Heat Transfer And Combustion in Multiphase Systems
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Lecture 01
Introduction to Multiphase

Welcome everybody this is the first lecture of the course on multiphase system basically transport phenomena in multiphase systems my name is Saptarshi Basu I am a faculty member in the Department of Mechanical Engineering at Indian Institute of Science. And so, under this particular course we are going to cover the basics of multiphase systems.

And we will take also some specialized topics under the multiphase system like for example droplet evaporation, droplet combustion, boiling, flow through porous media so some specific problems as such. So, initially we will start covering that what are the basic principles are for multiphase systems? What are multiphase systems in general? What are the thermodynamics and the transport governing equations for such multiphase system?

So, basically under this particular course we are going to follow a couple of books one is the Transport Phenomena in Multiphase Systems by Amir Faghri and Yuwen Zhang.
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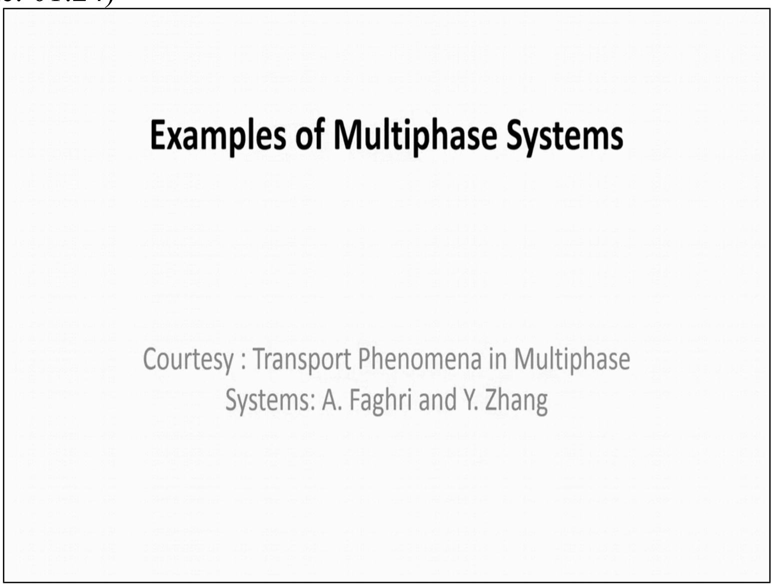

The other book that we are going to follow is Droplets and Sprays by Will Sirignano. So, that will cover the specifics of droplet evaporation and droplet combustion type of framework. So, we will cover these things in the subsequent weeks of this particular course.

So, the first lecture of this particular course we are going to give you some examples of multiphase systems and try to understand that why multiphase systems are so very useful?

Why multiphase systems are required? And why should we learn about multiphase systems in general? So, if we look at the first slide now you will find that these are this is a slide which actually says what are the examples of multiphase systems.

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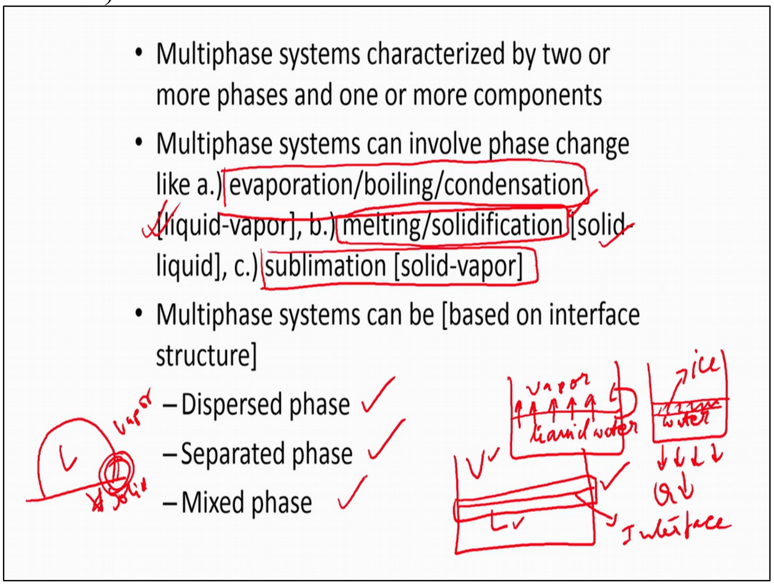

So, the multiphase systems in general are basically characterized by two or more phases and they can have one or more components as well. Now wait what do I mean by that by two or more phases for example if you have water and water vapour say you take a saucer in which there is filled with water and you keep it exposed in an open environment. What will happen is that there is liquid water and then there is water vapour okay.

So, basically there are two phase's water and water vapour okay. So, there are basically two phases in this multiphase system. However because this is kept open in the environment, air is also another component that is present. So, it is also an example of a multi-component system as well.

But if you take the same system and say you place it in a vacuum chamber that means you have sucked all the air out and you have put a saucer of water inside that vacuum chamber. So, what we will have is that basically liquid water and only water vapour. So, that will be a multiphase system which will be characterized by two phases and one component because water is only component that is present in this case.

Now multiple systems can also involve phase changes and what are phase change events like for example evaporation, boiling, condensation. Here the phase change happens between liquid and liquid and vapour. Let us look at this particular thing and so, you can see that evaporation, boiling, condensation this involves what we call liquid vapour transition.

Then melting and solidification is another state that is possible that is done between solid and liquid. Sublimation is another phase change phenomena which involves solid and vapour. So, there could be phase changes that could happen in a system like this, like for example going back to the example of a saucer of liquid water okay. So, this is the liquid water this is the corresponding vapour phase.

Now if you look at a system like this, water actually evaporates as we all know that if you keep a pot of water out in ambient what happens is that the liquid level starts to come down. So, naturally there is mass transfer that happens from here to here okay. So, this is a phase change phenomena in which liquid water is being transferred to the vapour phase okay.

Now, so, this is one example similarly you can have an example you have a liquid water say for example, you basically cool this that means you extract the heat out what happens is that this water starts to freeze, it starts to form ice okay. So, that is a transition in which we can call it solidification for example right.

Because it involves solid and liquid, so similarly there can be sublimation problems also naphthalene for example it actually the sublimate directly gets converted from solid to vapour. So, multiphase system you can all see it has a specific interface structure. What do I mean by interface structure, if you look at the same problem of that liquid water.

So, this is liquid water this is the vapour, you can see that the vapour and the liquid phase are basically separated by this particular structure correct. So, this particular structure is basically what is called an interface okay. So, the interface means it is separating surface okay, which basically separates the two phases. In this particular case it is liquid and vapours okay. It could be between solid and liquid could be between solid and vapour as well okay.

You have all seen if you take for example a droplet and place it on a surface like for example when you spill something right, you can take a droplet out and you can put it on a surface. So, this is liquid, this is the solid surface and this is the vapour right. So, this is a typical example in which this interface okay.

Specially this particular sector basically is a solid liquid vapour phase conducting. So, this is basically called a three-phase structure that you fall okay. So, the multiphase system based on their interface structures can be dispersed phase, can be separated phase it can be mixed phase as well. And we will see what each of these things means in the next slide.

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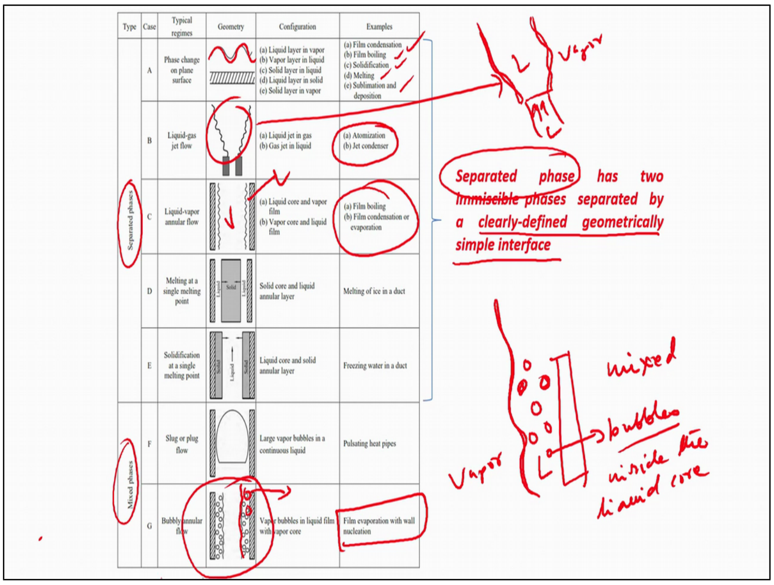

So, for example coming back to this particular question that, we have we said that we have something called separated phase, we have something called mixed phase and in the next slide I will show you what I mean by dispersed phase. Now separated phase has basically two phases which are separated by a clearly defined geometrically simple interface this is a very critical definition.

Simple geometrically simple interface is what actually characterizes a separated phase. In most of these cases let us look at a few examples. Like for example in thus; in the picture that you see over here the phase change say here for example there is a liquid layer on a solid surface. And the liquid layer has got a particular curvature that you see over here right okay.

So, this liquid layer is a very clearly defined interface correct because this interface is kind of very simple it has got a nice structure to it. You can almost define it by a functional form. So, examples of such systems will be like film condensation, film boiling, solidification melting, sublimation. So, this need not be only liquid layer it can be liquid layer on a solid surface solid layer on a vapour blanket.

It can be vapour layer in a liquid, so it can be a variety of things but the interface that you can see is very simple, it is just a variant phase. The next example can be for example when a liquid jet or a gas jet is coming out into the other phase like for example here if you take this is for example there is a pipe in which you are flushing in liquid okay. So, this liquid jet is coming out in an ambient vapour core.

So, this is the liquid this is the corresponding vapour core as you can see here also the interface is nice and simple okay it need not be flat and straight it is just a nice interface okay. Similar things can be seen in a liquid vapour annular flow kind of a system okay here in this case the inner part can be a vapour the outer part can be a liquid or it can be vice versa as well.

So, this example it works for atomization problem like for example in gas turbines and other applications. This works in the case of film boiling, film condensation, film evaporation etc okay. Similar things can be seen in the other applications as well not going into the details of that but you can just read up this particular portion.

So, it essentially means the surface that interface the separating surface between the two surfaces, two phases are basically a nice and simple geometric interface. Let us look into the mixed phase problem now. Now the mixed-race problem is a slightly more difficult problem to address it does not, it does have some features of a separated phase that there is a clearly defined interface.

But however if you look at this particular example over here what you see is that you do see a clear interface like this but at the same time you see this additional phase is being present inside that particular phase. So, it is like phase within a phase kind of a problem. So, you can see for example in this case there are vapour bubbles in a liquid film.

So, if I draw it if I magnify it, so this is initially the liquid phase, this is initially the vapour core right as you can see from the example but however some of the vapours have manifested itself as vapour bubbles. So, these are bubbles okay that are situated inside the liquid core okay. So, here it is a typical problem in nucleation okay. So, we will come to those kind of specific details later.

But here you can see it has a clearly defined interface but at the same time it has got this particular phase present within the liquid core. So, this is what we call a mixed phase it has got a feature of the separated phase as well as we will see it has got also the feature of a dispersed phase. So, if we look at the next one.

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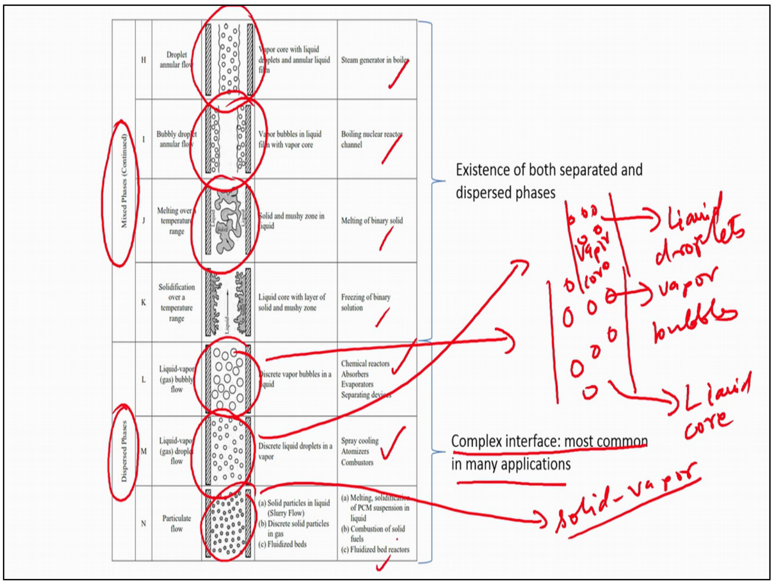

In the next slide that you can see if we look at the dispersed phase problem right now this is have got the most complex interface okay. Like for example if you look at this particular application over here you will see that this is basically like vapour bubbles, so these are basically vapour bubbles okay in a liquid core okay.

So, you can see readily from this particular problem this is a vapour bubble in a liquid core. So, the interfaces and there are multiple interfaces and the interfaces are complex and they are dispersed within the other. So, one phase is basically dispersed in the other. So, the same problem can be also in the other case as well that means there is now a vapour core and then there are this liquid droplets.

And they are used in multiple applications as we can see spray cooling, combustors, atomisers. It can be also be, the other one can be used in chemical reactors and things like that okay. It can also involve particulate matter, so it is a typical example of a solid vapour interface. So, in the solid vapour interface what you can see is that there are solid particles which are dispersed in a liquid flow.

So, the bear is also the interface is now between a solid and a liquid okay. So, the dispersed phase are very complicated, so this requires special handling and these are very common applications as well most of the applications that you will find will have dispersed phase. So, essentially what we can say is that on one end of the spectrum you have the separated phase, nice and easy problems to solve very well-defined interface.

On the other side of the spectrum you have the dispersed phase very complicated where this is one phase is actually dispersed in another. In between these two things you basically have what we call the mixed phase which have got characteristic of both the separated phase as well as the dispersed race okay, like for example applications like this if you look at this or this or the things that I showed you in the last slide.

So, it has got features of both the both things okay. So, and in on this side we have written all the applications that are that these kind of systems you will find. So, there you can see almost all the real systems that are there in the world right from gas turbine to spray cooling to thermal storage and we will see some of those applications a little later. You can find that all of them are multiphase applications.

All of them involve liquid vapour solid interfaces in some form okay. So, the real life problems are all more or less multiphase in nature okay. So, that is the reason why you should study multiphase flow as well okay.

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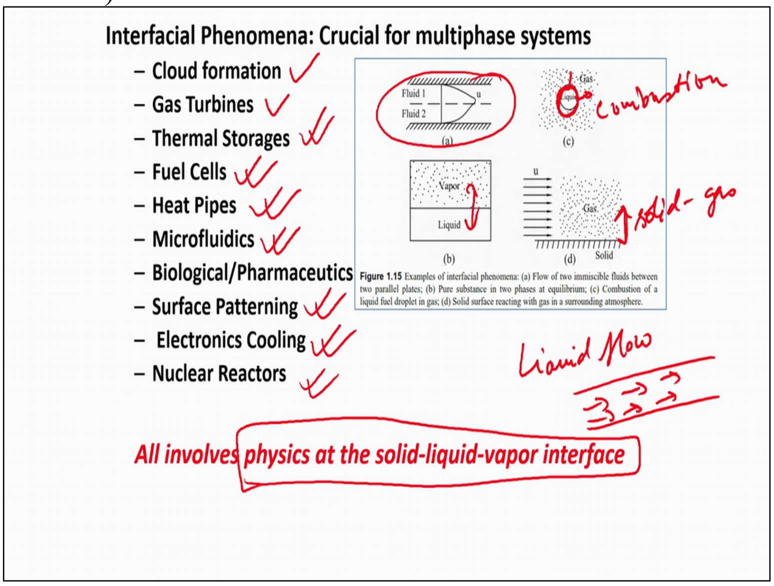

Now an important part of the multiphase system is studying the interfacial phenomena because individually when we just deal with a liquid flow say for example and one example of a liquid flow is say flow through a pipe this is an example that we can relate to each and every spectrum of your lifestyle.

Flow through a pipe is say its a pure liquid flow and we know the equations that actually govern the flow through a pipe okay. Similarly there are other applications when you can also flow gas through the pipe also I mean it would basically be the same but however when you actually have two phases involved okay. You have to not only take into account the liquid and the vapour or the two phases essentially.

But you also need to take care of the interfaces between these two phases and when you have an interface between these two phases you have to understand how the interfacial trial sport actually happens. Whether it happens from the liquid to the vapour or vapour to liquid or solid to vapour whatever it is you have to understand the transport mechanism that interface okay. So, interfacial phenomena is extremely hard and it is extremely important to study.

And if you are looking for that where are these interfacial phenomena is very useful for I take an example of the cloud formation. That is a very large scale event there one of the main thing is an interface. If you take another large scale system like a gas turbine, these gas turbines are basically what powers your; where we get all these lights and other things.

It can be it is this is the same gas turbines that are also used in your aero engines that means when a flight actually takes off this is the gas turbine that is used. It is also used for thermal storages these days a lot of emphasis is on solar thermal energies. So, in solar thermal energies sometimes the energy needs to be stored okay because the solar thermal energy is not always present.

So, you store the energy that you get out of the Sun in terms of something right. So, that thermal storage is also mostly done by face changing materials. So, thermal storage is also involves multiphase systems. Then you can, you have heard something called fuel cells also alternative sources of energy this also involves multiphase problems. Heat pipes which is extensively used in space applications also uses multiphase systems.

It is basically a multiphase system. Microfluidics used in biomedical to pharmaceutical or whatever applications that you can think of microfluidics also involves basically droplets okay, of two different phases okay. Surface patterning the things that you use to generate say for example electronic circuit boards okay or preparing specialized surface say for energy harvesting.

Those surface patterning also are done using multiphase framework. Similarly there are other applications like electronics cooling there are nuclear reactors all of these basically involves multiphase systems. So, all involves physics at the solid, liquid, vapour interface okay. And we need to know how this interfacial phenomena behaves okay.

And these are some of the examples this is a combustion application for example okay where you actually have a liquid droplet which is burning in a gas field. You can also have a solid surface which is reacting with a gas phase directly, so this is solid with gas directly. So, this is also an example of a multiphase system okay similarly.

You can have like two pure substances are in equilibrium this always happens that the water evaporation problem that I showed you it basically involves liquid water and water vapour in equilibrium. You can also have the pipe flow problem that I showed if you have two different phases okay, flowing; you can have a problem like that as well okay.

So, it is very common to have this kind of assistance and it is important to understand what happens at those interfaces, let us put it like that, this is the interface how the heat, mass and momentum gets transferred across those interfaces, so that is the main purpose of this course as well.

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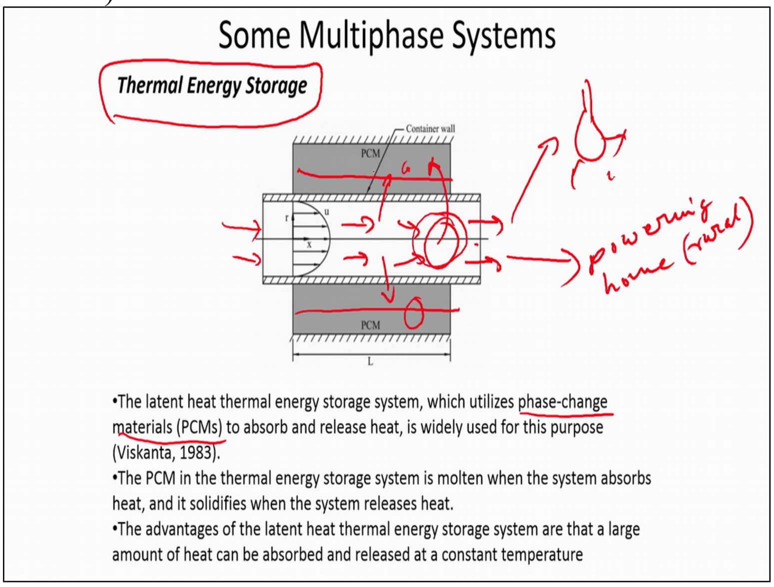

So, let us take quickly some simple multiphase systems okay and let us give you an idea before we go into the thermodynamics of multiphase system. So, let us take the first example, let us take this is for example thermal energy storage okay. Thermal energy storage as I said uses latent heat okay basically uses face changing material.

What happens over here is that this is the phase changing material what you see over here. There is a hot fluid or cold fluid whatever it is that flows through that inner pipe. If it is a hot fluid the heat gets transferred to this PCM. This PCM actually changes its phase and the energy of this particular fluid is actually stored here okay. So, imagine if this is coming from a solar tower and that is the heat transfer medium.

You flush this fluid through this pipe you store basically the energy which is nothing but the solar energy into this PCM but there just by melting the PCM okay. And similarly when you want to extract heat out of this PCM you pass a cold temperature fluid through it you extract the heat out of the hot PCM and then you use it for n number of applications like lighting your bulb. You can get light okay or you can use it for other applications as well okay.

So, like for powering your home powering home okay, specially in the rural sector this would be particularly important in India; from Indian perspective at least okay. So, these has got some major advantages. So, you are here you can see there is a phase change that happens in the PCM okay. So, it changes from solid to liquid and liquid to solid once again.

So, naturally you have to know how the heat is transferred across the interface. So, this is a thermal energy storage.

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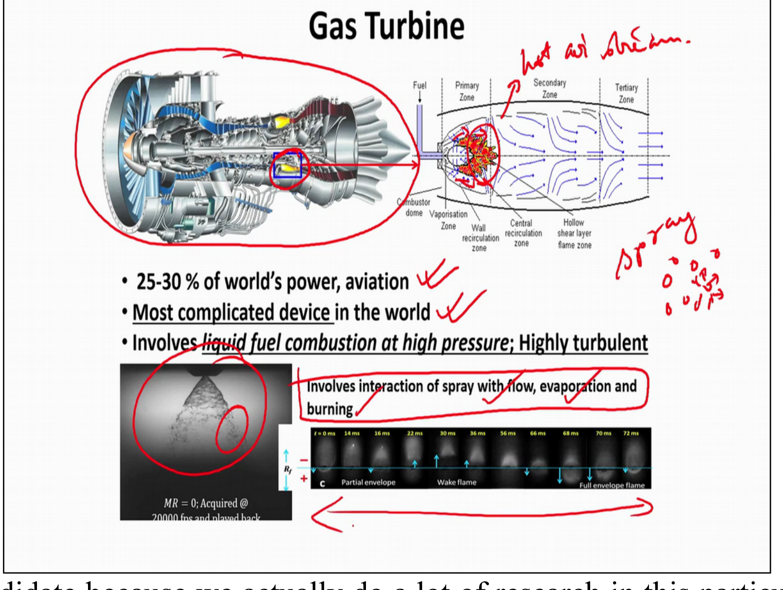

This is a big candidate because we actually do a lot of research in this particular area. This is what you see over here is basically a gas turbine okay. And the gas turbine is a very complicated machinery it provides 25 to 30 % of the world's power an aviation needs. So, you can see, this is; this has been the hallmark of power generation in the world and it is a very complicated device.

We will come to those kinds of things later but if you take a section a very small section which is basically this part of the gas turbine. This is where the maximum phase change or the combustion part actually takes place. What happens here if you take a zoomed-in view you have liquid fuel okay. In this case the liquid fuel can be jet fuel or any other type of fuel that is basically injected okay in the form of a spray.

Spray you have all seen right this is a duo spray for example that is like a spray right. So, this is injected in the form of a spray okay like for example here okay it is injected in the form of a spray into a hot air stream okay the fuel is injected right. So, what happens this is actually the spray means it is a combination of many small droplets right.

If you zoom into this particular area here you will find that there are many such small droplets. Now these droplets what they do is that they evaporate this fuel right. So, they evaporate, they actually mix with this hot air stream and they subsequently ignite. So, this red coloured thing that you see over here is basically the flame okay.

So, as it burns okay that is how you get the power you extract energy out of the fuel and you convert it to electricity or whatever propulsive power or whatever it is that you want to do with it okay. Now here the main backbone of this particular problem is how do you vaporise liquid droplets into the corresponding vapour form right.

So, it becomes a multiphase problem in itself right because it involves interaction of the spray with the flow, it involves evaporation and it involves burning this is for example a picture which shows how a droplet over here should actually burnt right. This is basically the flame what you can see over here are basically the flame okay.

So, it is obvious that a gas turbine is a very big machine right. So, at the heart of that you actually have a multiphase problem.

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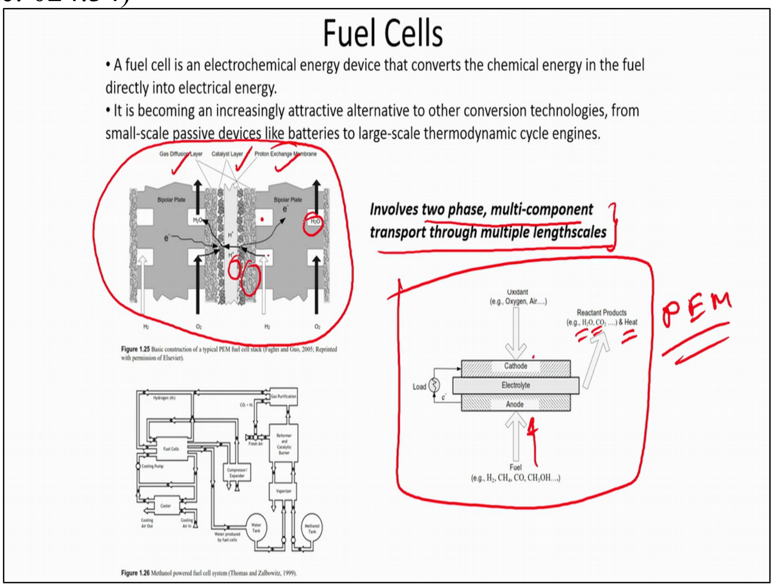

So, the next thing that we are going from gas turbine, if you are interested, if you are a renewable technology guy you move on to something which is called fuel cell right, fuel cell is an electrochemical device, electrochemical energy conversion device essentially which converts the chemical energy in the fuel directly to electrical energy okay.

So, in the core of a fuel cell it is a very simple mechanism actually this is the PEM cell actually Polymer Electrolyte Membrane fuel cell. So, in this particular fuel cell what happens is that oxygen is supplied into the it is it through the cathode, fuel which is hydrogen or methanol comes through the anode the reaction takes place you get heat and you get water and carbon dioxide as by products.

So, this is basically the mechanism of the fuel cell from a very global perspective. However if you look at the fuel cell complexities right over here what you can see is that the fuel cell is a very complicated machinery. It has got multiple layers like for example catalyst layer, gas diffusion layer, the proton exchange membrane.

There are passages which are of course like millimeter sized passages through which the gas and oxidizers or the fuel and oxidizers are actually passed. Here it involves two-phase multi-component systems and it also happens at multiple length scale for example here the pore sizes can be of the order of microns.

Here the pore sizes can be of the order of nanometers even. So, this involves flow through multiple messages okay. And at the same time this fuel, this water that is actually produced is not just produced in gaseous form it can also condense and it can actually block passages. So, there are n number of issues that are there.

And all of these things actually involve two phase multi-component transport issue. So, the fuel cell is not devoid of a multiphase nature of it okay.

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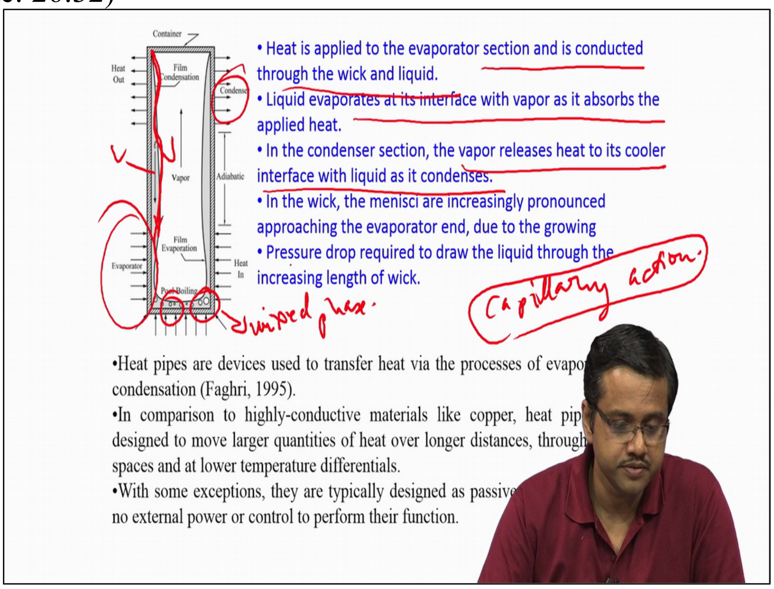

Similarly there is something called heat pipe. Now the heat pipe is another device in which you basically it is a passive device okay. So, what happens over here is that if you look at the diagram over there is that heat pipe is that you basically have once again a liquid and the vapour interface.

What happens over here is that heat is taken out in one section okay. So, the, from the basically the vapour core through the liquid and after that the heat is resupplied in the evaporator section right over there okay. So, what happens is that heat is applied to the evaporator section and is conducted through the wick and the liquid.

The liquid evaporates at its interface with the vapour in the condenser section that is in this particular section. The vapour releases the heat to the liquid as it condenses. So, this entire transport occurs basically through capillary action. So, the heat pipe is basically a passive device which basically transports heat from one section to the other and the core of it basically is a multiphase problem.

Because there is a liquid layer there is a vapour layer and then there is an interface which basically separates the two. In some cases you can also have vapour bubbles forming inside the liquid. So, if you remember the previous discussions is almost like a mixed phase here okay. So, the heat pipe is one of the key applications in space because you, it does not have any moving parts.

And it actually is very, very robust and it was very, very simple and it can actually transport very large quantities of heat okay. But this is without going into too much detail this also involves a typical multiphase problem as you can see from the diagram over there okay.

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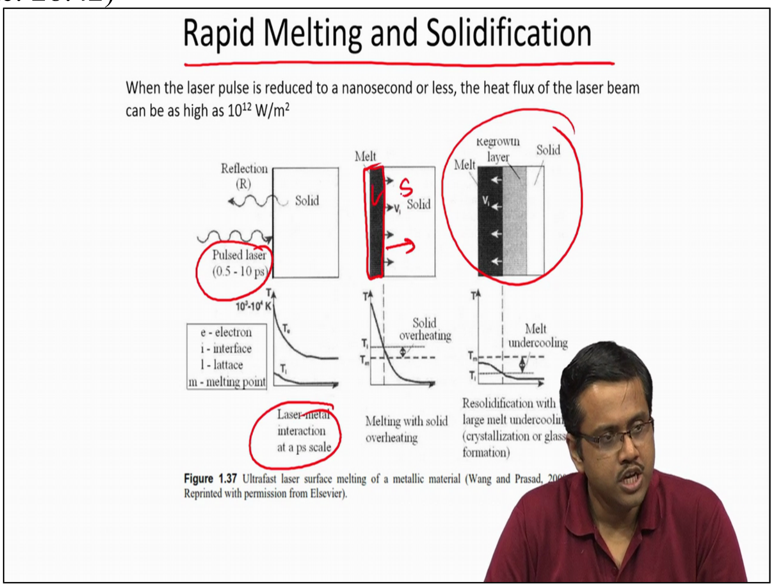

Similarly you can have other cases in which you can have rapid melting and solidification problems as well. For example in this case if a solid is irradiated with a pulsed laser. So, basically it is radiating heating. As soon as the pulse laser happens you develop a melt okay. And this melt front can actually propagate depending on the heating forget about these parts right now. Because these are not important we will come across to these parts later.

But this is one of the major things that is used in the laser heating of solids and melting of solids or laser metal interaction at very small time scales is an important problem that has that is there in many of the industries for processing as well as for manufacturing industries okay. So, this also involves as you can see a liquid solid interface okay. So, this entire thing as you can see over here okay also involves this kind of problems.

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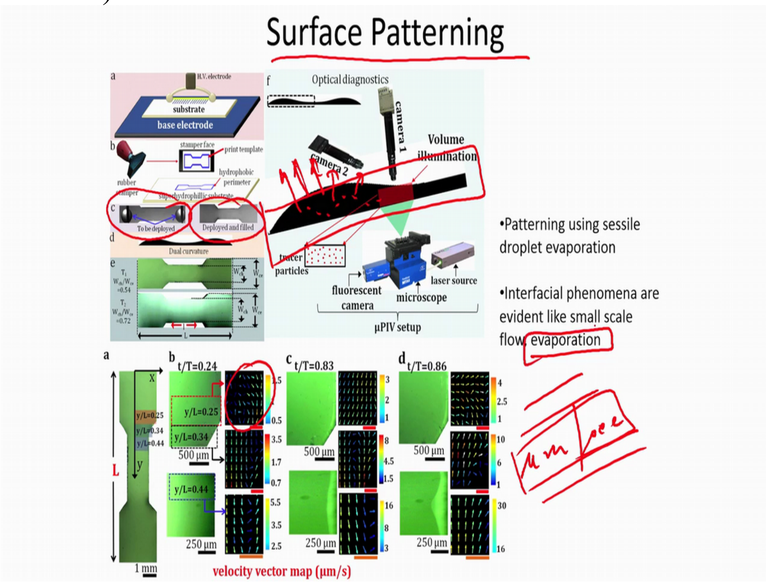

This is a for example another problem from our work which is called surface patterning. What is being done over here is that you basically deploy puddles of liquid or droplets essentially like in the form of a circuit okay. It looks exactly like this okay. Now this particular fragment of liquid actually evaporates.

This is of course got functional materials whatever is the thing that is you want to pattern the surface with this liquid actually evaporates when the pattern gets deposited on the surface in a particular shape and size. Of course this particular problem because it involves evaporation it involves flow like that we have shown over there in micrometer scale.

So, this is slow in micro meter per second scale. In the gas turbine the flows are highly turbulent. So, that the order of the flow is like hundreds of meter here, we are going into the micrometer range. So, the micrometer flows micrometer per second flows are there okay and it also involves evaporation as it evaporates it leaves behind this kind of patterns that you can see over here on the surface.

So, you can generate patterns at different scales just by using a liquid template. So, the liquid template over here involves interfacial phenomena like evaporation and flow. So, at this particular point we want to emphasize that we have covered in the first lecture; we have covered that what are the examples of the different multiphase system.

Of course we have not gone into the details. But we have seen that they can be; these multiphase systems can be extremely complicated they are very diverse. This is not just one particular area. So, it involves from electronic industry to power generation industry to chemical processing industry to any industry that you can think of this multiphase systems are only present everywhere okay.

So, it is important to know about the nature of this multiphase system. To know the nature of this multiphase systems in lecture two what we are going to do we will start looking at the thermodynamics of the multiphase systems with a little bit of recap of the thermodynamics that you may have learnt earlier. And we will particularly look at how it applies to the multiphase systems as such okay.

So, we end lecture 1 over here. We now will go on to lecture 2 to look at the thermodynamics of the multiphase system. Thank you.