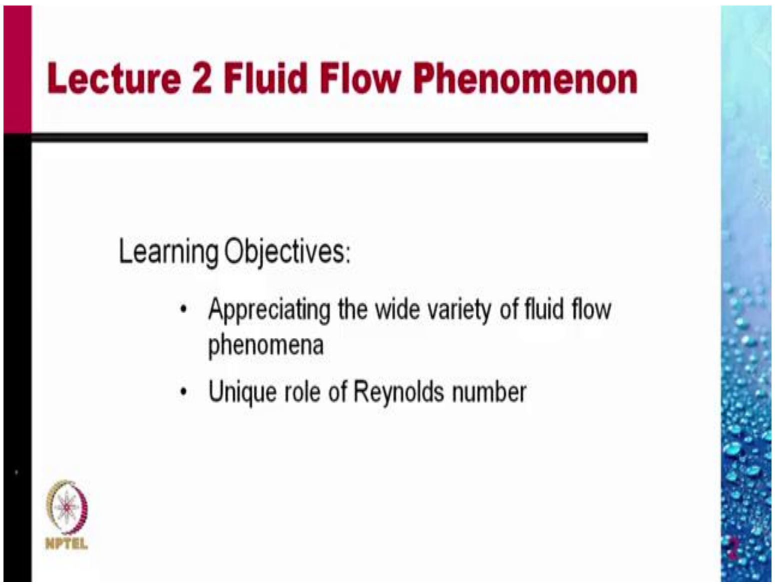
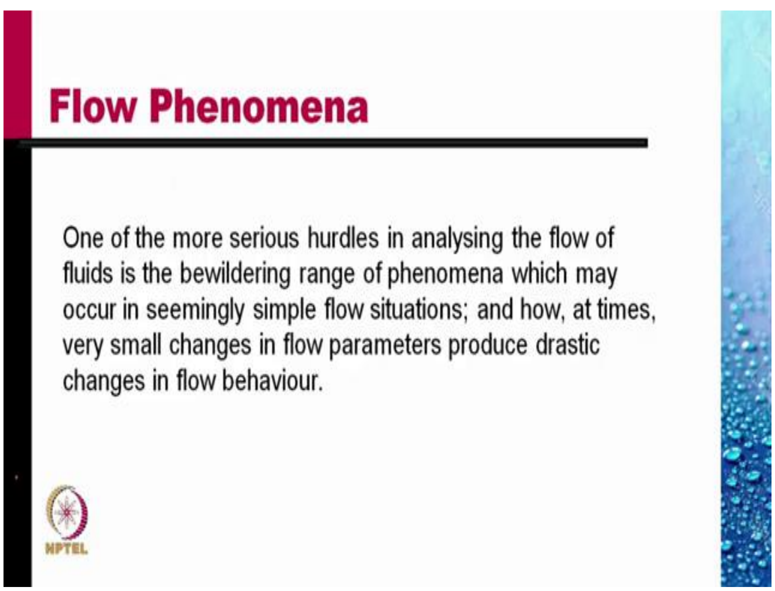
Fluid Mechanics and Its Applications
Professor Vijay Gupta
Department of Chemical Engineering
Indian Institute of Technology, Delhi
Lecture 2
Fluid Flow Phenomenon

Welcome back. In the second lecture will cover the fluid flow phenomena.

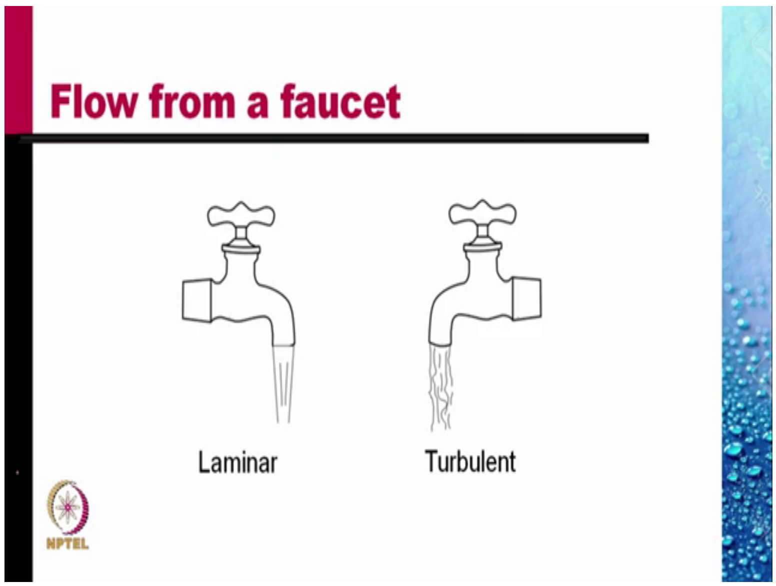
(Refer Slide Time: 00:25)





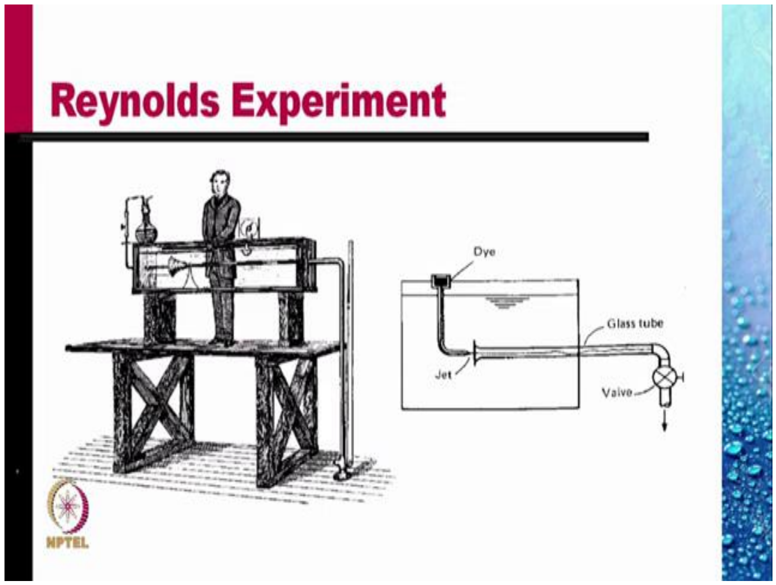
The learning objectives are: appreciating the wide variety of fluid-flow phenomena and to discuss the unique role that the Reynolds number plays in fluid mechanics. One of the more serious hurdles in analysing the flow of a fluid is the bewildering range of phenomena which may occur in seemingly simple flow situations, and how at times very small changes in flow parameters produce drastic changes in flow behaviour.

(Refer Slide Time: 00:57)



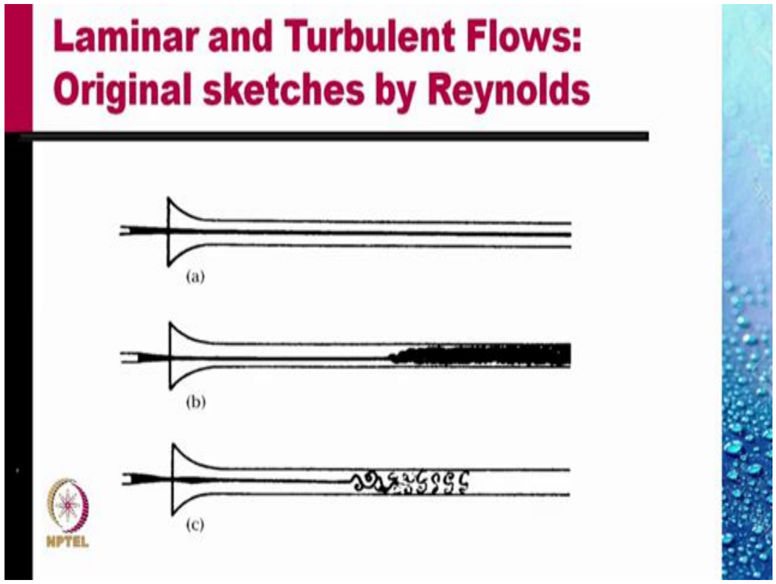
Consider the flow coming out of a faucet. When the flow speed is less, the water comes out as a smooth flow. But if you increase the speed, the water comes out as turbulent, with lot of swirling around within the stream. This clearly illustrates that two different flow regimes are operating in the two different flows. And quite clearly, the two flows cannot be analysed with the same basic principles.

(Refer Slide Time: 01:38)



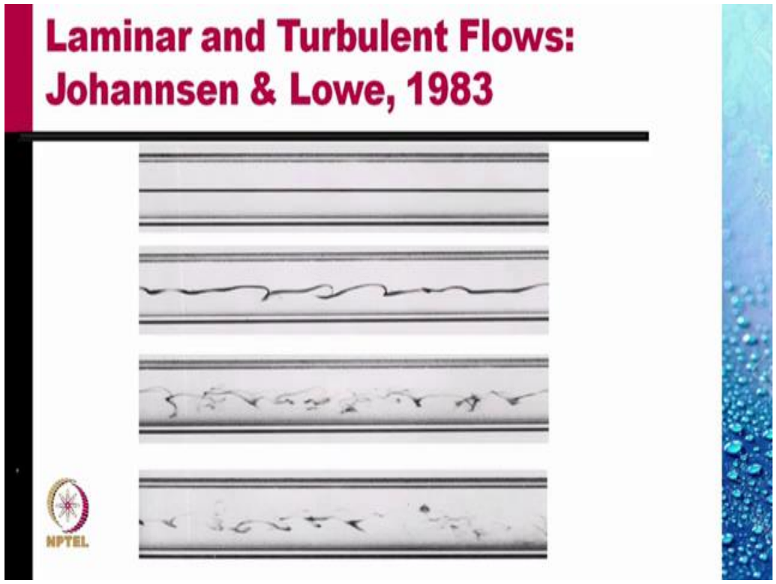
One of the first experiments connected with the varieties of flows was conducted by Professor Reynolds of England in 1880. In this experiment, he had a water tank and a pipe with smooth entrance. The pipe was submerged in water for some length, and then there was a valve that controlled the flow. Ink was injected at the centre-line of the pipe and the flow was observed.

(Refer Slide Time: 02:22)



These sketches are from the original paper by Reynolds in which they show that when the flow speed is very low, this streak of ink introduced at the centre of the tube comes out smoothly and flows down the tube. But, when we increase the flow speed a little bit, the ink spreads out downstream in the tube. At still higher still higher velocities, the streak of the ink is disturbed significantly, and a phenomenon knows a turbulence is set in.

(Refer Slide Time: 03:13)

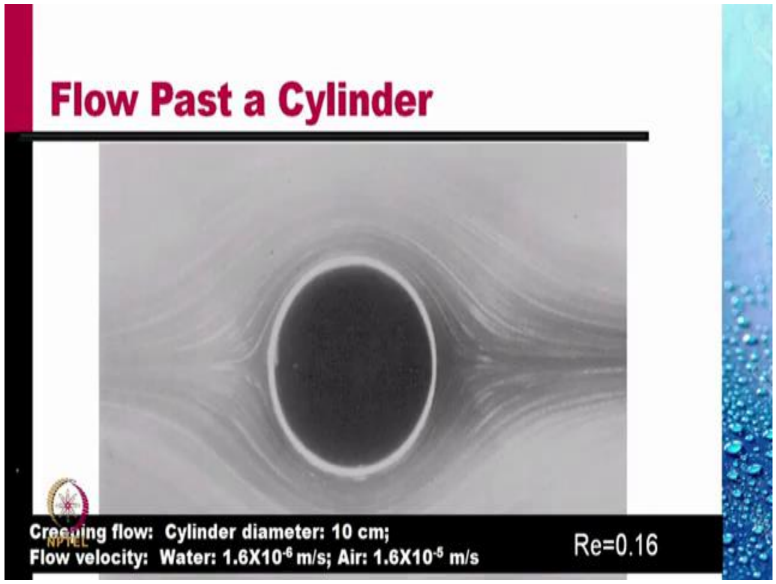


These pictures of the flow are from more recent experiments, and we can see clearly in the first picture, the streak is a straight line. In the second picture, it starts getting some waviness. In the third picture, there is a lot of disturbance and the ink is spread out across the cross-section of the tube. By the fourth one, it is completely broken down.

Reynolds explained it by saying that as the flow speed increases, turbulence sets in. The flow is said to be laminar to begin with. In laminar flows, the layers of fluid appear to be sliding over each other smoothly, while in the turbulent flow, there is a lot of mixing transverse to the flow. Reynolds also established that this transition from laminar to turbulent occurs not at a flow speed, but at a composite parameter depending upon the viscosity, the density, the velocity and the diameter of the pipe. When a combination of these parameters defined as $density \times velocity \times diametr/viscosity$ exceeds certain value, the flow becomes turbulent. So, if the diameter of the pipe is more, to get the same value of the parameter, you need less velocity of the flow for the turbulence to set in.

.

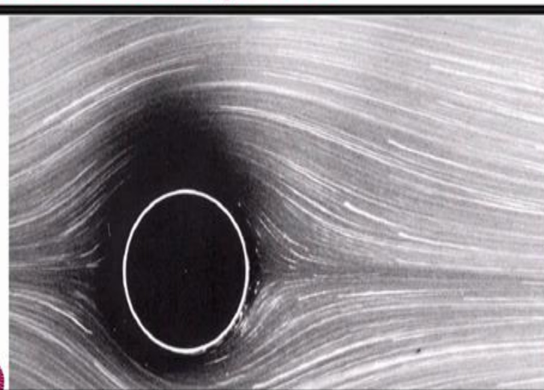
(Refer Slide Time: 05:11)



The following series of pictures shows flows past a cylinder. The flow is made visible by various devices. In this first picture, the flow is made visible by sprinkling a powder on the surface of the water flowing past the cylinder and taking a small-time exposure photograph. At a very low speed of fluid (for water a speed as low as 1.6×10^{-6} m/s, that is, 1.6 μm/s, when the cylinder diameter is 10 cm, the flow is symmetrical. You would notice there is very little asymmetry in the flow, fore and aft.

(Refer Slide Time: 06:09)

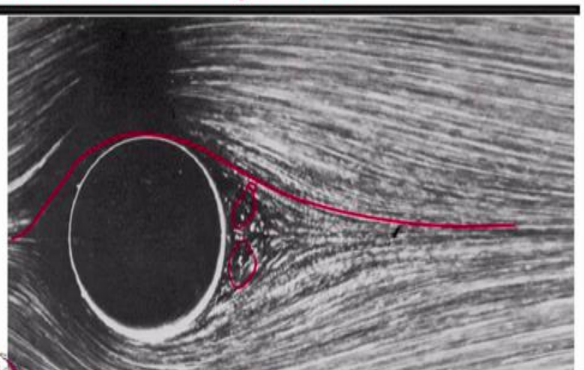
Flow Past a Cylinder



Creeping flow: Cylinder diameter: 10 cm;
Flow velocity: Water: 1.5×10^{-5} m/s; Air: 1.5×10^{-4} m/s

Re = 1.5

Flow Past a Cylinder



Separation: Cylinder diameter: 10 cm;
Flow velocity: Water: 10^{-4} m/s; Air: 10^{-3} m/s

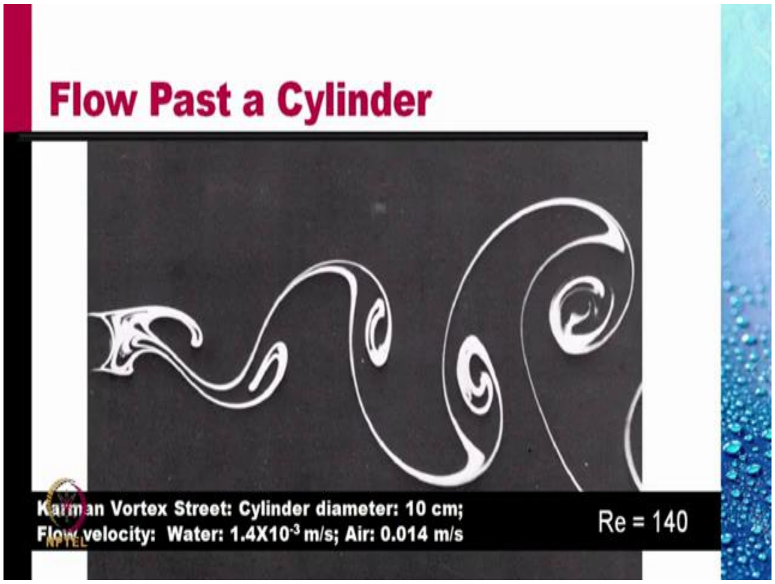
Re = 9.6

As we increase the flow velocity, and for water the speed is now 15 μm/s (for air that would be 150 μm/s) on a cylinder of diameter 10 cm, you can see a marked asymmetry in the flow. The flow is from left to right there is a stretching of the flow towards the right.

This asymmetry is a common phenomenon. As we increase the flow speed by another factor of 10, you could see the asymmetry to be more pronounced. Not only asymmetry, we see the beginning of vortices behind the cylinder: two vortices. One on the top around here, and one there, in which the fluid seems to be swirling around. In fact, a dead water region develops. The fluid from this region does not leave it. The flow coming in from here goes around and passes by, leaving this flow to be stagnant here.

At still higher speeds, we can see these vortices very clearly. This picture has been taken in water with a cylinder surface coated with a layer of condensed milk. As water flows, the condensed milk dissolves slowly and is seen in this picture in white light. The flow here leaves a surface, goes around and swirls back. Similarly, here. These are termed as attached vortices.

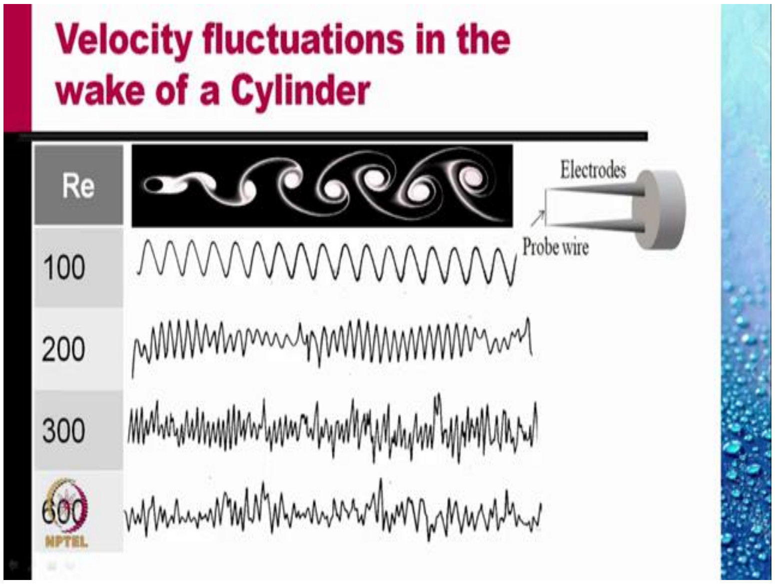
(Refer Slide Time: 08:29)



As the flow speed increases further a beautiful picture emerges. These vortices that were attached in the previous picture, are now shed from this cylinder, one at a time. First, at the top, then at the bottom, then the top, then at the bottom with a marked regularity. These vortices grow in size as they travel downstream.

The resulting picture has been named as the Von Karman Vortex Street, after the German Scientist von Karman who studied this. This is a very common phenomenon. The pattern like this is seen behind sand dunes in deserts, and behind rocks jutting out of slow-flowing streams.

(Refer Slide Time: 09:37)

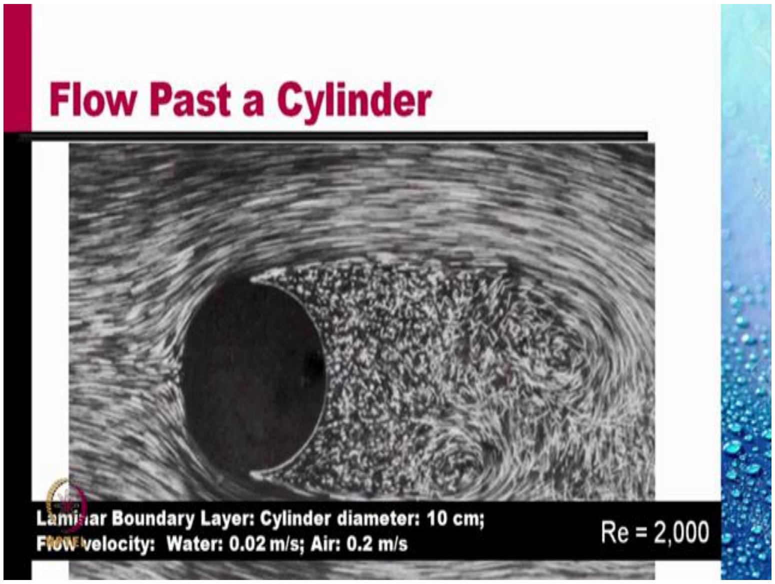


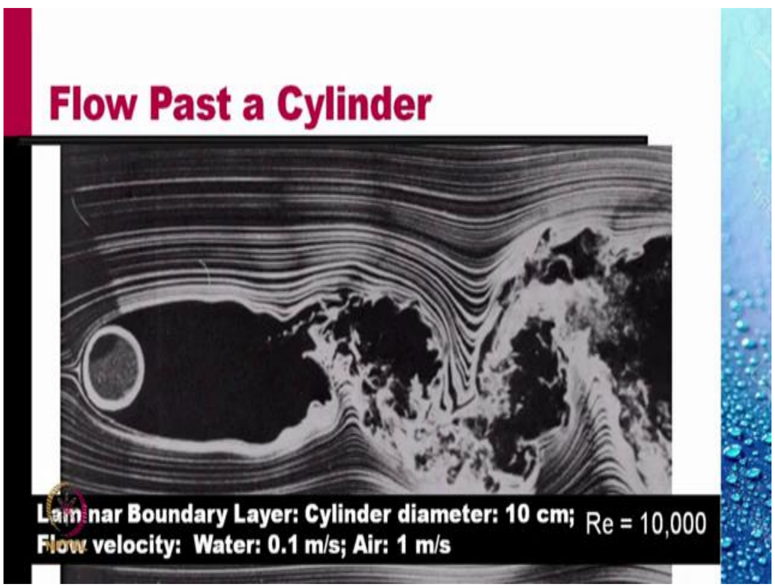
If you measure the velocities in the wake of the cylinder by a device, which is known as a hot-wire anemometer. This consists of two electrodes across which a very thin wire is stretched. This wire is heated with an electric current. As the flow takes place over this wire, the wire loses heat.

And if we can measure the amount of heat that is lost, we can estimate at what velocity air must be crossing the wire. This probe, being very small in diameter, has a very small time constant. And by using this, we can measure the fluctuations in velocity. We show here a few signals at various values of Reynolds number. You see Reynolds number is the parameter that we discussed in the Reynolds experiment equal to $\rho VD/\mu$.

When the Reynolds number is about 100, you get an almost sinusoidal signal from the hotwire probe. This represents that the vortices are shed at a fixed frequency, very regularly. As the Reynolds number increases, the first thing to notice is that this frequency increases. Second, the regularity breaks down, till at Reynolds number of about 600, the regularity completely disappears and we get what appears like random fluctuation of signals. This is the turbulent flow.

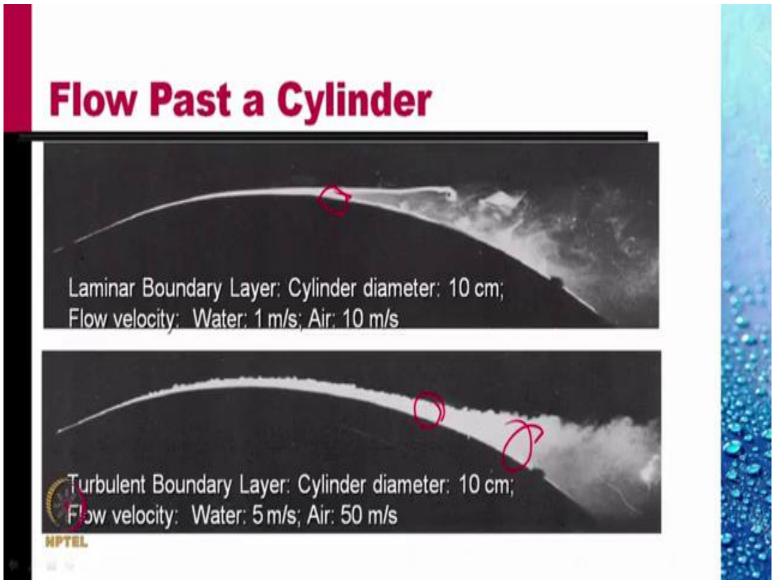
(Refer Slide Time: 11:50)





We again go back to our cylinder at a Reynolds number about 2000, which for a cylinder diameter of 10 cm translates to water velocity of 0.02 m/s, or 2 cm/s, or in air about 20 cm/s. We get a turbulent wake. In the wake you can see turbulence. If we increase the Reynolds number further to about 10,000, you can see the turbulent wake very clearly. You would appreciate how far we have come up from the first picture we showed, with the flow almost similar looking ahead of the cylinder and behind the cylinder. Here there is no symmetry fore-and-aft.

(Refer Slide Time: 12:53)

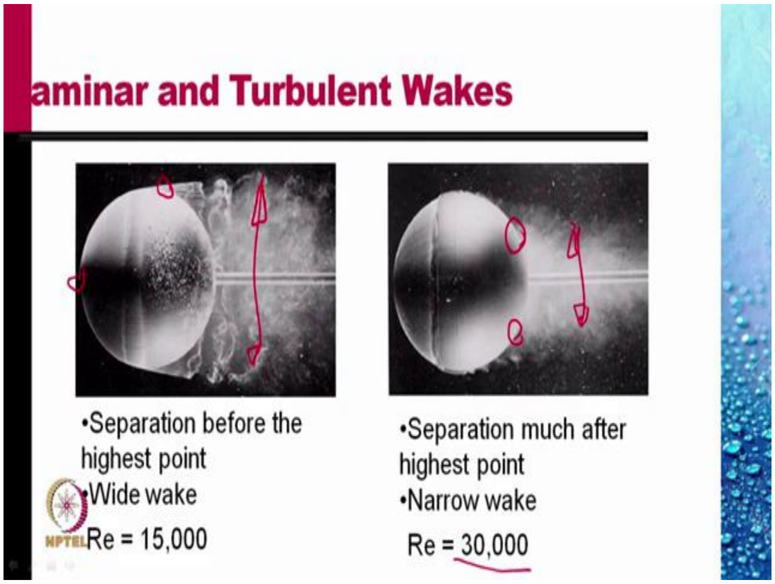


And still higher Reynolds number, that is, when the velocity in water is 1 m/s, you see a layer that travels around the cylindrical surface in the top picture, and it separates from the top surface at a point nearly here. We say a boundary layer has developed on the cylinder. A boundary layer, as we will discuss later on in the course, is a thin layer within which the viscous effects of the flow are confined. We will have occasion to discuss this in greater details later on in the course.

But for the moment, you assume that outside this thin layer, which is shown with white smoke in this flow about a cylindrical surface, all the variations of velocity are within this region. Outside this region, the flow is non-viscous. In the picture below, when the water velocity is increased five times, or the Reynolds number increases 5 times, you see that this boundary layer is now turbulent, and the separation is delayed. Separation is somewhere here.

The boundary layer is thickening and is separating at about the second location that we showed. In turbulent boundary layers, then, the boundary layers separate from the body. What happens after the boundary layers separates? As you see in both the pictures, the smoke has now penetrated in more parts of the flow field.

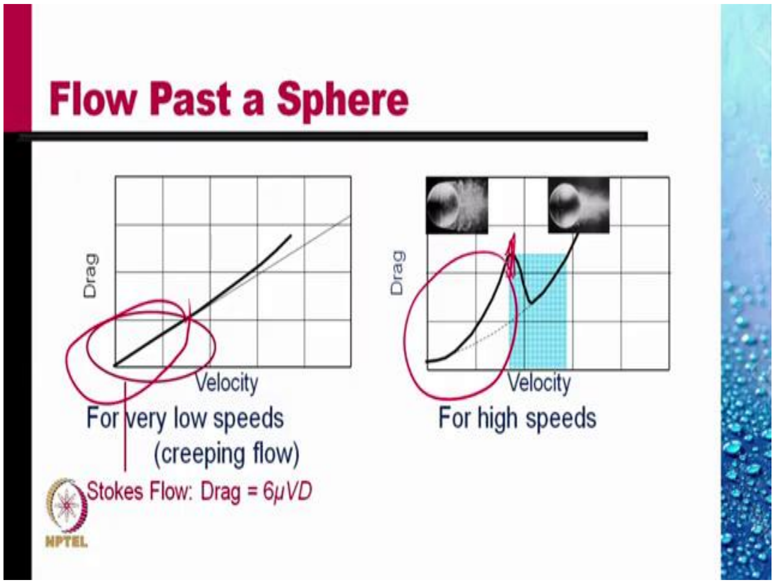
(Refer Slide Time: 15:04)



We have this picture here in which we have a sphere rather than a cylinder. The smoke is injected at the leading point of this thing, at about here, and the flow is taking place from left to right. And for a Reynolds number of 15,000, we see that the flow separates at about this point, slightly before the highest point. This results in a wide wake where smoke is being distributed. This large scale disturbance results a large drag on this sphere.

However, if we increase the Reynolds number to about 30,000, the flow separates at about this point much further down this spherical surface, and the extent of the wake is narrower. We will see later on in the course that a narrower wake indicates that the drag on the body is far less.

(Refer Slide Time: 16:40)



In this picture we have plotted velocity versus drag starting from very low velocities. At very low velocities, so low that the Reynolds number is less than 1, we see that the drag is linearly proportional to velocity. This is the regime of flow that you studied in your high school. You had studied the formula Stokes formula: the drag is $6\mu VD$. This is applicable only in this very narrow range of Reynolds numbers, Reynolds number less than 1.

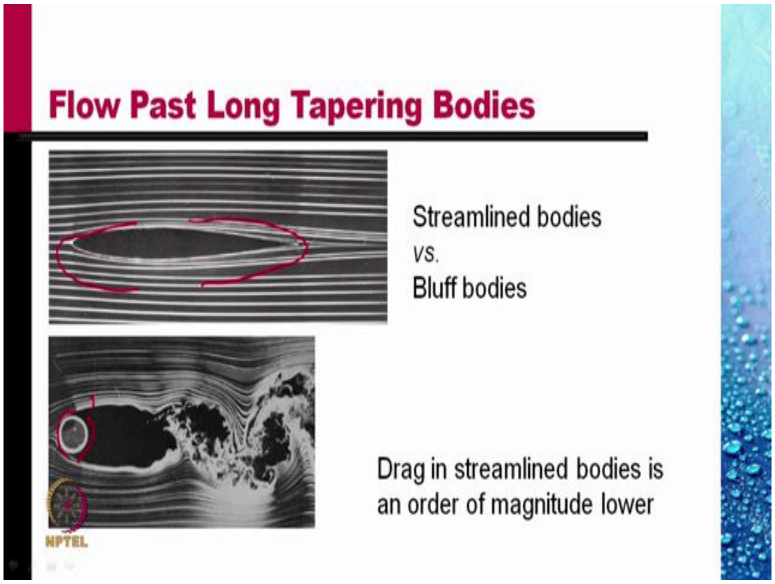
Typically, that would mean that for a fluid like water, the velocities would be in µm/s and the dimensions of the bodies would also be that low. Only very fine dust particles, microbes and such biological entities have a Reynolds number as low as that while moving. The water droplets in clouds when they are very small, of the orders of µm size, also have Reynolds number which are very low.

So, it is for very small microscopic world that we can use the Stokes formula: drag is equal to $6\mu VD$. As the Reynolds number increases, that is, the velocity increases, the drag deviates from this straight line, and at larger speeds of the flow, the drag curve is like this. Notice that this is a parabolic curve. But we see a strange phenomenon as the velocity increases further. The drag increases parabolically like V^2, but then, at certain velocity, actually certain Reynolds number, there is a sudden decrease in drag, and then the drag increase again, with a relation which is parabolic again, but with much lesser coefficient.

You see, it is only after the velocity increases to the right edge of the blue rectangle shown that the drag has caught up with the drag which was at the left edge of this blue rectangle. So, in all this region, the drag is less than what was at the left edge of the blue rectangle. What is happening? Simple, at lower velocities the flow in the boundary layer is laminar, but at the larger velocities, the boundary layer flow is turbulent. Like we saw, in the laminar flows the wake is wider.

So, the drag is proportionately higher. But when the velocity is larger, that is, the Reynolds number is larger, the wake is narrower. The separation of the boundary layer, which is now turbulent, is much delayed. The wake is narrower, and the drag is lower. We will see later on in the course that the pressure distribution along this, along the sphere, changes drastically in the two regimes: the laminar and the turbulent.

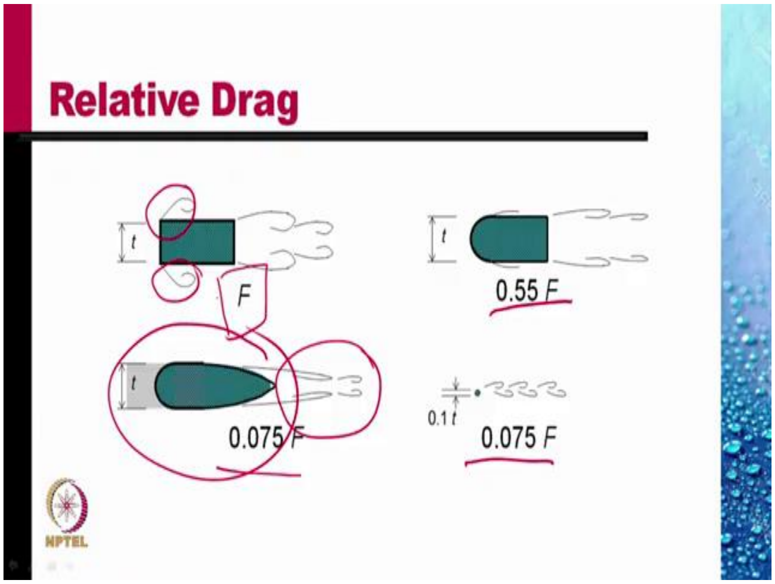
(Refer Slide Time: 21:17)



Another interesting thing to note is, what is called streamlined versus bluff bodies? In a streamlined body with a rounded nose and a long tapering tail, like the cross-section of an aircraft wing, which is termed as an aerofoil, the flow is smooth. There is very little separation, and there is very narrow wake. This flow has been visualized in a-wind tunnel using smoke as tracer particles.

In the lower picture, we have a cylinder, which does not have a long tapering tail, it is a bluff body, and in this we get a large wake, a highly disturbed flow. In the first case of the streamlined body, the pressure at the front, which is pushing it, recovers at the back, and the pressure is pushing it forward from the back. And so, these pressure differences cancel out and we have low drag. In the second case, the pressures in the front of the body are much larger than the pressures at the back. And so, there is a large drag. Drag of streamlined bodies is an order of magnitude lower.

(Refer Slide Time: 23:07)

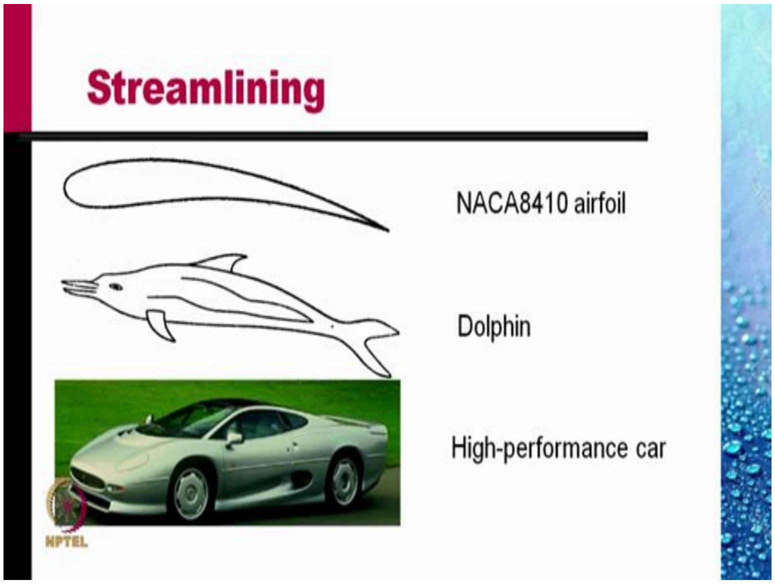


This slide illustrates that if we take a rectangular body of thickness t and we have a flow past this: we have four cases here. In all four cases, the velocity is the same, fluid is the same. In the first picture with the rectangular body, the flow separates right at the nose. It results in a large wake and with the drag which is F. In the next case, we have just rounded the nose. The flow does not separate at the edge like in the first case. So the wake is narrower and the drag is about half of what it was in the first case. In the third case, in addition to having a rounded nose we have attached a long tapering tail. Because of this, the wake is still narrower, and we get a drag which is less than one 10th of the drag in the first case. In the fourth picture, I have compared the drag on a circular cylinder of the frontal diameter only 10 percent of the frontal diameter of the long tapered-tailed body on the left, and they have the same drag.

So, a cylindrical wire very small, one 10^{th} of the size, has a same drag as the tapered, streamlined body of the picture on the left. Remarkable. In fact, you would have noticed that when the aircrafts were first invented, they used biplanes which were strung with a lot of cables, those cables contributed to a lot of drag, even though those cables were very thin.

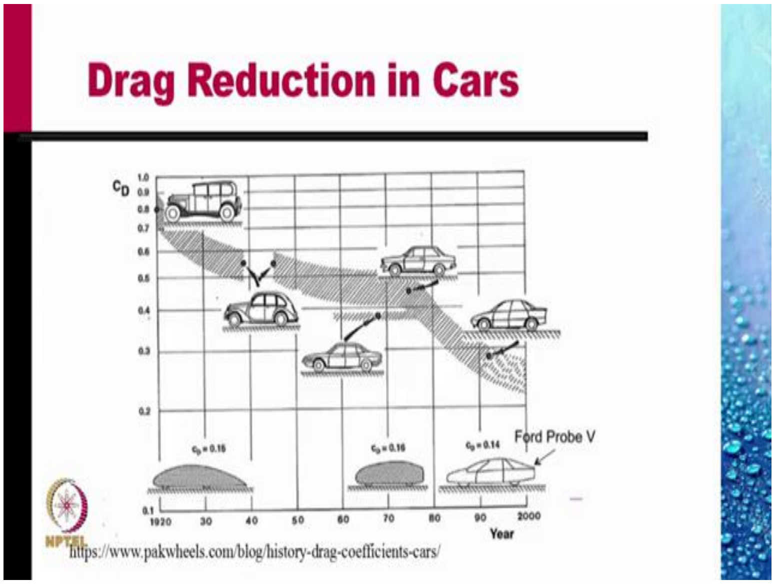
In fact, later on, they started replacing these cables with cables which were with airfoil shaped or which had a cross section like this, so that the drag could be reduced. In fact, the aerodynamic drag of the spokes of a bicycle wheel is quite substantial. Those spokes are cutting through air with circular cross-section, and so, add a lot of drag, because there are a lot of spokes moving at the same time.

(Refer Slide Time: 26:38)



On the top is a NACA8410 airfoil used in many early aircrafts. The nature evolved itself in such a manner that the dolphins have a shape which is quite like that of NACA8410 airfoil. It is because dolphins like to swim through water, and having lower drag would give them advantage. In fact, if you look at high performance cars, they have streamlined shapes: shapes which do not have protrusions which add to drag. There are no sharp corners. They appear to be smoothly flowing.

(Refer Slide Time: 27:36)



This graph shows the evolution of the cars through 1920s to year 2000. And we see how the shape of the cars changed and how the drag coefficient decreased. Drag coefficient is a non-dimensional number that indicates how much drag is. It is given $C_D = Drag/\frac{1}{2}\rho V^2 \times Area$. More the drag coefficient, more is the drag, and you see how the drag coefficient is decreasing.

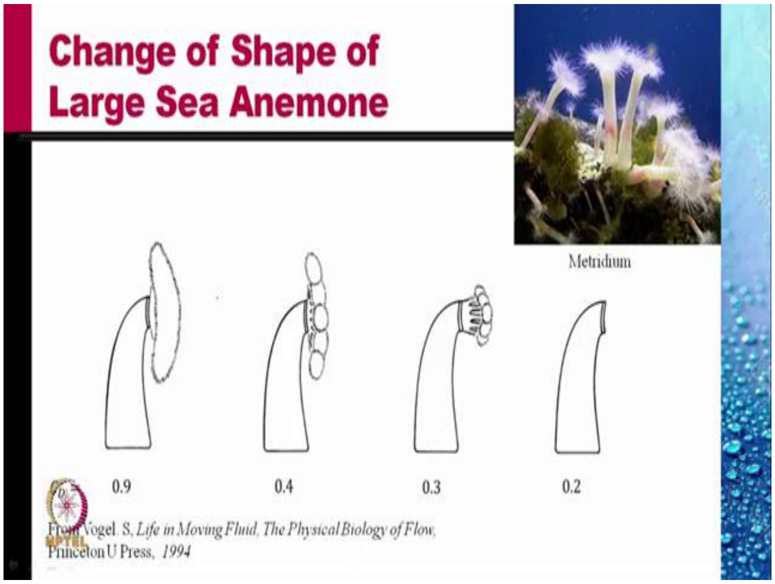
(Refer Slide Time: 28:23)

Drag Reduction in Cars

Car Model	C_d Value
WOLKSWAGEN XL1	0.19
Mercedes-Benz CLA	0.22
Tesla Model S	0.24
Mercedes-Benz S-Class	0.24
Toyota Prius	0.25
Hyundai Sonata Hybrid	0.25
Peugeot 508	0.25

https://www.pakwheels.com/blog/history-drag-coefficients-cars/

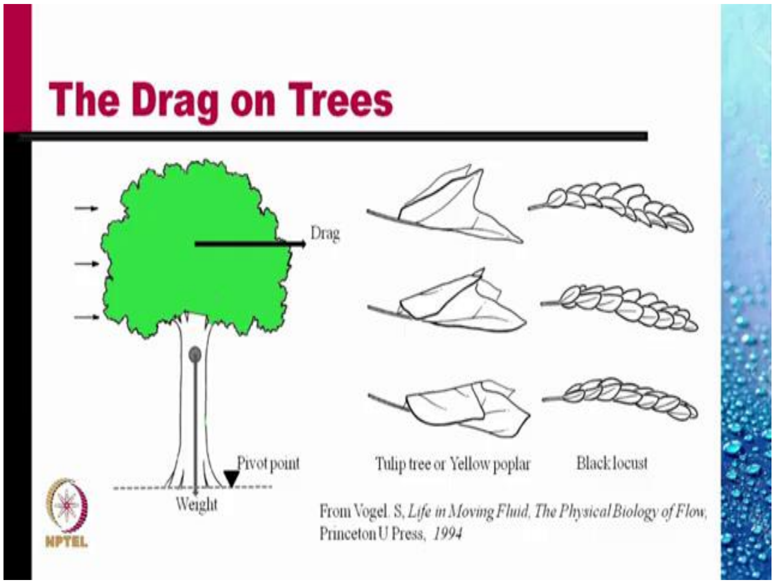
In fact, the drag coefficients of modern day cars are so low.



Nature also does wonderful things. Large sea anemones are predatory animals that live on the bottom of the sea. They catch small marine life in their tentacles. They are not rigidly attached to the floor. So, they are very sensitive to the drag of water which is moving. We have seen that at low speed, an anemone looks like this, with a Cd of 0.9. As the speed increases, the fibrous tentacles divide themselves into groups making small pods so that the flow could pass through them, and the Cd decreases drastically to 0.4, based on the same area.

At still larger speed, they narrow down, reducing the drag coefficient further to 0.3. And at still larger speeds, they completely turn themselves in, and the drag coefficient decreases. These have been taken from a very interesting book: *Life in a Moving Fluid*, whose reference is given here. I would recommend this highly.

(Refer Slide Time: 30:22)



Drag on trees: if the trees are standing in a wind, the canopy of the tree offers large drag. Because of large drag, the tree tends to topple over. There is a pivot point about which the drag would tend to topple the tree. Of course, the weight of the tree acting from the center of gravity would like to keep it straight.

But, for large trees, this drag could be substantial. The drag is because of individual leaves. There is no bulk canopy, only individual leaves. The scientists have found out that the shape of the leaves changes for a tulip or a yellow poplar tree. You see the as you go from top to bottom, the leaf folds over and offers lesser area to the flow.

And it offers lesser area means it reduces the drag. The black locust leaves as the wind blows; they close up offering lesser resistance. This also has been taken from the book of Vogel: *Life in a Moving Fluid*. The book contains a lot of other examples of how the moving fluids affect the life of the organisms living in water. I think it should be clear to you by now, that the fluid-flow phenomenon changes as the Reynolds number changes. And unless we have a clear understanding of what kind of flow is taking place, we cannot model it properly. This why we have analyzed or presented to you these different phenomena right in the beginning of the course, so that you are familiar with the terminology and could visualize what is happening.