Energy Conservation and Waste Heat Recovery
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Lecture – 46
Direct Conversion - Thermo Photo Voltaic Generation (TPV)

Good morning friends, welcome to the next lecture of Energy Conservation and Waste Heat Recovery and today, what we will do is we will start from where we left of in the last lecture when we were discussing thermo ionic generators. Remember again thermo ionic generator if we recall is a direct conversion device, whereby we can use thermal energy and directly convert it to electrical energy without having to depend on any moving parts any mechanical conversion and so on.

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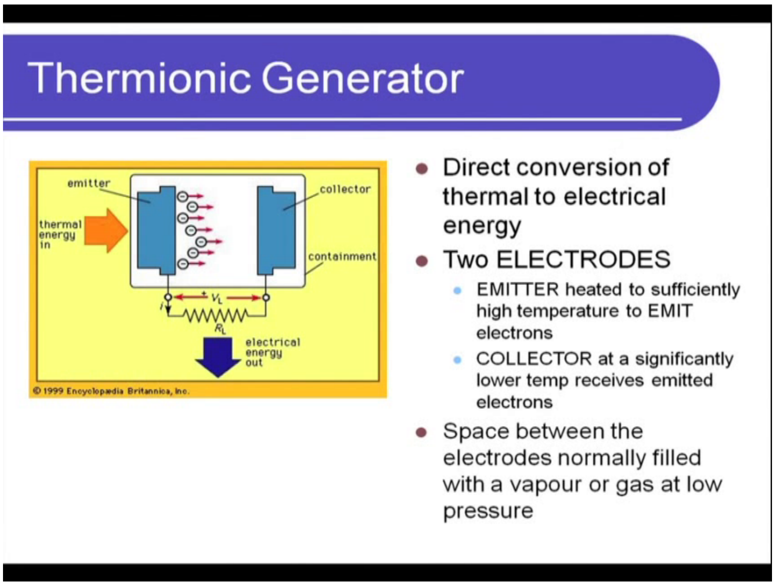

So, as we saw last time and just to recap looking at this power point slide, it is a direct conversion device it consists of 2 electrodes, the first one is an Emitter and which when heated to sufficiently high temperature will emit electrons and the reason why it emit electrons or it emits electrons is because at a certain high at sufficiently high temperature, some of the electrons have sufficiently high kinetic energy which is above the what we defined as work function for that material and these electrons therefore, as it as it attains energy above the work function can detach from the surface and move towards the collector surface.

The collector is at significantly lower temperature and therefore, as it receives the electrons what happens is the electrons give up their energy and come down to the level of the Fermi which is known as a Fermi level of the collector surface. So, in the process it gives up thermal energy which is rejected as heat from the collector surface. Now as we saw last time the emitter and collector materials are chosen such that the Fermi level of the collector is higher than that of the emitter.

So, therefore, what happens is the electrons that are now collected at the collector surface has higher Fermi level which is the stable state than that of the emitter. So, therefore, now if we connect the collector and the emitter externally the electrons will tend to flow through the external load.

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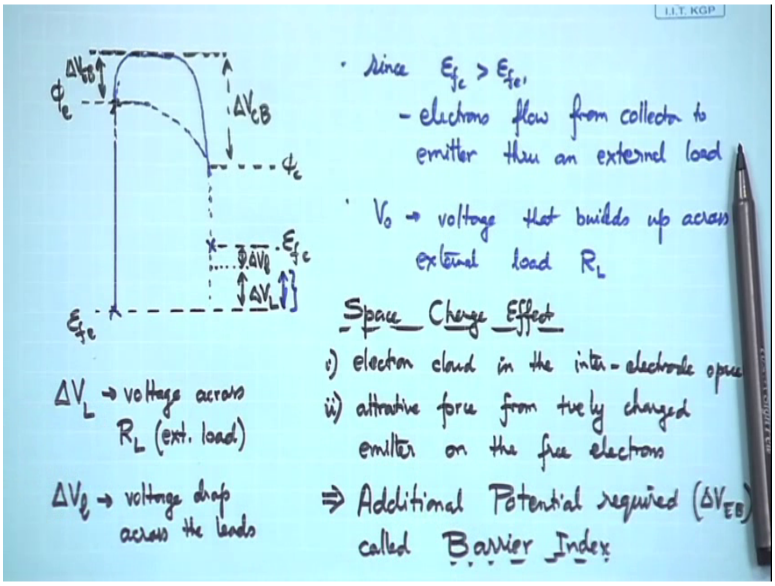

So, this is what we saw here if you look at the sketch that I have drawn this is similar to what we drew last time, this is the at the collector at the emitter surface what happens electrons attain an energy level which is equal to the work function or higher than that and. So, therefore, it detaches and comes towards the collector where it settles down to this level which is the Fermi level.

Now, this Fermi level of the collector is higher than that of the emitter. So, therefore, as we the electron since let me write down since epsilon f of c is greater than epsilon f of e the electrons flow from collector to emitter through an external load. If you connect the collector and emitter what we will see is if we if we close the circuit then they will have an external current flow from the collector surface to the emitter surface.

So, therefore, what happens is as the current starts to flow then what happens there is a voltage that develops between the 2 which will depend on the value of the resistance that of the load that we have connected. So, let us call that V 0. So, V 0 is a voltage that builds up across the external load RL. Now what is RL again recall maybe from the from the slide itself we see that the RL is this external load and the VL is a voltage that we will measure once the current starts flowing from emitter to collector remember the electrons are flowing from collector to emitter therefore, the direction of current flow will be the direction of electron holes or in the opposite to that of the electrons which is from emitter to collector.

So, this is how we get electrical energy out as we saw clear. So, far good, but what happens is the following let us come back here. So, there are certain other things that we need to keep in mind. So, as the current this is what we call the space charge effect clear. So, what happens as the electrons start flowing from the emitter to the collector, there will be a buildup of the negative electron cloud in this inter electrode space clear and so this is going to slow down the movement of the electron from the emitter surface to the collector surface. So, I repeat this again as the electrons start flowing from the emitter towards the collector there will electro what we call an electron cloud that will form in the in inter electrode space and the net effect of this is to slow down the movement of electrons from the collector from the emitter to the collector. Apart from that see as the electrons dissociate from the emitter surface the emitter becomes positively charged.

So, therefore, the attractive force it will trend to attract the opposite charged electrons the negatively charged electrons towards it and this will also slow down. So, these 2 actually oppose the thermo ionic generation the buildup of the voltage of the thermo ionic generation or the current flow, all right. So, therefore, just having that energy level at the work function of the emitter it may be to initiate the thermo ionic generation, but to sustain it is not going to be enough.

So, therefore, in reality what happens is we are going to need these level the energy level to go higher than just the work function. So, actually the electrons have to go to a higher level and then come down like this and why is this required because of what we called space charge effect space charge effect. What is it number 1 the electron cloud in the inter electrode space and number 2 attractive force from positively charged emitter on the free electrons.

So, therefore, what is the net effect net effect is there is an additional potential that is required. So, there is an additional potential that is required and that is called we will denote it as delta V EB this will also called sometimes as Barrier index just it helps to know these names. So, what happens I will now write it down? So, this therefore, this additional potential is delta V EB the barrier index clear.

So, the barrier index of the emitter. So, therefore, we will accordingly call this as delta V CB clear then what happens there will be some losses because of the connecting wires and leads. So, we will call it delta V small L and the rest will be delta VL. So, let me write it down delta VL is voltage or potential difference across RL which is external load and delta V small l is drop or voltage drop across the leads or connecting wires.

So, finally, this is what we are going to get and if it is going to depend on the value of the current so there are additional physics that will from where Richardson Dutchman equation from where we can get the charge density and so on, but we are not going to get into all that all those details as part of this course. It suffices we have I think a fair understanding based on the discussion that how the thermo ionic generation works? What happens?

Why it; what is it that gives rise to this current flow when we sufficient heat the emitter surface to sufficiently high levels and we saw that why it does it because some of the electrons from the emitter surface attained enough energy to overcome the work function and therefore, goes towards the collector whose Fermi level is higher than that of the emitter. So, therefore, if you now connect an external load the electrons will flow from the collector to the emitter, through the inter electrode space the movement is from emitter to collector through the external load when you close the loop the movement of electrons is from collected to emitter.

So, therefore, which essentially means there is a current flow from the emitter to the collector and if you now attach an external load you can get electrical energy out of it and then we saw a few things about the you know about the different energy or the potential levels that are required we talked about space charge effect for which you need an additional potential beyond the work function. So, that the thermo ionic generation can be sustained, all right; so this kind of wraps up our discussion on thermo ionic generation.

So, what we will do next is we will study a fourth type of direct conversion device which is even though this one started or was first proposed and shown to work in 1960s, but; however, the research on this was limited and it is only the last 10 years that research has really picked up. So, this class of direct conversion device is known as Thermo Photovoltaic.

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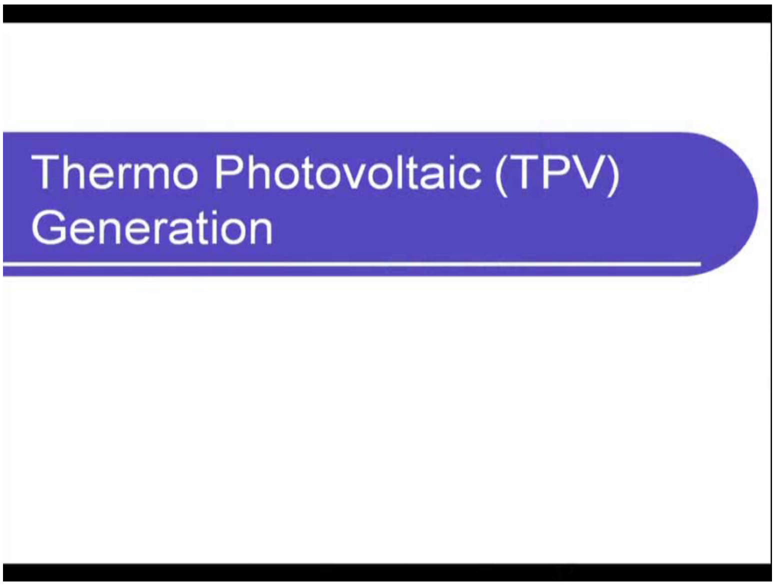

So let me write it down Thermo-Photovoltaic generation or TPV. So, this one actually what we will do is we are not going to get too much into physics or mathematics we are going to limit ourselves only to how this functions what are the components and so on.

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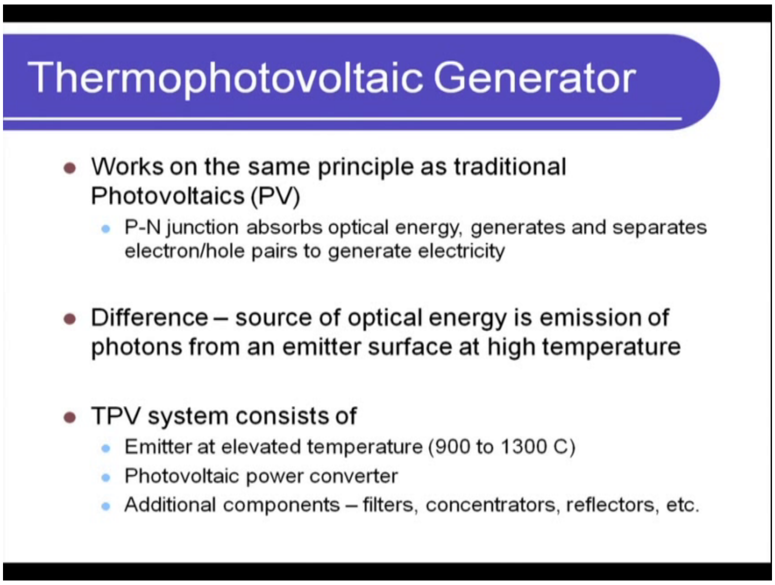

So, what is the thermo photovoltaic let us look into this so thermo photovoltaic as the word photovoltaic suggests, it works on the same principle as a traditional photovoltaic cell a photovoltaic cell I think most of us have seen the solar collectors on our rooftops which are primarily Photovoltaics what it happens is a photovoltaic cell essentially is a P-N junction the inputs to the P-N junction is optical energy. So, as the photovoltaic name suggests these cells these P-N junctions as it receives optical energy it can generate and separate electron hole pairs and this is how it generates electricity.

So, photovoltaic as the name suggests photo to volts which means a direct conversion of optical energy. So, therefore, photons to electricity clear. So, this is how the photovoltaic works as we know in a very nutshell. So, what is thermo photovoltaic; thermo photovoltaic actually works on the same principle as photovoltaics, but the only difference here is the optical energy the optical energy that the photovoltaic cell receives is not from the sun or the source of the optical energy is not solar energy, but; however, it is thermal energy.

So, what do I mean by that. So, here also we have a certain material or a surface which is an emitter similar to thermo ionic in thermo photovoltaic also we have an emitter here also we have to heat it up to sufficiently high temperature, but what is the difference here the difference is these surfaces this thermo photovoltaic or the surfaces that the emitter surface used for thermo photovoltaic generation at that sufficiently high temperature emits photons.

So, what is emitted unlike electrons in thermo ionic in this case the emitter surface emits photons or packets of light energy? So, at high temperature, a TPV system or thermo photovoltaic generator system therefore, at a minimum consists of an emitter which is at an elevated temperature. So, I have shown a range of temperature which typically works in the infrared region. So, you need an emitter which is heated to an elevated temperature and has the properties where at those temperatures it can emit photons and then you have a photovoltaic power converter which is the PV cell which receives those photons and converts it to electricity, but; however, this is the these are the 2 minimum components, but typically what we have is we also have some additional components like filters concentrators reflectors etcetera which we are going to talk about.

So, again once again if I have to define it in a nutshell thermo photovoltaic is again photovoltaic conversion where we use semiconductor and P-N junctions to generate electricity from optical energy. The difference here is that the source of that optical energy is not sun or solar energy, but it is photons that are emitted from an emitter surface which is heated to a highly elevated into an elevated temperature. So, as is shown in this slide this is what we are seeing here that if the surface is heated to sufficiently high temperature, then we are the surface is able to emit photons which will be then absorbed or by the photovoltaic power converter clear.

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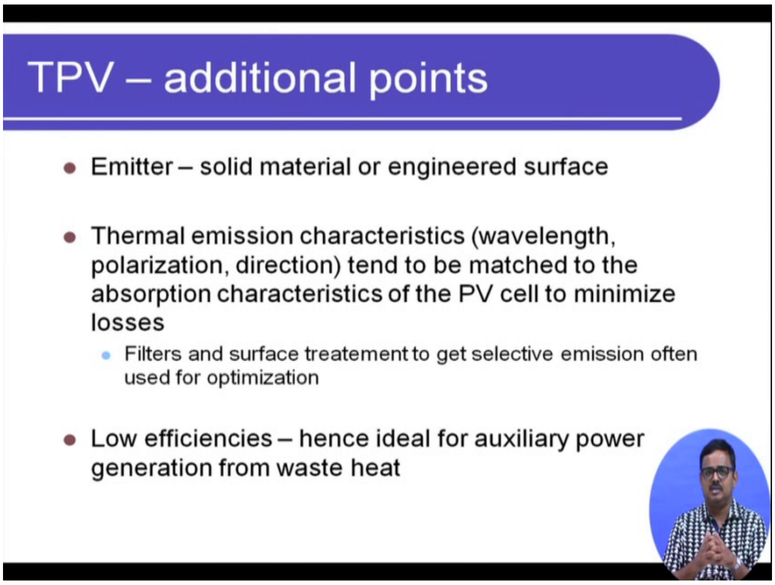

So, what we will do next is some additional points. So, what is this emitter surface? The emitter surface can be a solid material, but more importantly the research that is happening is going towards engineered surface. So, that why engineered surface this is because the thermal emission characteristics of the emitter surface in order to maximize or optimize the performance of the thermo photovoltaic generator and minimize losses the thermal emission characteristics has to be matched with the absorption characteristics of the photovoltaic cell.

So, something is emitted from our from our knowledge of let us say radiation heat transfer right when you have electromagnetic radiation what are the different properties the radiation happens over across all wavelengths, but definitely at certain wavelengths it is higher than at other wavelengths, right. So, when we talk about thermal emission characteristics of a surface we mean it is a spectrum over a wavelength over a range of wavelength it also has directional properties clear right. So, it is emitted in all directions across the across 360 degrees there is polarization and so on.

So, an emitter surface will have these it is own emission characteristics and the absorption at the surface which is absorbing here in this case the photovoltaic cell will have it is own absorption characteristics. So, the best matches when the emission characteristics of the emitter surface matches with the absorption characteristics of the photovoltaic cell, because our aim is whatever is emitted should be absorbed and that is what will give it the maximum efficiency or minimum losses.

So, in order to do that of course, engineered surface treatment etcetera is important, but also sometimes what we use is or not sometimes people are people are looking at it use filters and surface treatment to get selective emission characteristics etcetera. So, these are all being done today to increase the efficiency and minimize losses. So, that most of the emission that happens from the emitter surface is absorbed as a at the photovoltaic cell there also this photovoltaic reflectors etcetera, there lot of you know lot of new research across different groups including MIT takes us Austin and several other universities where this research is happening.

So, it is a very interesting field right now it has lots of you know it has great application I would say in waste heat recovery clear, but unlike or, but what is or rather similar to most other direct conversion devices the efficiency, if we just look at the efficiency of the amount of thermal energy that we need to give to the emitter surface versus the amount of electricity electrical energy that we are able to extract out of it if we define the efficiency in those terms the efficiencies are low when we say low is maybe 10 percent or in round about that range.

So, definitely it cannot replace, you cannot think of this to replace our traditional power plants or even other means of generation of electricity, but; however, this is ideal, but this is very good I it is very good for auxiliary power generation from waste heat. So, if you are in a regular power plant similar to all the other direct conversion devices that we talked about if you are wasting a lot of energy, in the form of thermal energy use that to heat up the emitter surface and as you heat it up and if you are able to reach the temperature range like 900 to 1300 is one range that I talked about if you are able to reach the temperature range where the emitter start surface starts emitting photons. And you engineer the surface such that the emission characteristics are close to that of the absorption characteristics of the photovoltaic cell, then we will be able to convert the electricity convert the emitted or; whatever is the emitted photons to electricity directly at the PV cell all right.

So, that kind of brings us to the end of this section or discussion on direct conversion devices. Let us do a recap of what we discussed as part of direct conversion device we started by saying that the direct conversion devices are means direct conversion devices are means by which or are technologies by which we can convert thermal energy directly to electrical energy.

Now what is what is so great about this remember in a regular power plant steam turbine cycle the energy input is in the form of fuel which is burnt. So, that is heat energy thermal energy, but what do we do with that we use that thermal energy to heat up a working fluid, which flows through a turbine in the vapor form and rotates the turbine to generate mechanical energy. The mechanical energy the rotating turbines is then converted to electrical energy through a generator.

So, fuel heat mechanical energy then electrical energy. So, in this case what happens is I already have the thermal energy indirect conversion device I already have thermal energy which is supplied to this direct conversion device and get electricity out of it no moving parts no working fluid clear. So, as part of this we started by discussing the first technology which is thermo electric generation. So, what was thermo electric generation it was a p and n junction it is a PN 2 1 1 P doped or positively doped semiconductor 1 negatively doped semiconductor, which are connected electrically in series and thermally in parallel and we have a series of them.

So, what we do is on one side we apply the waste heat source that we have. So, that the temperature is elevated the other end or other end of the thermoelectric device or these PN junction pair or the or the PN pairs thermoelectric pairs that is maintained at a lower temperature. So, this temperature gradient that happens across the thermoelectric device results in the generation of electricity because the charge carriers which is holes in case of the P doped semiconductor and electrons in the case of N doped semiconductors tend to move due to their higher energy levels will tend to move from the hot junction towards the cold junction.

So, we started this is how a thermo electric generator works and what we did next was we did a lot of analysis to calculate how to calculate the efficiency of these thermoelectric generators to figure out under what conditions we can maximize the efficiency we can maximize the work output which do not necessarily mean the same and so on right. And we also talked about applications of thermoelectric generators and one of the things very interesting ones that we saw was it has been already in use in space shuttles in Apollo and mass mover it has been there because there the cold temperature is readily available because outer space is at very low temperature 3 to 5 Kelvin right and the heat source was given through radioactive reactions.

So, that was thermoelectric generator which we studied, I also talked about you know a research story where bismuth telluride was able to give high Z value how because we were able to grow it an Nano scale where the electrical; electrical conductivity was kept constant and thermal conductivity went down because the phonons could not pass through whereas, electrons could pass through those length scales right. So, that was a slide research story, but very interesting one that we talked about.

The next technology that we discussed was magneto hydrodynamic or MHT generation magneto hydrodynamic depends on or works on the principle of faradays laws of electromagnetic induction, where what we said is if a conductor if an electrical conductor and a magnetic field move relative to each other which it gives rise to an electric field in the third direction. So, in an MHT duct or magneto hydrodynamic generator duct what happens is we have this high temperature gases, which when heated to sufficiently high temperature will emit electrons these are gases emitting electrons, but the amount of the amount of temperature that you need is very high. So, we seed it with small ceding alkaline or cesium vapors or small seed we seed the combustion gases with very slow concentration one percent or so.

So, that this emission of electrons happen at a much lower level and again when if is a lower level we are talking about 3000 Kelvin and then we say that we are going to make this ionized gas move through a duct across which we apply a magnetic field and then if we and as a result what we have is we have a magnetic field and a conductor moving relative to each other and therefore, on from the other 2 walls we could generate a dc current or dc voltage all right and how is this going to help us we say that you know the modern furnaces can reach temperatures of up to 300 Kelvin, but; however, the gas or the steam turbines or even gas turbines that are used in industrial applications we are typically limited due to material constraints to around thousand Kelvin or so.

So, therefore, we are not being able to utilize the high temperatures that we can go that the furnace technologies allow us to go to. So, this is one case where we can have combustion at very high temperature, generate the gases at around 300 Kelvin use a magnet or hydrodynamic generator to a to generate some electricity and let the gas come down to temperatures below 200 Kelvin where it loses it is ionization potential and there after use that combustion gas for heating up the water in the boiler and convert it to steam and also for air preheating. So, that was magneto hydrodynamic generation second one.

Next what we studied was thermo ionic generation here also you have an emitter surface which is a material a solid which is heated to high temperature and at that high temperature, when it when some of the free electrons or the outer electrons attain energy levels higher than that of the work function corresponding to that material it goes to a small gap towards another material which we call the collector which is at a significantly lower temperature where it gets collected the emitter and collector were chosen such that the Fermi level of the collector is higher than that of the emitter.

So, therefore, when the collector collects this electrons it is at a higher potential and. So, if we now attach an external load across the collector and the emitter we will have an external current flow from the emitter to collector and this is how we get electrical energy out of it right. And finally, the fourth technology that we talked about is thermo photovoltaic generation here also you have an emitter and a collector the collector is a photovoltaic cell it is a PN junction same in this works on the same principle as that of a solar photovoltaic right.

Except that the optical energy in this case is provided by the emitter surface which when sufficiently heated emits photons remember in thermo ionic it emitted electrons here it emits photons and then what we do is the research today is on. So, that the emission characteristics of the emitter surface matches with the absorption characteristics of the PV surface so that we have a very efficient conversion of the emitted photons to electricity.

So, it is an efficient conversion of the photons; however, the process of converting a thermal energy to electrical energy still is in efficient efficiencies are much lower compared to even conventional power plants. So, therefore, any of these technologies be thermo electric thermo ionic thermo photovoltaic or MHT none of these MHT is a little different however, but the other 3 at least none of these can replace conventional power plants; however, all these are very useful can be viewed as very useful options if we want to convert the waste heat from a power plant to electricity.

So, additional generation of electricity is possible through all these techniques and last point that I want to make for that is true for all these 4 technologies is these are all essentially heat engines and therefore, their maximum efficiencies limited by Carnot efficiency, all right. So, with that we come to an end on this section on direct conversion devices where we studied 4 different technologies and in the next lecture what we will do is we will move on to a new topic so.

Thank you very much and we will meet you in the next lecture.