Introduction to Flight
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Lecture No. 04.1
Viscous Flow and Reynolds Number

Welcome to the 5th lecture which is the beginning of capsule number 3. In this capsule, we are going to continue further our discussion about fluid mechanics. So, this particular capsule is called as basic fluid mechanics part 2. And in this we will look at two lectures. Today we discuss some fundamental phenomena in fluid mechanics. We discuss viscous flow, Reynolds number and boundary layers.

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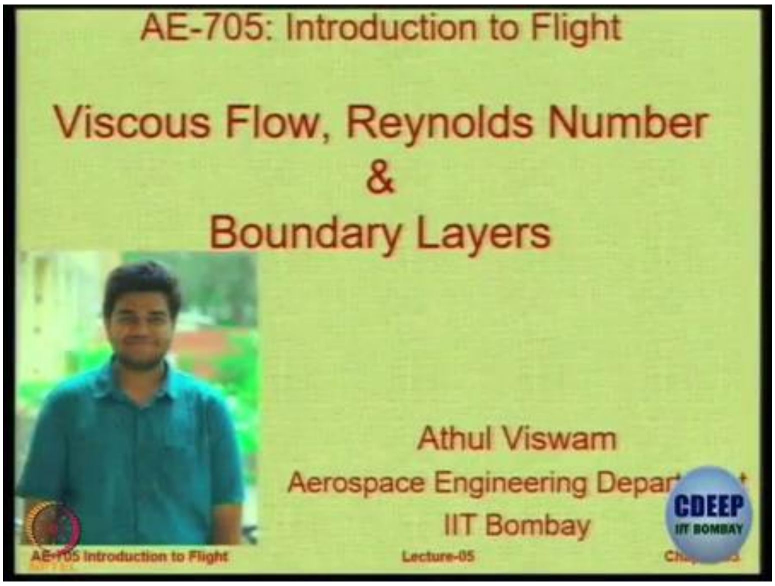

The bulk of the content for this lecture has come from this student Athul Viswam, who is a third-year undergraduate student from aerospace department. He undertook the same course AE-152 last semester and during the summer he has been helping me in creating content for this course, so this particular capsule, the first lecture has been created by Athul. So, thanks to Athul for helping me out.

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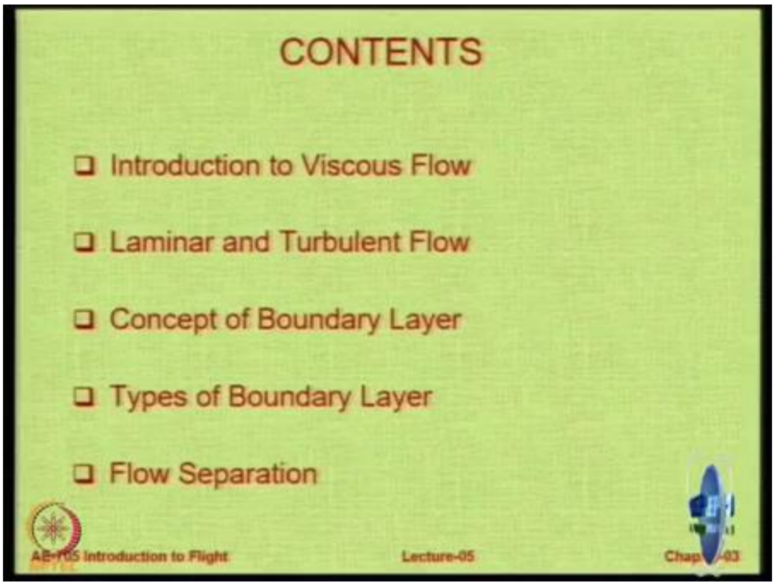

Let us look at broadly, what is our road map for today. We start with the introduction to viscous flow and then we proceed to the consequences of viscosity in the flow, which is a laminar and turbulent flow. We then proceed to the concept of boundary layer, which follows automatically from a discussion regarding viscous flow. We looks at types of boundary layers. There are 2 basic types as most of you know, we just have a close look at them and finally we look at flow separation. So, this is the roadmap for today's presentation.

Let us start with a very simple experiment. And in this experiment we are going to see the behaviour of a few fluids.

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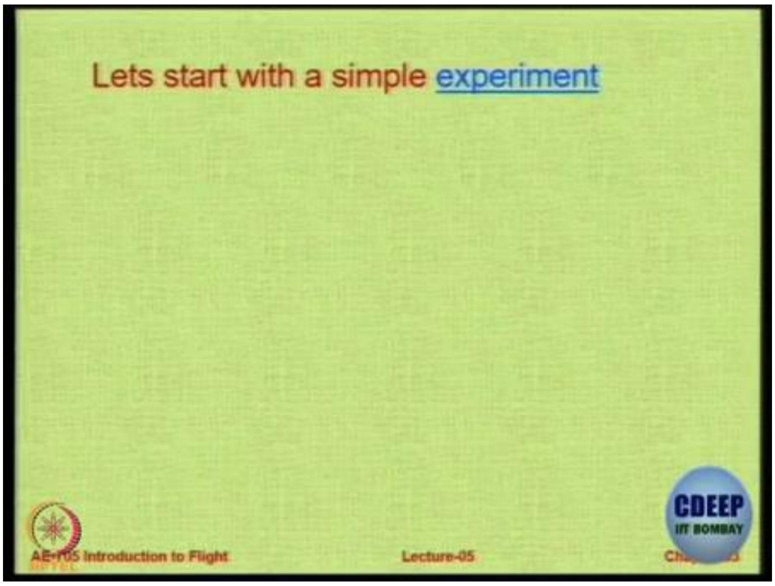
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So what do we see here?

Video: We drop a marble into the water.

Professor: We see four jars filled with four different liquids and in each of them we drop a small ball.

Video: Next, we drop a marble into the corn syrup.

Professor: So, in the third one again we are going to drop the same ball.

Professor: So look the colour can be deceptive.

Video: And lastly we drop the marble into the honey.

Professor: And the last one is the one in which it will take the maximum time to reach down. Okay, so four jars identical with four liquids. But there is a difference in the behaviour. So, the question is why is there a difference in the behaviour of the same ball in the same jar, just because of the presence of the fluid? Okay. And the reason for that, is because some fluids are thick and some fluids are thin.

When you drop a ball in thick fluid it takes more to go down, when you drop it in thin fluid then it goes much faster, okay.

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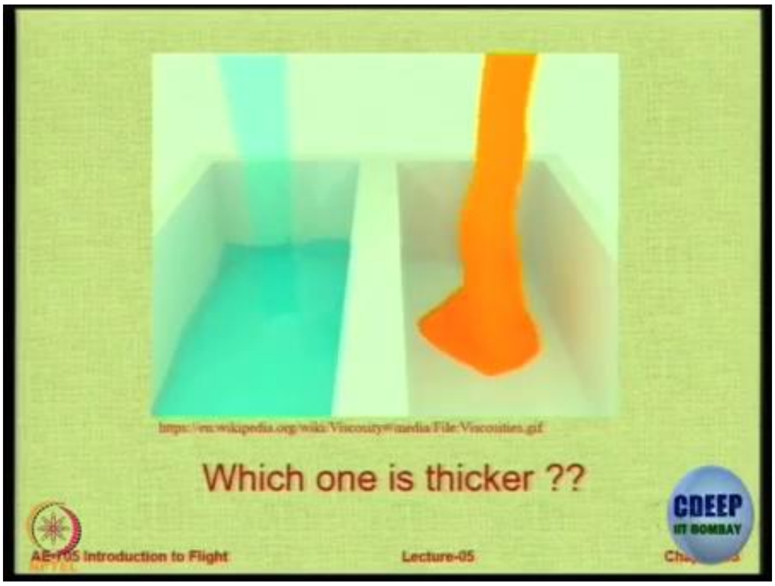

Alright, so here is another animation which shows two containers in which two fluids are being dropped. We notice that in one container on your left, the light blue coloured liquid it flows rapidly and tends to fill the container very quickly on the other hand we have this orange coloured fluid which takes much more time to occupy the volume of the container. So which one is thicker? It is obvious the one which is orange in colour is thicker because it is taking more time to fill in.

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Okay, so recently we had a very interesting race in which, the worldwide hero lost out to Justin Gatlin, but this is just to revive old memories. This is the world record winning race.

Professor: 9 comma, says the speaker. 9 point 58 seconds. Okay, so just like we have these runners who run we also have particles in a fluid that run against a resistance.

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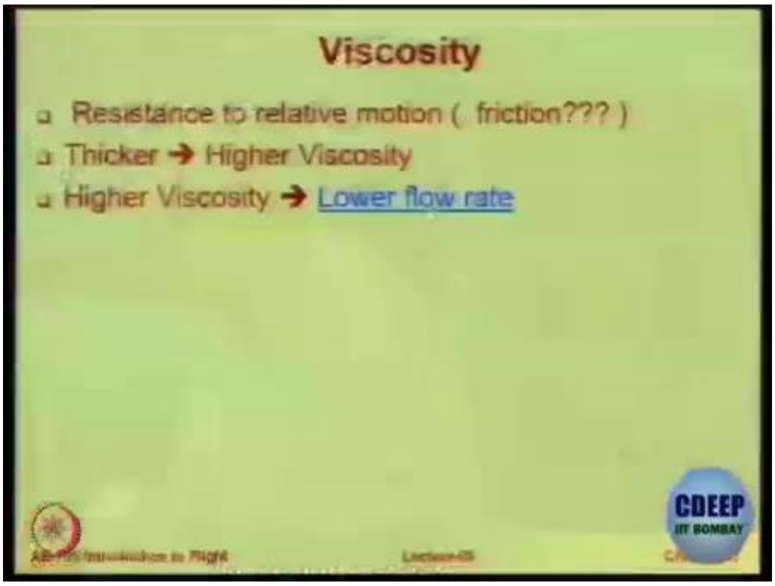

So let us see and let us see how viscosity the property of the fluid helps us. So, essentially what is viscosity? Viscosity is basically a property of a fluid. And this property manifest itself through a resistance to relative motion, okay. Primarily because of friction, okay. So, if a fluid is thicker, it will have a higher viscosity. If a fluid is higher viscosity, it will have a lower flow rate. Let us have a look.

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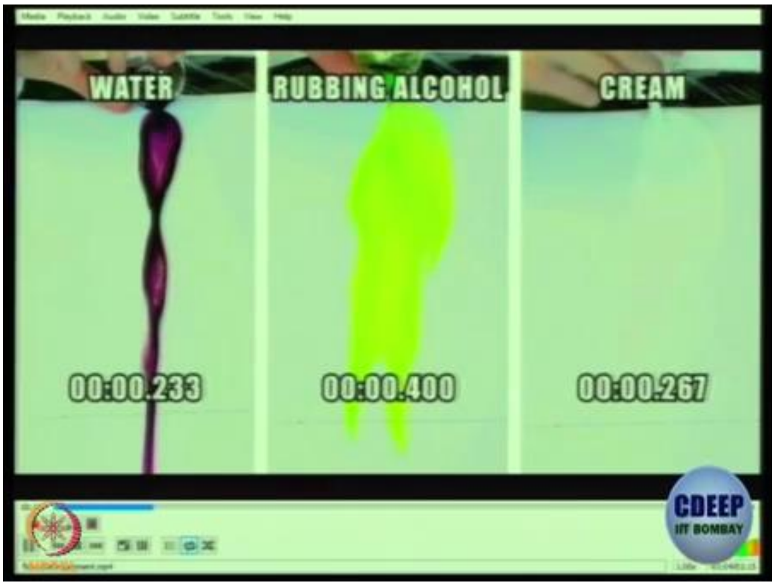

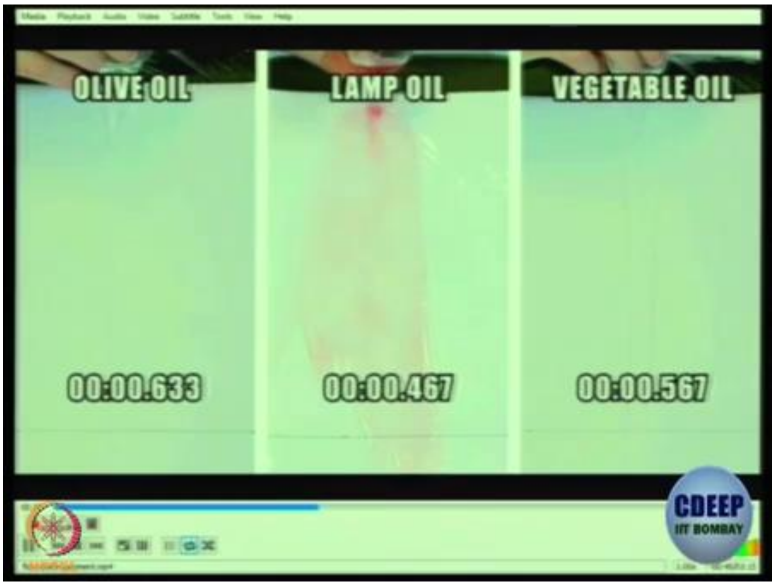

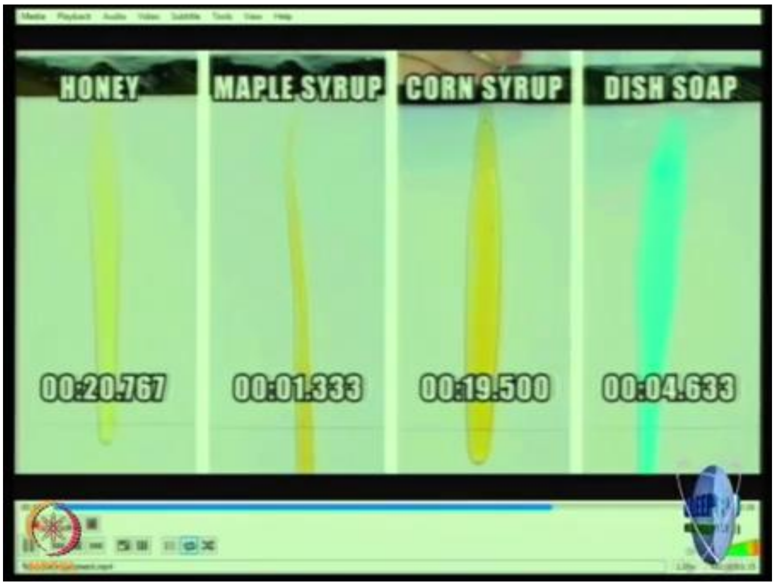

Video: Now we measure out equal proportions of our ingredients into our little containers.

Professor: So you have these small containers.

Video: In the first two of our race, we have water, rubbing alcohol and cream. Water finishes first with the time of point 233 seconds and rubbing alcohol finishes last with a time of point 4 seconds. In the second heat of our race, we will be racing olive oil, lamp oil and vegetable oil. Lamp oil finished first with the time of point 467 and olive oil finished last with the time of point 633 seconds. In the final heat of a race we are going to be racing honey, maple syrup, corn syrup and dish soap. First to cross the finish line is maple syrup with a time if 1 point 33 seconds followed by the blue dish soap with the time of 4 point 633 seconds and then slowly but surely the great corn syrup crosses the line with a 19 point 5 seconds, and then finally honey with a 20 point 767 seconds. Here are the results of our race.

Professor: So just like we saw the race between athletes, you have a race between fluids.

Video: Water cross the finish line first meaning that it has highest flow rate and lowest viscosity. Honey was last across the finish line meaning it has the lowest flow rate and highest viscosity.

Professor: Okay, so Usain Bolt basically is water goes fastest. All right, now a question throughout this presentation when you see this particular symbol, we will ask a question and I would like you to ponder over this question and answer using the moodle page. Do not answer here. This is the question to be done. So, the question is just like we have viscosity of fluids, Gases are also considered to be fluid. So, do gases also have viscosity and can you get some information maybe some videos which shows the viscosity of gases and the effect of the viscosity of gases on the floor. So, that is homework.

Proceeding further, now it is it is good to know about viscosity and now let us do some basic calculations about viscosity using the Bernoulli's principle about which we have studied.

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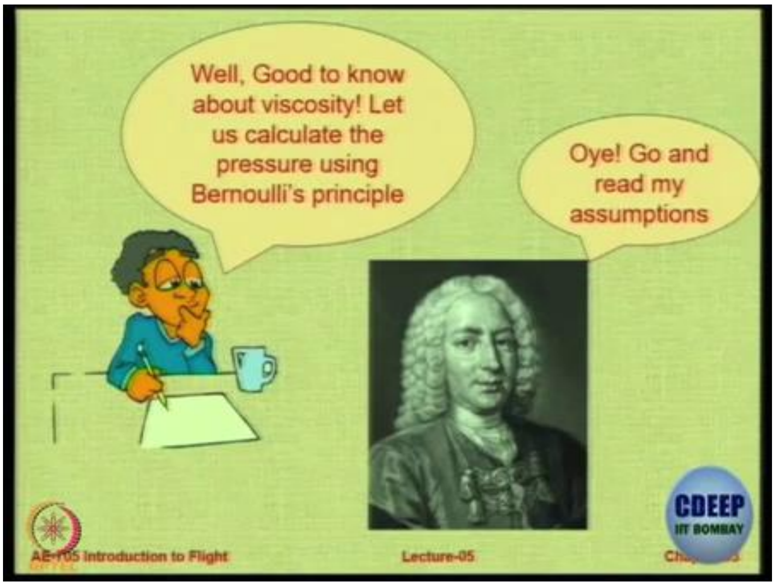

So to do that basically we just have to go and read the assumptions. Now this was a question in one of in the in the quiz last time. What are the assumptions under which the Bernoulli's principle is valid and one of the choices was that the fluid has to be non-viscous, okay. So does Bernoulli principle apply when the fluid is viscous? So, we have to go and check out.

Okay. So let us look at first the most fundamental flow which is the flow in a pipe. In this video we are going to colour the flow a using a small dye and the speed of the flow is going to increase with time so you can see you can see the effect of that.

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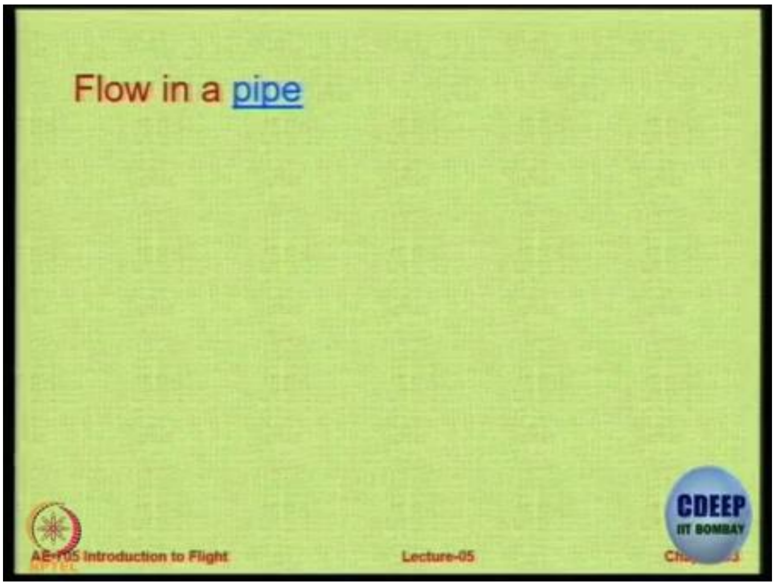

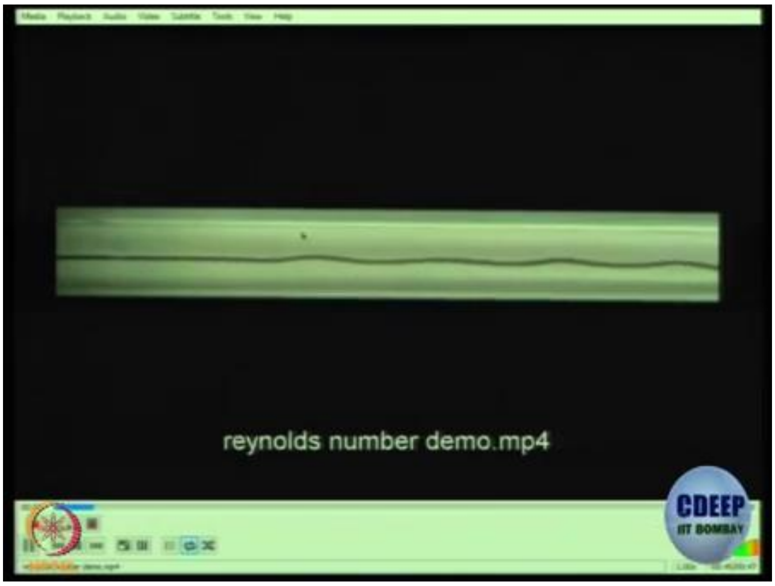
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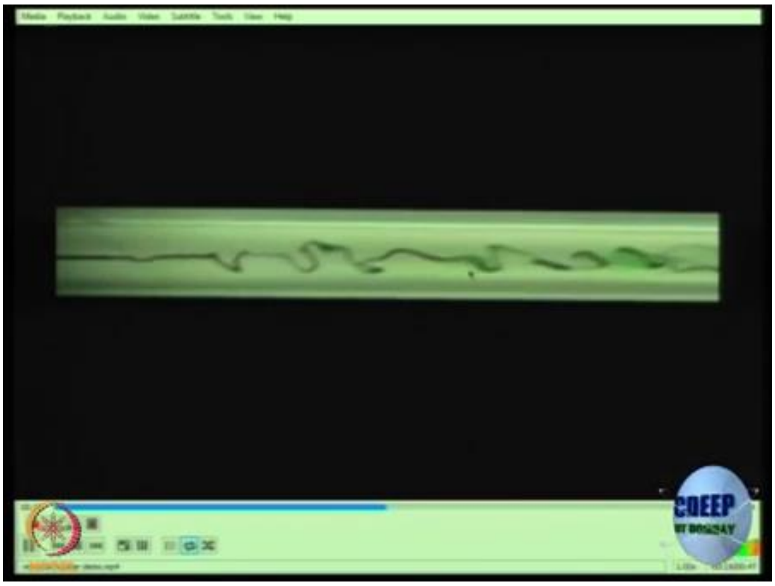

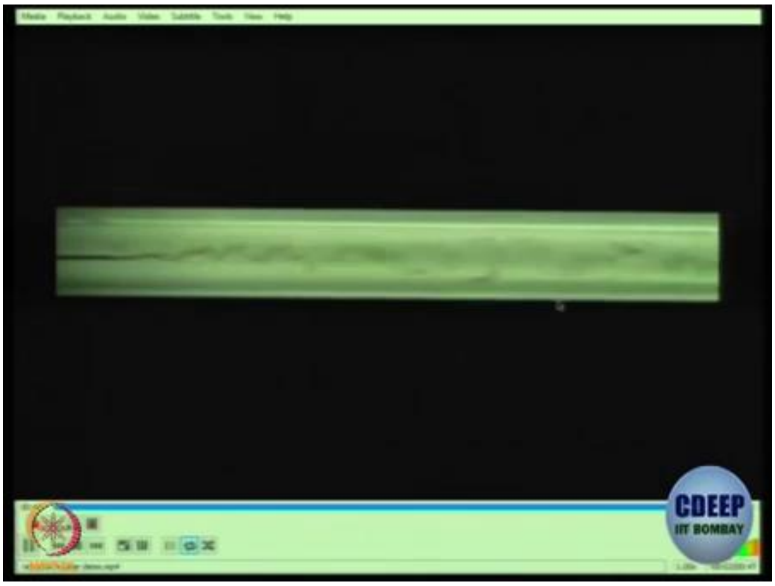
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So this is low speed flow, at low Reynolds number which are not defined so far but I will define very soon, slowly the speed of the fluid is increasing. So you can see that the pattern behind the pattern as you go ahead is changing. Much higher speed flow the pattern changes much more rapidly, but you can see there is oscillatory structure and to some extent that is some uniformity in the structure.

But as you increase a speed to a very large value, then there is a lot of dissipation of this fluid. And you can see there is a very high level of mixing of the dye in the water. Let us watch it once again from the beginning. Low speed flow hardly any oscillations if they are, there are they are symmetric and they are of low amplitude as the slow flow speed increases these oscillations become higher and higher in amplitude, okay. The structure is now this is actually unsteady flow because it is time varying and what are you seeing are the stream lines, streak lines, path lines or time lines. What are these? These are stream lines?

Student: streakline

Professor: These are streak lines. Correct. Okay, so what we see is that the velocity of the flow in a pipe affects the flow pattern. So when you have very low speed flow. Then you have what is called as a laminar flow. Which has little or no oscillation when you have a much higher speed flow you have a flow called as turbulent flow where as you saw a lot of mixing takes place and there is a particular speed for a given pipe dimensions. Beyond which the flow converts itself from laminar to turbulent.

Okay, so what about external flows? This was inside the pipe. So, over an aeroplane wing which does not have any border on the top and the bottom. Do we have do we have a possibility of laminar flow over the wings? So, this is another question on the moodle. Can we encounter laminar flow in actual airplane wings? If the answer is yes, you have to give proof of that. It could be a video from a reliable source. It could be some kind of a photograph or a paper or a publication anything that we can depend on.

Please remember there are many frivolous things on the internet also. For example one most common problem that you see is people showing the working of Bernoulli’s principle, but actually it is Coanda effect. So you will see many such videos, you have to be very careful do not believe anything that blindly some that puts such that somebody puts up. Do not believe blindly that somebody puts up on the internet, apply your own logic and justification before you post it because if you post something which is wrong, you are responsible for it. You cannot say I found something on the internet. This is not a clerical exercise where you just give a google search, you find something you post it. You have to own up to what you post and if there are mistakes, it is okay. We all make mistakes, I make mistakes. So. we can rectify our mistakes.

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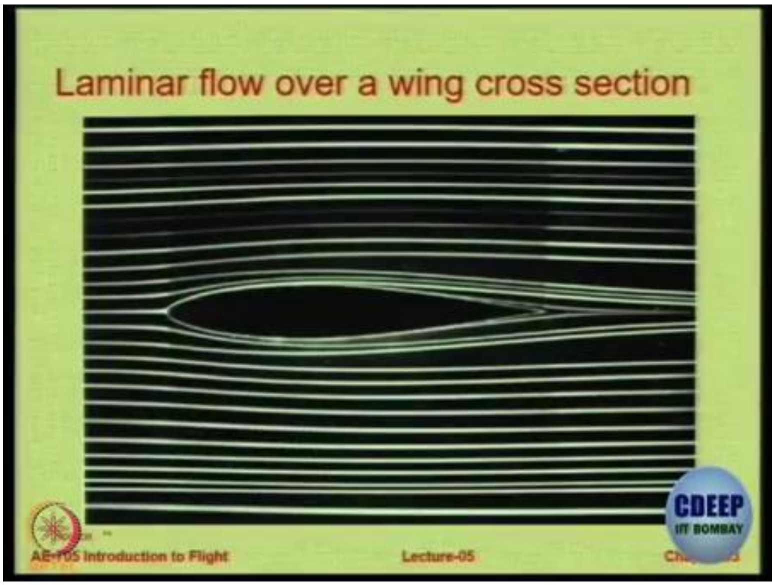

So let us see laminar flow over a wing cross section, but this is inside a wing tunnel. Okay so there are two main sources for this particular presentation. They are marked as double star and I think hash and at the end there is a slide which explains what these sources are. So, once I upload this presentation on moodle, you will have an idea what the sources are. So, you can see here, it is clear visually also that the flow is smoothly going over and below the wing. And I do not see too much of disturbance on turbulence behind, okay. So visually it seems that the flow is laminar. But remember this is in a wing tunnel. So this is still internal flow. My question was can we have laminar flow on a wing which is exposed to external flow.

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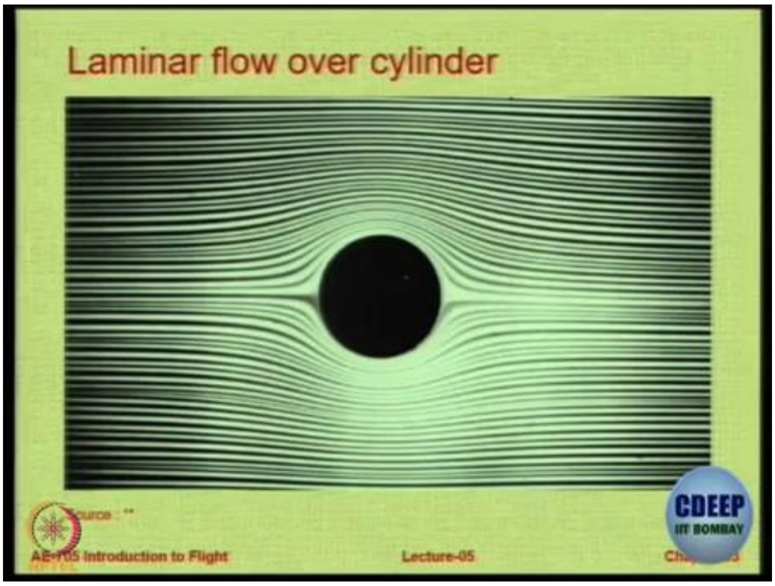

This is over a cylindrical body. So, here also it is almost perfectly symmetric. This is not a computer simulation. These are actual experimental results, but using dyes for visualization.

So here also we see that it is almost perfectly symmetrical. So here also we can assume that the flow is absolutely or almost perfectly laminar.

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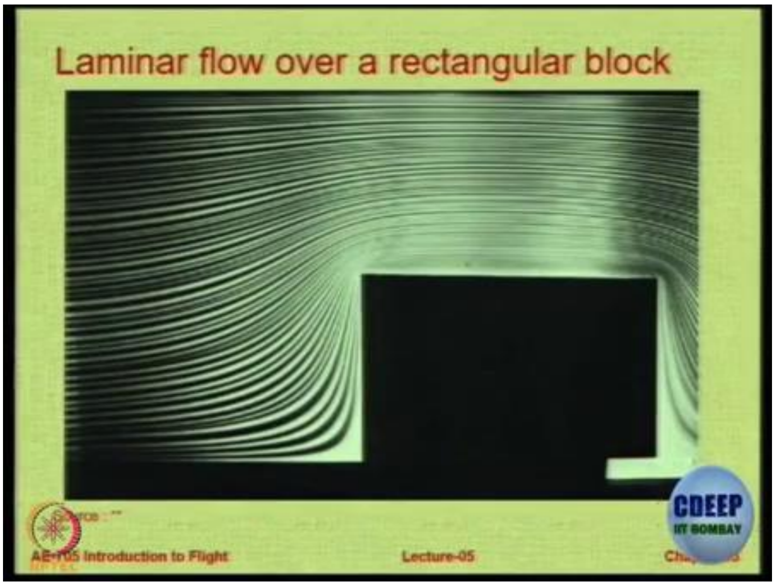

Proceeding further we have a rectangular block. And interestingly even here the flow can be laminar. So, the shape of the body alone does not guarantee or insist that the flow will become turbulent or laminar. As we saw over a wing, over a cylinder, over a rectangular block you can still have laminar flow. So, shape is important but not very very important. It is not the only parameter. There are other parameters also which decide about the flow being laminar or otherwise. Yes, mic.

Professor: Intentional, this is actually basically an experiment called as a backward facing step. So, what you see is a rectangular block, but intentionally, they have created a small gap because they also want to investigate what happens if you have let us say a water tank over a building which will have some kind of an overhang or a projection behind. So it is intentional. They wanted to study in one experiment, flow behind a rectangular body and also flow behind a backward-facing step. So, that gap is intentional. I think you are talking about this particular gap. Okay. This gap this gap is intentional and notice the flow here is flowing you do not see much turbulence still, okay. So by the law the flow is still laminar.

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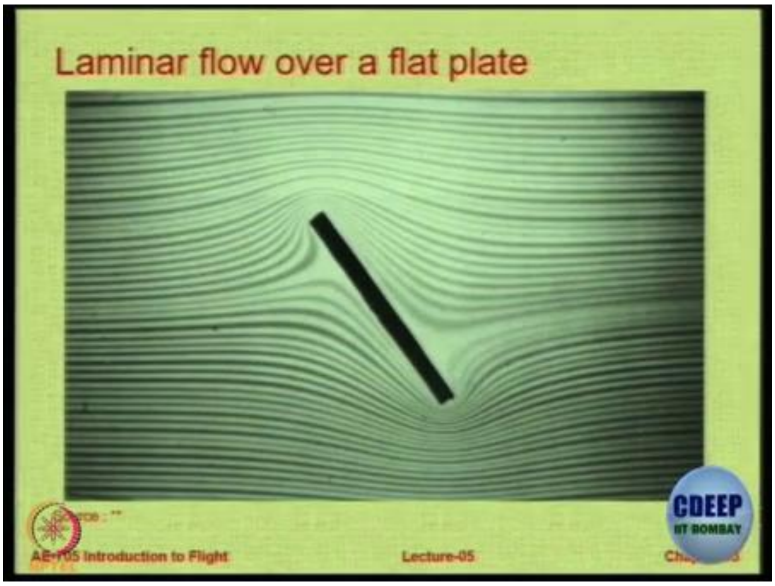

Now, let us go to the question that we had asked in the class. We had this question in the quiz, oscillating flat plate. Here the plate is not oscillating, here the plate is fixed. But at a very high angle and still you see that the flow is laminar. So this is another myth many people have many people think oh if the angle of attack or if the angle at which the body is placed is high. The flow will become turbulent. Not necessary. You can have a very blunt body. You can have a body at a very large angle still the flow can be laminar. Not always true, but can be also true. So in other words the orientation and the shape of the body alone is not responsible for the flow to become laminar or turbulent.

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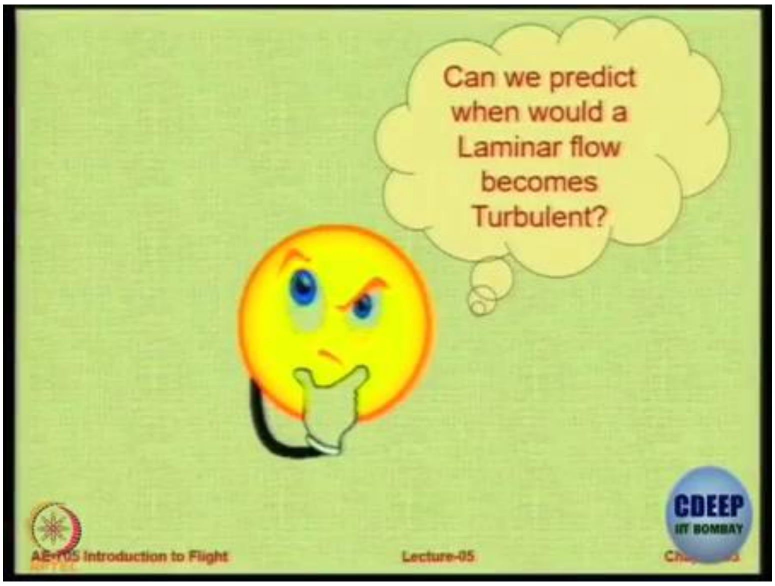

This is a question which I would like you to talk about. How can we predict, first of all can we predict when would a laminar flow become turbulent? And if the answer is yes we can predict. Then the question is what is the parameter or what is the mechanism with which you can be very sure. So, this was a problem that was being addressed by many fluid mechanics people in the beginning.

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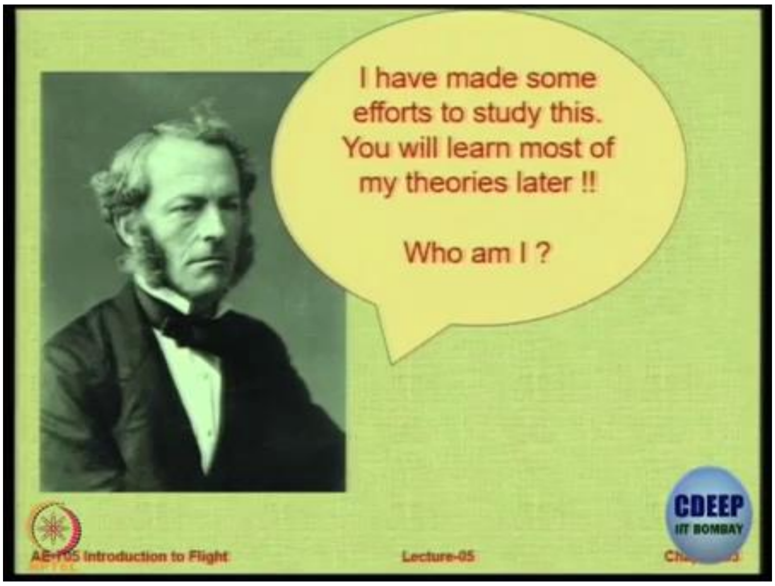

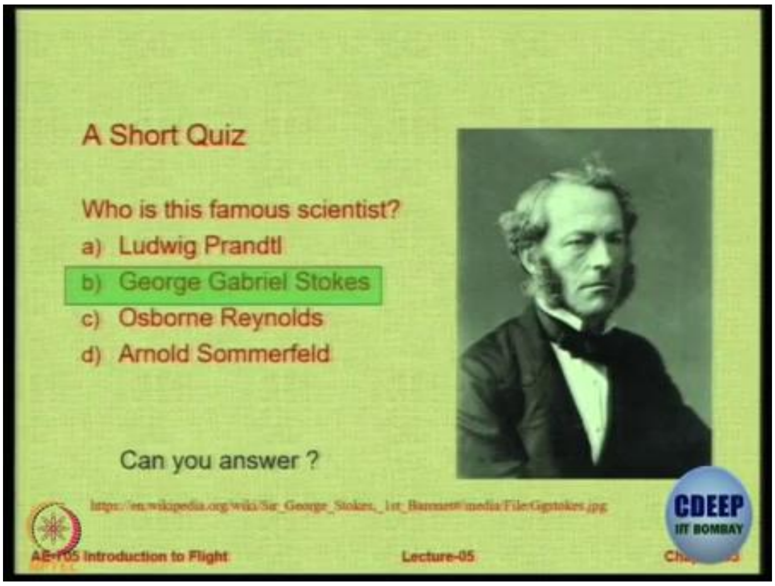

And this person he made some efforts to study this phenomena, okay and we will but then my question is who is this guy? So if you know the answer I would (urge) urge you to raise your hands. Why why let us do the following. Let us have a proper quiz, okay. So, I will give you a four choices. And I would like you to tell me, now off course all cannot be right. All may be wrong, it could be a fifth guy who did it and more than one cannot be right because if x did it y did not do it.

So, here you can use your illumination skills which you have picked up in your examinations. Right so please tell me. If somebody knows raise your hand. And obviously after two answers if they are wrong we do not want to go ahead because then you can guess. Okay. Take a mic please. If there is a mic around just tell me what do you think? Who is this person? Osborne Reynolds, the answer is wrong. This is what I expected. This is what I expected you all to answer that is why this question, because we talked about Reynolds number because we talked about turbulent flow people automatically assume it will be Reynolds.

Oh it is not Reynolds. It is a trick question. See what is a trick question. What does what does it say? It says that I have made some efforts to study. He does not say I have discovered it. He does not say I am the first person but he is the guy who actually did lot of efforts to study it. So, let us go on to yeah someone there.

Student: My name is Rahul. Sir, it is Prandtl, Ludwig Prandtl.

Professor: Okay Ludwig Prandtl. That is also a good guess but it is a wrong answer, okay. It is a wrong answer because Prandtl is a very famous name in fluid mechanics, so it is a good guess. It is intelligent guess that man was great. We call him as the father of aerodynamics. So, he must have done some good job. Maybe he did this job. So now we have only two remaining, okay. We have Arnold Sommerfeld and we have, so now can you guess? Now you have only 50 50 chance, okay. So you toss. Yeah, so the answer is Stokes. Remember the Navier-Stokes equation, he is a guy half of it, Stokes.

Also remember that is a Stokes theorem also, that is what we will study. We will study about this particular theorem later on, okay. Right, so, it is George Gabriel Stokes who was the first person to study this but he could not formulate it properly. It was Reynolds who came ahead just like Gatlin has overtaken Bolt, okay.

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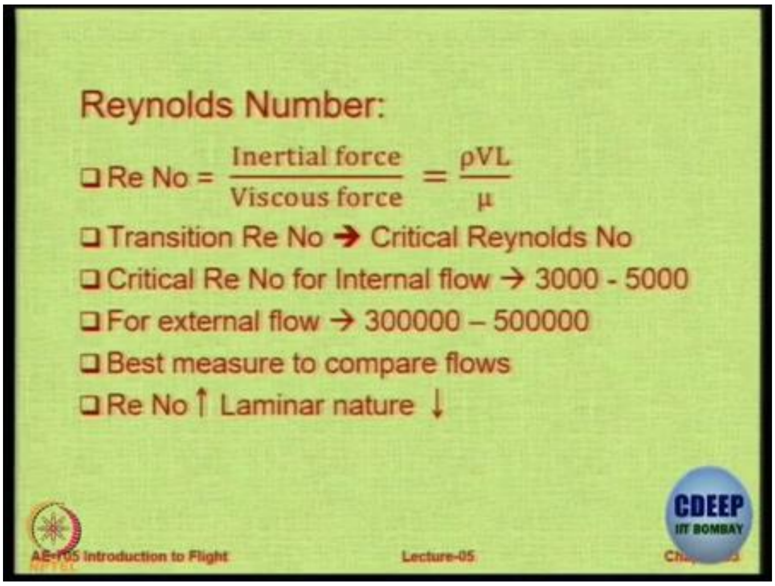

So, let us understand Reynolds number. Basically, it is a ratio. Ratio of two forces and therefore it is dimensionless. The inertial force which resists the motion because of inertia and the viscous force which creates a resistance to the motion, okay. So, I would say the other way round inertial force basically tends to follow what is happening and viscous force is opposing. So. the ratio of that is called the Reynolds number and there is a critical value of Reynolds number for a particular fluid flow condition. It is different for pipes, it is different for plates, it is different for bodies. We call that as a critical Reynolds number because that helps you decide or identify the point of transition, okay.

So, the transition Reynolds number is called as the critical Reynolds number. So, this is our key not the shape, not the fluid properties, alone, not the angle. It is the Reynolds number of the flow that decide whether the flow is going to be laminar or turbulent. So that some typical values if the flow is internal, it is between 3 to 5000. If the flow is external it becomes 100 times more 300000 - 500000 and it is the best measure to compare 2 flows, the Reynolds number. And obviously as the Reynolds number increases the flow becomes less and less laminar or the laminar nature reduces till you reach a critical Reynolds number after which the flow becomes turbulent, laminar flow stops.

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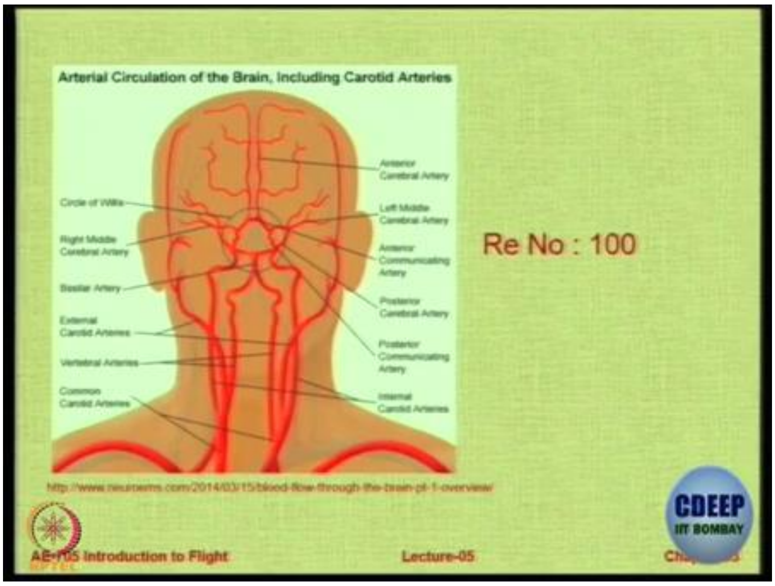

So, if you look at a human blood flowing in the veins and the arteries, the Reynolds number is around a 100. Why? Because blood is a very viscous vehicle viscous fluid. So, if the numerator is viscosity and that number is high, the Reynolds number will come down. So, there are people including in our department who are looking at the fluid mechanics of blood flow. In fact, interestingly we have a PhD student who is an MD in cardiac surgery and he is now a PhD student studying flow of blood through artificial valves. So, if you get time, please visit their aerodynamics laboratory, you will find we have created a small setup where we try to mimic the flow of blood through the heart especially through the artificial valves. So there we need these kind of studies.

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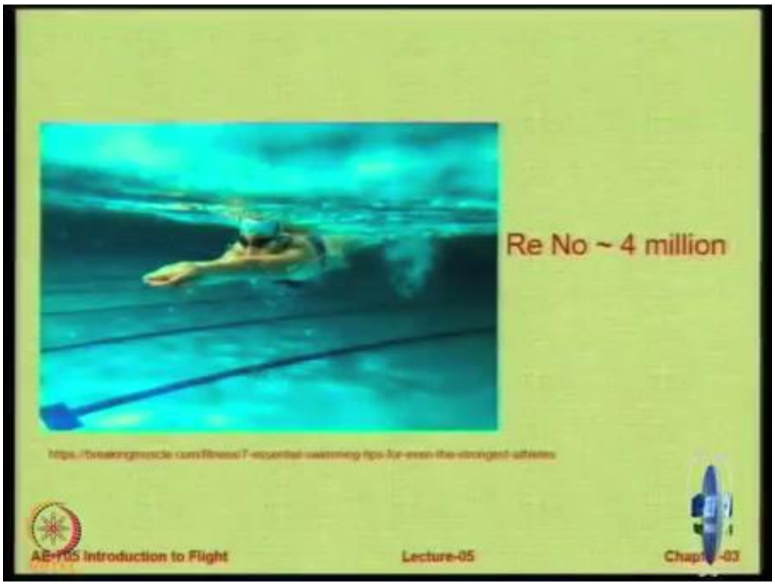

A swimmer operates at around 4 million Reynolds number, of course it depends upon the length of the swimmer and the speed of the swimmer also, but this is the approximate value. So from 100 we go to 4 million. Large ships like this, they operate at Reynolds number of a few millions. So what is the Reynolds number? First of all, there is a question there, so can you name this ship? Anybody here who is a fan of ships? What ship is this? Let us go back to moodle, fine. You can search and put it on moodle.

Now, what would be the Reynolds number of typical aircraft? Between around 6 millions to 10 million typically. 6 to 10 million is the Reynolds number. So when we talk about aircraft and about aerospace engineering flows, we normally speak in millions. These typical UAVs that you fly these remote control plane that you fly what will be the Reynolds number? It would be around point 3 to point 5 million.

Now interestingly, there are many students who take up aero modelling as an activity and they make these remotely controlled planes. Is there anybody in the class who has made remote control planes? Or is interested in making RC planes? Just raise your hands, okay. So in our class we have Sohrab who is actually a very accomplished aeromodeller, okay. So Sohrab question addressed to you because of your experience.

In your experience of flying remote-controlled planes. You must have attempted to get the aerodynamic characteristics of a particular aerofoil from the wind tunnel data or from the reports, but when you actually fly did you observe any difference between the reported values of say the maximum lift coefficient against what you actually got. What is your typical experience? We are actually going ahead. We are talking about lift co-efficient. We are not discussed it yet, but just wanted to know.

Student: So, if I look at lift co-efficient, in reality it is slightly less because you got, your wing is not completely smooth in reality, it has got little notches and things like that. And they transit the flow from laminar to turbulent.

Professor: No that is not the main reason actually even if I make a perfectly smooth wing, when I make an aero model, I will not get the maximum lift coefficient, which I get for the same wing when I make a big aircraft. The main reason for that is there is a Reynolds number effect on the aerodynamic characteristics which many students do not know. So what they do is they pick up data about a particular shape or aerofoil from a from from some source, they make an aircraft, they do calculations and then they say we are not getting the performance and then they assume what you assume that oh it is because of the bad finish etc. That is one reason, but I will show you there are other reasons also.

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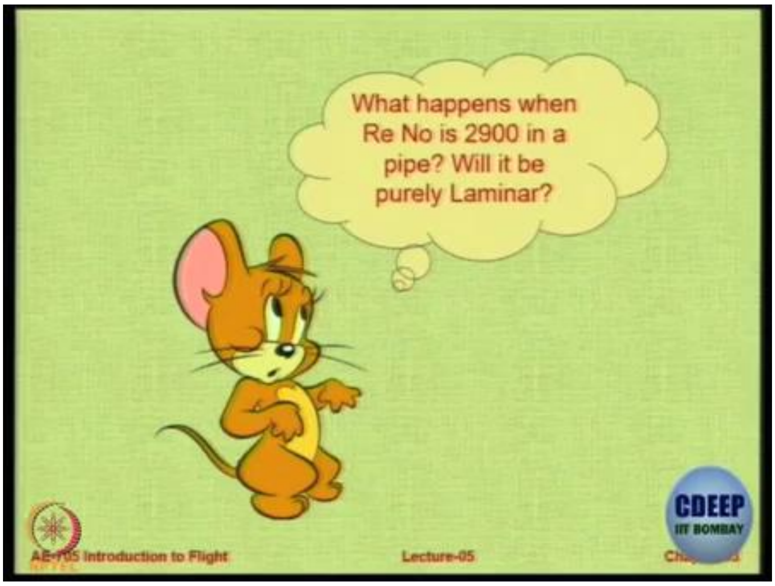

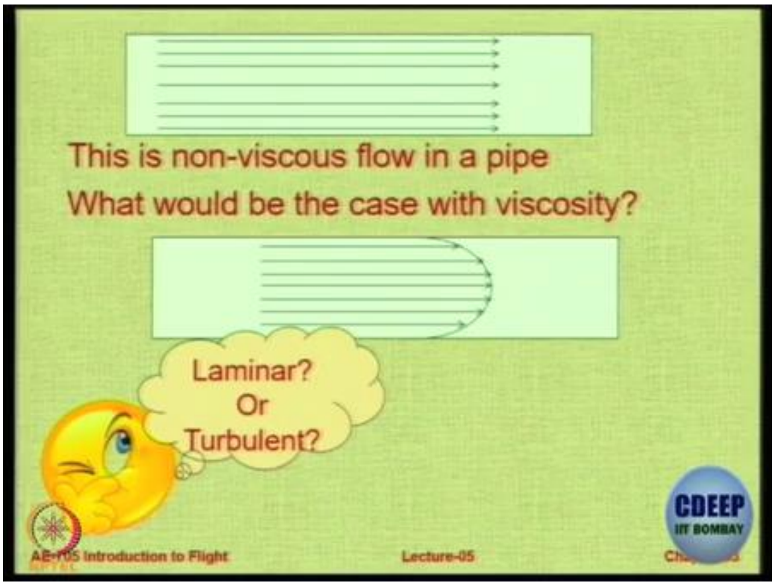

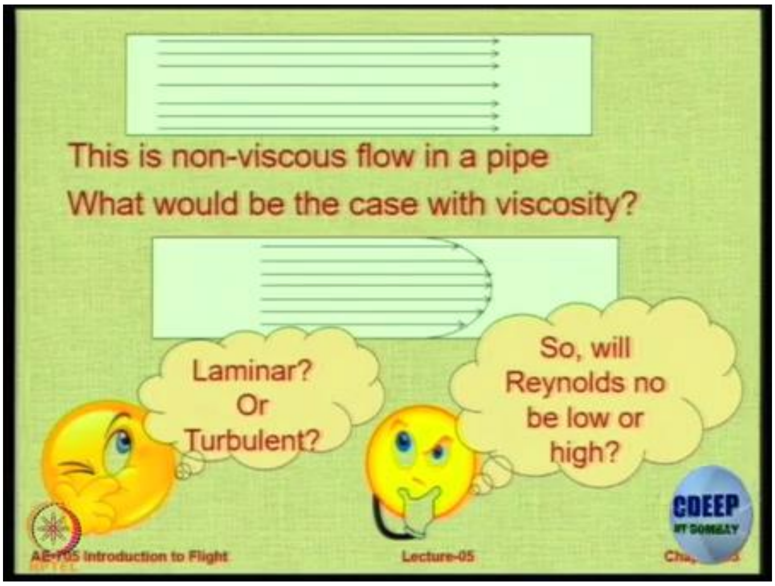

Okay, let us go ahead. So let us see there is a critical Reynolds number of 2900 for a pipe. Let us see what happens to this particular flow when you move so what do we normally do basically is so this is a flow in a pipe, this is not a computer simulation. This is just a photograph or a sketch, okay. So this is a non-viscous flow in a pipe. Is it possible to have non-viscous flow? Is it possible to have a fluid with no viscosity?

That is the reason why I cannot show you a video. Nor can I show you any off course I can show you a computer simulation in any CFD tool I can put viscosity 0 and get some results but I chose not to do it. I chose just to show you a sketch. So this is theoretical flow. You will never see this in real life that you have a pipe. And the flow continues along straight lines parallelly. It is only in theory. Okay, what will happen if you have viscosity? Tell me, what do you what do you think will happen because of viscosity? Yes.

Student: Is the pipe is circular?

Professor: it is circular cross section pipe ya.

Student: So, there will be a parabolic velocity profile.

Professor: Okay why will it be parabolic?

Student: Because of the velocity gradient which is created due to the viscosity, like the the fluid at the edge which is in contact with the surface of the pipe.

Professor: Top and bottom okay.

Student: Will have a smaller velocity as compared to the fluid.

Professor: So if I correct you, do you think you it will have any velocity or will it be a zero velocity?

Student: Technically it is zero that is we called, it is boundary condition,

Professor: It is a no slip condition it is no slip condition. So so so that means essentially we have something like this, Okay. So in the centre of the pipe the friction is only between the 2 fluid particles. At the edges you have friction between the fluid particles and the pipe wall. So you typically get this kind of a variation of velocity. Now the question is, is it laminar or turbulent? Do not go by just the looks, there has to be some logic. Let us see, okay. So, if the flow is laminar, which is what it appears to be, then what will be the Reynolds number? Will it be low or will it be high? It has to be low, okay. It has to be low. So one can keep on increasing.

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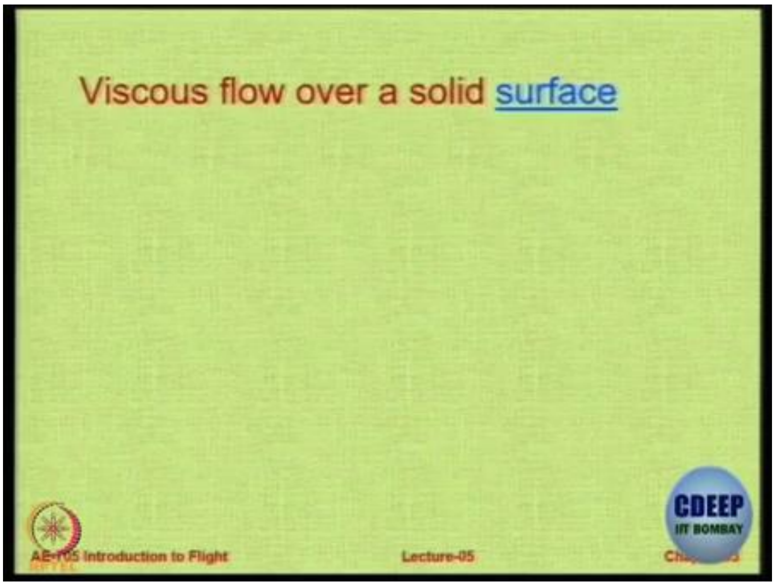
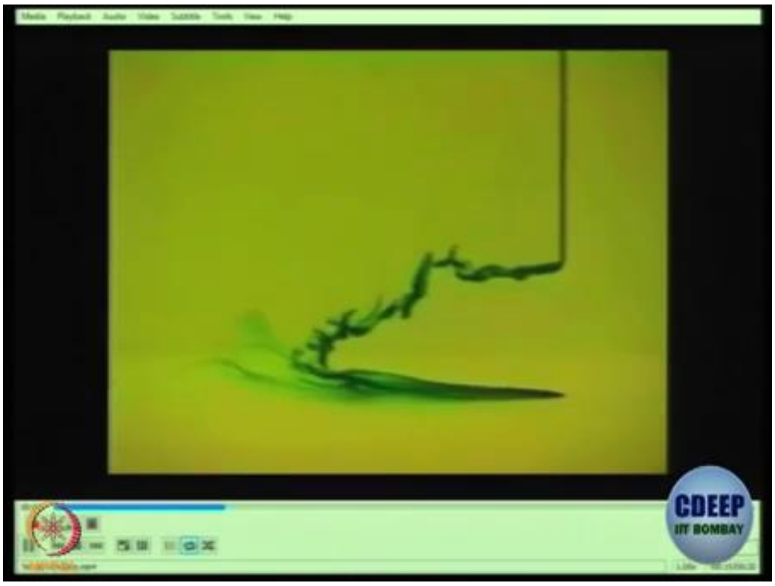
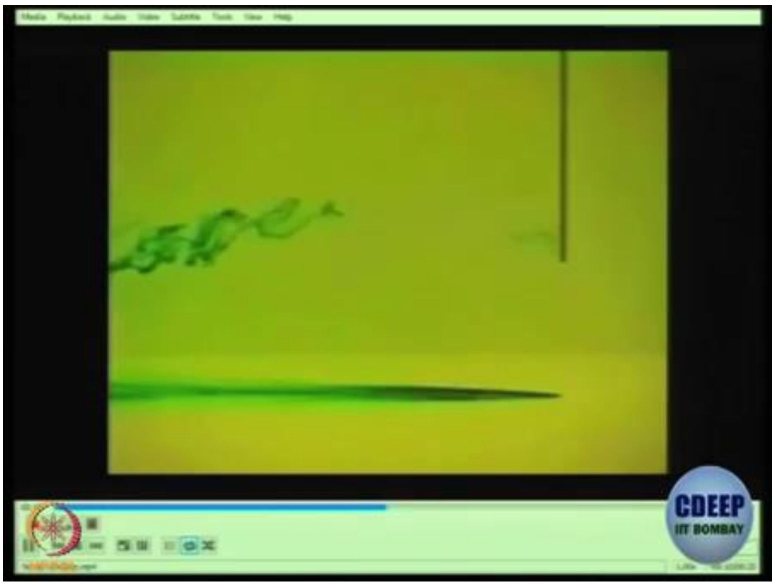



No slip condition.mp4


CDEEP
IIT BOMBAY


CDEEP
IIT BOMBAY

Now let us see let us see a video about viscous flow over a solid surface. This is an experiment. So you introduce a small pipe in the flow, you touch the floor and then you release the fluid and you take it up slowly, okay. So interestingly the fluid which was there at the bottom has remain stationary This is the proof of what I was suggesting to you that in case you have a flow over in a pipe or in any container, the fluid that touches the surface is at rest.

That is why we need a brush to clear of that the presence the particle remains, okay. The fluid is flowing, but the particle remains. Why is it flowing because you can see those things moving but on the surface it is not moving. That means the surface velocity is zero, okay. So this is because of friction. The friction between the fluid particles and the surface.

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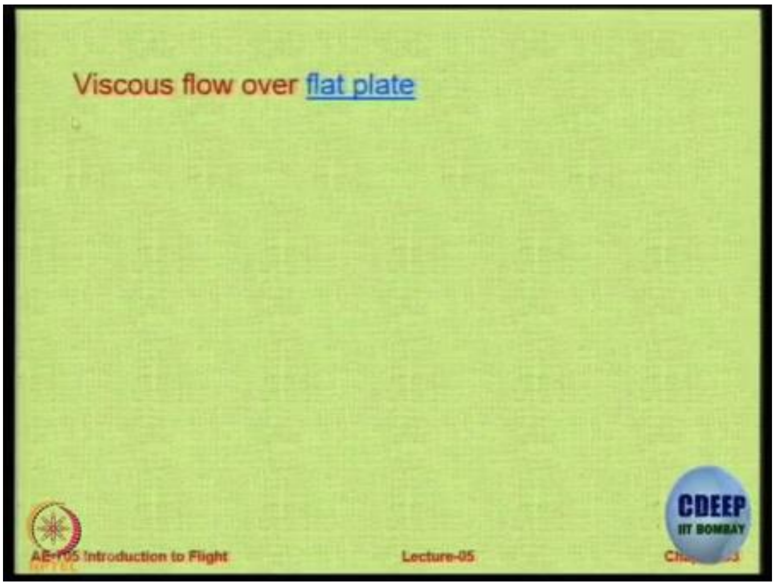
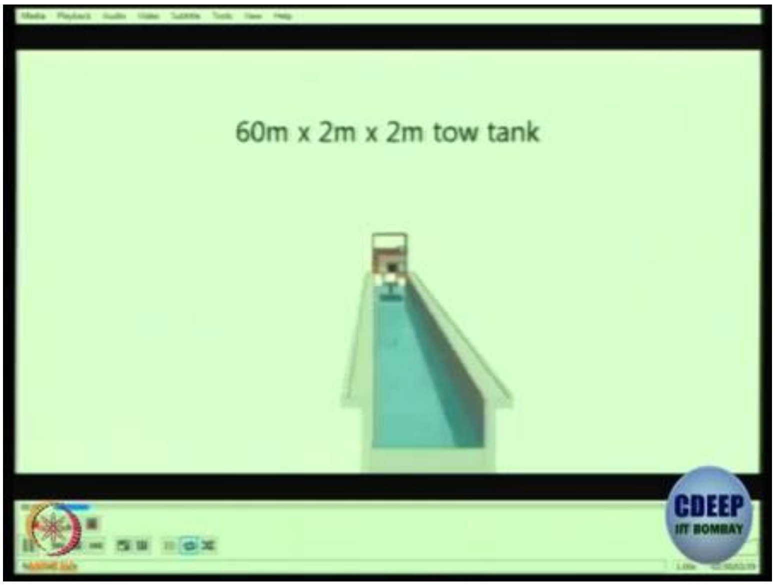
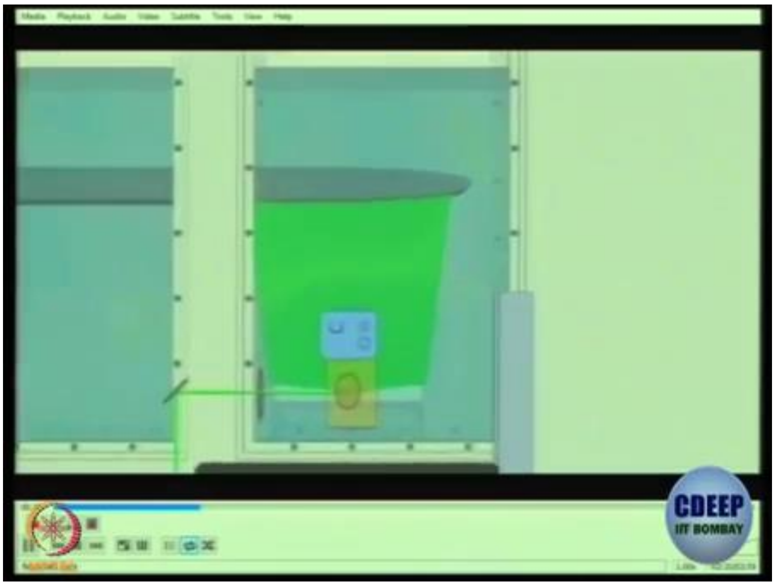
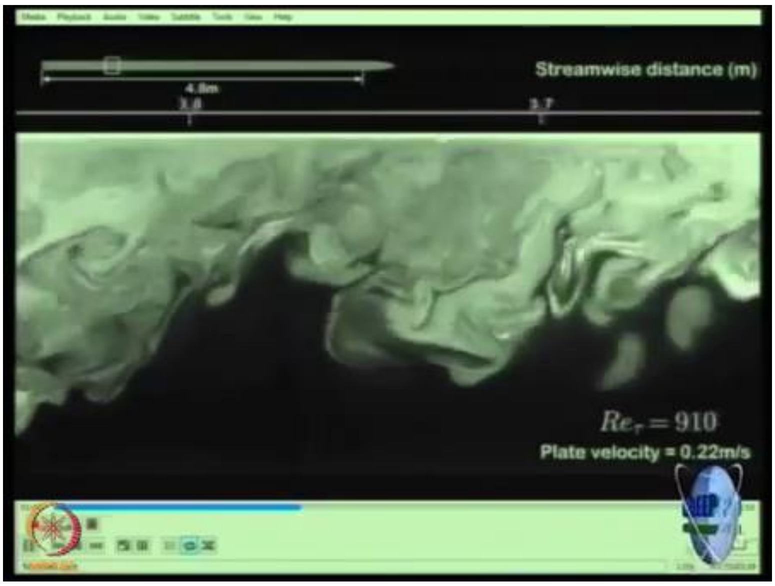
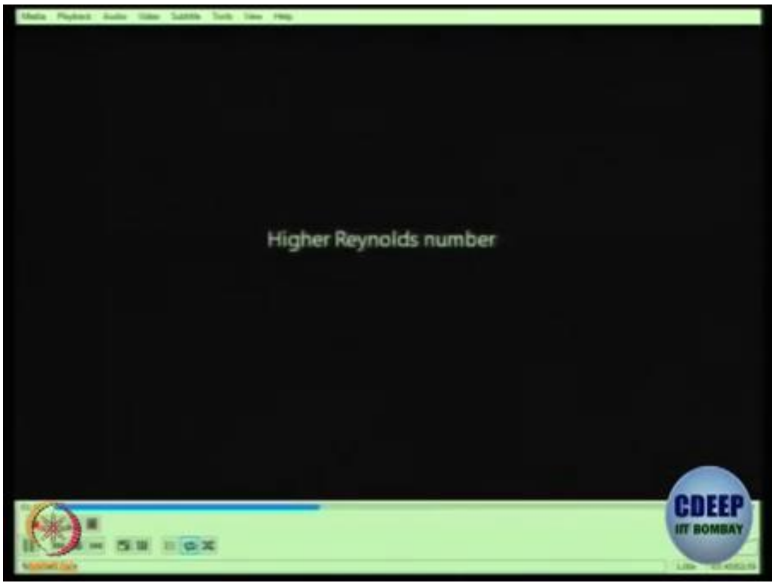


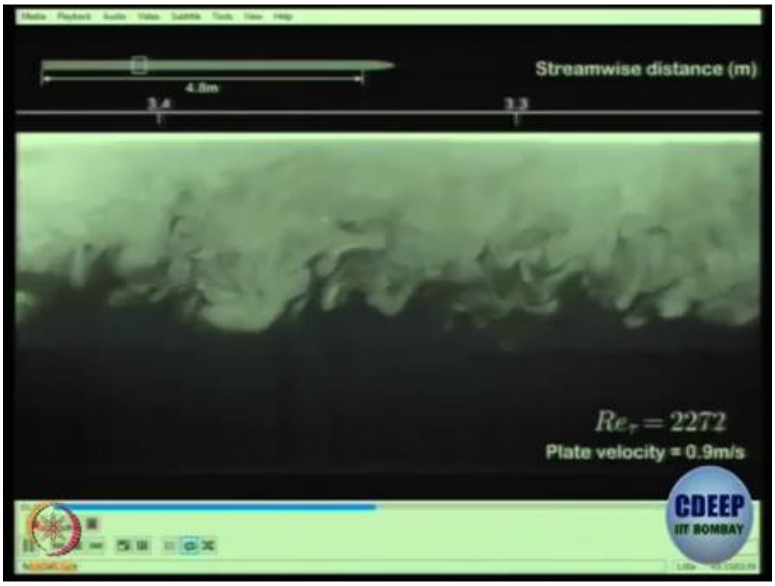


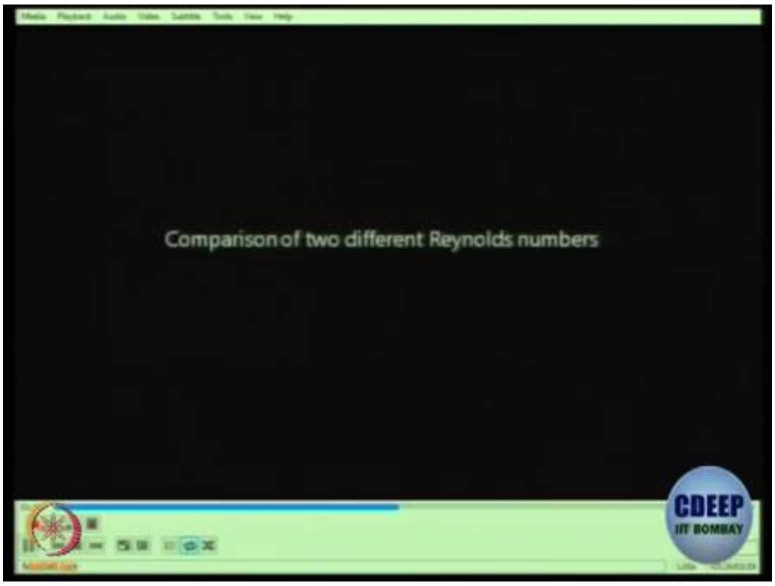

Side windows for optical access
CDEEP
IIT BOMBAY


CDEEP
IIT BOMBAY


Streamwise distance (m)
4.8m
$Re_\tau = 910$
Plate velocity = 0.22m/s


Higher Reynolds number
CDEEP
IIT BOMBAY


Streamwise distance (m)
4.8m
$Re_\tau = 2272$
Plate velocity = 0.9m/s
CDEEP
IIT BOMBAY


Comparison of two different Reynolds numbers
CDEEP
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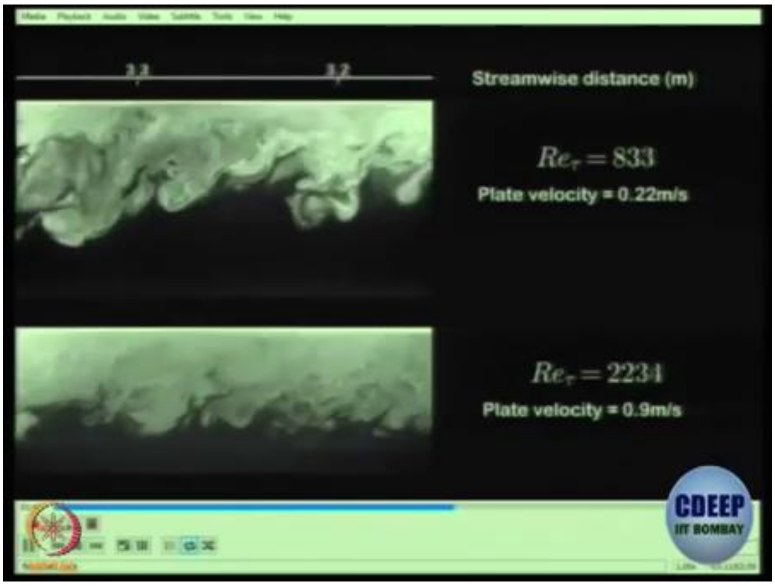
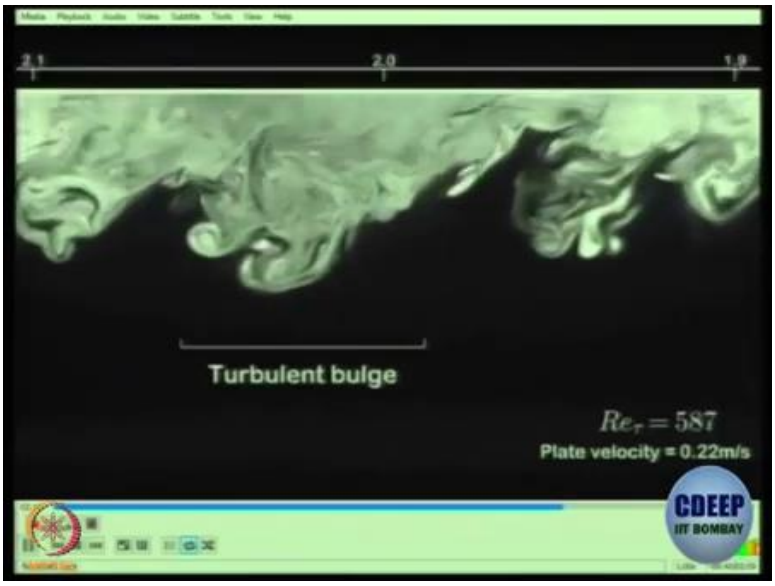
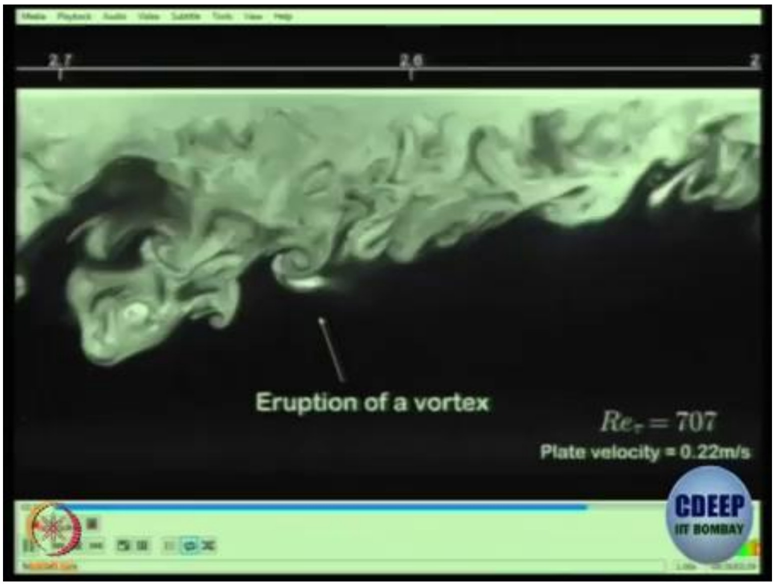
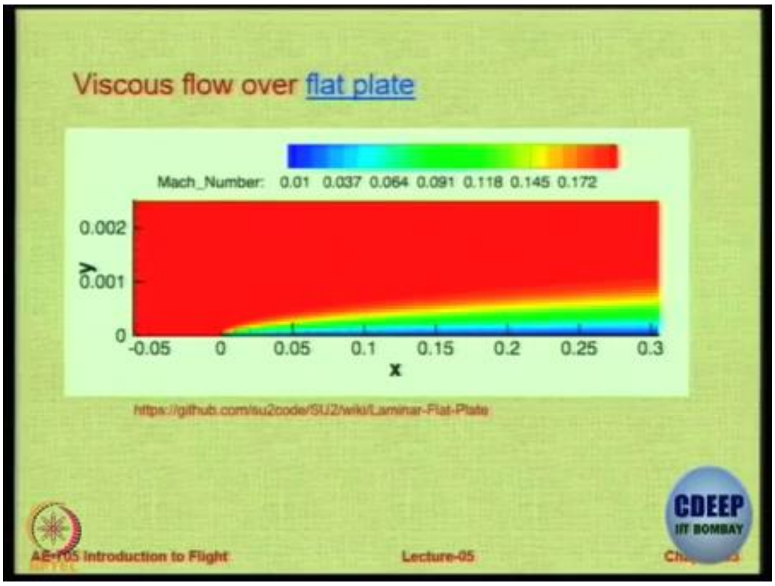
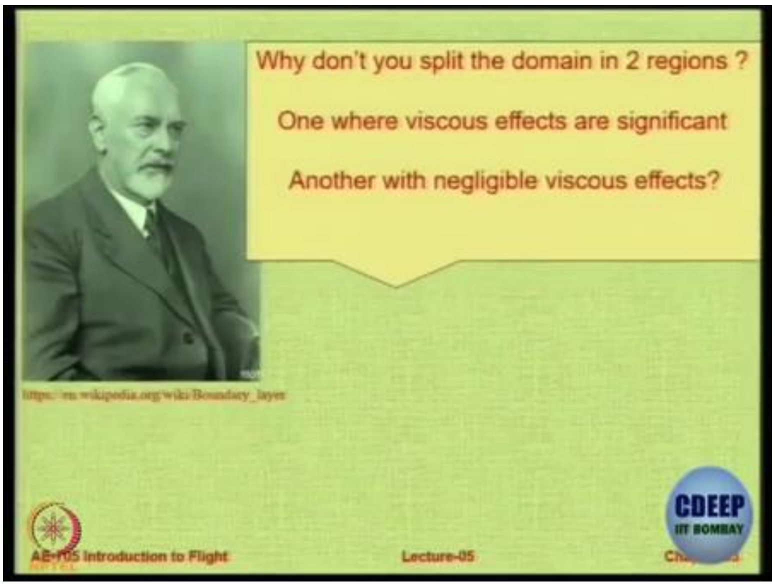

3.3
3.2
Streamwise distance (m)
$Re_\tau = 833$
Plate velocity = 0.22m/s
$Re_\tau = 2234$
Plate velocity = 0.9m/s
CDEEP
IIT BOMBAY


In slow motion
CDEEP
IIT BOMBAY


2.1
2.0
1.9
Turbulent bulge
$Re_\tau = 587$
Plate velocity = 0.22m/s
CDEEP
IIT BOMBAY


Eruption of a vortex
$Re_\tau = 707$
Plate velocity = 0.22m/s
CDEEP
IIT BOMBAY


Viscous flow over flat plate
Mach_Number: 0.01 0.037 0.064 0.091 0.118 0.145 0.172
0.002
y 0.001
0
-0.05 0 0.05 0.1 0.15 0.2 0.25 0.3
x
https://github.com/su2code/SU2/wiki/Laminar-Flat-Plate
CDEEP
IIT BOMBAY
AE-105 Introduction to Flight
Lecture-05


Why don't you split the domain in 2 regions ?
One where viscous effects are significant
Another with negligible viscous effects?
https://en.wikipedia.org/wiki/Boundary_layer
CDEEP
IIT BOMBAY
AE-105 Introduction to Flight
Lecture-05

Now, let us go to the flat plate. So you have a camera which is stationary. So it is Eulerian approach. The camera is stationary and there is a automatic carriage that toes a plate. So the channel is stationary, the camera is stationary, but this plate is moving in the fluid, plate with sharp edge. So, the camera is stationary, it takes a picture. So you can see now the plate velocity is very low. And you inject fluorescent dye. Notice how the structure of the flow field changes as the velocity of the fluid is increasing and hence the Reynolds number is increasing.

Now we go to higher Reynolds number. See the difference in flow field. So, this is the name given to this particular phenomenon where you have a very large mass called a turbulent bulge and then you have these vertical structures inside. You can see those vertices which are continuously generated and they are word and they are bursting also. So when when we study these things in more detail that is when we look at these kind of pictures. Okay, so here is just a snapshot of some CFD calculation. CFD stands for Computational Fluid Dynamics in which we simulate the fluid flow using certain standard equations that can be used to model the flow.

So you can see that the fluid is almost stationary very very low values of Mach numbers on the surface and as we go above and when you go to when you go to the thin region outside, you have a very much higher speed flow of point 712. So with this basically you can say that when there is a flow over a flat plate, the flow pattern can be divided into 2 clear-cut segments. One segment is the red area where the fluid velocity is uniform equal to the free stream velocity of whatever point 172 or point 175. And the viscous effects are limited only into a small area below the yellow and green curves lines. So that is the only area.

So, if you want to do a very simple analysis, let us say you have some equations available with you which are applicable only for in-viscid flow and you have a flat plate to be investigated. So, what you can do after looking at this picture we only have to conclude is if I replace the flat plate with a body of that shape. What shape? The shape below the yellow coloured and if I do an non viscous analysis on a body of that shape, I will probably get the same results as on a flat plate with viscosity because the viscous effects are confined only in that small area.

So this is called as flow partitioning and this is the contribution of Prandtl. Prandtl was a person who first observed these boundary layers, and he said, oh we can divide it into two segments and then live with in-viscous calculations in the non-boundary layer area. This particular area may appear to be very small, but what is happening inside is very very drastic and dramatic, okay. So, basically viscosity has spoiled the flow field. Yeah. The answer is here. So you have a flow acting over a flat plate. And we see that the effect of viscosity is confined only in this small zone, which is coloured yellow, green and blue where the velocity of the flow is lower than point 172.

So what is happening here is the free stream Mach number is something like point 172 or point 175. So, ahead of the plate there is no problem. The flow is still not sonic so there will be no effect felt. So the flow will remain at the same Mach number, but when the plate starts a small area starts getting built up over the plate in which the flow velocities are reducing. And finally they reach the red value. So analysis of a flat plate in viscous flow is equal to analysis of a body of that shape, shape equal to the shape of this yellow green band. Put in non-viscous flow. So this is what it is. So this person said why do not you split into two regions? And that is called as a boundary layer.