Convective Heat Transfer

Prof. Saptarshi Basu
Department of Mechanical Engineering
Indian Institute of Science, Bangalore

Lecture – 04
Introduction to external forced convection

So, welcome to lecture 4. So, in the last lecture what we did was we covered the basics of the conservation equations we found that why convective heat transfer is important across multitude of applications. Now in this particular lecture we will first start with an interesting concept called heat lines and we will see what that is this was first coined by professor Adrian Bejan and since then it has been used in several books and several lectures. After that what we are going to do we are going to take our first canonical problem.

So, we will first look at like flow over a flat plate what the flow over a flat plate looks like and how we can analyze the whole thing using the conservation equations that we already derived.

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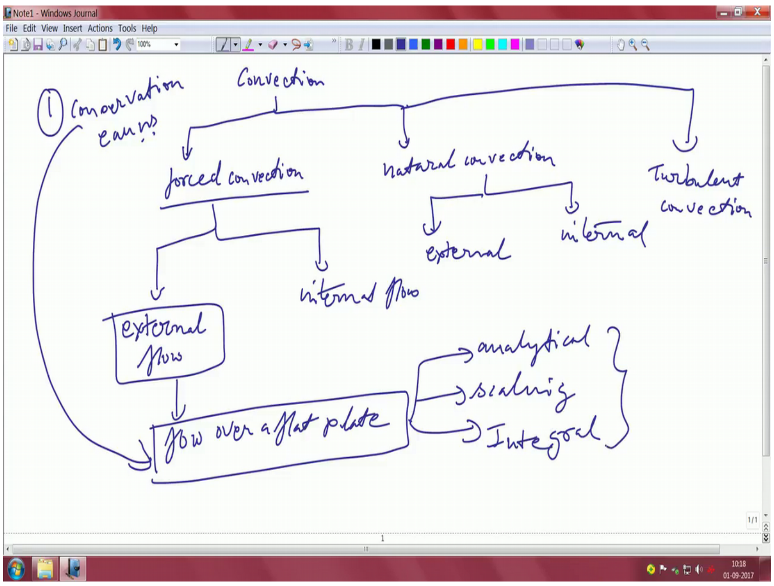

Now, the basic if you look at the ppt or the journal. So, convection the course structure will be we will first do what we call forced convection. This is the convection under the influence of something it can be pressure gradient velocity gradient whatever it is. We will also cover a class of problem after that called natural convection natural. Convection is like essentially buoyancy driven.

So, under forced convection there are basically 2 parts. That we will cover in details, one is a external flow and this is where the flow over a flat plate comes into the picture and different varieties of external flow and then there is a internal flow. Internal flow is like flow through pipes channels in closed channels things like that. Similarly, natural convection will also have 2 parts we can have external you can also have internal and then we are going to look at that turbulent convection.

So, that will give you an idea that how the course will be structured. So, we have already covered like our stage 1. The conservation equations are already done because these conservation equations form the basis of any subsequent work that we are going to do. So, under external flow we are going to first take today later on during the lecture we are going to take flow over a flat plate. The most canonical problem that you can get and different varieties of flow over a flat plate or flow over an inclined plate variations of that. Now this is very important because that will enable you to see that how from conservation equations we can use to solve this particular problem. And as I said our methodology will be 3-fold we will use analytical.

We will use something called a scaling concept and then we are going to use something like semi analytical in this case it will be integral approach. So, that is how it is going to be structured. So, first before we go to the flow over a flat plate let us first look at the concept of heat lines. So, heat lines is an interesting concept as I say it which was first introduced by Adrian Bejan.

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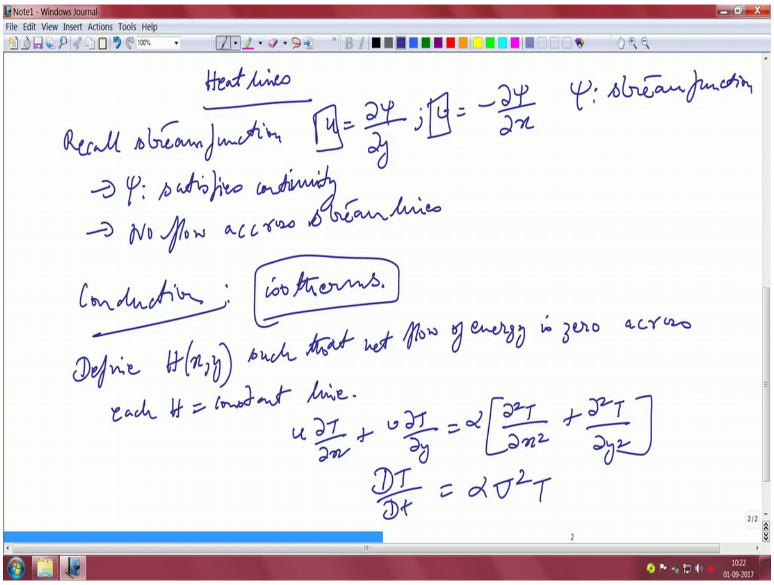

So, let us see what heat lines are. Now the heat lines if you recall the your analysis of stream function, if you do you recall something called a stream function any fluid mechanics book this will be very common right recall stream function, what is stream function?

Stream function is written something like this right. Where shy is basically your stream function isn't that. So, correct. So, u is the x component of the velocity v is the y component of the velocity. Now why is stream function used it is used for basically visualizing the flow field and as you know that the stream function automatically satisfies the continuity there cannot be any flow across a stream line. So, stream functions this satisfies continuity correct, that is the first thing and no flow across stream lines these are some of the concepts that you already know from your fluid dynamics course.

But however, in conviction things becomes if we want to represent like we represent the flow using stream functions or stream lines. Is there some analogy in convective heat transfer also where we can represent the heat flow in a very similar way? Now conventionally in conduction how do you represent the heat flux through the isotherms, that is how you do it through the isotherms. So, the heat flux heat flow is always perpendicular to the isotherm locally perpendicular to the isotherms, but that is for no flow condition.

So, the isotherms is an effective way of representing the heat flux or the or the temperatures. So, long there is no flow, but when there is flow the isotherms no longer represent the same. So, let us. So, following professor Adrian Bejan define something called H x y such that this is an arbitrary definition such that net flow of energy in this case heat is 0, across each H equal to constant line. So, this is exactly similar to the definition of the stream function. In the stream function this H is basically shy and there is no flow mass flow across the shy equal to constant line.

So, each stream line is represented like that like shy equal to constant here there is net no net flow of energy across those whatever is called this function H which we are going to call it as the heat lines. Now how do you evaluate this heat function then, if we call that stream function let us got this heat function and whatever for constant H equal to constant lines are basically called heat lines, like shy equal to constant lines are basically called stream lines. So, how is this going to be evaluated? So, let us look at the basic definition, that is basically what we wrote in the last class remember this is nothing but the conservation equation.

So, this was basically that DT by Dt correct is equal to alpha square T. Discarding viscous dissipation viscous dissipation effect and any heat generation. So, discarding those 2 this was the equation that was there earlier this is the same equation that we are using now. This is the basic conservation of energy equation written in this particular way.

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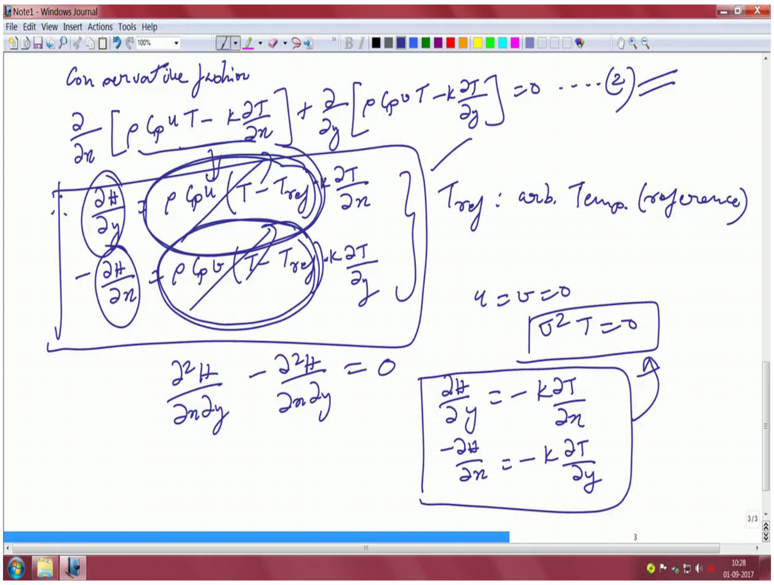

Now, if we write it in a conservative way. Conservative way means incorporating the conservation of mass. So, let us write it in the conservative fashion. Let us call this equation something say 2 while the previous one therefore, then we can name it as equation one perhaps this can be equation 1 this is definitely equation 2.

So, this is the conservative form of writing the energy equation right. So, therefore, let us define this d H by d y this is not enthalpy this is the heat function remember that always. So, this is written as sorry T minus some T ref k dT d x similarly minus d H by d x recognize rho C p v T minus T ref k Dt dy got it. So, the main form of this particular equation if you can see over here is that we have written it in a conservative fashion and then all we are doing is that we are casting this in terms of another variable.

So, that is what we are trying to do over here. So, there will be this minus I am sorry minus here so that is how this is written. Now in this particular problem if you look at it what is T ref? T ref is any arbitrary temperature any arbitrary reference temperature. So, this is a reference value can be anything that you want to put that is basically to take care of the constant all.

So, that the constant because when you are differentiating into one once more you need a constant right. So, it can be also taken as the lowest temperature of the system. Now when you look at this particular equation you will find that it automatically satisfies too this definition. If you plug this in over there it will automatically satisfy the definition because it will become d H square dx dy that will be one of the term.

The other term will be so equivalently they will be equal to 0. So, that is what you are going to get if you define it in such a way. So, basically it is the interior that we have represented it in this particular fashion. So, this satisfies what we call the conservation of energy. So, to say like the stream function satisfies the conservation of mass this satisfies the conservation of energy. Now if there is no u and v; that means, you go to the situation where it is a purely conduction driven problem. The advection term disappears. So, advection term disappears means you basically get this to be equal to 0.

So, this is basically your conduction equation correct that you already know. So, then in that case what it becomes d H dy becomes minus k dT dx all right because this part is gone. Similarly, minus d H dx becomes equal to minus k dT dy because this term will be gone. Again, identically you will find that this will satisfy whatever the conservation equation the conservation equation is this right now, because there is no velocity component. So, in this particular case the heat lines becomes the same as the isotherms it becomes almost the same the definition is just the same like your velocity potential stream function is the same definition once again comes over here.

So, this gives us a very composite idea so in the limiting case where there is no flow it is basically becomes the same as your isotherm concept, but when there is flow you have actually these additional terms which comes into the picture, do you see this terms these additional terms comes into the picture, which basically represents deviation of the lines right. So, it is no longer the same as your isotherm.

The convective heat transfer mode represents all these deviations these additional terms which comes due to the velocity component only. So, this is a useful way if we want to visualize. So, if you plot this H now in a flow field you should be able to describe the heat flux or the heat lines or the flow of heat rather quite imaginatively because it is exactly like the stream function with all the problems that the stream functions also have got it.

So, this is a useful way of starting the thing, though this is not frequently used in the literature because we still use the temperature field even now, but in some case if you want to know the flow of energy. Then this particular concept becomes very useful. So, let us look into the next one, which will be now we will go to the external flow.

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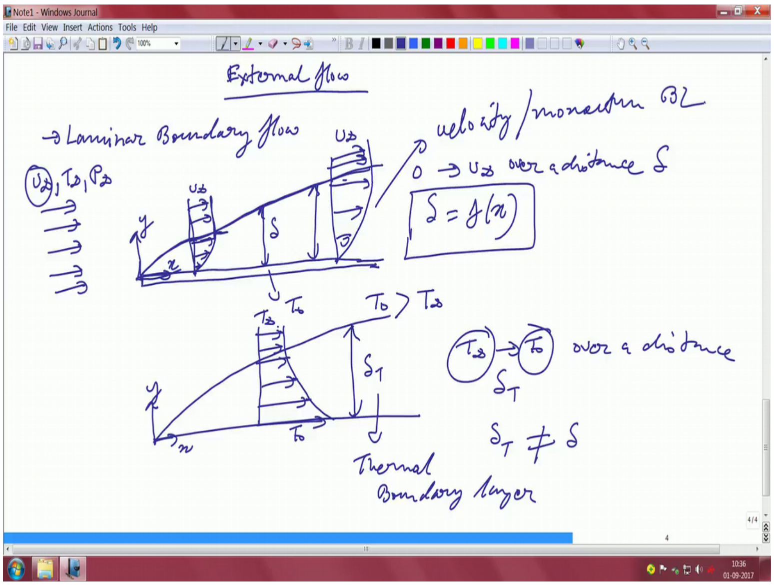

So, external flow here we will introduce a few concepts. So, first concept will be the laminar boundary layer. So, all the flows from here on will be kind of laminar unless otherwise mentioned. So, it is a concept of laminar boundary.

So, the simplest case that we can think of let us consider this as a flat plate which continues it is a very long flat plate fix our coordinates here which is x and y. There is a flow uniform flow which is approaching the plate. So, the situation is like this you have a plate which is being held. So, if you look at the screen you will see that there is this is like a plate and it is being held in the flow field with the flow going over this plate. So, there is a flow going over a heated plate or a cold plate it can be either one of them. So, in one case heat will be transferred from the plate to the free stream or it can also receive heat from the free stream into the plate depending on the situation.

So, let us take this temperature of this plate is T naught. T naught is any temperature and this flow is approaching the plate at a velocity U infinity T infinity and P infinity, where these being the free stream velocity, free stream temperature, free stream pressure. Our coordinate starts from x y which is at the leading edge of the plate this is called the leading edge of the plate. So, as the flow comes and encounters the plate what happens if you have taken a course on what we call the laminar boundary layer or viscous fluid flow. You will know effectively what happens that the plate immediately slows down the fluid which is in the vicinity of it the fluids, which are actually very close to the plate or on the plate actually comes to a desktop because of the no slip boundary condition.

So, the fluid cannot move over the plate the fluid layer which is sitting on the top of this plate particular plate. So, what we start to develop is what we call the boundary layer. So, the boundary layer is what actually develops so if you look at once again the presentation you will find that this is how the boundary layer actually looks like. So, this is how the boundary layer develops forgive my drawing it is develop something like that.

Now so the velocity what happens is that this is the boundary layer where the effect of the plate is felt; that means, the viscous effect of the plate is felt very close to this boundary layer and this layer is given by delta. So, this delta is some number we do not know what that number is as of now so this is the distance over which the flow actually senses that there is a plate and the fluid actually slows down progressively.

So, if you look at the typical velocity profile anywhere within the plate what you will find is the following. So, let us take this as the edge so the fluid velocity is basically 0 at the surface of the plate. It progressively increases just by a little bit till it reaches the edge of the boundary layer which is delta over here and after that it becomes equal to u infinity. So, above the boundary layer the flow velocity is the same as the free stream velocity, whereas at the surface of the plate the flow velocity is equal to 0. So, it goes from 0 to U infinity over this distance l. So, the flow goes from 0 to U infinity over distance delta.

Now, this delta is not a constant. It is actually a function of the distance from where you are measuring. So, it should be a function of some x. So, it should be it wherever you are measure for example, delta here is; obviously, more than the delta here. So, this delta here of course, I have shown that it increase so it increases in a certain way this delta. So, it is a function of the distance from the leading edge from where you are actually measuring the whole thing correct. So, this is how the velocity profile actually looks like. So, progressively if I draw the velocity profile over here it will look something like this, and at the free stream it will become U infinity.

So, that is how the velocity profile actually looks like. So, it once again goes from 0 to U infinity over a distance delta. So, in this particular case let us assume one other thing that the plate is heated. So, T naught is greater than the T infinity which is a free stream. And so, the incoming temperature incoming flow incoming pressure or all constant. So, they are all uniform is only after they encountered the plate the velocity profile starts to show something like that. So, what will happen to the temperature profile. So, this is the same thing that I am redrawing once again this is the same x and y remember T naught is greater than T infinity. So, at the surface of the plate what do you think the fluid temperature will be it will be the same as the temperature of the plate because they are in thermal contact with each other.

So, once again you will get a profile which is similar to this all. Whereas, this is the profile. So, here it will be T naught and it will be T infinity at the edge. So, once again it goes from T infinity to T naught, over a distance let us call that distance delta T, this delta T is not the same as delta we will see soon see y in some cases it can be, but in most of the cases it is not. So, once again we get a profile something like this if you look at it. So, here also we see that over this distance delta T. The temperature goes from T infinity to T naught. So, this particular variation of delta T, this is called the thermal boundary layer. This is the region where the temperature field sees the effect of the plate this is called basically the velocity or the momentum boundary layer clear up to this part.

So, as we can see there are 2 takeaways as soon as the flow comes in contact with a plate first the momentum gets affected. Similarly, the temperature also gets affected this as we saw that the momentum from the conservation equation the momentum field is in built all right into the temperature field. So, as soon as a momentum gets influenced the temporal also gets influenced, but they do not get influenced over the same length scale all right one is delta, one is delta T.

Whether they are same or they are different that we will see slowly later, but there are 2 distances. One distance across which the momentum effect is felt; that means, there is a plate the flow senses that there is a plate beyond this distance delta the flow senses that there is nothing. So, it is almost akin to the case that if you are if you are walking in a very crowded place.

So, let us say there is a particular shop which is selling a lot of say there is a sale going on so there is a lot of people who has converged. So, if you are very close if you are passing by that shop you will feel that there is something that is going on. So, you feel that effect, but then if you are if you go away say over 500 meters you do not feel anything that there is a shop there is a sale going on things like that. So, here essentially the same thing is applicable here the flow does not sense that there is a plate. So, similar with temperature similar with respect to the momentum in both cases beyond the certain distance the plate neither sees the temperature of the of the plate; that means, there is no heat I mean it does not sense that there is a heated plate placed at the flow field and same happens in the case of momentum as well. So, that is the most important takeaway concept over here.

So now if that is the thing let us look at that why this entire thing of boundary layer and other things are important from an engineering perspective. Yes, there is a boundary layer, yes there is a region over which the flow and the temperature profile do get affected what as an engineer if you are an engineer, if you are looking from an engineering perspective, you might want to ask the question why do I need to know all those things. Cannot I get away with the whole thing and not bothered that there is some layer over which the flow and the temperatures are affected. These layers are very small actually they are very small compared to the extent of the plate. So, if the plate is big length scale l this is at least one order; that means, at least 10 times lower than the length scale of the plate.

So, to give you an analogy if this is one meter long this will be one tenth of a meter that also is putting too much, but it is restricted over a very small length scale, regardless of what that value is that is different, but we know that the it is only over a certain distance over which it actually influences a small distance. So, from an application engineer point of view you want to know why is this important at all. I might as well not bother about all these things. So, the application 2 questions that the application engineers have to answer.

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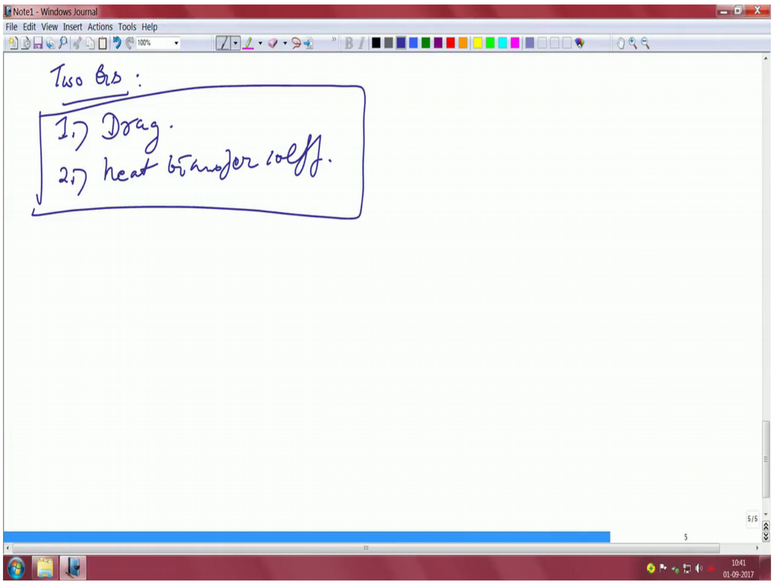

And I would put these 2 questions in bold as an application engineer you will be bothered with it. One is the drag and one is the heat transfer coefficient. Why the drag is important if there is a plate in a flow field you want to know what is the drag on this plate because say if you are designing a submarine, if you are designing a boat, if you are designing an Aeroplane, whatever it is that you are trying to design drag is the main important thing because drag means that there is a resistance to the flow; that means, you are feeling a resistance your aircraft or whatever that is you are designing.

You are facing some kind of a resistance. So, to overcome that resistance you need to spend some energy you need to put fuel and things like that. So, drag is the actually a quantity that determines that how much money you are going to put in. Similar goes for the heat transfer coefficient ask any engineering guy they will be interested any industry guy they will be interested what is the heat transfer coefficient that you have. So, heat these are all compiled in those nice handbooks that you have right there if there is a plate the heat transfer coefficient will be this.

So, these correlations are required for a design engineers point of view from a thermal design engineer. He wants to know what is my heat transfer coefficient if the heat transfer coefficient is high i will design it in a certain way if it is low i will design it in some other way. So, these 2 questions as you will appreciate forms the fundamental questions that any thermal systems engineer or any engineer as a matter of fact working in this field we will need to answer. Is this linked with the boundary layer question; that means, is this linked somewhere that you need to know about the boundary layer to know about this drag and heat transfer coefficient you bet yes.

So, in the next lecture we will see that how this actually translates that how to answer these questions, you need to know that how the boundary layer actually behaves. So, we will see you in the next lecture starting from here.