Convective Heat and Mass Transfer

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Module No. # 01

Lecture No. # 02

Flow Classifications

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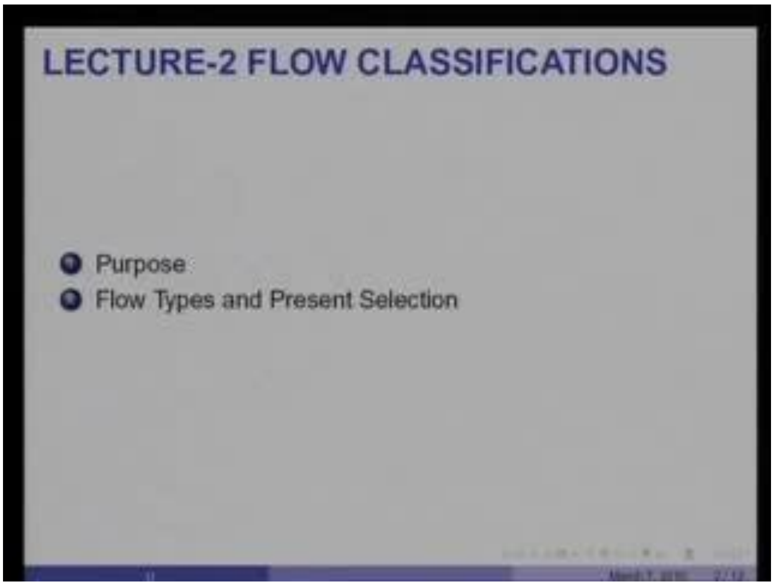

In this second lecture, called flow classification, I will first explain the purpose of the lecture, then tell you something about the vast scope of convective heat transfer through the flow types and how we are going to select from this vast canvas only a few situations that are of still practical interest.

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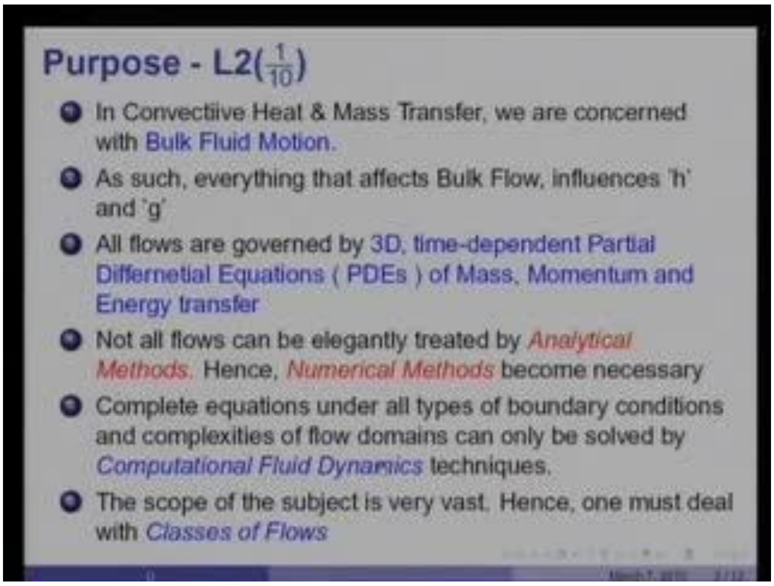

So, in convective heat and mass transfer, we recall that we are concerned with Bulk Fluid Motion. As such, everything that affects bulk flow influences heat transfer coefficient - h and the mass transfer coefficient - g.

All flows are governed by three-dimensional, time-dependent Partial Differential Equations of Mass, Momentum and Energy transfer. But not all flows can be elegantly treated by analytical methods.

Hence, we require numerical methods to solve these equations. The complete equations, under all types of boundary conditions and complexities of flow domains, can only be solved by the technique called Computational Fluid Dynamics. It will solve the entire three-dimensional, time-dependent Partial Differential Equations.

Therefore, the scope of the subject is very vast in terms of its physics, in terms of applications and in terms of mathematical complexity.

We need to reduce this complexity so as to make it tractable through about 40 lectures in a classroom situation. Therefore, what I am going to do is to classify the kind of flow situations that are of interest, and from this, I will give you the selection made for this particular course.

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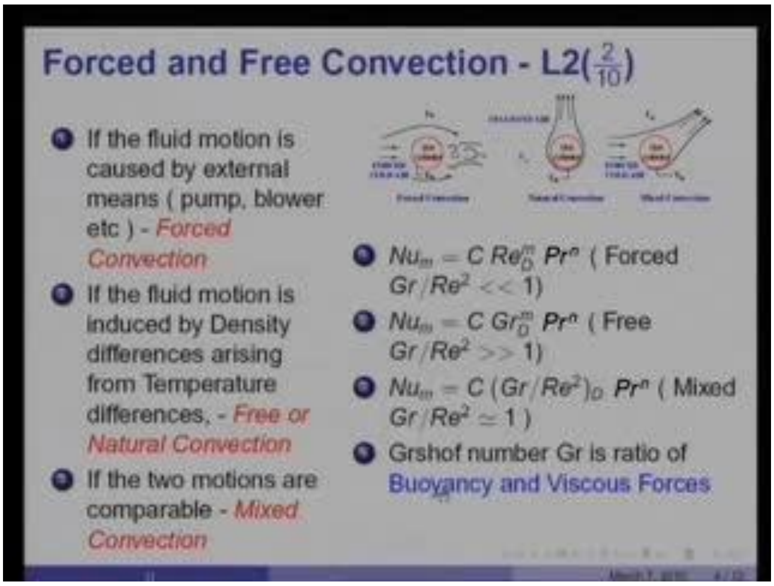

The first step of flow classification is well known to you - called the forced and free convection. So, consider a hot cylinder, say a tube or anything like that, across which the cold fluid is flowing.

If the fluid motion is caused by external means, such as pump, blower, etcetera, we call it forced convection heat transfer. In this case, the temperature differences are such that density differences due to temperature differences induce very little or no motion at all.

The entire motion is really driven only by the power provided by the pump or a blower, as a case may be. Such a situation we call heat transfer by forced convection. On the other hand, if this cylinder was kept in stagnant air, you would see the fluid motion would still because but it will be upwards, acting against gravity – g, which is downwards.

Since the cylinder is hot, the density near the cylinder is low and the temperature of the stagnant air is very low; therefore, its density is high. As a result of the density difference, the lighter fluid simply climbs up against the action of gravity. We call this natural convection. In moving past the cylinder in this manner, it picks up heat and transfers it to the ambient. So if the fluid motion is induced by density differences arising from temperature differences, we say the situation is completely free or is a natural convection situation. But many a times the external flow is not high enough to suppress all motion due to density differences, and in such a case, we would have the two motions which are comparable.

Such a situation would result in the net flow downstream of the cylinder going somewhere to the northeast. It is a combination of northward flow in natural convection and eastward flow in forced convection; therefore, it would claim somewhere northeast.

Such a situation we call mixed convection. Now, of course, you have come across experimental correlations of this type, Nu from the cylinder- the Nusselt number from the cylinder- would be constant into Reynolds number, raised to the power m, Prandtl number to the power n. And this we say is a.

In this situation the Grashof number divided by Reynolds number square is very small. In other words, all natural convection motions are suppressed and we have essentially forced convection.

In this situation, we have Gr by Re square is very much greater than 1. In fact, the forced convection does not even exist and therefore, when the Grashof number divided by Reynolds square is very large we say it is a natural convection situation.

If Grashof by Reynolds square is of the order of 1 then we have a mixed convection situation. In natural convection Reynolds number gets replaced by Grashof number; whereas, in mixed convection both Grashof and Reynolds are present and Prandtl number, of course, is present in all cases.

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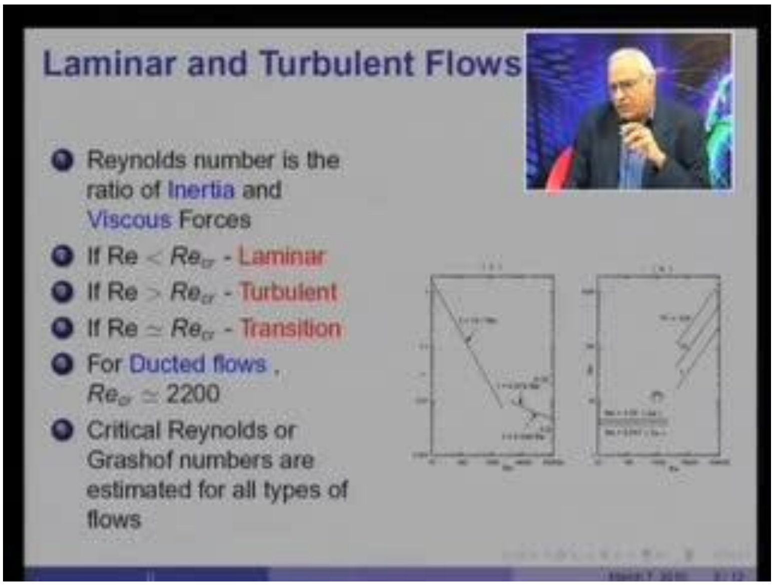

The Grashof number Gr is the ratio of the buoyancy forces and viscous forces. Most often we are interested in forced convection heat transfer.

Reynolds number is an important criterion. Reynolds number is the ratio of Inertia forces to Viscous forces. As you all know, when the Reynolds number is less than critical Reynolds number, the flow in the tube will be laminar and the friction factor versus Reynolds number relationship on a log log plot would be linear.

It is f equal to 16 divided by Reynolds number- a very well known solution to laminar flow inside a tube.

If Reynolds number is greater than Reynolds critical, then we have turbulent flow- the friction factor would be doing that.

For these two cases, the heat transfer would look something like this- the Nusselt number would equal 4.36 if constant heat flux was applied at the wall; it would be 3.67 if wall temperature was kept constant.

All this is known to you in laminar flow. Notice that the Nusselt number is independent of Reynolds and Prandtl number, in an and it is essentially a constant. But as soon as the Reynolds number exceeds the critical Reynolds number the Nusselt number becomes a function, both of the Reynolds number as well as of the Prandtl number.

What about the in between region we call the critical region or the transitional region, in which the laminar flow essentially is converted to a turbulent flow? For Ducted Flows as you all know, Reynolds critical is about 2200. In the range, say, about 2200 to 3000 would be the critical Reynolds number range.

Like critical Reynolds number, there is also critical Grashof number in natural convection. So in all kinds of situations that we will be studying, critical Reynolds and Grashof numbers have been experimentally studied. Theories exist to estimate them, but usually the theories fall far short of what is expected from experimental results.

It is extremely difficult to identify all causes of transition to turbulence and theories can only capture some of the if a cause is or transition to turbulence

So laminar and turbulent flows, as well as the transitional flows, are important classifications from the point of view of convective heat transfer. In fact, many of our equipment is deliberately run in the transitional Reynolds number range. Simply because it is in this range that there is a very sudden increase in heat transfer range.

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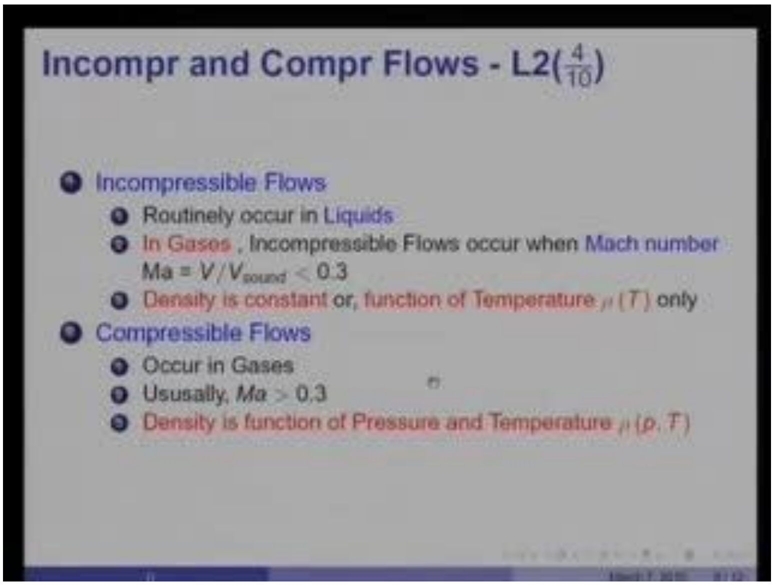

A third classification is Incompressible and Compressible Flows. Now, of course, Incompressible Flows routinely occur in liquids- we all know liquids are Incompressible.

The distinction is really applicable to gaseous flows. In gases, we say the gas flow is Incompressible if the Mach number- defined as the velocity of the fluid divided by the velocity of the sound in that fluid- is less than 0.3.

Since you know that in ambient temperatures the velocity of sound in air is about 300 meters per second, what we are saying is, under ambient conditions, if the velocity was less than about 100 meters per second, the gas flows could be considered as being Incompressible.

Now of course, it so turns out in majority of our heat exchangers and other equipment, gaseous flows are indeed at low velocity- having velocities much lower than 100 meters per second. Therefore, gaseous flows can also be considered as Incompressible as far as practical convective heat and mass transfer equipment is concerned.

There are applications like in gas turbines, combustion chambers and in turbines. You do have situations where Mach number could exceed 0.3, but then, we are not at the moment concerned with such an extreme situation.

What is implied in an Incompressible flow is that, the density is either constant or it is a function only of temperature. If it was a forced convection situation, of course, the density variation with temperature would be very small.

But if it is a natural convection, then the density variations would be significant. In Compressible Flows, which occur mainly in gases, usually Mach number is greater than 0.3. Mach number would be equal to 1 for sonic Compressible Flow; it would be greater than for supersonic flows. Main distinguishing feature of a Compressible Flow is that the density in this case is a function of pressure and temperature both. Not only temperature, but both pressure and temperature. Remember, Compressible Flows occur only in gases.

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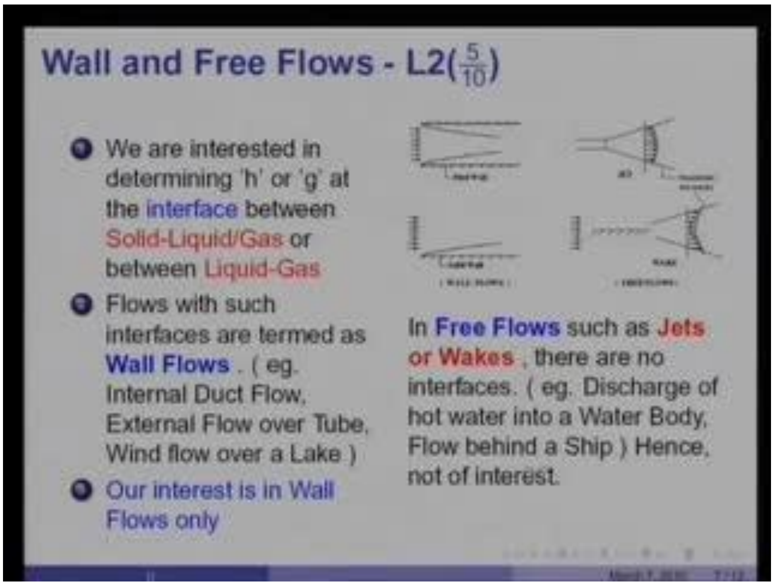

Another important consideration is Wall Flows and Jet and Free Flows. Remember, we are interested in determining h and g at the interface between a surface and a fluid flowing past it.

The surface may be solid or liquid, and the fluid flowing past it may be liquid or a gas. So, naturally we are only interested in flows which are bounded by walls because it is only there where heat transfer coefficient is defined.

But in fluid mechanics one also is interested in what are called Free Flows- such as those that are formed in the form of a jet, say, air issuing or a gas issuing from a nozzle or a wake- that is, a flow behind a ship would be a wake flow.

These flows of course, are not bounded by walls but nonetheless, one can identify an imaginary surface in which significant velocity variations occur. Therefore, it is of interest in fluid mechanics but not so much in convective heat transfer simply because there is no bounding wall, and our interest is in determining h and g which are defined only at the bounding wall.

The flows with interfaces are termed as Wall Flows. Internal Duct Flows, External Flow over a tube, Wind Flow over a lake etcetera are examples of Wall Flows. And our interest is in Wall Flows, as I said, but not in Free Flows such as jets and wakes, because there are no interfaces. The examples are jet discharge of hot water into water body and flow behind a ship etcetera- these are not of interest.

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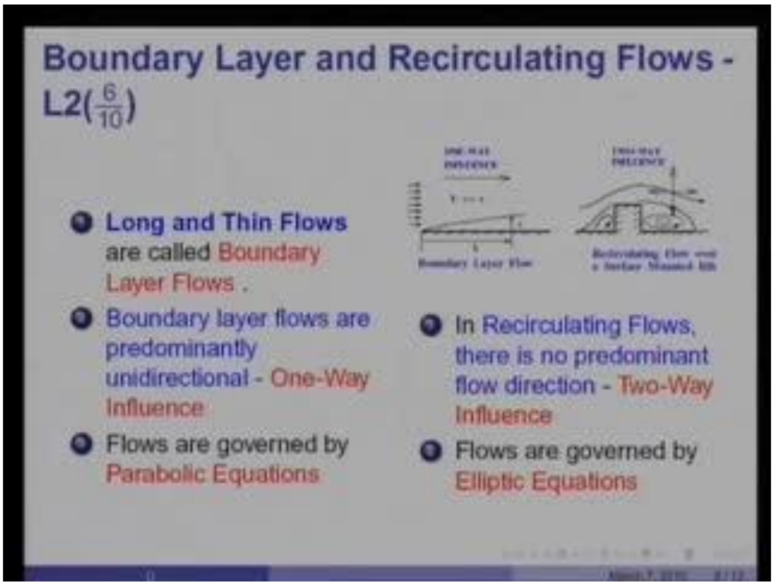

Then there is the very important classification called the Boundary layer flow and a Recirculating flow. Boundary layer flows are flows that are long and thin. That means, if you consider a surface past which a fluid is flowing then the viscosity affected region would be very thin- of the order of delta, and the dimension x would be far greater than delta. So we call such flows- long and thin flows. The velocity - u also would be considerably bigger than the velocity - v. Because of the predominantly unidirectional flow, they are also sometimes called one-way influence flows. By this we mean, in the predominant direction of the flow, the conditions at a cross section would be influenced completely by the conditions upstream of that cross section.

Conditions downstream cannot influence the conditions at this cross section x. Therefore we call them one-way influence flow. But, for example, consider now a case of a surface on which a rib has been mounted; then, although the predominant direction of the flow is this way- close to the surface where heat transfer is taking place, you would have the recirculating regions. In these regions, of course, as you can see, the influences would travel both from downstream as well as from upstream.

And therefore Recirculating Flows are often called two-way influence flows. As we go along we shall note during mathematical treatment, that Boundary layer flows, because of their one-way influence are governed by parabolic partial differential equations; whereas, the Recirculating Flows are governed by elliptic partial differential equations

By and large it would be fair to say that it is extremely difficult to obtain exact analytical solutions to elliptic equations; whereas, at least some progress can be made in obtaining analytical solutions to parabolic equation. Therefore, we would largely concentrate on situations that are governed by parabolic equations.

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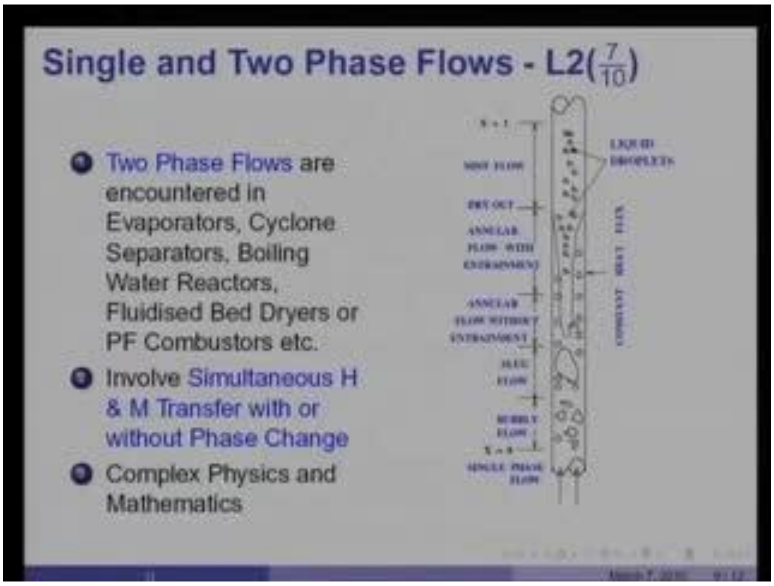

Then, of course, the single and Two Phase Flows; this is of course of great interest in mechanical engineering- particularly in boilers. What happens in boilers is that you have, say, single phase water entering at the bottom of a tube and heat transfer by radiation and convection- as we saw in a p f furnace. Heat flux is falling on this surface.

As a result of this, first nucleation sites would be established when the temperature of the wall increases and small bubbles of vapor would begin to form and they would penetrate inwards into the core of the flow. Such a zone is called the bubbly flow regime.

As we go downstream, the temperature of the wall continues to rise and the number density of bubbles also increases. So much so, that some of the bubbles actually coalesce with each other and form large bubbles which are, sort of, confined and surrounded by smaller bubbles.

The large bubbles move like slugs and therefore, such a region is called the slug flow region. If you go further down the tube, you will see the slugs get elongated and bubbles continue to be formed at the water surface.

So we have inner core of vapor- long inner core of vapor- and a thin outer core of liquid interspersed with tiny bubbles. Such a flow is called annular flow without entrainment- that means there is no fluid entrained in the core.

But if you go further down, you will find the interface between the liquid water and the water vapor becomes very unstable and it causes rupture of the interface: sputtering out water droplets into the core of the flow. So water vapor and water droplets, sort of, coexist in the core of the flow, while the water still surrounds the inner surface of the tube. Such a situation is called the annular flow with entrainment where the water droplets are getting entrained into them.

If you continue to heat further, you will see a situation is reached where nowhere in the cross section is any liquid water found, and you essentially have the tubes in contact with water vapor only.

Now, as a rule, the heat transfer coefficient- the magnitude of the heat transfer coefficient in gases and vapors- is much lower than the magnitude of heat transfer in liquids.

As a result of this there is a sudden drop in heat transfer coefficient near what is called a dry-out point. And, as a result of that, the temperature of the surface of the tube would rise very suddenly to a very high value.

So much so, that sometimes even a tube might melt. So the objective is, of course, to make sure that such a situation does not arise in practical equipment and that the temperature is maintained well below the meltdown temperature of the surface.

So, post dry-out, you essentially have very tiny droplets which appear like a mist in an essentially vapor flow. And still further downstream, you will see all these droplets would be converted to water vapor and the dryness fraction of steam would be 1; whereas, it was 0 at the bottom of the tube.

So essentially, then you have flow with phase transition from liquid water to complete vapor. But in-between there are regions of two phases- water and water vapor. In the bubbly flow- the dense phase, the water phase dominates the vapor phase; as you move towards slug flow, the lighter phase- the vapor phase, begins to dominate the flow.

When you go to these annular flows, vapor flow vapor phase occupies a much bigger volume than the liquid flow. Then, when you come to the mist flow region, of course, the vapor phase almost completely dominates the liquid phase. And beyond x equal to 1, of course, you have the purely water phase.

So, such Two Phase Flows are extremely complex in their physics because there is a continuous change in the structure of the flow; there is a simultaneous heat and mass transfer accompanied by phase change.

But then, there are also situations like fluidized bed dryers or pulverized fuel combustors and so on and so forth in which phase change takes place. Particles from solid phase move into gas phase coupled with chemical reaction.

You have situations of cyclone evaporators, you have situations of evaporators, cyclone separators, situations of evaporators, boiling water reactors, fluidized bed dryers- all these are situations involving simultaneous heat and mass transfer with or without change. Extremely complex physics and mathematics are involved.

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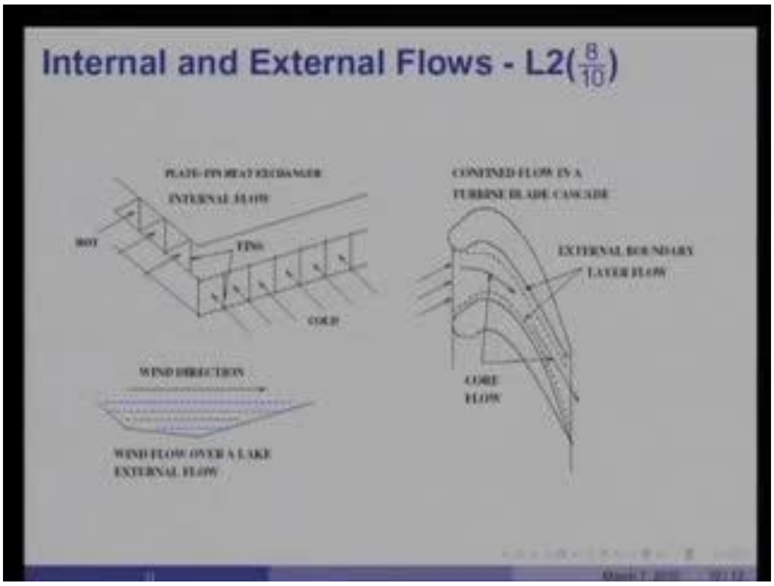

Whereas, in Single Phase Flows, the physics is relatively much more simple. Yet another classification is Internal Flow and External. I said we are interested in Wall Flows, but there are varieties of Wall Flows.

Internal Flows are those we call Ducted Flows. So, for example, here is a case of a twin fin heat exchanger or a plate fin heat exchanger. In this: there is a plate at the top, plate in the middle, plate at the bottom.

Between the bottom two plates the flow is from southeast; whereas, in the top two plates the flow is from southwest. There are also the plates separated by means of fins which are forming triangular cross sections here, whereas here they are squared cross section.

I show this because normally our understanding of a duct is that it is a circular tube. as you go up in shell and tube heat exchanger But you can get ducts of a variety of shapes- triangular, square, rectangular or elliptical and so and so forth.

Such flows are called Internal Flows because they are bound on all sides by a solid wall. But as I said, if we consider Wind Flow over a lake then clearly that interface is between water surface and the wind; we have a situation of a flow bound by wall on one side- that is the water surface, but on the other side it is a completely free expanse. Such a flow we consider External Flow. These two are very easy to understand, but in mathematical modeling sometimes we actually treat a confined Ducted Flow if you like, also as an external flow. Where does that happen?

For example, if you consider a gas turbine then the turbine blades are mounted on a disk at prescribed pitch. Such a situation is called a cascade of blades and the oncoming flow will flow through the passage created by the pitch.

The flow would enter so and would leave the turbine blade from near the trailing edge. Of course, from heat transfer point of view, what we are interested in is the heat transfer at the wall. It so turns out, that in such flows, in the core of the flow, the temperature would almost be uniform and so the velocity would be more or less uniform.

Whereas, then, greater parts of variations of velocity and temperature would be confined to an extremely thin region- close to the surface of the blade. The top surface of a blade is called the suction surface, the bottom surface is called the pressure surface. Therefore, this blade disc would move in that direction.

You will notice, because these regions where temperature gradients exist are very small compared to the total distance between the suction side and the pressure side, so much so, that for all practical purposes, we could treat this Boundary layer development on the suction surface as an External Flow in which it is bound on one side by the solid surface- the suction surface, but on the other side is a completely free expanse.

Likewise, we could treat the pressure surface in the similar manner where the Boundary layer is growing on the pressure surface- the surface is the interface where the region below the Boundary layer would be a free expanse.

Although, truly this is a confined flow, we can simplify and concentrate our attention on a very thin region. Incidentally, it is in this thin region where velocity and temperature variations take place, and as a result these variations essentially imply that there is a resistance to heat transfer and momentum transfer, and is also confined to regions very close to the wall.

Therefore, it is worth considering only those regions to obtain practical information, which is also mathematically much more easy to track. So the classification of Internal and External Flows is an important one, because, we often call certain External Flows, which actually occur in ducted or confined situations.

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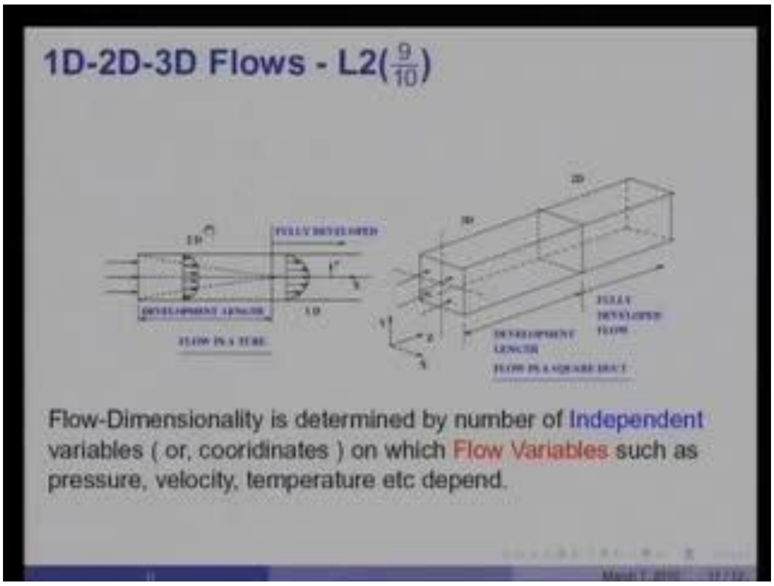

Finally, the dimensionality of the flow; this is very important. The dimensionality of a flow is concerned with a number of independent variables associated with the flow. That means, the number of independent variables with which fluid properties such as, pressure, velocity and temperature, vary.

So, in effect, there can only be the maximum number of dimensionality of a flow can be three x y and z. So, you can only have maximum three-dimensional flows.

If I consider, for example, flow in the entrance length of a tube, then you will see Boundary layer development will take place. But after a certain length, the Boundary layers will merge and the velocity profile, which was in this case function of both x and radius r, is no longer function of x at all; because, the flow has become fully developed and the velocity is a function of radius r only.

You are all familiar with these terminologies- development length and fully developed length. But notice that in this case, in the development length, flow variables such as pressure, velocity and temperatures are functions of independent variables x and r; whereas, in the fully developed region they are functions of x.

I emphasize this connection of dimensionality with independent variables because very often people think of dimensionality of the flow as being concerned with the number of velocity components, which is not true.

For example, if I had a swirling flow, an axisymmetric swirling flow, it will still be called a two-dimensional flow because all the three velocity components, v x, v r and v theta are functions of radius and actual distance.

The third dimension is not involved, because we are talking about an axisymmetric flow.

So, the development length flow is two-dimensional but the fully developed flow is only one dimensional in the flow in a tube.

But if you now consider flow in a non-circular section tube, like, let us say, square section tube, you will have development length in which Boundary layers will glow on all four surfaces and the flow in this region would be three-dimensional.

But once you reach fully developed flow, then the flow velocity would be function only of the cross sectional coordinates y and z and therefore the flow will be essentially two-dimensional. So, dimensionality of the flow changes within this same tube or a duct and it is very important that we appreciate the differences between flows in association with the dimensionality. By and large, one and two-dimensional flows are relatively easy to track than three-dimensional flows in classroom situations.

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Scope of the present lectures the- all the things marked in blue are the ones that I shall be concentrating on, while making very brief references to those which are marked in black.

The first classification is between forced and free convection; I will be largely dealing with forced convection. There are Laminar and Turbulent Flows including transitional flows, I will consider all those types. There are Incompressible Flows and Compressible Flows. I will be largely confined to Incompressible Flows; because, as I said in most of the equipment, particularly in mechanical engineering, the Boundary layers are, I mean, the flow velocities are essentially less than about 100 meters per second.

We will all only be concerned with Boundary layer type flows. Essentially, flows with predominantly one-way influences, simply because they are mathematically much easy to track in a classroom situation.

Recirculating Flows require numerical methods and use of computer and I will therefore not be dealing with Recirculating Flows in the classroom. Wall Flows- by definition, since we are interested in heat and mass transfer coefficient- we will only be concerned with Wall Flows and not with Free Flows.

And then, as I said, Two Phase Flows are very complex to handle analytically and therefore I would deal essentially with Single Phase Flows. Finally, again one and two-dimensional flows will be emphasized because they are simpler to handle analytically; three-dimensional Flows will be ignored.

In the next lecture, I will continue with the laws of convection.