Advanced Measurement Techniques in Fluid Mechanics and Heat Transfer
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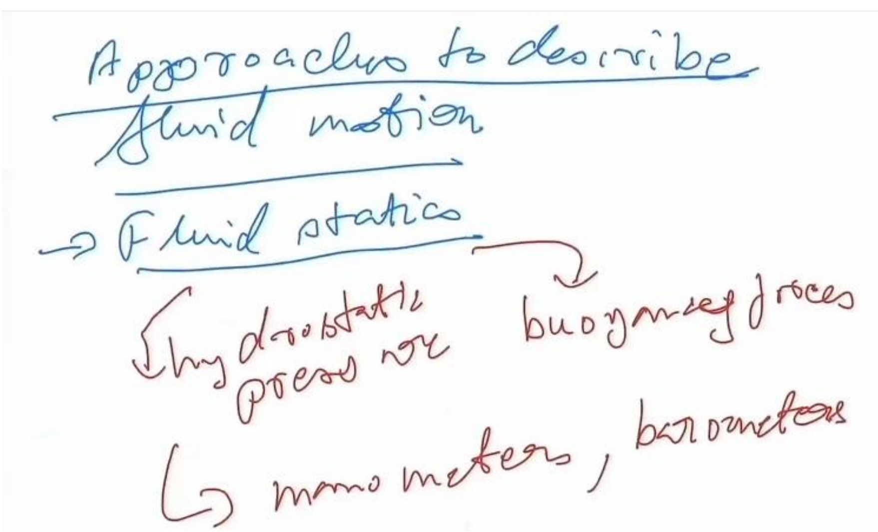
Week – 01
Lecture - 02
Introduction to Fluids – 2

All right, so as we can see over here, the approaches to describe fluid motion are the first things we said we would talk about. The first one is basically fluid statics. Okay, this means when the fluid is at rest or there is rigid body motion; this does not cause any deformation, and it cannot sustain shear stresses. Fluids cannot sustain shear stress. So in fluid statics, the three normal stresses are equal in magnitude to each other and to the pressure. The static fluids are subjected to gravity, which causes the development of hydrostatic pressure and buoyant force.

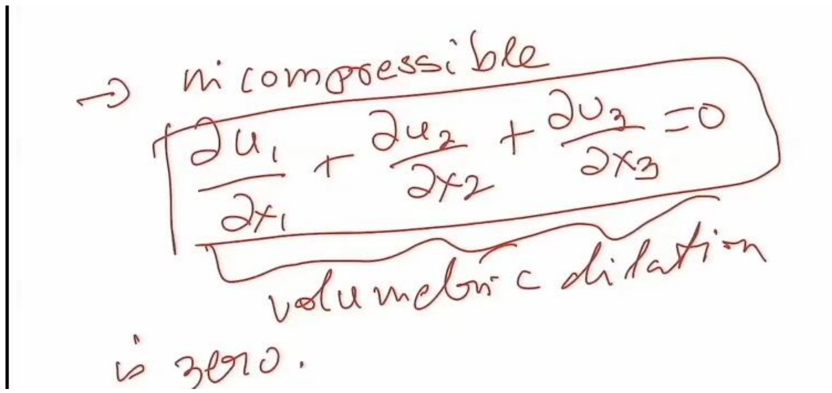
Here you will get things like, you know, hydrostatic pressure, and you also get buoyancy and buoyancy forces, all right? And the three normal stresses are equal in magnitude to one another and to the pressure. So static fluid analysis is useful, and it is used in measurement devices like manometers. nanometers, barometers. This is where fluid statics is actually used.



So that is what it is. Then, of course, you have fluids that are basically incompressible. The incompressible fluids will have the issue that, you know, if you look at it,

$$\frac{\partial u_1}{\partial x_1} + \frac{\partial u_2}{\partial x_2} + \frac{\partial u_3}{\partial x_3} = 0$$

This is, in other words, called the volumetric dilatation being zero. Zero is very similar, so this is what happens when you are dealing with an incompressible fluid. All these derivations are there elsewhere, so you can get ideas about this.



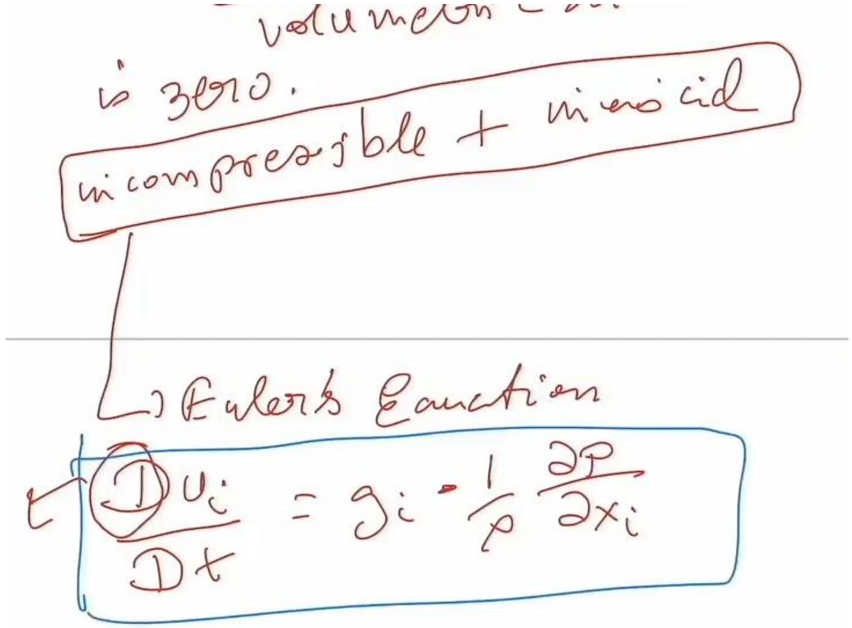
This is incompressible when you have incompressible and inviscid. That means there are no viscous forces acting on it. The viscous force and friction are basically neglected. This leads to what we call Euler's equation.

So it's called Euler's equation. So this is what Euler's equation is. Remember, this was the substantial derivative. Then there was this. This is the term.

Then you have:

$$\frac{Du_i}{Dt} = g_i - \frac{1}{\rho}\frac{\partial P}{\partial x_i}$$

So this is basically Euler's equation. So the continuity and the Euler forms a closed system that is sufficient for determining the fluid velocity. So from here, you can determine the fluid velocity and the fluid pressure. Integration of this, if you integrate this equation, integrate Euler's equation, okay, um, along a streamline.

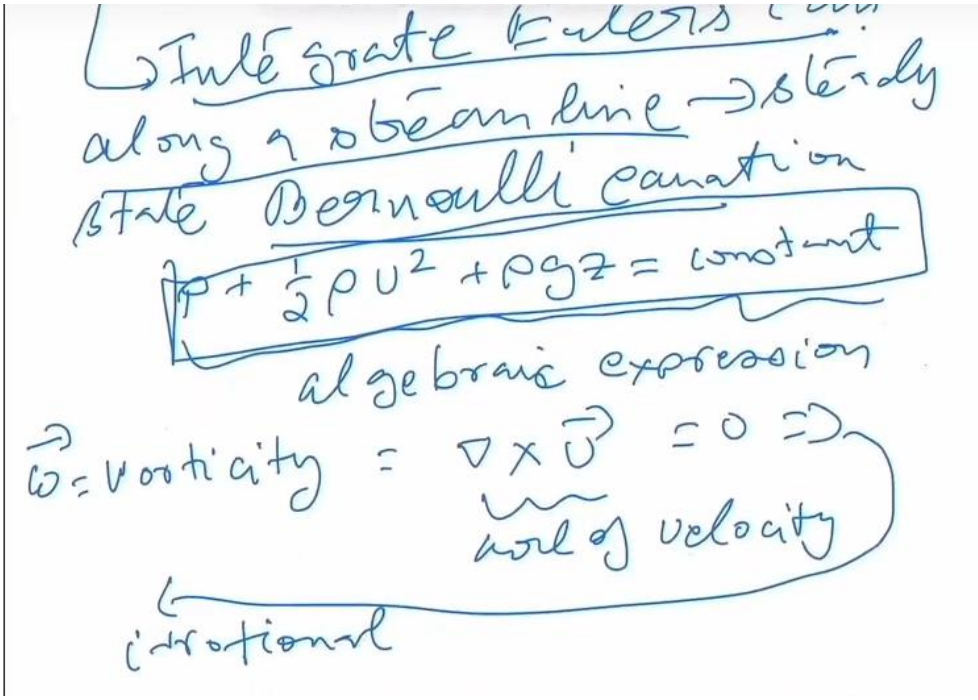


Okay, well, as you know, the fluid velocity is tangential to the streamline, so at any point in the streamline, the fluid velocity is tangential at that particular point. So, when you integrate it along a streamline, you get what we call the steady-state Bernoulli's equation. Bernoulli's equation. And this is also routinely used in many, many ways, you know. So this is an algebraic expression that basically relates pressure; if you do this:

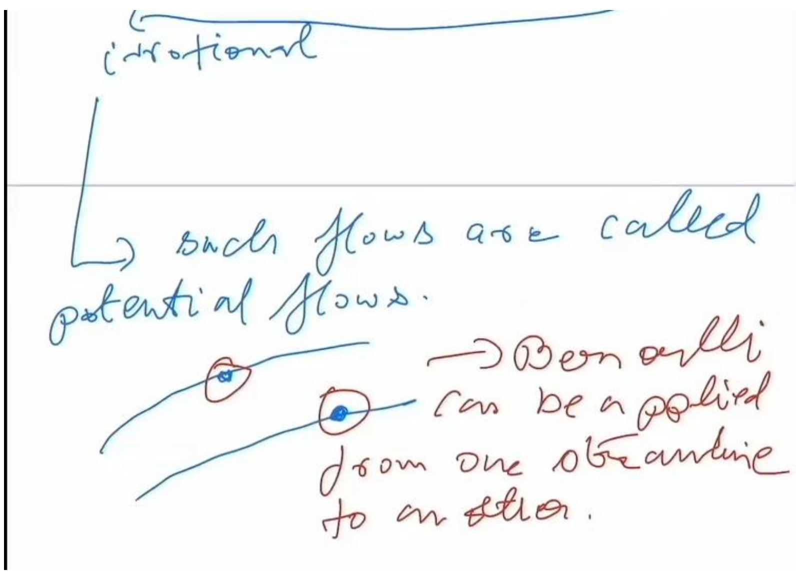
$$P + \frac{1}{2}\rho u^2 + \rho g z = Constant$$

Okay, so you can see that this is an algebraic expression. All right, this is further simplified by the assumption of irrotationality. Okay, so that means vorticity. Let's define vorticity; vorticity is basically into u. This is nothing but the curl of velocity, so this becoming zero implies the flow is irrotational.

Okay, so this is called the vorticity. We can write it as omega; you can write it in any other way; it doesn't really matter. Okay, as you can see, this is no friction. You get Euler's equation when you integrate it across a streamline; you get Bernoulli's equation, which is an algebraic equation that basically links fluid velocity and pressure. Okay, so it links fluid velocity and pressure—that's all that it does.



Okay, then when the flow is irrotational, such a flow is called a potential flow. So, such flows... Potential flows are called potential flows when the flow is irrotational. You can apply Bernoulli's equation from one streamline to another.

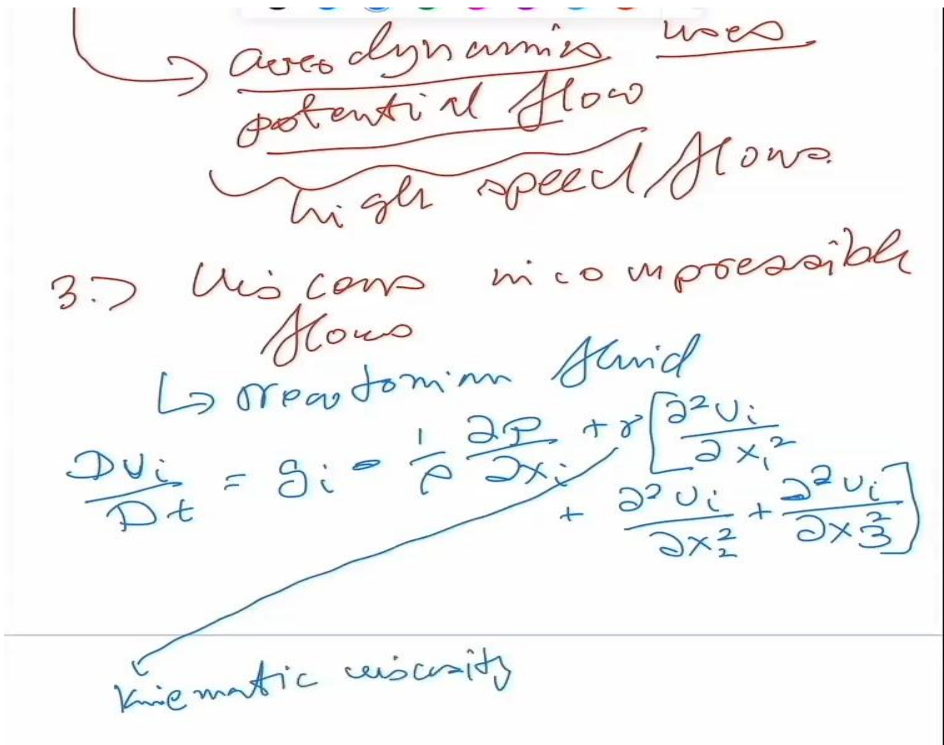


This is important, and potential flows are very commonly used in aerodynamics. Aerodynamics, the potential flow, is very, very common. Okay, the potential flow is very well-known in aerodynamics, right? So, you know, it uses potential flow. All right, so you know, this approach is acceptable in wind tunnel applications where the friction level is low or in high-speed flows, extremely high-speed flows, and high-speed flows.

So this is routinely used in those kinds of situations. And then, of course, you have the viscous, incompressible flow. Okay, so your continuity equation still remains the same. So this leads to a Newtonian fluid. We're dealing with a Newtonian fluid.

This leads to the celebrated equation called the Navier-Stokes equation. So do it by that. Remember, this is a substantial derivative : $\frac{Du_i}{Dt} = g_i - \frac{1}{\rho}\frac{\partial P}{\partial x_i} + \nu\nabla^2 u_i$

This is the Laplace. Okay, so this is basically called the kinematic viscosity.



The main parameter that drives these flows is called the Reynolds number, which basically represents the ratio of inertia forces divided by the viscous force. In the limiting case of vanishing Reynolds number, the inertial effects become negligible, and this equation reduces to the Stokes flow, which contains no nonlinear terms. Remember the nonlinear term contained here is nonlinear. So you can get Stokes flow in the range where the Reynolds number or the inertial effects are negligible.

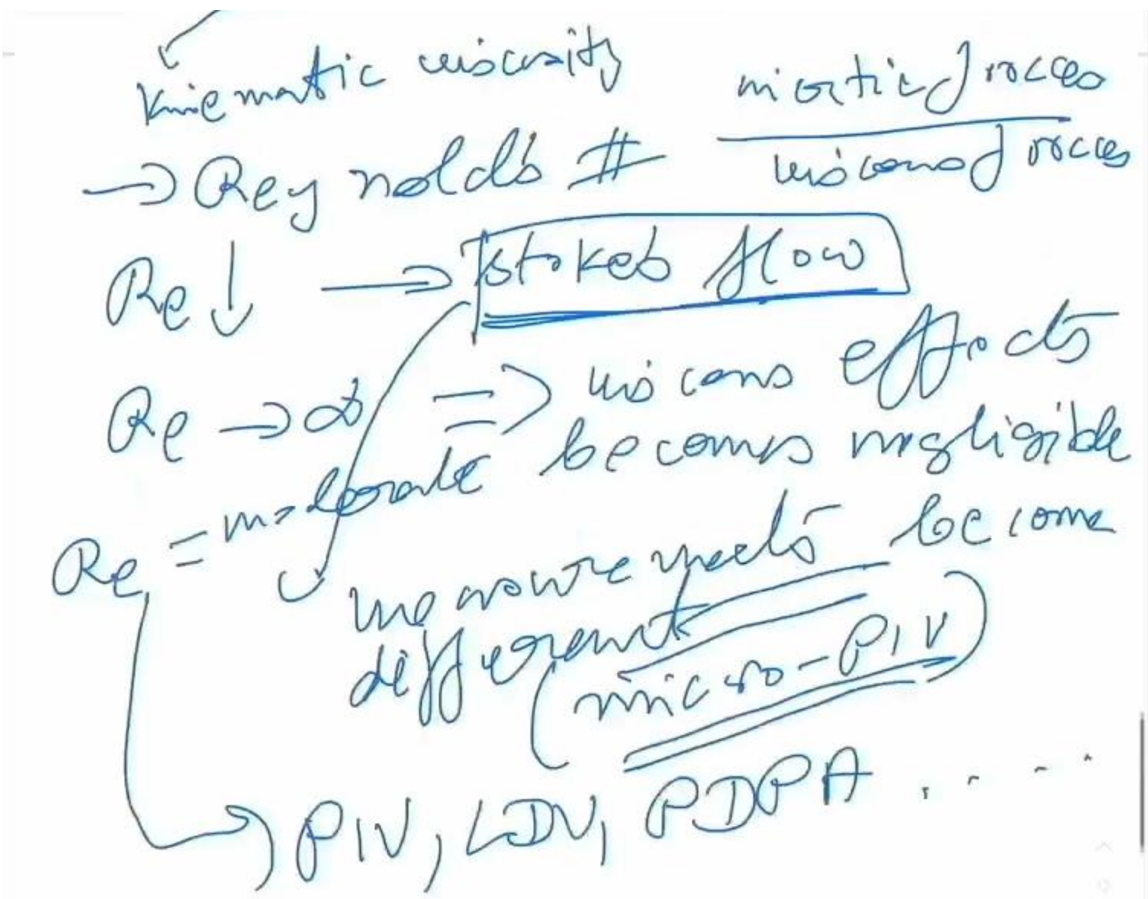
That essentially means very low Reynolds number events. And that is called Stokes flow. When the Reynolds number, represented as Rd, is very small, you can go to Stokes flow. The Stokes flow regime is very small. So the solutions and the measurements that you use in the Stokes flow are very different from high Reynolds number flows.

So they are very different. They are radically different. So as the Reynolds number goes to infinity, you will have dominance. The viscous effects become negligible. So this is also a fact: the viscous effect becomes negligible.

At high Reynolds numbers, one must consider friction; however, this limit contradicts the physical fact that as the Reynolds number increases, the flow becomes unstable and eventually turbulent. Now, when you take a course on turbulence, you will see that you must consider friction because that's where, you know, the cascade actually ends.

So the... So all these things you have to keep in mind. So, for low Reynolds numbers, you have Stokes flow. So the measurements here, measurements become different. When we do micro PIV, we will see something like this. And the flow Reynolds number is very small.

We use micro PIV. And for Reynolds number, which is moderate, we will use PIV, LDV, PDPA, et cetera. But this is what the Navier-Stokes equations actually look like. So this is the Navier-Stokes equation.



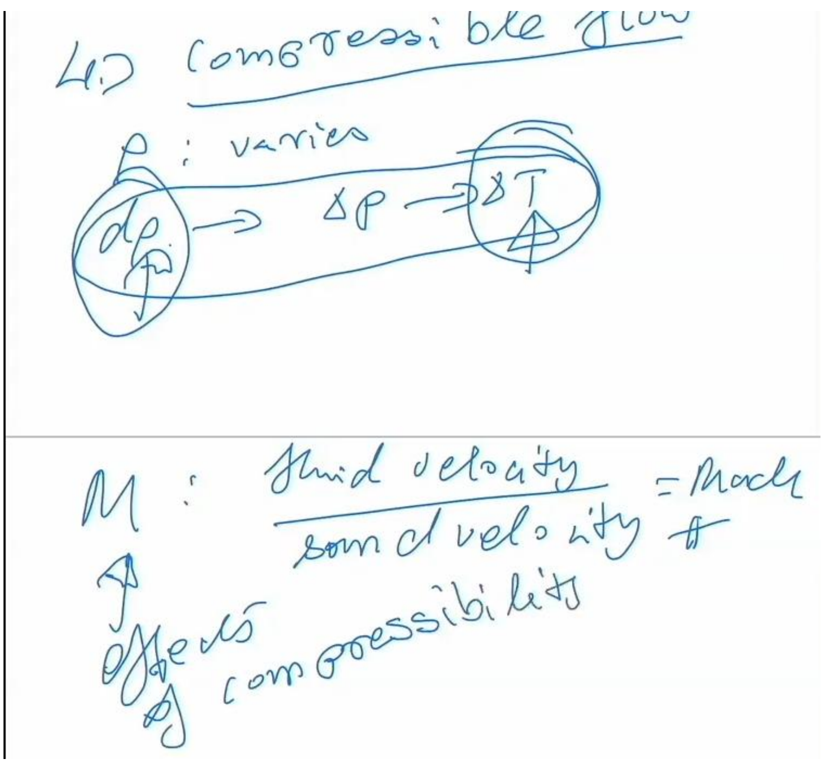
So then comes the last one, which is called compressible flow. When you do compressible flow, the density varies.

And the density changes are also related to pressure changes and are also accompanied by temperature changes. So, density changes. Differential density is linked to actual differential changes in pressure. It leads to ΔP. It also leads to ΔT and all these factors.

That is what happens in compressible flow. A compressible flow model contains, besides fluid velocity and pressure, two additional unknowns, which are basically density and temperature. This requires additional equations. So density and temperature are the two additional things that are brought about by this. To simplify compressible flow, friction is often neglected.

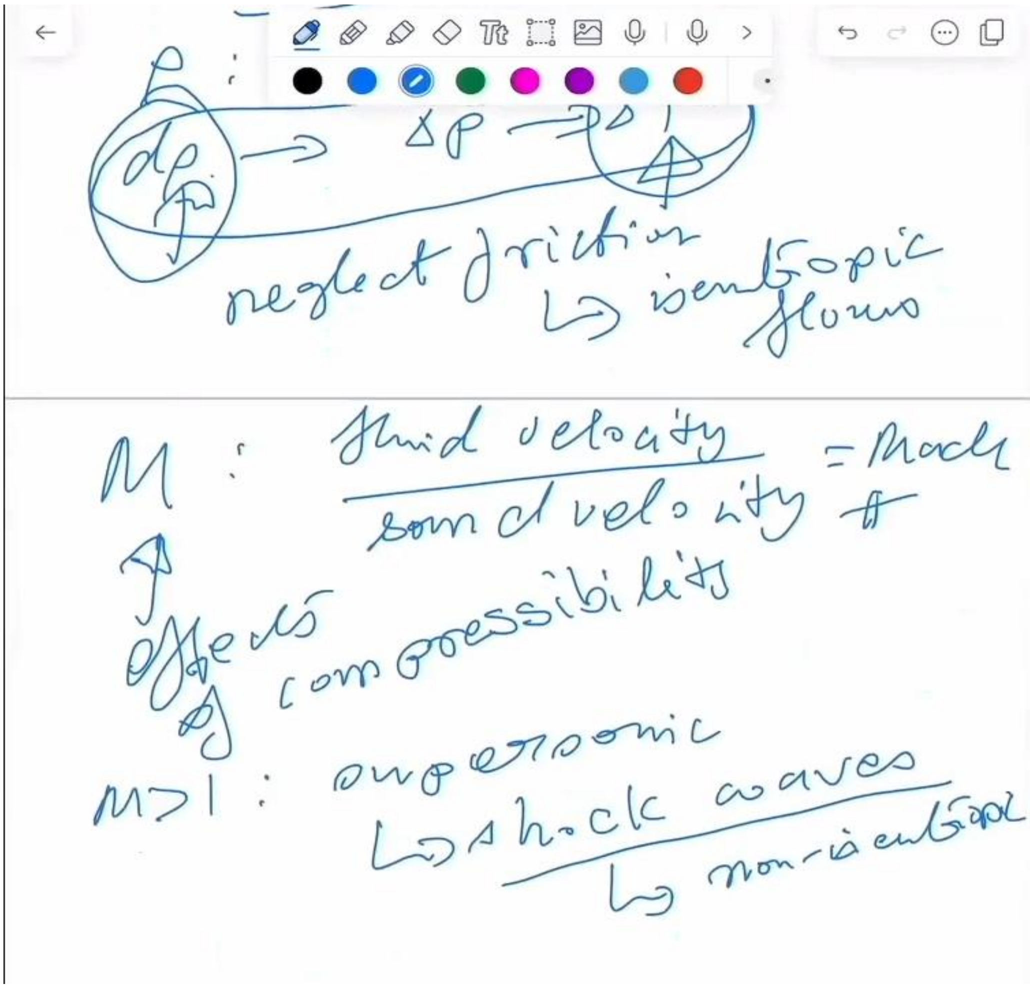
If you neglect friction, isentropic flow is what is commonly advocated. It's commonly an approximation in compressible flow instrumentation. When you do this, allowing for density changes permits the modeling of the propagation of weak disturbances with a finite velocity, which for isentropic flow is called the speed of sound. So the ratio M, which is the fluid velocity to the sound velocity, is called the Mach number. Okay, so the Mach number, which is a dimensionless parameter, describes the effects of compressibility.

Effects of compressibility. Okay, it can be viewed as a ratio of inertial forces to the elastic forces.



So when the Mach number is greater than one, the flow is called supersonic. That means dramatic and sudden changes in fluid velocity and thermodynamic properties occur. You get things like shock waves across which the pressure varies quite a bit. And these shock waves are actually irreversible and non-isentropic.

OK. As you can understand, when you are dealing with compressible flow, when friction is neglected, this becomes what we call isentropic flows.



All right. Then lastly, of course, you have turbulent flows, our second last, turbulent flows. This is the flow that we mostly encounter.

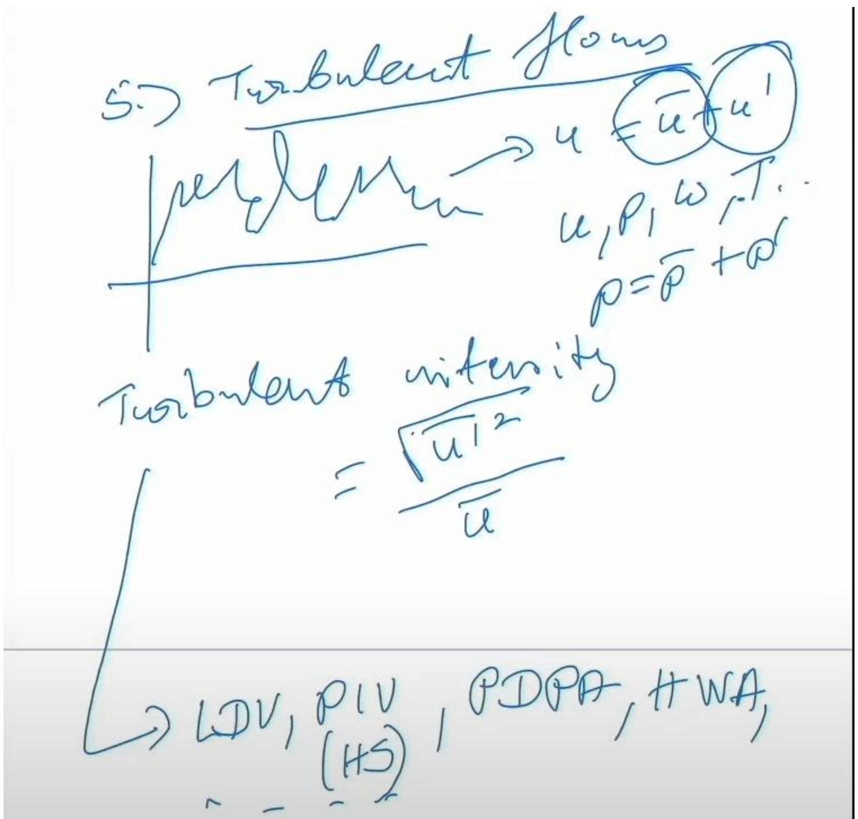
So this has complex fluctuations. So, there is a mean. Look at the turbulent flow. This will look something like this, for example. So this is, for example, the U. The U is broken up into a mean component and a fluctuating component.

So there is a mean, and then there is a fluctuating component. I mean to tell it very crudely. And the velocity, pressure, vorticity, all the variables U, P, omega, et cetera, et cetera, even temperature if you have one. So these will vary randomly in space and time. So randomness requires a statistical description.

So there is a mean, and then there is a fluctuating component. For pressure, there will also be a mean and a fluctuating component, and so on and so forth. So these things will be there. And so important parameters here are something called turbulent intensity. Intensity, so when it is turbulent intensity, it is the ratio of the root mean square fluctuations and the corresponding mean velocity.

So, root mean square fluctuations divided by the mean velocity. So this is like your turbulent density. The measurement of turbulence is achieved with special instrumentation. So, if you want to measure turbulence, use LDV.

You use high speed PIV probably. Then you use PDPA. You used hot-wire anemometry. Okay, and so on and so forth. All the techniques that we are going to talk about later can be measured using these kinds of very sophisticated instruments.



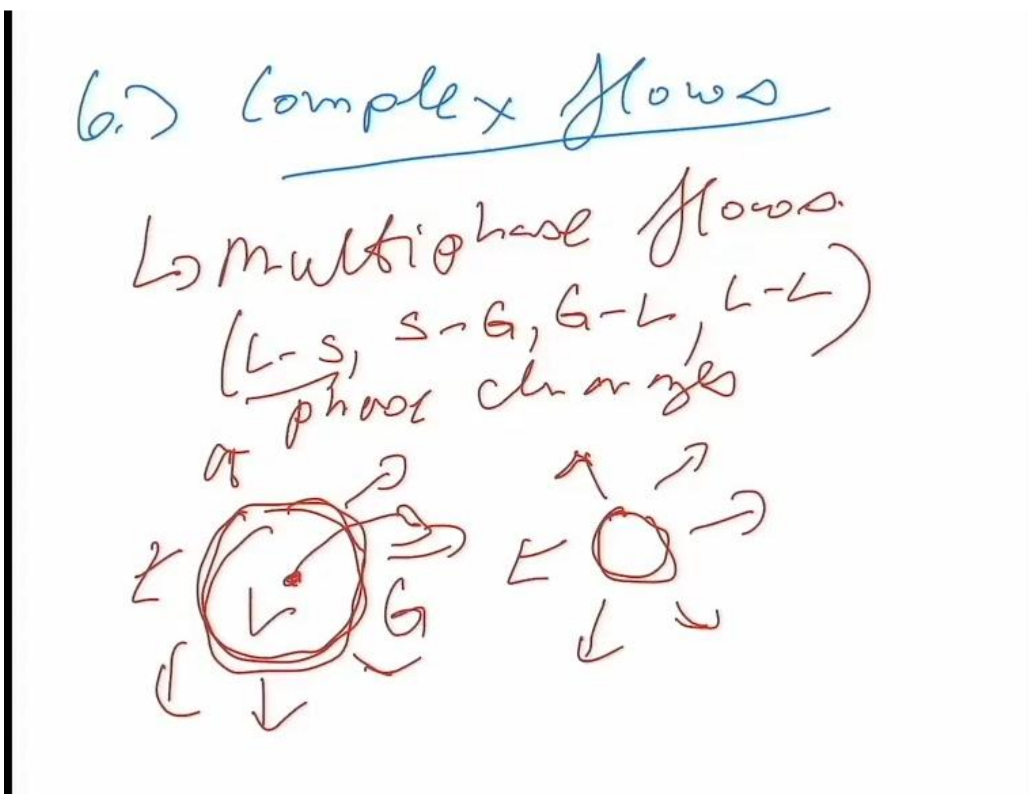
Once you get this, you can use several methods in turbulence; actually, you need to take a course or several courses in turbulence. There are special methods like phase averaging, and then you can have things like conditional sampling.

And so these have been devised to find out the turbulent cascades, the temperature, and the coherent structures, and stuff like that. Lastly, you have what is called complex flows. Complex flow. We are calling these flows complex because, for example, we are going to show many examples of this.

This is, for example, a multiphase flow. Multi-place flows can include liquid, solid, solid gas, gas liquid, and liquid liquid, which are the most common. There can also be phase changes; for example, when you have a droplet and it evaporates, it becomes smaller in size. There is a phase change, which actually happens. Liquid is being converted to vapor, and this actually shrinks.

So therefore, you can have interfaces. For example, this is a gas-liquid interface. There can be several interfaces for this kind of flow. The multiphase flows will traditionally have sprays and droplets, which we are going to see. These are usually measured using the PDPA.

You know, PIV and LTV once again. And we will see some very cool examples of this from my research lab. So you can see what they actually are.

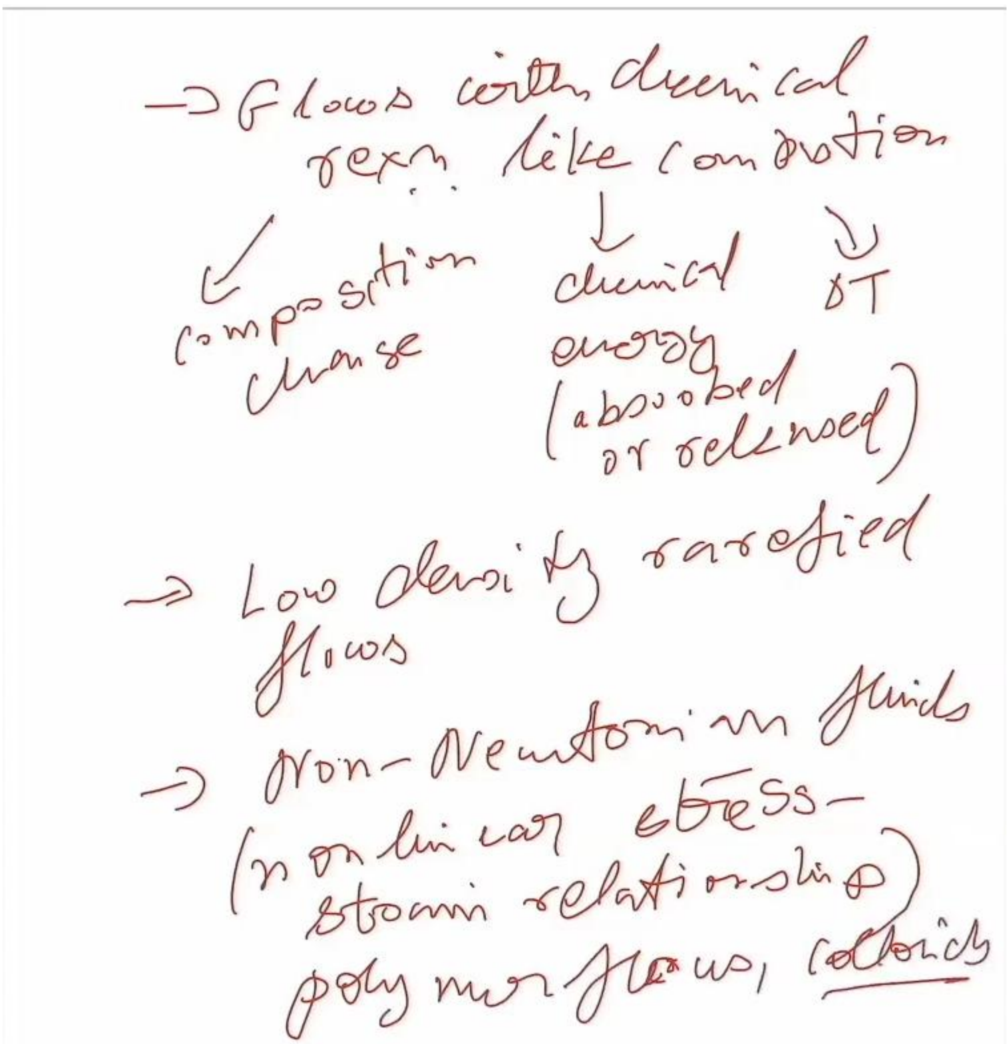


And then you can have flows with chemical reactions, such as combustion, for example, where you burn stuff, okay? So this basically involves changes in composition, the release or absorption of chemical energy, and a change in temperature.

So this leads to composition change. Composition change. And then, of course, you have chemical energy. Chemical energy comes from the bonds. And then you also have changes in delta T, which is the temperature, supposedly because things will get hot. And chemical energy can be either absorbed or released.

So these are flows with them. Then you can have low-density, low-density, you know, rarefied flows. Where the continuum hypothesis is inappropriate. So you have molecular and atomic phenomena. Then you have non-Newtonian fluids, which are also called complex fluids.

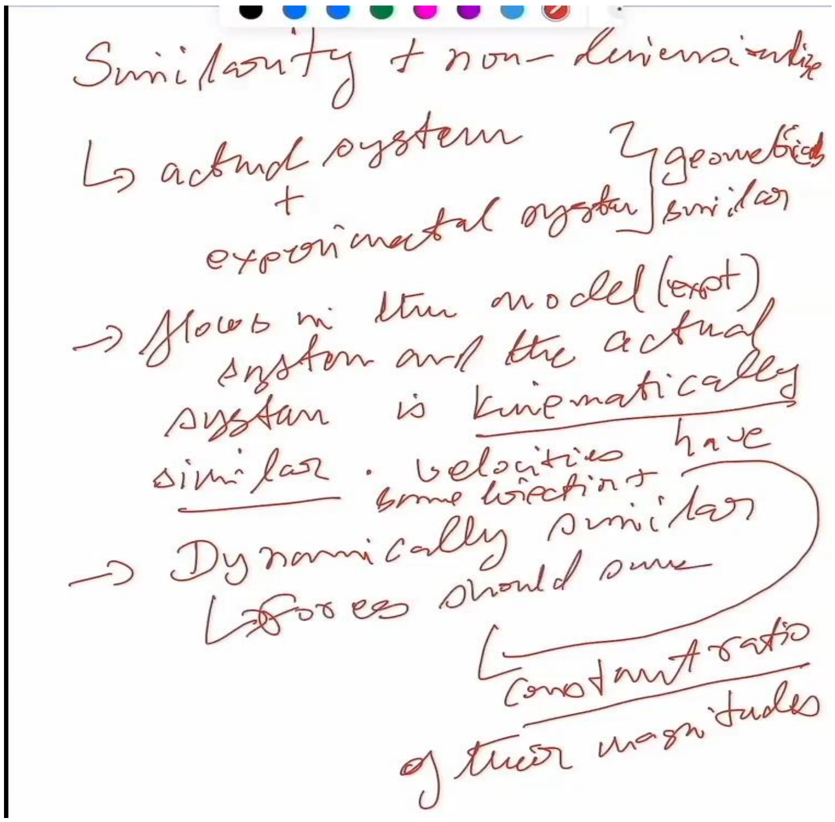
We will also show some examples with respect to that. This is basically what we call a nonlinear stress-strain relationship. Nonlinear stress-strain relationship. Example polymer flows, you know colloids; we have done much work on this. Again, you rely on the same type of instrumentation that you can think of and use the same for doing this, and then you can have things like magnetohydrodynamic flows also.



That is also an important parameter. Similarly, when you study fluid mechanics, you depend on something called similarity. Non-dimensionalization is important because whenever you non-dimensionalize things, you can use the results across experiments and systems. You need to identify the parameters that basically describe the system in a non-dimensional space, so there are no dimensions attached to it; for example, length, mass, and time are all non-dimensionalized. So you conduct an actual system of interest under actual operating conditions, and then by using this similitude or concept of similarity, you allow the application of this information to other systems that it represents. The essential requirement is that the actual system and the experimental model, since this is an actual system, do this all the time; we do it on some other system, but then we say that it is the actual system and the experimental system.

For example, they should be what we call geometrically similar. Okay, so they will be geometrically similar. In addition, the flows in the model and in the actual system are kinematically similar, so the flows in the model system, the model of the experimental system, and the actual system are kinematically similar. Kinematically similar. So kinematically similar means the velocities of the corresponding positions have the same direction and a constant ratio of their magnitudes, for example. So for complete similarity, you should also have what we call dynamic similarity.

So they should also be dynamically similar. Okay, that requires the corresponding forces to have the same directions and a constant ratio of magnitude. Here, for example, the velocities, okay, have the same direction, and plus, you know, a constant, you know, ratio of their magnitudes. Constant ratio; remember it is the ratio of their magnitudes. Magnitudes here, the forces should have the same forces and should be the same, just like velocity and velocity.



That means the same direction but a constant ratio of their magnitudes. So when two forces are similar, the results collected in one may be used in the prediction for the other, following proper scaling, which is resizing. That means measured flow properties are normally dimensionless because what we measure is an actual velocity with a number. Non-dimensionalization is the process of converting these measured properties into non-dimensional numbers by utilizing the appropriate scales. So this results in an independent of the system, so to say, and acts as a guide, basically. So some of the most common non-dimensional parameters will be looked at in the next class, where we are going to see what is common about these non-dimensional parameters.

This should be something interesting to look at. So we can start by looking at the Navier-Stokes equation, for example, and then try to see what the common non-dimensional parameters in fluid mechanics are. So your measurement should give you ideas about what these non-dimensional parameters are. So it is quite a large group. Of non-dimensional numbers that have already been present in fluid mechanics, heat transfer, and related fields, heat and mass transfer, basically. So these groups appear naturally when all terms in the governing equations are converted to their dimensionless forms by dividing all properties by their appropriate scales, which is called similarity analysis.

So we basically do what we call a similarity analysis. But you have to know what the scales are by having a very thorough understanding of the fluid mechanics of the problem, so to say. All right. Thank you.