Energy Resources and Technology

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Lecture - 1
Thermodynamics: The Fundamentals of Energy

So, this course, Energy Resources and Technology, essentially will deal with the fundamentals of energy conversion, will deal with the conventional sources of energy, will deal with the non-conventional sources of energy, but initially we will have to talk about the basics on which the whole edifice of energy will stand and the basics stand on the ground of the laws of thermodynamics. Some of you may have done some courses on thermodynamics, some of you may not have. So, I guess, I need to start from the basics, but in doing so, let me tell you that not only those who have done a course on thermodynamics, but even the people who have done research on thermodynamics, done path breaking contributions in thermodynamics, all of them are very uncomfortable about this subject.

Why? The basic reason is that all other laws of nature, all other theories, rules that we have discovered in physics, they all have been discovered in order to explain something that happens in nature. You observe something and in order to explain that you propose a law, a rule, a theory. Take the Newton's law. You observed something, the fall of the apple from the hand or the motion of the moon, whatever it is, but some observation to explain which needed a law. Then, take for example, the Maxwell's equations. You had the observational basis, Faraday's observations, Ampere's observations, Coulomb's observation about the relationship between the electricity and magnetism and in order to explain that, you had a set of laws. But, the reason the thermodynamic laws are very uncomfortable especially the second law is that it was not discovered that way. It was not discovered by observing something and trying to explain it; it was discovered in trying to explain away a failure.

What is it? By the way, before we go to the second law, do you remember what the first law was, first law of thermodynamics? Just the law of energy conservation; energy can neither be created nor be destroyed. So, that of course was or the first category that means you did observe that happening. So, if you for example, spend mechanical energy and found that is converted into heat, then people tested how much was the mechanical energy, how much was the heat obtained and they found that equal, so in order to generalize that, the law was proposed, fine. But, the second law was very peculiar, in the sense that that was not proposed that way. So, what failure? You see, it has been the dream of man for, ever since eternity, to devise some kind of perpetual motion machine that means something that will work all by itself. At the advent of the industrial revolution, when people found that you do need coal in order to run the industries, then started the attempt to try to find out some way by which you can obtain motion without really spending anything - perpetual motion machine and a huge amount of effort was spent, like about 100 years, people kept on trying and trying and trying.

To give you some examples, early 18th century there was a patent filed in the, there was ……… (5:08) a patent was filed in the French patent office that said that the inventor had devised a way of obtaining a perpetual motion of a ship, ship going in the sea. His idea was that there is a large amount of water …. in the ship, So, he said that what I will do is simply suck in water by means of, by means of, something from the outside and cool down the water by just 1 degree and he calculated that if you suck in a reasonable amount of water and simply by cooling it by 1 degree you get sufficient amount of heat, in order to propagate through the sea from one continent to another.

Do you see any problem with that? The patent application was rejected, by the way. So, do you see any problem with that? It really did not work. Probably you understand why, right? There was only one temperature. You need two, in order to generate; but, that will come later, I will come to that later. So, the point is that when people kept on trying and trying and trying for more than 100 years to devise a perpetual motion machine and failed, then people said that okay, it is, it may be true that there exists a law of nature that prevents us from doing that. So, let us state it as a law of nature that it is impossible to make a perpetual motion machine. So, that essentially is the starting point of the second law of thermodynamics.

There is another reason for which scientists are somewhat uncomfortable about the second law of thermodynamics. That is all other laws of physics are time reversible. What does it mean? It means that the Newton's law, the Maxwell's law makes no distinction between the positive direction of time and the negative direction of time. If you substitute in a Newtonian equation, in place of t you put, if you put minus t, it will be perfectly the same; perfectly all right, perfectly logical and sensible equation. If you want to visualize what exactly I mean by that that they do not distinguish between the positive and negative directions of time, Feynman had a nice way of visualizing that.

You know, you heard of Feynman, right, Richard Feynman. He was an excellent scientist, excellent teacher and he devised a nice way of visualizing what do you mean by the positive and negative direction of time? He said that suppose you have got a video camera like that one that is filming me and you, film an event and then run it in reverse. If you see something wrong happening, then obviously in that event, there is some kind of arrow of time, some positive direction of time. But, if you feel, if you by seeing it being run it in reverse, if you cannot distinguish between whether it is right or wrong, then obviously there is no direction of time involved in it.

Imagine, suppose I have got a ball in hand and I drop it and suppose it falls and imagine that this is a perfect elastic material, so that it rises to the same height, perfect Newtonian collision and goes up and suppose you film that event and run it in reverse, what do we see? Same thing, no difference really; so, that tells you that the typical Newtonian mechanics has no distinction between the positive direction and negative direction of time. Imagine that in this room there are huge number of molecules, right and imagine the way the Galileo's travels were written - a person who becomes small enough to become a Lilliput.

Imagine you have become a Lilliput not only of the size of an inch, but of the size of a molecule and you are inside this room. What do you see happening around you? You will see molecules coming, colliding, going away again, all around you and imagine that that event you are holding a very, very tiny camera and you are filming and running it in reverse. Will you be able to see any difference? In that you will not even be able to talk about any meaning of time. Time has a meaning only when the two things, the positive way of running the video and the negative way, the opposite way have some distinction. Then only time has a meaning, otherwise time ….. does not have a meaning, time does not have an arrow. So, you see, there are, by all the other laws of physics the time does not have an arrow. Time does not have a direction. There is no distinction between past and the future, but actually there is, right. Actually there is a distinction between the past and the future.

How do you figure it out that there is a distinction between the past and the future? Again takes request to Feynman's visualization and do that on any natural event say you have gone to our Harris shop and you have ordered a cup of tea. The fellow comes with a cup of tea, but imagine that just before he places it on your table, he tips and the cup falls from his hand, something that happened, right and suppose you have taken a video camera and pictured that event and after coming home, you have run it in reverse. What will you see? You will see these splattered splinters of the cup on the floor, with the tea on the floor all over and all that will come together and the splinters will again sum up into the whole cup and the whole thing will fly up on your hand, right. It even makes this fellow smile means that the direction of time, the arrow of time is ingrained in our sense of humor, which is right. Many of these things that you see in nature are of that type; there is an arrow of time ingrained in it. But this is a very natural event, right.

Imagine another event. Suppose a child has gone to the seashore in Puri or Bihar or some place like that and he builds a sand castle; most of the children do and then, at the end of the day his parents take him away. So, what happens to the sand castle? Slowly, by the action of nature, by the action of the waves, it will be again the same sand, sandy beach, right. Now, if you film that process and run it in reverse, what will you see? A castle spontaneously rising from the sand, right; something that never happens. So, there also there is a, some kind of an arrow of time ingrained.

Imagine a third event. Suppose there is cylinder, a cylinder with gases and there is a partition in between and in the left side there is only oxygen and in the right side there is only nitrogen and imagine the left hand side, to facilitate the visualization, imagine the oxygen molecules are red in colour and the nitrogen molecules are blue in colour, so these two different types of molecules. Now, suppose you run a video camera and remove the partition. What will you see? They will slowly mix. Come back home and run it in reverse. What do you see? That a perfect mixture, looking violet, will slowly separate out into two parts, red and blue, something that never happens in nature. So, you see if you actually do this procedure on things that happen around you, you will find that there is a direction of time. But, all the laws of physics say that the time is perfectly reversible. So, there is something wrong; something additional is needed. That additional thing is the second law of thermodynamics.

So, let us see, let us try to figure out what actually happened in all these cases. In all these cases, take the case of the sand castle, take the case of the cup in the waiter's hand. When the cup is in the waiter's hand, it had some order in it, right; the whole cup, the tea in it and then when it fell, it became disorderly. The situation of, you are not allowed to come in, you are not allowed to come in. So, the cup that had a typical order in it and when it fell, the order was lost. You had the situation of the sandcastle. The sandcastle has a shape, a size, an order. Due to the action of nature that became disorderly. The cylinder with gases, when they are separated, that had some order. When they are mixed, the order became disorderly.

So, intuitively that gives the idea, I mean, I will later propose it as a law, but intuitively it is not difficult to visualize that by this spontaneous action of nature, order is going towards disorder, right, in all these cases; never the opposite is happening and that is exactly why you are seeing the past different from the future. So, can we then state it as a law that nature has a spontaneous tendency to lose order? It naturally goes from orderly state to disorderly state. In the natural process that is the way it goes. There are pointers, I will come to that little later, but there is another aspect to it.

When the cup was whole with the tea in it, it contained information, right. You could measure the radius of the cup, the diameter of the cup, the shape, the structure, the strength; these are all information. You could measure and say that this cup is defined by 1, 2, 3, 4, 5, 6, so many numbers, so that contains information. When it broke, obviously that information is lost, right. When the sandcastle was there, it had some height, some width, some structure and naturally it had contained information and when it became again the sandy beach, the information was lost, right.

In the case of the cylinder, of course there was information contained in the situation, where the two sides had different constituents. In the sense, there you could say that if I am looking for an oxygen molecule, I can only look in the left hand side. If I am looking for nitrogen molecules, I can only look in the right hand side that contains the information, right, these statements. So, we can also then make the statement that nature has a natural tendency of losing information, has the natural tendency of losing information. In general, these things are stated in a rather scientific way, not in the verbal manner in which I am stating. A scientist will say that a closed system if left to itself, a closed system means something that has no interaction with the surroundings, a closed system if let to itself will spontaneously lose its orderliness, will spontaneously lose its information. So, these are the way these are remembered. These are also alternative statements of the second law of thermodynamics.

You can easily state that I will state the second law of thermodynamics simply by saying that for a closed system there will be a spontaneous loss of information that is it. That is a perfectly valid statement of the second law of thermodynamics. Now, these are verbal statements and in Science, we need to deal with numbers. So, when we say orderliness, we would like to quantify that. When you say disorderliness, we would like to quantify that. Now, how to quantify orderliness, how to quantify disorderliness, how to quantify how much information it contains? Now, I am saying something rather, serious. Suppose there is something and there are huge number of ways in which that particular arrangement can be made, say these two pens. I can keep them in this way; I can keep them this way, I can keep them this way, many possible ways. So, I can keep them this way, this way, this way, this way.

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Now, if I keep it this particular way, then out of many possibilities I am making a choice, right and that choice contains information in it. So, if we have to approach the question of quantifying orderliness, we will need to talk about out of various ways of arranging a particular thing, what is the probability of having a particular structure? Notice, notice this statement I am making. Let me clarify that in terms of the cylinder, the cylinder with two partitions, with one partition, with two compartments, this compartment containing oxygen that compartment containing nitrogen. What is the, what is the probability of this state, how will you approach this problem? You will say, if suppose I have one molecule, it could be in this side, it could be in that side. What is the probability of finding it in the left hand side? Half, one half. I have another molecule. What is the probability of that being in the left half? Again half. I have another oxygen molecule. What is the probability of that being in the left half? Again half. So, what is the probability of all three being in the left hand side?

That is if the probability of one to be in the left hand side is half, what is the probability of two to be in the left hand side? Half square; law of the multiplication of the probabilities. What is the probability of the third one to be also in the left half? Half cube; so, if there are one million molecules, what is the, million oxygen molecules, what is the probability of all of them to be in the left hand half, left half? Half to the power million; so, that half to the power million should be quantifying its probability, probability of that whole status. So, there are one million oxygen molecules, one million nitrogen molecules, what is the probability of this to happen is like half to the power million. That is a very small number; that is a very small number. That is exactly what says that it is a very orderly state. If it is mixed, then what is the probability? 1; you see, if it has to be in the whole, you cannot say whether it is in left hand side or right hand side, it has to be in whole. So, you will have the situation that while divided it is a very, very low probability, while mixed up it is high probability. So, the lower the probability of that particular state, the more information it carries, the more orderly the state is, right. So, when we say that it went from orderliness to disorderliness, it actually went from a very low probability state to a high probability state. Can we make that statement? Still, now you need to quantify that.

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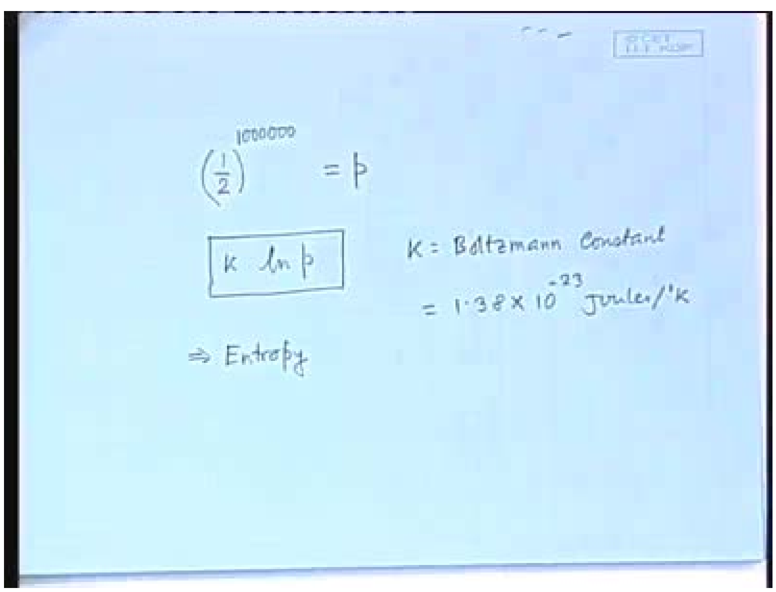

So, what did we say? We said that the probability of one to be, one oxygen molecule to be in the left side was half. The probability of a second one to be in the left hand side was half to the power 2 and for 1 million molecules to be in the left hand side was say, I will have to put something like 1000 000; is it a million? This is a very large number, sorry, very small number; this is a very small number, so small that that you cannot enter in a calculator. So, if I give you a problem to solve in the examination, to use this number, will you be able to use this? No; so, something needs to be done to it, something needs to be done to this number, in order to make it handleable.

What is the natural thing to be done? Take a logarithm; take a logarithm, this fellow comes forward and it is no longer all that smaller number. So, this is the whole probability, this is the probability p. So, in order to make it handleable, say, we will say, ln p in which case this fellow comes forward and half remains. So, it is more or less a handleable number, but still it is not very handleable, in the sense that 1 million molecule is not the right kind of number. In a cylinder there are far larger numbers, so it is still a very large number, difficult to handle. So, what we do is we multiply it by a constant, which is a very, very small number, so that the whole thing is a handleable quantity and this k is the Boltzmann constant, k. So, it is a very small number, very small number which when multiplied with this, you give a, you get a more or less handleable quantity. This is called the entropy. So, entropy is something that quantifies the orderly or disorderliness of a system. It is a concept that is related to the probability of a state.

If something can be arranged in various possible ways, what is the probability of a particular state? You answer that question, obtain the probability, take the logarithm and then, multiply it by the Boltzmann constant, you get the entropy. So, that is the concept of entropy. Naturally, the entropy is related to the probability, is related to the orderliness, so can you relate these two, so far, the prosaic concept of the orderliness and the numerical concept of the probability?

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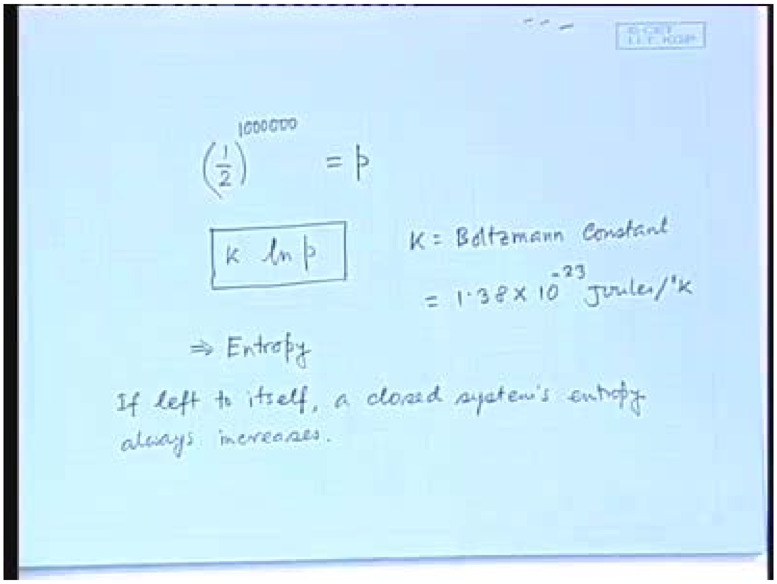

The more disorderly a system the higher the entropy, the more orderly a system the lower the entropy and therefore, the second law of thermodynamics can then be molded in the language of the entropy, where we will say if left to itself ....., that is it, alright and this is what gives the arrow of time. This statement essentially tells us why is there an arrow of time, why is there a distinction between the past and the future? Essentially this is the basic. So, we have actually made three statements of the second law.

The first statement says that if left to itself, a closed system always loses its orderliness and goes towards disorderliness. We said that if left to itself a closed system tends to lose its information and we said by quantifying it, that if left to itself a closed system's entropy always increases. That is very fine, that is very fine, but then we do have orderly structures around us. If this is all true, then obviously the natural conclusion would be that there should not be an orderly structure. How do we then survive? We do survive. A plant grows, for example, from seed to a whole plant; as it grows, you can see that information is being created, right. It produces leaves that have specific structure, that have specific composition; so, there is information. Out of material that were, earlier some were dispersed, disorderly. So, the opposite also happens. So, natural question should be that, if Sir, you say this is true, this is a law, then how can that happen?

Yes, that can happen only in an open system. A plant is an open system; it is not a closed system. Open system in the sense that it interacts with the environment and thereby, it somehow manages to reduce its entropy. That somehow, I will come to a little later, but that is true for all living organisms. One of the characteristics of all living organisms is that they are open systems and unless they are open system, they cannot survive. If you say enclose somebody in a coffin and leave just like that, it will die. The entropy will increase and the whole thing after sometime, you will find a disorderly mass. So, the only way living systems can survive is by, now, this is a new concept, by sucking in orderliness from the environment. Whatever the, in the whole disorderly mass that was around it, the plant for example that sucks in whatever small amount of orderliness that was there around it and discharges some material in a disorderly form. So, it sucks in orderliness and discharging material in the disorderly form. That is what we also do, right.

We eat, we breathe, so we get material from outside by being an open system and we also discharge and there is a qualitative difference between what we take in and what we discharge, in the sense that what you take in has more orderliness than what we discharge and by doing that we maintain our orderliness. So, a system can maintain its orderliness by, now notice the term, by sucking in negentropy from the environment. So, I am introducing a term negentropy. What does it mean? It means that normally if something is disorderly and within that, some bit of orderliness is there, some concentration of some material is there, that in that sense sort of represents a pocket of orderliness, a pocket of orderliness. You can survive only by sucking in that pocket of orderliness from the environment and releasing material in a disorderly state. So, that is the only way we can survive. That is the only way a society can also survive.

Society is an orderly thing. Notice that in order to survive, the society takes in whatever was the amount of negentropy that was there in the environment and discharges material in a very disorderly state and the society can also survive by doing that. So, the point is that the society survives on negentropy stock. Whatever small amount of orderliness is there in our environment, the Earth environment, the society survives only by sucking in that, utilizing that and then discharging the material in a disorderly state.

Let us come back to the question of the seashore and the child. You had a situation where the child built a sandcastle, left it and it was …… to the ground by the action of the sea. Can the child come the next day and build it again? Yes; so, it is possible to reverse the action of nature, right. The cylinder with oxygen and nitrogen that had oxygen this side, nitrogen that side, you had opened the cylinder partition and then it got mixed up. Can we separate it out? Yes, we can; by industrial process by which oxygen and nitrogen are made, we can always separate it out. The cup that fell from waiter's hand, supposing it did not break, can't we pick it up and put it there? Yes, we can. If it broke, then also it is possible, at least in theory, to put it back again. Can't we do that? So, even though the law of entropy says that nature has an inherent tendency of going from orderliness to disorderliness, we do reverse that process, right. It is possible to reverse that process.

How? What actually happens in terms of basic science? When the child goes and builds it again, he spends energy, right. What actually happens when you separate the oxygen and nitrogen? You have to spend energy. What actually happens when the waiter picks up the cup? He spends energy. So, energy has to be spent in order to reverse that process; energy has to be spent in order to reverse that process. It is possible to reverse the process, but that is possible only by spending energy.

Naturally, when the society has to survive, the society has to build its industry, its houses, its clock, its computers, everything. These are all very, very orderly things, very, very orderly structures. They contain a lot of information and in order to produce that out of the thing that we have in nature, you have to spend energy. So, that is an essential role of energy. So, what is the essential role of energy? To reverse the process that would naturally occur, unless there is some intervention and we intervene by using energy. The only way we can intervene in that process, in that natural process is by using energy. That is why energy is so very important in the whole societal process; without energy, the society cannot survive. So, is that point clear?

Now, this negentropy let us clarify what it is. When it, when you talk about the sapling growing and it is sucking in negentropy from the environment, what exactly is the negentropy stock? It is those macromolecules that are there in the soil. That is what it is sucking in and the macromolecules constitute the relatively more orderly structure than the mass of the material that is around it and the sapling survives by sucking in those. We survive by eating vegetables, meat and stuff like that. Those are, for us, the sources of negentropy through which we survive. What is the source of negentropy for the society? As I said, the society can survive only by sucking in utilizing the negentropy stock that is around it. So, what is the negentropy stock? See, the Earth had it been a completely homogenous mixture of the constituent things that are there like, what is there in the Earth? The Earth contains silicates that means silicon, oxygen and stuff, iron, nickel, cobalt and stuff like that; manganese, things like that.

Now, if all these were very homogenously mixed in the Earth, do you think we will be able to make anything? No; so, the negentropy, negentropy stock is in the common mass of the disorderly mass, if there is a pocket of concentration of any of these, like the iron ore, the manganese ore, these are the pockets of concentration of one of these things, so that then is the negentropy stock, that is the negentropy stock. So, the negentropy stock is essentially the relative orderliness that is found in the nature. Now, in order to utilize that, in order to extract the iron from the iron ore, in order to extract the manganese from the manganese ore, you need to spend energy. Now, the energy is also available as a negentropy stock; energy is also available as a negentropy stock, in the sense where is energy available?

Energy is available in the oil fields, energy is available in the coal fields, coal mines and the coal mines are essentially some place where there is a higher probability of finding carbon; that is the coal mine, right. Oil mine is out of the whole mass of disorderly material, there is some place, where there is a higher probability of finding hydrocarbons. So, these are the oil mines, so oil fields; so, we suck in that and use that. So, the energy resources are also negentropy stock; but, the negentropy stock is not only the energy resources or the material resources, altogether we have the negentropy stock and the complication is because, there are some which are material sense negentropy stock, there are some which are entropy sense negentropy stock.

So, you first have to utilize the entropy, the negentropy stock related to the energy sources, produce utilizable energy, use that in order to extract the useful material. That means when the steel is made, sometimes back it was an iron ore; from there, in order to extract it, you have to spend energy, in order to put it in the blast furnace you have to spend energy, from the blast furnace to a whole cube of iron, you have to spend energy. In order to purify that into steel you have to spend energy and that in order to make this particular cylinder, you have to spend energy. So, the whole process contains various points, at which you have to spend energy, in order to get the final thing.

So, the energy engineering essentially consists of understanding this whole process through which it came from the ore stage to the final product which is useful to man and in order to produce the final product that is useful to man, you had to spend energy and in order to do that, you have to locate the negentropy stocks, both the material negentropy stocks as well as the energy negentropy stocks. For the energy engineers, it is more meaningful to try to identify and understand the energy negentropy stocks. So, we will talk about that in this course. So, this is the essential grounding on which we will build up in the next few classes, but probably you are used to a different concept of entropy, right.

Those who have done some course in thermodynamics are probably used to or more used to a concept that change in entropy is dQ by T, right? Yes; this is the concept of the absolute entropy of a body and the change in entropy that happens in the thermal process is represented by dQ by T. Where there is a heat transfer that is represented by dQ by T. But, remember that is a very constant concept in the sense that if you have two cylinders and you remove the partition, one with oxygen another with nitrogen, with the same temperature there is no thermal process, there is no thermal mixing. Yet, you know now that there was increase in entropy. What was dQ? Zero; so, change in entropy you cannot really visualize only in terms of dQ by T, but yes, dQ by T is the change in entropy, whenever there is a heat transfer. Now, the moment you understand that and the moment you understand the law of thermodynamics that left to itself the entropy always increases, you can easily obtain, you can easily derive the maximum efficiency of a converter. Can you do that?

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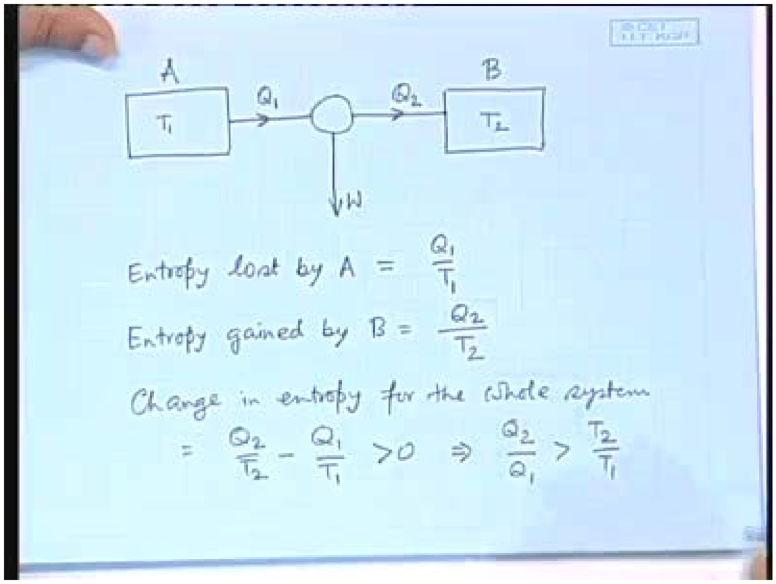

See, suppose you have something, the reason that the idea of the ship going through the sea, sucking in water and utilizing only the amount of heat obtainable by cooling it by just 1 degree that did not work was because, in order to utilize that you need to have a passage of heat from a source to a sink. Without having a sink, without having another temperature, you cannot have that. In fact, nowadays there are such converters which utilize the temperature difference between the top of the sea and bottom of the sea; so, then, that you can do. But, simply by utilizing the water from the top of the sea at the same temperature, you cannot. So, you need one source at a temperature, say, T 1 and another sink at a temperature say, T 2 and suppose there is some kind of a converter; I am not talking about what converter it is, this one which gives out an amount of mechanical power W and we are asking what will be the efficiency of such a system? So, here is the body A, here is the body B.

The amount of heat taken from the body A is Q 1 which is at temperature T 1, amount of heat that is discharged into body B is Q 2. So, how much entropy is lost by this body A is Q 1 by T 1, dQ by T. How much heat went that is Q 1 at what temperature T 1 therefore Q 1 by T 1. Entropy gained by B is similarly Q 2 by T 2; so, Q 1 by T 1 and Q 2 by T 2. So, the whole system, how much is the change in entropy? Obviously Q 2 by T 2 minus Q 1 by T 1. So, ……, right and that by the just stated law of thermodynamics should be positive, entropy always increases. This tells you what? Q 2 by Q 1 should be greater than T 2 by T 1, right.

Now, how much is the efficiency of the system? The amount of energy output is W, amount of energy input is Q 1.

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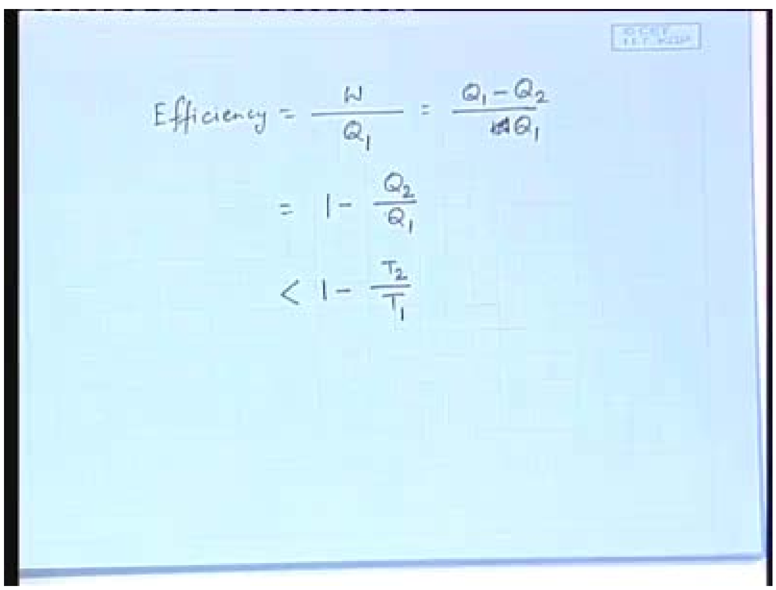

So, efficiency is …. and how much is your W? By the first law, it is nothing but Q 1 minus Q 2. So, this is, sorry,… This is nothing but 1 minus …., right. Now, we have already seen that Q 2 by Q 1 is greater than T 2 by T 1, which means the efficiency is always less than … That is it. So, the moment you assume, you understand that entropy of an isolated system cannot, cannot decrease it always must increase, immediately for anything that converts heat energy into mechanical energy, this must be the maximum amount of energy available.

We will continue with this in the next class. Only let me tell you at this stage that, this tells you that not the whole of the heat, even though the first law says that the energies are equivalent you can convert one form of energy to another, but the second law says then that you cannot convert heat energy to electrical energy or mechanical energy at 100% efficiency, you must have two different temperatures and the efficiency limit is this - 1 minus T 2 by T 1; remember this T 2 and T 1 are absolute temperatures, not centigrade, is that absolute temperatures. For example, inside a power plant, inside a power plant, what, is there a class up next? Probably, okay, we will come to that in the next class. There seems to be another class after this. So, that is all for this class today. We will reassemble tomorrow and continue with it. Thank you.