Selection of Nanomaterials for Energy Harvesting and Storage Applications
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Lecture - 14
Thermoelectric Nanogenerators & Electromagnetic Generators

Hello my friends today, we are going to discuss about a new chapter based on Thermoelectric Nanogenerators and the Electromagnetic Generators. So, basically we are going to discuss about the two parts, one is based on the temperature that is the thermoelectric nanogenerators. Another one is about the magnetic force, so that is why it is electromagnetic generators. So, we are going to discuss both the mechanism in this particular lecture. So, if you remember in my last lecture, we have also discussed about that pyroelectric nanogenerators.

So, basically the difference between the thermo electric and the pyroelectric nanogenerators is that pyro basically it depends upon the temperature with time. And in the thermo basically, we are measuring the efficiency in terms of space means area, so that is temperature in terms of area, so that is only the basic difference in between the pyroelectric and the thermoelectric. So, in this particular case also the same thing, whatever the waste energy we are getting from different sources.

So, basically we are collecting those sources and then we are converting that particular heat energy into the electric energy. So, either it can be some kind of combustible gases or may be it can from the sunlight. So, whatever the sunlight we are not using, then that type of energy or maybe our body temperature also, so that temperature basically we are collecting and then we are converting into the electricity.

So, basically nowadays you can see that lots of energy basically we are wasting, because in the winter time when you are heating the water, so basically that time the water is highly heated up, or maybe we are flowing some kind of heat source like in terms of maybe hot air, or maybe some kind of hot gas, or may be hot fluid throughout the pipe. So, due to that some heat is coming outside the pipe itself. So, if you are able to collect those kind of heat energy, and be able to convert those heat energy into the electrical energies because that is the wastage of the thermal energy.

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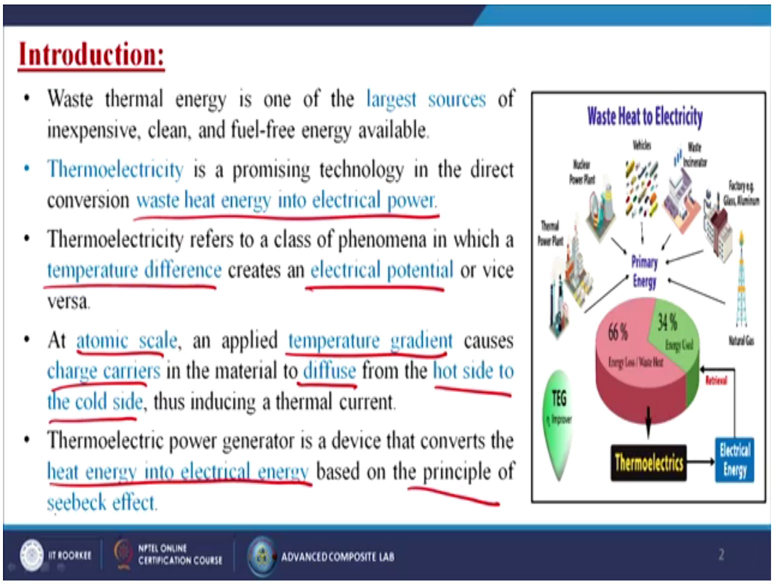

So, basically the waste thermal energy is one of the largest source of in expensive, clean, and fuel-free energy available. Yes, of course, because we are not going to generate, or may be burning any kind of materials, or maybe we are not generating any kind of toxic gases, or maybe it is not harmful to the environment, or maybe the human being.

So, thermoelectricity is a promising technology in the direct conversion that is waste heat energy into electrical power. Thermoelectricity refers to a class of phenomena in which it temperature difference creates an electrical potential or maybe the vice versa. At atomic scale, an applied temperature gradient causes charge carriers in the material to defuse from the hot side to the cold side, thus inducing a thermal current.

So, as I told already, so when we are transferring the heat source from one place to another, so due to the transferring of the heat source basically if we are able to collect that transfer mechanisms, so we can converted into the electrical energy. Thermoelectric power generator is a device that converts heat energy into electrical energy based on the principle of seebeck effect. So, that is the name of the scientist who has invented this particular technology that is why it is known as the seebeck effect. I will come into the detail into the subsequent slide that what is the seebeck effect.

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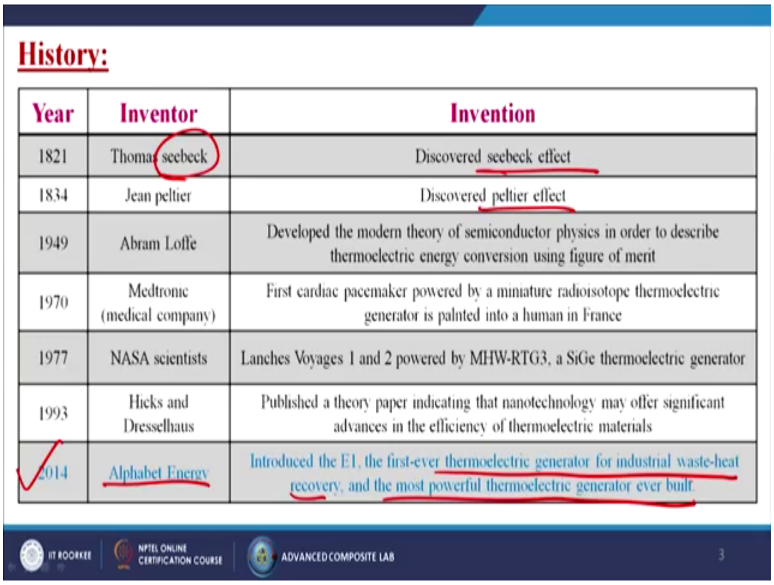

History:

Year	Inventor	Invention
1821	Thomas seebeck	Discovered seebeck effect
1834	Jean peltier	Discovered peltier effect
1949	Abram Loffe	Developed the modern theory of semiconductor physics in order to describe thermoelectric energy conversion using figure of merit
1970	Medtronic (medical company)	First cardiac pacemaker powered by a miniature radioisotope thermoelectric generator is palnted into a human in France
1977	NASA scientists	Lanches Voyages 1 and 2 powered by MHW-RTG3, a SiGe thermoelectric generator
1993	Hicks and Dresselhaus	Published a theory paper indicating that nanotechnology may offer significant advances in the efficiency of thermoelectric materials
2014	Alphabet Energy	Introduced the E1, the first-ever thermoelectric generator for industrial waste-heat recovery, and the most powerful thermoelectric generator ever built

So, basically if we talk about the history, we can see that in the year of 1821, Thomas seebeck, which I was talking about from his name only that Seebeck effect has come, so who discovered the seebeck effect? Then 1834, Jean peltier who is also the famous scientist that time, who discovered the peltier effect, basically that is also the heat transfer mechanisms. So, that he has effect invented the peltier effect by which basically this device is working. Next, we came through 1949, 1970, 1977, 1993, and at last now we are standing over here that is the 2014.

Till now also, so many development has done in terms of some new material fabrications, which can give you the better efficiency in terms of energy. So, this is invented by the alphabet energy systems introduced the E1, the first ever thermoelectric generator for industrial waste-heat recovery, and the most powerful thermoelectric generator ever built. So now, we can understand that from industry huge, suppose if it is a thermal based industry, or maybe chemical based industry due to some chemical reactions, or maybe thermal power plant a huge energy is generating.

So, we are not utilizing that hundred percent of that particular energy. Some energy we are wasting, so if we are able to catch that particular waste energy, and if we are able to convert that particular energy into the electricity. So, that will be the added advantage. So, what is thermoelectric power generation?

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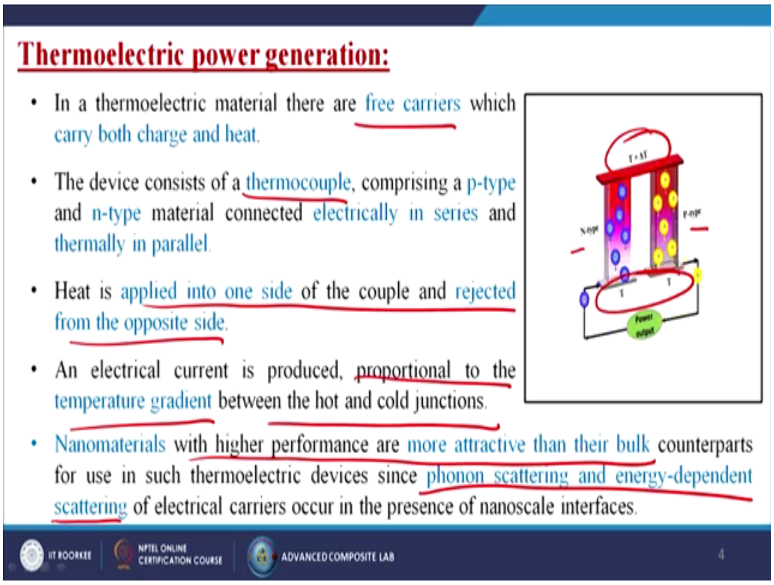

So, in a thermoelectric material there are free careers which carry both charge and the heat. The device consists of a thermocouple, comprising a p-type, and a n-type material connected electrically in series and thermally in parallel. So, now, in that particular case you can see that it is connected, in a series connections that n type material and the p type material, but thermally they are the parallel one. So, now, heat is applied in to one side of the couple and rejected from the opposite side. So, now, in this particular case basically we are giving the temperature.

So, T plus del T, means T was the initial temperature and whatever the change in temperature that is the del T. So, T plus del T, now we are getting the temperature in this particular region. So, an electrical current is produced, proportional to the temperature gradient between the hot and cold junction. Nanomaterials with higher performance are more attractive than their bulk counterparts for using such thermoelectric devices, since phonons scattering and energy-dependent scattering of electrical carriers occur in the presence of nanoscale interfaces.

So, what happened actually, so when we are using this kind of nanomaterials, when we are passing the temperature through that nanomaterials, so it is generating the electricity. So, the material is having that particular capacity.

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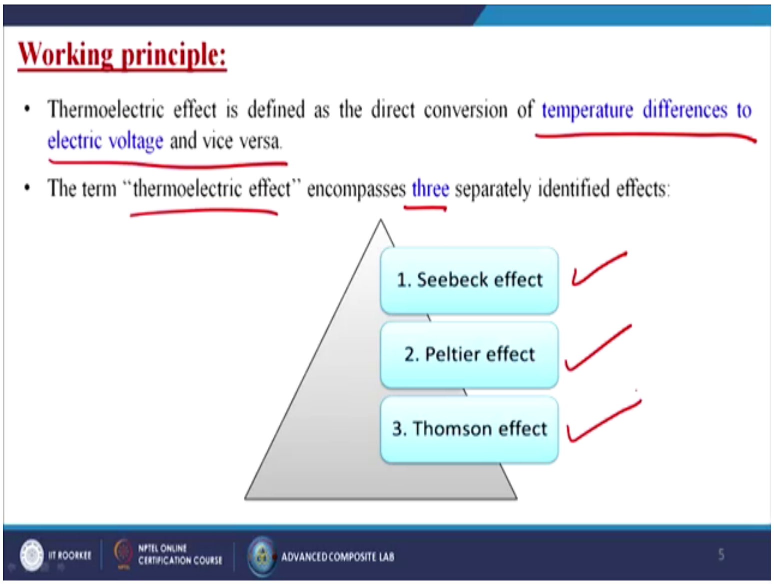

So, now what are the working principle? Thermoelectric effect is defined as a direct conversion of temperature difference to electric voltage and vice versa as I told you already. So, whatever will be the temperature difference, the same temperature difference in terms of electricity we are going to get as an output. So, the term thermoelectric effect encompasses three separately identified effects. One is called the Seebeck effect, then Peltier effect, and last one is the Thomson effect.

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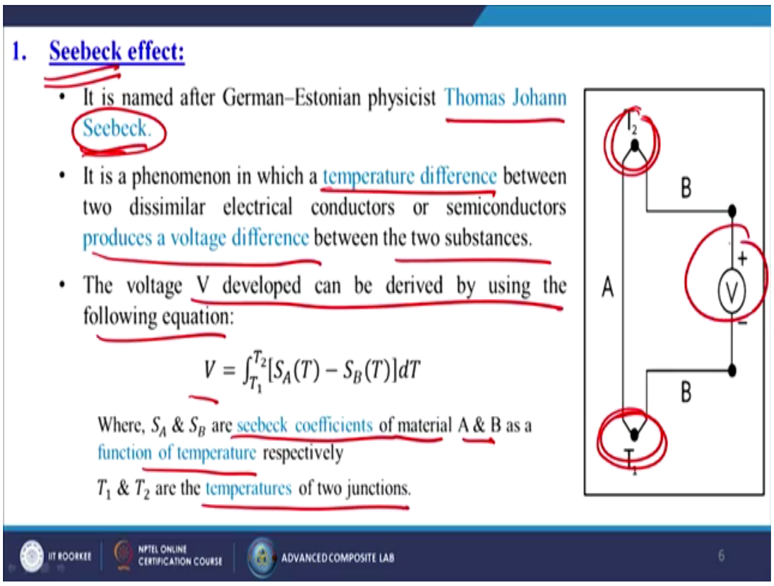

Now, what is Seebeck effect? So it is named after German-Estonian physicist Thomas Johann Seebeck, as I told already. So from his name only the effect, or maybe he has a invented this particular technology that is why it is known as the Seebeck effect. So, it is the phenomenon in which a temperature difference between two dissimilar electrical conductors or semiconductors produce a voltage difference between the two substances. So, basically in this particular case this T 1 and T 2, the materials are different. They are not electrically same. So, when we are giving the heat, so that material is changing and then they are generating the electricity.

So, the voltage V developed can be derived by using the following equations, which is nothing, but capital V is equal to integral T 1 to T 2 S A T minus S B T d T. Where, S A and S B are Seebeck coefficients of material A and B, which we can get from the material properties as a function of temperature respectively. T 1 and T 2 are the temperatures of the two junction. So, as I told already, these materials temperatures are different and materials are also different. So, now, when you are heating those materials both the materials behaves differently. Now, due to that they are producing the electrical current inside the circuit and through that circuit just we are taking it out to the as a output.

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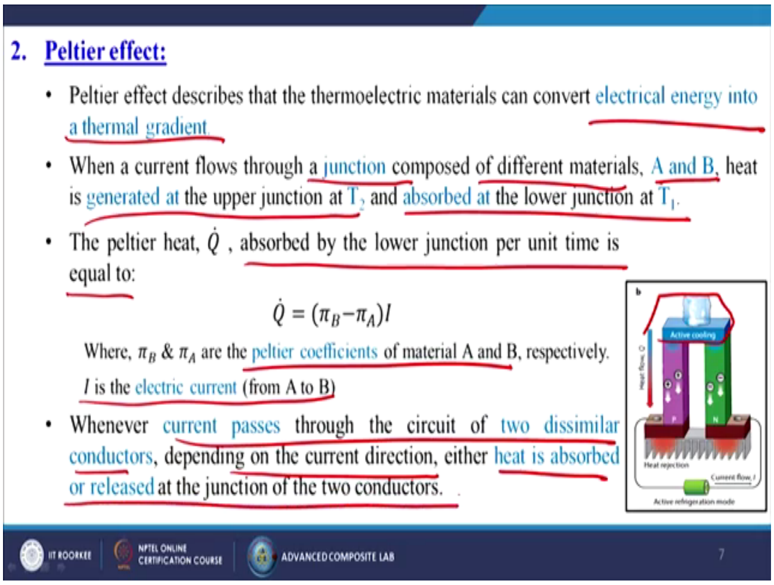

Next one is called the Peltier effect. Peltier effect describes that the thermoelectric material can convert electrical energy into a thermal gradient. So, sometimes it is little bit the vice versa one. In the earlier case we are giving the temperature it is converting into the electricity, in this particular case we are giving the electricity it is giving you the temperature or maybe the heat. When a current flows through a junction composed of different materials, A and B, heat is generated at the upper junction at T 2 and observed at the lower junction at T 1. So, in these particular case what is happening heat flow is taking place, because these material is totally cooled one because we have kept the ice over there and the bottom part it is rejecting the heat over there.

So, heat flow basically it is coming from the top to the bottom. So, the peltier heat Q prime, absorbed by the lower junction per unit time is equal to Q prime is equal to pi B minus pi A into I. Where, pi B and pi A are the peltier coefficient of material A and B, I is the electric current from A to B. Whenever, current passes through the circuit of two dissimilar conductors, depending on the current direction, either heat is absorbed or released at the junction of the two conductors.

So, if I am having two wire and if I give the temperature, so at the junction either one material will observe, or maybe one material will release the heat. So, just there will be a heat difference in between the two conductors and through that we can utilize it and we can generate the electricity.

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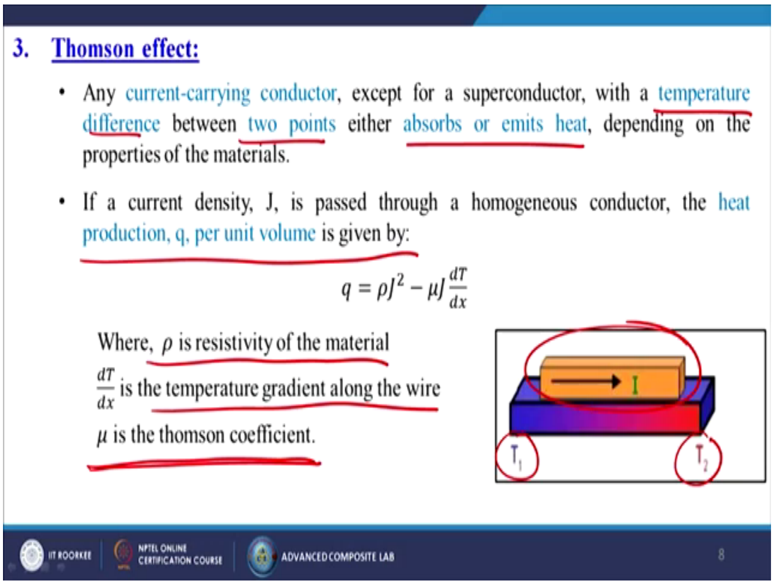

Now, the third one is called the Thomson effect. So, any current carrying conductor, except for a superconductor, with a temperature difference between two points either absorbs or emits heat, depending on the properties of the materials. If a current density, J, is passed through a homogenous conductor, the heat production, q, per unit volume is given by q is equal to rho j square minus mu j d T by d x. Where, rho is nothing, but the resistivity of the materials. dT by dx is the temperature gradient along the wire.

So, basically mu is the Thomson coefficient. So, basically what is happening, I am having one materials and when top of that materials, when I am passing the current conductor, so automatically the temperature difference will be there or maybe the vice versa things also what we have seen into the Seebeck effect.

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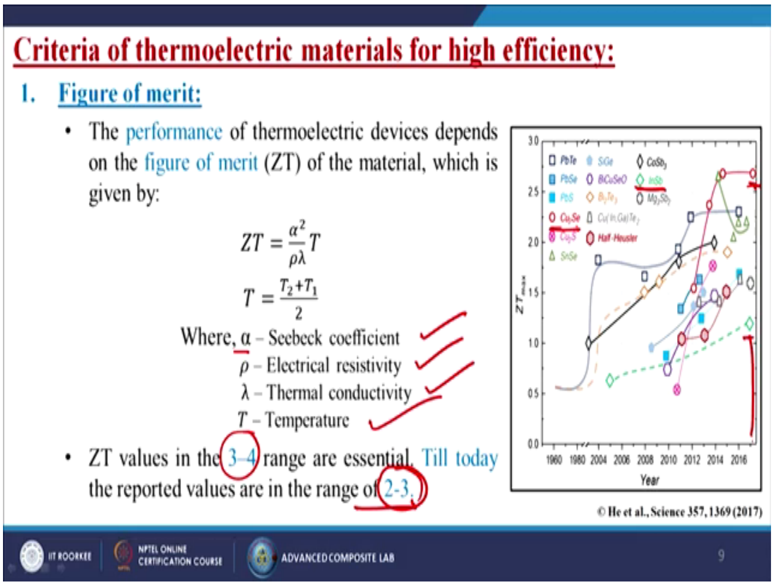

So, now what are the criteria of thermoelectric materials for high efficiency? First one is known as the figure of merit. The performance of the thermo electric devices depends on the figure of merit of the material, which is given by capital Z, capital T is equal to alpha square by rho lambda into capital T. Where, capital T is nothing, but the T 2 plus T 1 by two. Where, alpha is the Seebeck coefficient, rho is the electrical resistivity, lambda is equal to thermal conductivity, and capital T is the temperature.

So, capital Z T values in the 3-4 range are essential. Till today the reported values are in the ranger 2 to 3. So, basically now scientist has reached up to 2 to 3, our aim is to reached up to 3 to 4. So, this is the basically how it has been progressed with different materials. Now, we can see now we are standing almost here, so basically now people are using this that indium and antimony combinations, people and using these materials; that means, c u T a c selenium, copper selenium materials, or maybe sometimes people are trying to make more other type of combination, so that they can reach to 3 to 4.

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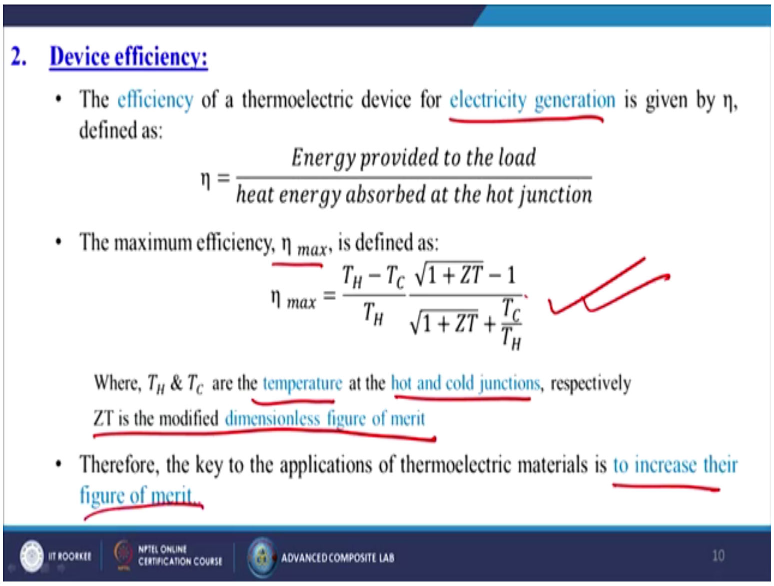

Next second one is known as the device efficiency. So, the efficiency of a thermoelectric device for electricity generation is given by eta, defined as eta is equal to energy provided to the load, by heat energy absorbed at the hot junction. The maximum efficiency eta max is defined as by this particular equation. Where, this T H and T C are the temperature at the hot and cold junctions, respectively and Z T is the modified dimensionless figure of merit. Therefore, the key to the application of thermoelectric materials is to increase their figure of merits that means we are going to increase the moral value.

Now, let us discuss about that what are the materials means on, which properties basically we can choose the materials for the thermoelectric nanogenerators. It does not means that any materials, I will make and it can work as a thermoelectric nanogenerators, it should have certain criteria. What are those?

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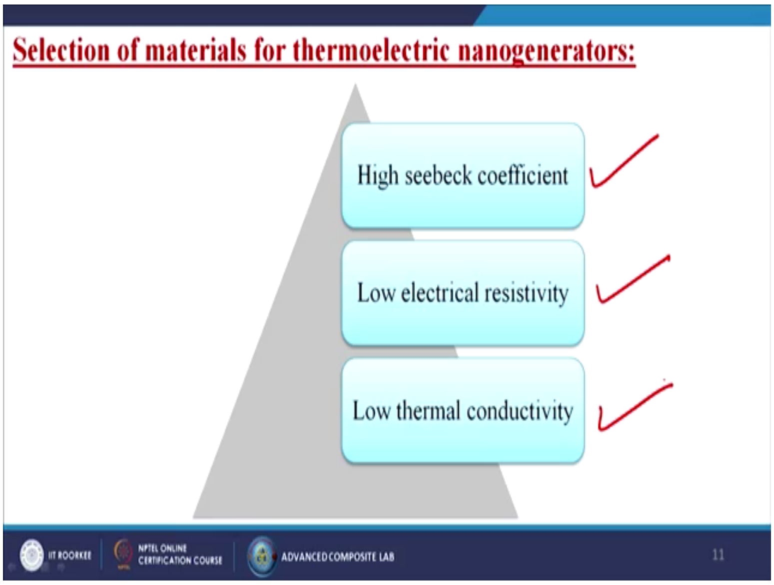

The material should have high seebeck coefficient, low electrical resistivity, and low thermal conductivity. So, these three are the prime considerations for choosing any kind of thermoelectric nanogenerators.

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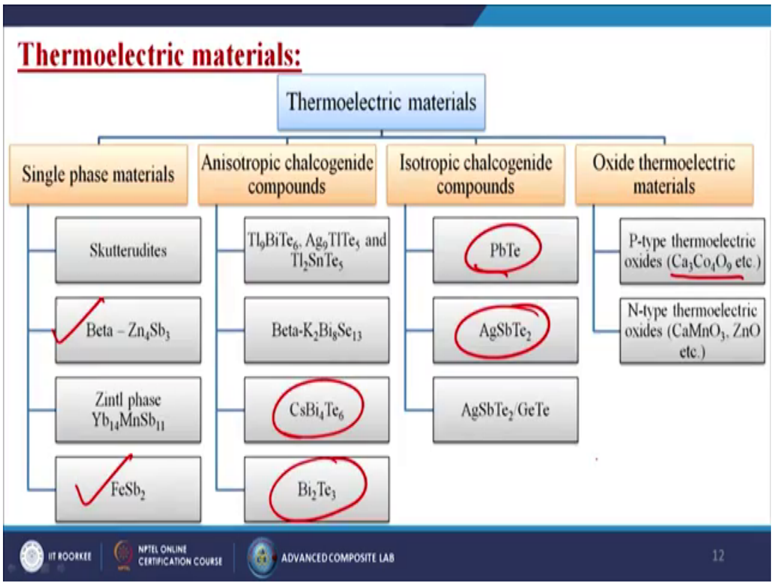

So, let us give some examples that what type of materials, nowadays we are using. So, if we talk about the single phase materials, so now you can see this is the list for the single phase materials like beta Zn 4 Sb 3, or maybe FeSb 2. So, these all are the different materials. If we talk about the anisotropic chalcogenides compounds, so basically it is a combinations of different materials. So, you can see its some Bi 2 Te 3, or maybe CsBi 4 Te 6. So, it is a compositions of the caesium, bismuth and the tellurium. So, these kind of materials.

If I talk about the isotropic chalcogenide compounds like lead tellurium combinations, or maybe silver, then antimony and tellurium compounds, or may be some others. If we talk about the oxide thermoelectric materials, it is p-type thermoelectric oxides having combinations of the calcium cobalt and the oxygen, or maybe the n-type thermoelectric oxides having the combination of calcium manganese oxygen. So, now it is the same thing I am telling you that we have to choose the materials or a maybe we have to prepare the materials in such a manner that will satisfy these all properties and it will increase you the efficiency.

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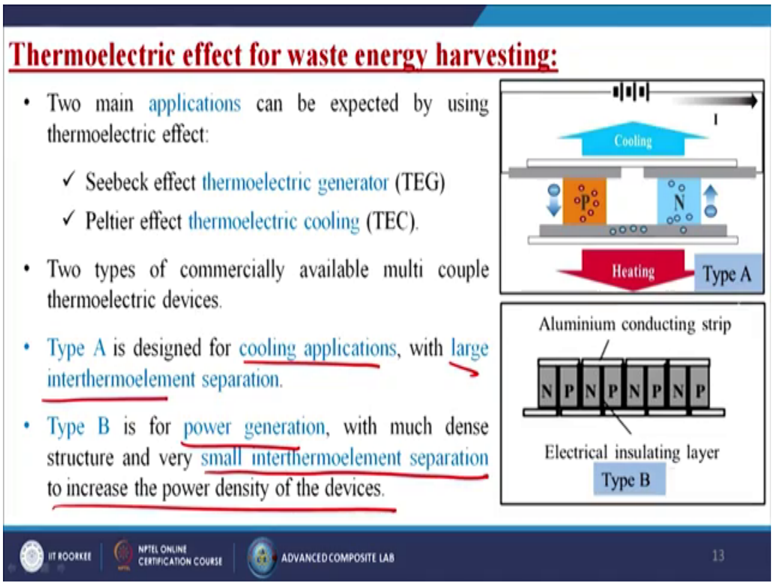

Now, what is the thermoelectric effect for waste energy harvesting? Two main applications can be expected by using the thermoelectric effect; one is called the Seebeck effect thermoelectric generator. Another one is called the Peltier effect thermoelectric cooling. Two types of commercially available multi couple thermoelectric devices are available one is type A, another one is type B.

So, what is type A? So, type A is designed for cooling applications, with large interthermoelement separation. And type B is for power generation, with much dense structure and very small interthermoelement separation to increase the power density of the device. So, when we are talking about the type A materials. So, basically we are one materials we are giving the heating, one material we are giving the cooling, and then due to that the charge is transferring.

But when we are talking about the type B, so basically we are using the n-type materials and p-type material simultaneously, and then we are having some aluminum conducting strip from the both the sides and in between the n and p you are having that insulating materials and that can be generated for a large electric compositions or may be the large power generations.

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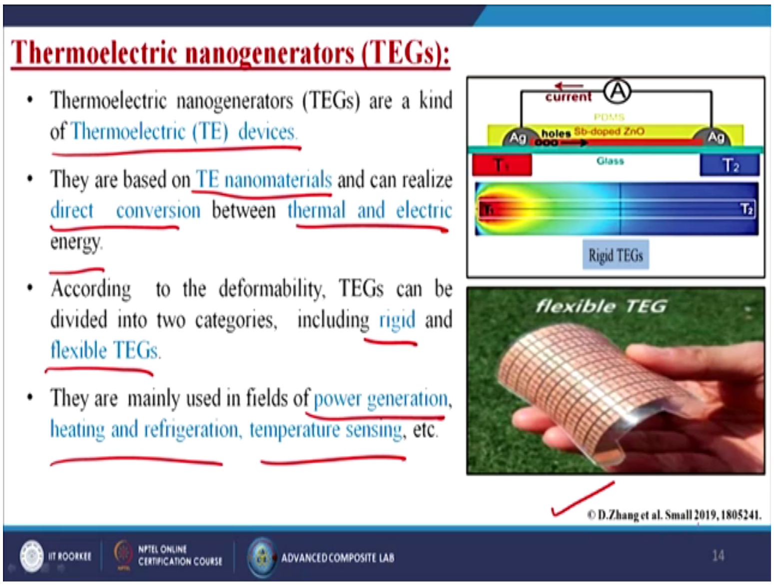

Now, let us discuss about the thermoelectric nanogenerators or maybe in short basically you are calling it as a TEGs. Thermoelectric nanogenerators are a kind of thermoelectric device; that means, this Seebeck effect, Peltier effect, or maybe that Thomson effect. So, basically these effects or may be these mechanisms we are using for the materials and we are generating the electricity. So, they are based on TE nanomaterials; that means, thermoelectric nanomaterials and can realize direct conversion between the thermal and electrical energy. According to the deformability TEGs can be divided into two categories, including rigid and flexible TEGs.

They are mainly used in fields of power generation, heating and refrigeration, temperature sensing, etcetera. So, these all are the examples you can see that Zhang et al, so they are working on this kind of materials, and recently they have published this particular journal paper, see there and they have worked on the flexible TEGs also so; that means, that you can wear it or maybe you can put it anywhere and you can generate the electricity.

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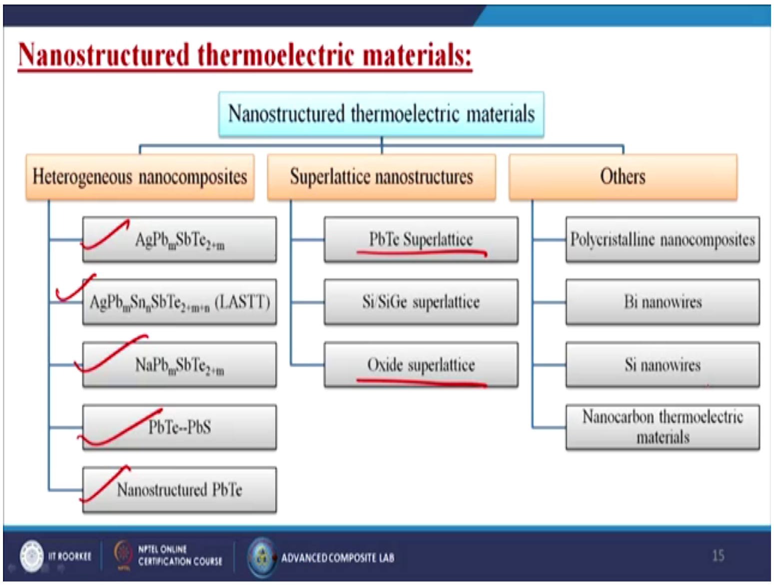

Next nanostructure thermoelectric materials, so when we are making a materials into the nanometer range so basically, so that is also the heterogeneous nanocomposites. Now, we can understand by seeing these particular material structure. Lots of materials we are adding each together so; that means, it is a combination of materials just to get the more efficiency. Nanostructured lead tellurium people are using, or maybe they are using the lead tellurium, lead sulphur combinations. So, it is a different types of compositions basically they are using.

If you talk about the super lattice nanostructures, basically lead tellurium, super lattice materials or maybe oxide superlattice materials people are using, if we talk about the other kind of materials. So, basically polycrystalline nanocomposites, then bismuth nanowire, then silicon nanowire people are working on to it and they are trying to use it for thermoelectric nanogenerator.

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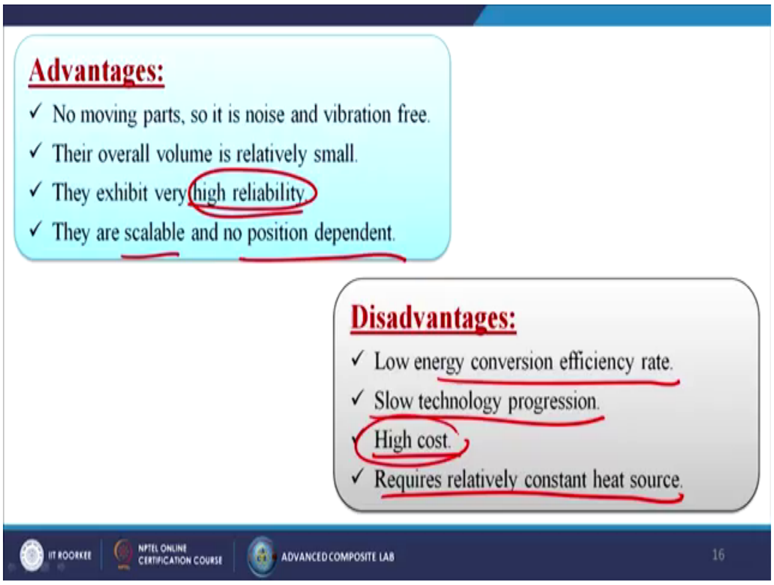

Now, what is the advantages? So, no moving parts, so it is noise and vibration free. Simply you are having that materials and now you are applying the temperature on to that and it is generating the electricity. So, it is a very small device, you can easily carry from one place to another place. It is lightweight, cost wise it is also very cheap. And not only that, it does not have a very target that you need some kind of transfer mechanisms to take it from one place to another. Volume is also very small. They exhibit very high reliability that is the important parameters and they are scalable and no position dependent, so anywhere you can put it over there.

Of course, these nanogenerators are having certain kind of disadvantages. So, basically low energy conversion efficiency rate. So, that is why the people are working on compositions of the different materials to increase its efficiency. Slow technology progressions, high cost, requires relatively constant heat source. High cost in terms of when we are going to use some king of rare earth materials or may be some kind of advance materials that time it is costly.

But when it will come into the market and we will go for the bulk production from the research point of view it is high cost, but if it will come into the market and automatically we are going for the bulk production, so automatically the cost will be reduced. What are the applications? So, basically you can see in that cup of tea or may be cup of coffee if I am having that particular flexible sensor and I can put it, because what when I am pouring the tea or coffee inside the cup. So, outside it is heated up and we never thought that we can use that particular heat energy to generate the electricity, so that is the beauty of this particular technology.

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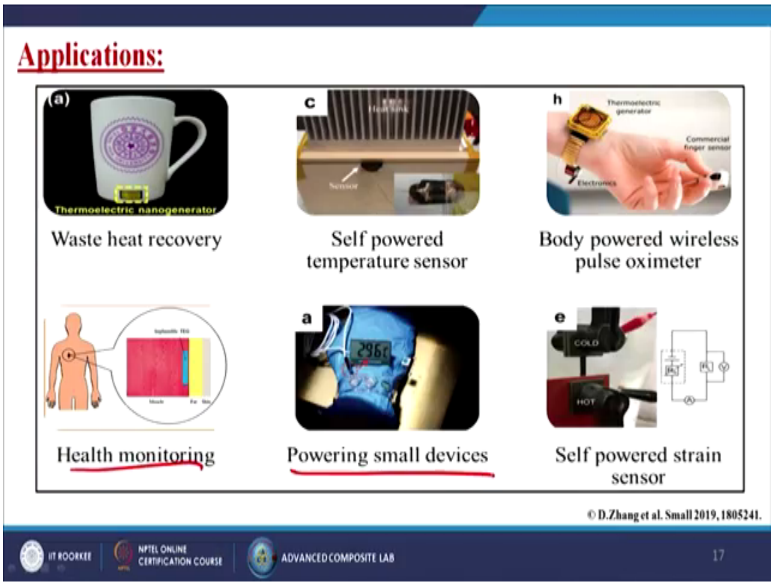

Self powered temperature sensor, body powered wireless pulse oximetre. So, these all are the technology basically we are taking the heat from our body parts and then we are measuring our own oxygen content inside our body or maybe that percentage of oxygen presents inside our body. Health monitoring, powering small devices, self powered strain sensors, so these all are the examples, where we can use these particular technology.

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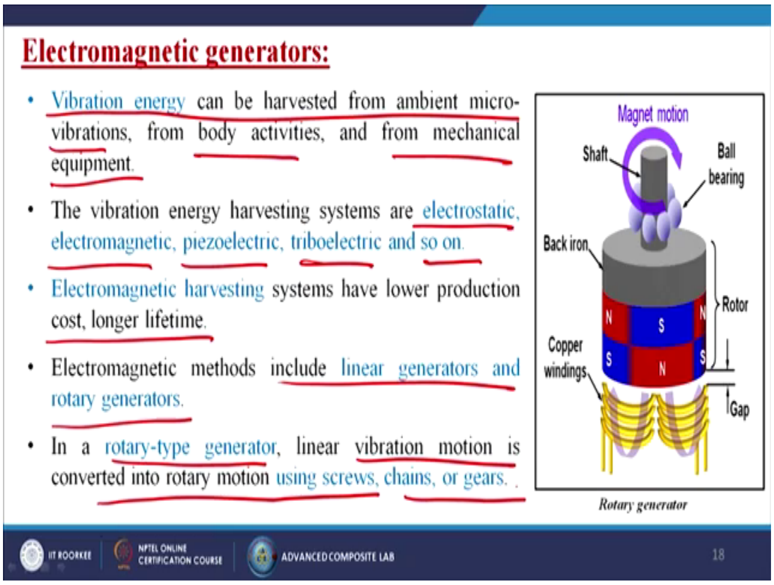

Now, we have come to the second part of this particular lecture, which is nothing but about the electromagnetic generators. So, it is a vibration energy can be harvested, from ambient micro vibrations from body activities and form mechanical equipment. The vibration energy harvesting systems are electrostatic, electromagnetic, piezoelectric, triboelectric and so on. Electromagnetic harvesting systems have lower production cost, and the longer lifetime. Electromagnetic methods include linear generators and rotary generators. In a rotary-type generator, linear vibration motion is converted into rotary motion using screws, chains, or gears.

So, simple what happened? Either I am giving the electricity to that particular materials, so that it can generate some kind of magnetic or maybe electromagnetic field due to that maybe some motions or vibrations is creating or maybe the vice versa once also if the material is having that capability. If I give certain kind of motion or vibration to that particular materials it can generate the electricity.

So, in this particular case what happened, in the shaft best example in the fan, so we are using that magnet. So, basically the when the magnet is rotating, so in, this particular case we are giving the electricity and the magnet is rotating. If I do the opposite thing also if I rotate the magnet and due to that the electricity can be generated. So, this is the basically principle of this particular technology.

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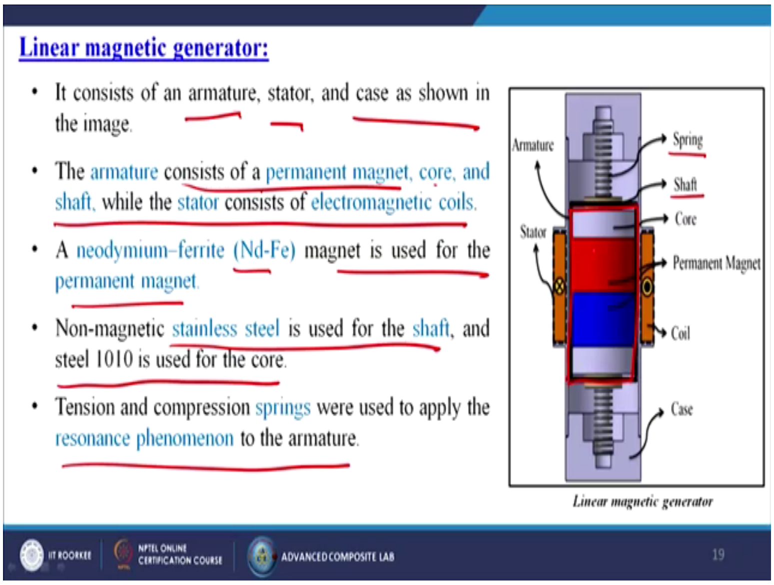

Now, if we talk about the magnetic generator, it consists of an armature, starter, and case as shown in that particular image. So, this is basically the case, I am having that coil. So, as I told already, I am using the permanent magnet over there. Now, the armature consists of a permanent magnet, core, and the shaft, while the stator consists of electromagnetic coils. So, this is basically the armature unit over there. And then a neodymium-ferrite Nd - Fe magnet is used for the permanent magnet.

So, in this particular case you can see we are using the permanent magnet. Non magnetic stainless steel is used for the shaft and steel 1010 is used for the core. Tension and compression springs were used to apply the resonance phenomenon to the armature itself. So, now, in this particular case due to that magnetic field what is happening? this material is moving inside the whole case systems.

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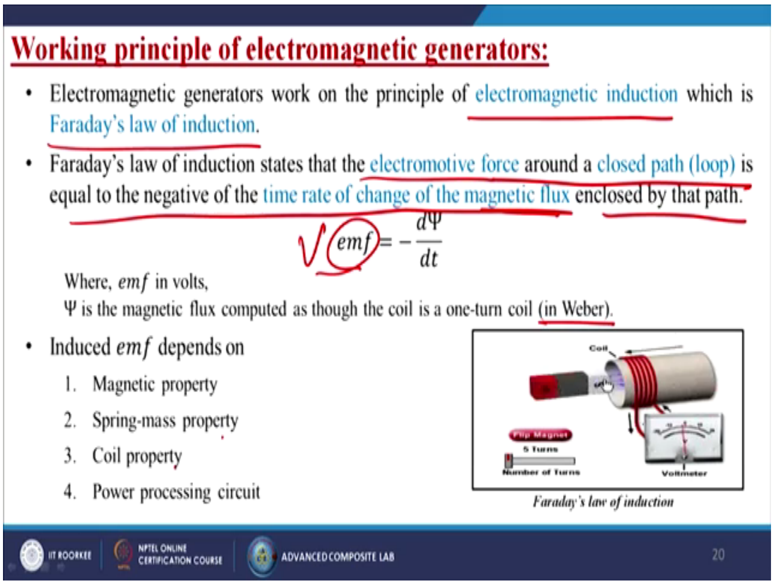

Now, what is the working principle of electromagnetic generators? Basically the electromagnetic generators work on the principle of electromagnetic induction, which is Faraday's law of induction. Faraday's law of induction states that the electromotive force around a closed path or loop is equal to the negative to the time rate of change of the magnetic flux enclosed by that particular path.

So, what is emf? It is nothing but the minus d psi by d t. Where, emf is in volts. So, this units is in volts, psi is the magnetic flux computed as though the coil in a one ton coil that is in Weber. Induced emf depends on magnetic property, spring-mass property, coil property and the power processing property. You see, so I am having that coil, so when I am moving that particular magnet inside this particular tube. So, what is happening? The electricity is generating the volt is forming that is which is nothing, but this emf, which is best on the Faraday's law of induction.

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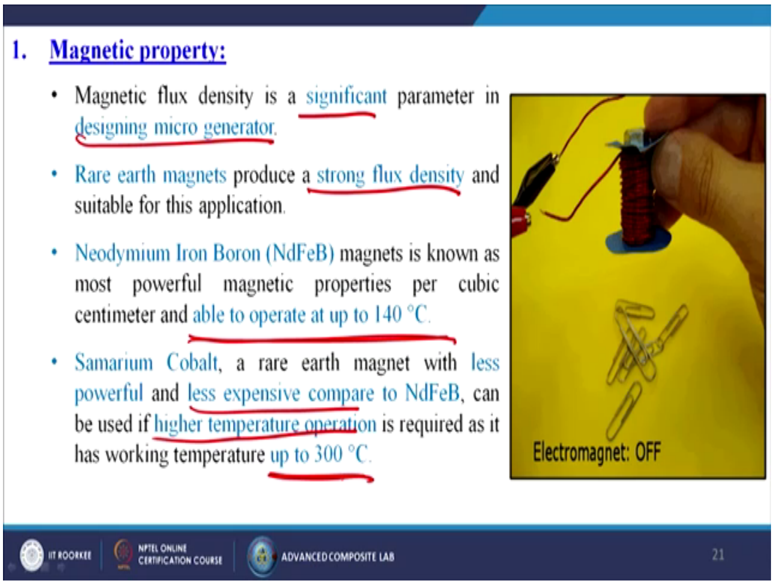

Now, it depends upon the magnetic property. Magnetic flux density is a significant parameter in designing micro generator. Rare earth magnets produces strong flux density and suitable for these particular applications. Neodymium iron boron magnets is known as most powerful magnetic properties per cubic centimeter and able to operate at up to 140 degree centigrade.

Now, you can understand at the time of operations if little bit temperature will rise also that it can sustain up to 140 degree centigrade. Samarium cobalt, a rare earth magnet with less powerful and less expensive compared to neodymium iron boron, can be used if higher temperature operations is required as it has working temperature up to 300 centigrade.

Now, when I am giving the current, so, what happened? The magnetic force is generating and due to that just it is catching all the gems clip over there. And if I stop this particular circuit, so automatically the electromagnetic force will go and it will not attract any metal.

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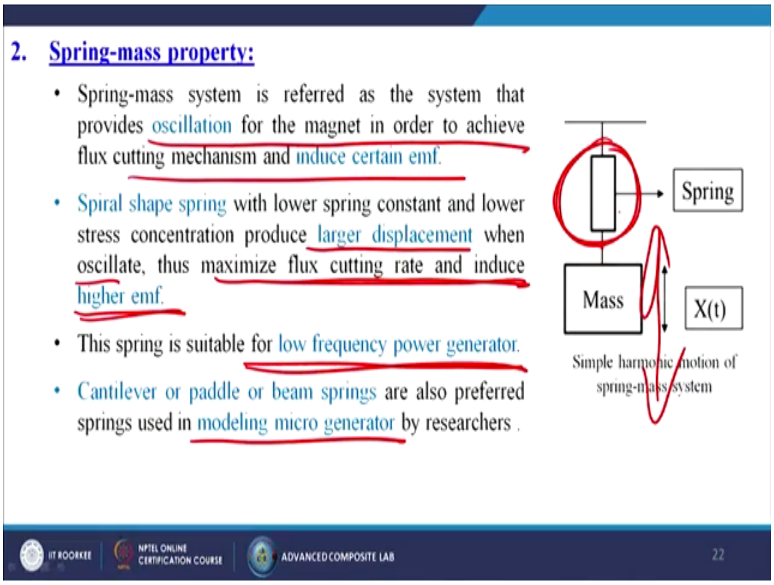

Next one is called the spring-mass property. So, basically the spring-mass system is referred as a system that provides the oscillations for the magnet in order to achieve flux cutting mechanism and induce certain emf. Spiral shape spring with lower spring constant and lower stress concentration produce larger displacement when oscillate, thus maximize flux cutting rate and induce the higher emf.

So, in this particular case what happened? So spiral shape spring with lower spring constant, so here we are using the spring over there. So, produce the larger displacement when oscillate, thus maximize the flux cutting rate and induce the higher emf. This spring is suitable for low frequency power generator. Cantilever or paddle or beam springs are also preferred using used in modelling micro generator by the researcher itself.

So, in this is particular case what happened, if the spring constant of this particular spring is higher, so that it automatically this mass will not free flow. So, it will become more stiff, but if the spring is having the low spring constant, so that time the mass will move in a very high range, so basically that principles we are using over here.

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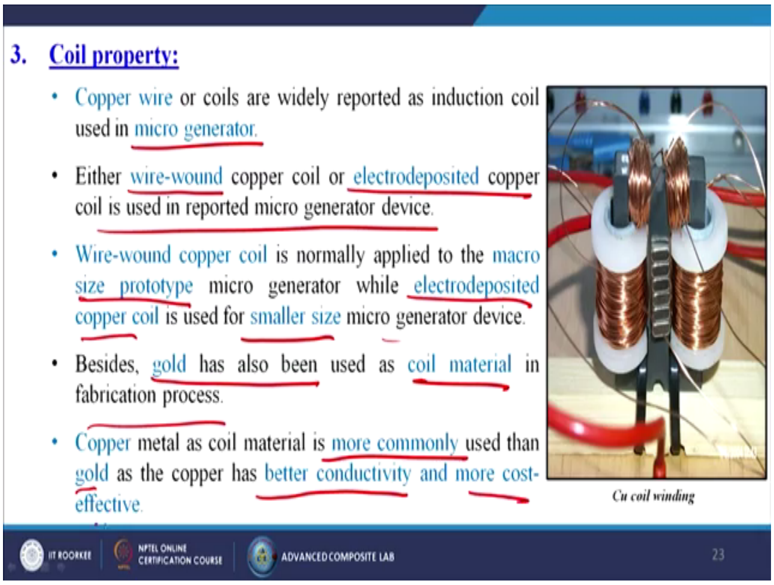

Next one is called the coil property. So, basically the copper wire or coils are widely reported as induction coil used in micro generator. Either wire-wound copper coil or electrodeposited copper coil is used to reported micro generator device. Sometimes we are doing certain kind of coating on to the copper coil also. Wire-wound copper coil is normally applied to the macro size prototype, micro generator while electro deposited copper coil is used for smaller size micro generator device.

Besides, gold has also been used as coil material in fabrication process, but that is for the high end recruitment purpose because it is too costly. Copper metal as coil material is more commonly used than gold as the copper has better conductivity and more cost effective, so that is why people are using more copper wire than the gold wire.

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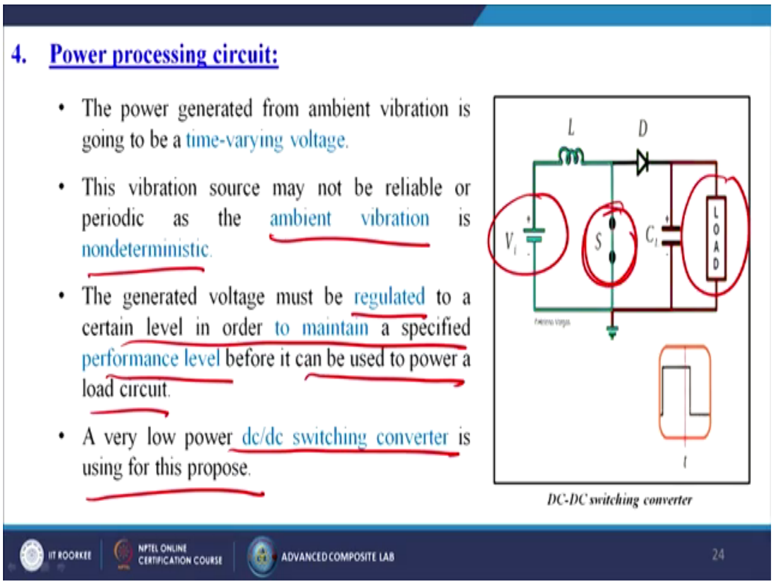

Next power processing circuit. The power generated from ambient vibration is going to be a time-varying voltage. These vibration source may not be reliable or periodic as the ambient vibrations is nondeterministic. So, in this particular case what happened, so I am giving the potential difference in this particular case. So, when I am attaching this two, then only the electricity is going to that particular load itself. So, the generated voltage must be regulated to a certain level in order to maintain a specific performance level before it can be used to a power load circuit.

So, now, from here I can control the load or maybe that voltage. A very low power dc dc switching converter is using for this particular purpose. And also in this particular case, when we are making it on and off, so what happened? So, if I am having some kind of vibrations, which is not continuous. So, simple I can control that one, and I can generate the electricity continuously.

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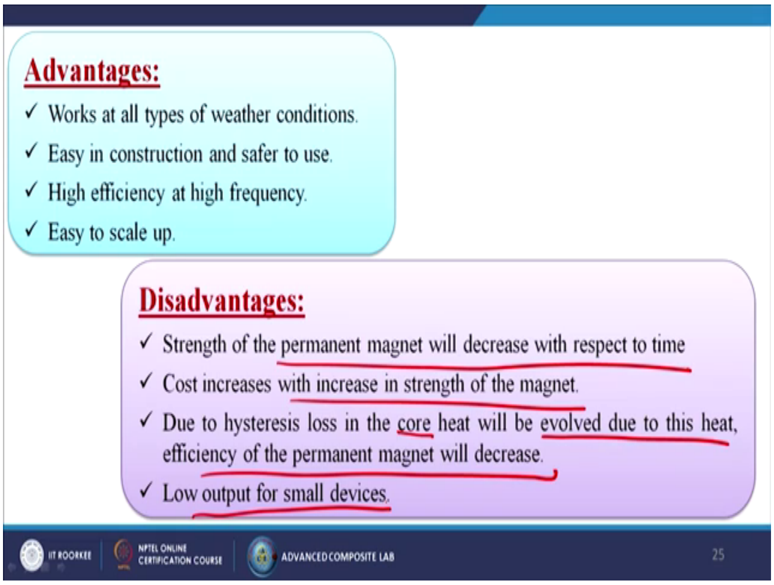

Now, what are the advantages? Works at all types of weather conditions, easy in construction and safer to use, high efficiency at high frequency, easy to scale up. Of course, there are certain disadvantages. Strength of the permanent magnet will decrease with respect to time. Yes of course, because it is the inherent property, so after certain time the magnetic property can degrade. Cost increase with increasing strength of the magnet. Due to hysteresis loss in the core heat, will be evolved due to this heat efficiency to the permanent magnet will decrease; low output for the small devices. So; that means, basically we need a higher or may be that powerful magnet to generate the more electricity.

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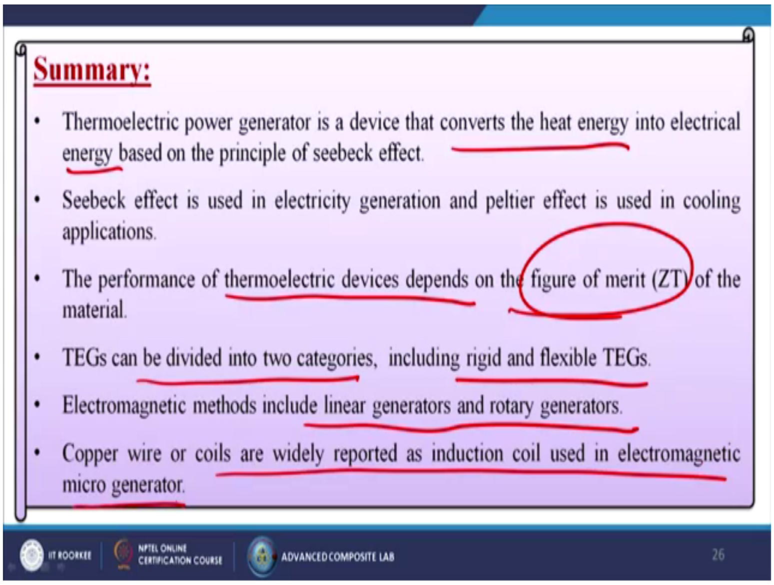

Now, we have come to the last part or maybe the last slide of this particular lecture. So, basically the thermoelectric power generator is a device that converts heat energy into electrical energy based on the principle of the Seebeck effect. Seebeck effect is used in electricity generation and Peltier effect is used in cooling applications.

The performance of thermoelectric device depends on figure of merit; this is the main parameter over there of the material. TEGs can be divided into two categories, including rigid and flexible TEGs. Electromagnetic methods include linear generators and rotary generators. Copper wire or coils are widely reported as induction coil used in electromagnetic micro generator; sometimes we are using the gold wire also.

Thank you.