, we were discussing about a steam turbine unit where the so called inventor stated that - instead of having a furnace which can transfer heat to the boiler, we can use part of the energy from the generator and then use a resistance heater to boil water, and we saw that such a devices, such a system would basically create energy, and so, it violates the first law.

(Refer Slide Time: 50:14)



Now, we can simply the same system which we discussed earlier. Now, here, the same inventor let us say then claims after he finds that it is a violation of the first law. He claims that we can well, if that is a violation, let me modify this system and let me know remove the condenser. Recall that we had a condenser here through witch heat was rejected.

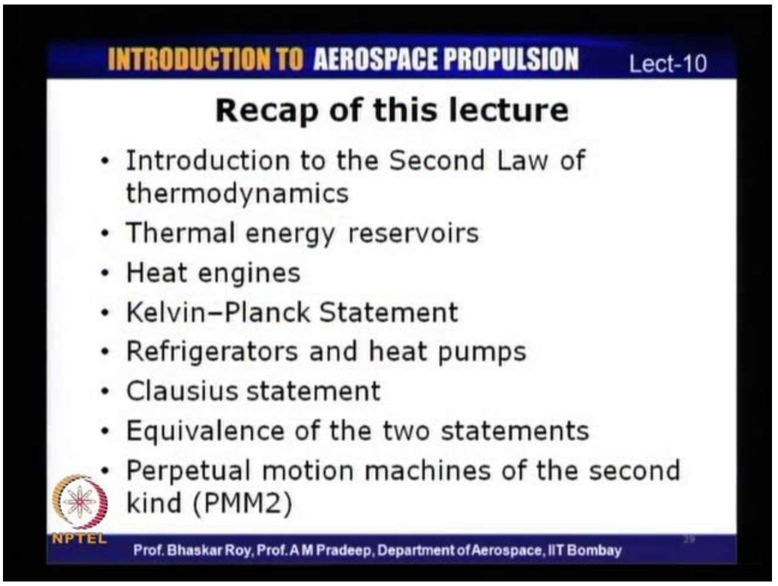
So, he said let me now remove the condenser because that is you’re just wasting heat through the condenser. You do not need a condenser at all, but I will still retain the furnace, which means instead of the resistance heater, we are still using the furnace. So, furnace is one through which you transfer energy to the boiler and boiler generates steam; steam goes to the turbine; turbine generates work output. Part of the work output is used for driving the pump, and exhaust from the turbine is pumped again back to the boiler.

So, it obviously looks like there is no nothing wrong with the system. Well, you do not need a condenser, which means there is no Q out from the system. You are saving um heat rejected by the system, but now that we have understood what is the Kelvin Planck and Clausius statement and second law and so on.

We can clearly see that here we have a system which is receiving heat at Q in and generating net work output and there is no Q out from the system. So, such a system will have an efficiency of 100 percent, and as per Kelvin Planck’s statement, this is a clear violation of the second law of thermodynamics that, you cannot have a system which continuously receives heat and generates a work output without rejecting any heat to the surroundings. And so, this is a clear violation of the Kelvin Plancks statement of the second law of thermodynamics, and so, is it is an infeasible device, and similarly, there are numerous other examples of devices which have been proposed over the years. So, such devices are classified as perpetual motion machines of the second kind.

So, this brings us to the end of this lecture, and during this lecture, what we did was - we had some discussion on the second law of thermodynamics and we understood why we basically need a second law of thermodynamics, what is the need for defining a second law of thermodynamics.

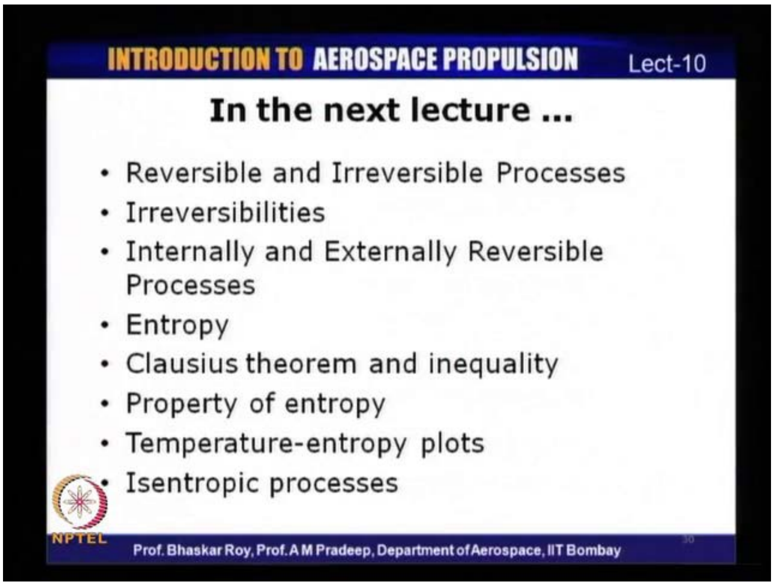
(Refer Slide Time: 52:29)



We also looked at what are thermal energy reservoirs basically sources and sinks, and heat engines are devices which covert heat into work output and reject some amount of heat, and then we discussed about the Kelvin Planck statement of the second law of thermodynamics, and after that, we had some discussion on devices which are refrigerators and heat pumps, which transfer heat from low temperature to a high temperature with a work input, and as a consequence of this, we also have had defined the Clausius statement of the second law of thermodynamics which basically states that you cannot transfer energy from low temperature to high temperature without any work input.

We also, we also, discussed about the equivalence of these two statements of thermodynamics - the Clausius and the Kelvin Plancks statement, and towards the end of this lecture, we had discussed, we had discussion on perpetual motion machines of the second kind which are devices which violate the second law of thermodynamics.

(Refer Slide Time: 53:43)



In the next lecture, what we shall do is to have discussions on what are known as reversible and irreversible processes, and we shall discuss about the sources of these irreversibilities and the two different types of irreversible processes internally and externally reversible processes.

We shall then discuss about a very important property known as entropy which is a basically a consequence of the second law of thermodynamics, and then, we shall discuss the Clausius theorem and the Clausius inequality. We shall discuss about the property of entropy - the temperature entropy plots - and towards the end of the next lecture, we shall also discuss about what is meant by an isentropic process. So, that brings us to the end of this lecture and we shall have discussion on these topics during the next lecture.