

# **CFD APPLICATIONS IN CHEMICAL PROCESSES**

**Prof. Arnab Atta**

**Department of Chemical Engineering  
Indian Institute of Technology Kharagpur**

**Week-10**

**Lecture 47: Turbulence Modeling**

Hello everyone, welcome back to another lecture on CFD applications in chemical processes. Today, we will start a new topic, and that is the CFD modeling of turbulent flows or systems with turbulent motions. Because turbulence is encountered in most industrial and practical flows that we see in nature. So, the natural turbulence that occurs can be found in rivers, oceans, the atmosphere, and wind. And in chemical processes, such as in heat exchangers, stirred tank reactors, and different kinds of reactors where enhanced heat and mass transfer are required.

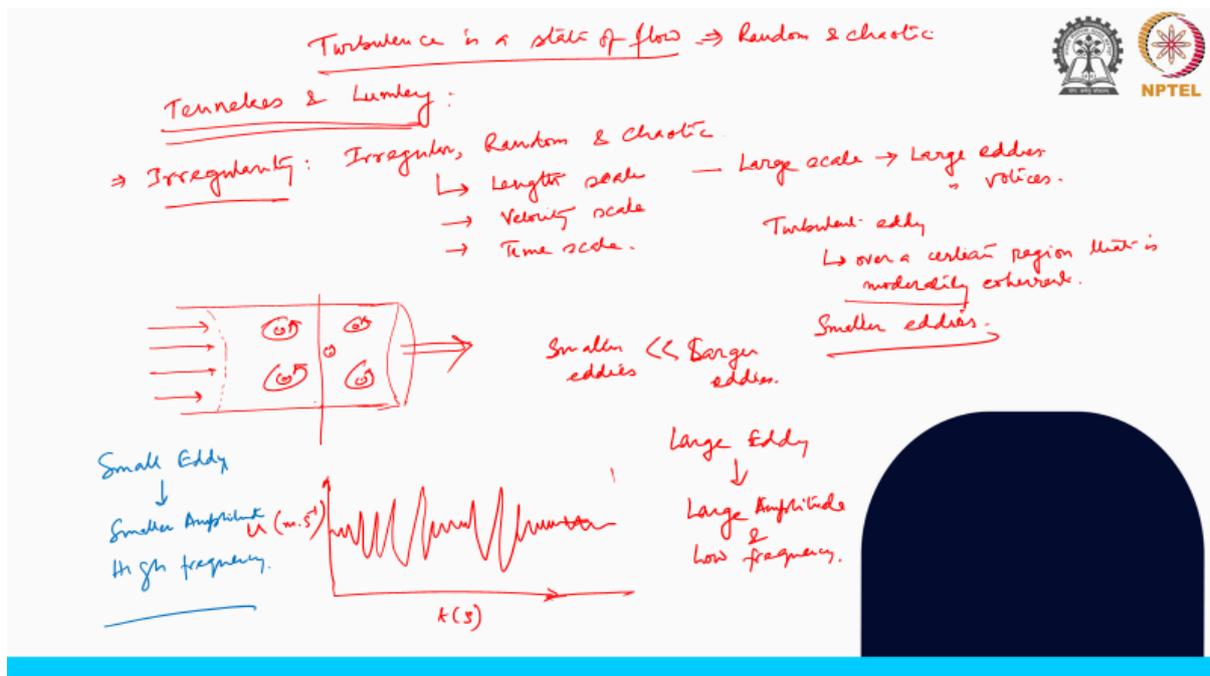
Now, the point is this most flow that we see in industrial applications are turbulent and that is the reason for that is that enhanced and mass transfer. However, along with this enhanced heat and mass transfer comes enhanced momentum transfer. Now, in several places or cases, that is not desirable—it is undesirable in several instances because that higher rate of momentum transfer results in higher drag and friction. On the other hand this enhanced rate of heat and mass transfer are critical in several industries and this is in the order of magnitude higher than the simple molecular mixing or molecular rate of enhancement of this heat and mass transfer.

Now, the point is that turbulent flow It also introduces vortices or we know that turbulent flows come with vortices eddies and that in fact, helps us in several cases where we require enhanced phase-phase interactions in multiphase flows as well. Because now we have understood in multiphase flow modeling how critical phase-phase coupling or phase-phase interactions are, as they dictate the choice of the CFD model. Now, this is further complicated when we have turbulent multiphase flow.

because in turbulent multiphase flow what happens due to this vortices or say the swirling motions of the flow this dispersed phase further breaks it may breaks in those multiphase flow and that results in controlling the interfacial area of this phase phase that actually dictates this phase phase interactions of the coupling terms. So, that is why understanding turbulence and its magnitude is very important in CFD modeling. So, in order to determine which turbulence model is best for your case or our case, we first need to understand the limitations of those models. We will not go into the very depth of the turbulence modeling how those strategies are developed or different because we also

have here in turbulence modeling several strategies like in multiphase flows or multiphase modeling. So, here also, we will not go into the very details of those model derivations, the strategies' derivations, or the governing equations' derivations. We will see a brief outline of those strategies, where they are applicable, or what the limitations of those strategies are. Now, the point is. We observe turbulence regularly—say, for example, if we have an ignited stick and a flame or smoke that we observe going away from it.

What we realize is that the smoke from this ignited stick, or the initially ignited stick from which the smoke arises, actually swirls away from the source. And far away from the source, what we see is that these swirling motions gradually decay and eventually become laminar flow. And also, what we see at the very beginning is that near the ignited stick, the smoke has a swirling motion, and that is dominant. So, actually there are different characteristics of this turbulent flow although the definition is not such hard and first, but based on the characteristics of the turbulent flow we try we will try to understand its magnitude and its impact on the modeling strategies.



As I said the degree of turbulence would dictate the modeling strategy choice along with the point that I have mentioned earlier is that the desired level of accuracy by which we want to capture the turbulence. Because this turbulence is not only at a particular length scale or time scale; it has several degrees of length scale or time scale associated with it, even at a single point. So, first, we will try to understand what the features of turbulent flow are. And before that if we try to find a generic say definition of turbulent flows, it has been said that the turbulent flow motion is an

irregular condition of flow in which various quantities show random variation with time and also space. So, the statistical averaging of certain quantities is clearly identified. So, turbulence is essentially a state of flow. which you can identify by the random motion and its chaotic character. So, if we try to understand its characteristic behavior, then there are certain things that have been mentioned or the researchers have categorized it, specifically Tannekes and Lumley.

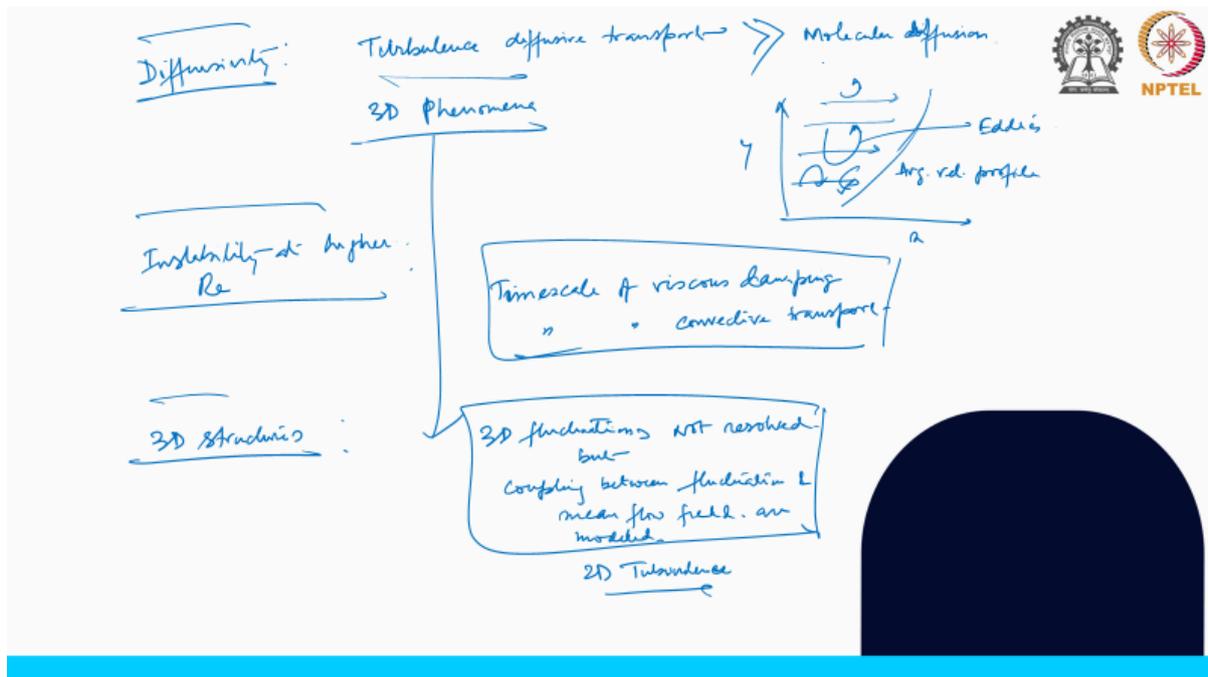
They mentioned certain characteristics of this turbulent flow, and to start with, one of the main characteristics is the irregularity. So, turbulent flows are irregular, random, and chaotic, as mentioned earlier. And it consists of a wide range of length scales, velocity scales, and time scales. So, the large-scale or, say, the large-scale motions in turbulent flow are usually called large eddies or large vortices.

So, a turbulent eddy is essentially the motion of turbulence in a turbulent flow over a certain region and is at least moderately coherent. So, turbulent eddy is a turbulent motion over a certain moderately coherent, ok. Now, the same region can also contain smaller eddies.

Smaller eddies mean the length scale of these eddies is small compared to the larger ones. So, they coexist, and in fact, it may happen that the smaller scales exist inside the larger eddies. So, it looks like something that if I have a pipe flow of turbulent flow So, here if I have these are the larger eddies I have smaller eddies inside it. So, this is the smaller eddies these are the larger eddies.

So, these are the different eddies that we see. So, what we see here that inside the larger eddies the smaller eddies can also coexist in such cases. So, that is the point becomes that which length scale you would like to observe in your modelling. So, we will come to those discussions, but at first let us understand what are further these characteristics that can have. So, the smaller eddies in fact, are in the so, if I say the smaller eddies are several order magnitude lesser than the larger eddies.

So, these eddies essentially what happens while it moves it rotates, it stretches, it breaks into more eddies. So, a larger eddies can break into multiple smaller eddies and that happens while it flows. Now, the point is the statistical models that is why it is applied to these cases for this practical solution of the turbulent or the practical modeling of the turbulent flows. Now, particularly what happens when say we try to find an instantaneous velocity or the velocity field for a particular say location. when this eddies passes through that point it actually shows us the fluctuating velocity.



So, if we have say an observation point as I said like this and if I try to plot if we plot this thing with time and velocity here. millimeter per second. So, what we observe is that this kind of a noise or the velocity that we observe as the time passes as the flow happen. Now, the thing is that while these smaller eddies and larger eddies both pass this point or point of observation, it is a certain point in the turbulent flow field. It shows that the larger eddies, when they pass, cause the fluctuations.

So, if I have the larger eddy that is passing through this point, it shows large amplitude and low frequency. On the other hand, smaller eddies show smaller amplitude and high frequency. Small amplitude and high frequency are shown by the smaller eddies. The other characteristic of turbulent flows is diffusivity.

This is one of the most critical or most important characteristics of turbulence. So, turbulence diffusive transport This happens due to chaotic motion in the flow, which allows faster mixing rates of species, momentum, and energy than molecular diffusion. So, turbulence diffusive transport has a much higher order of magnitude than molecular diffusive transport or molecular diffusion. Now, since turbulence, from the previous characteristics we have seen, rotates, stretches the eddies, and all these things happen in 3D.

So, turbulence is inherently a 3D phenomenon. So, turbulence is always a 3D phenomenon, but then you would argue that you possibly have seen or people have already spoken about 2D turbulence modeling. The point is In this case, it is always the 3D cases that are happening, but these smaller scales are truncated or filtered out in those modeling stages where it is assumed as a simple 2D phenomenon. So, the point is this.

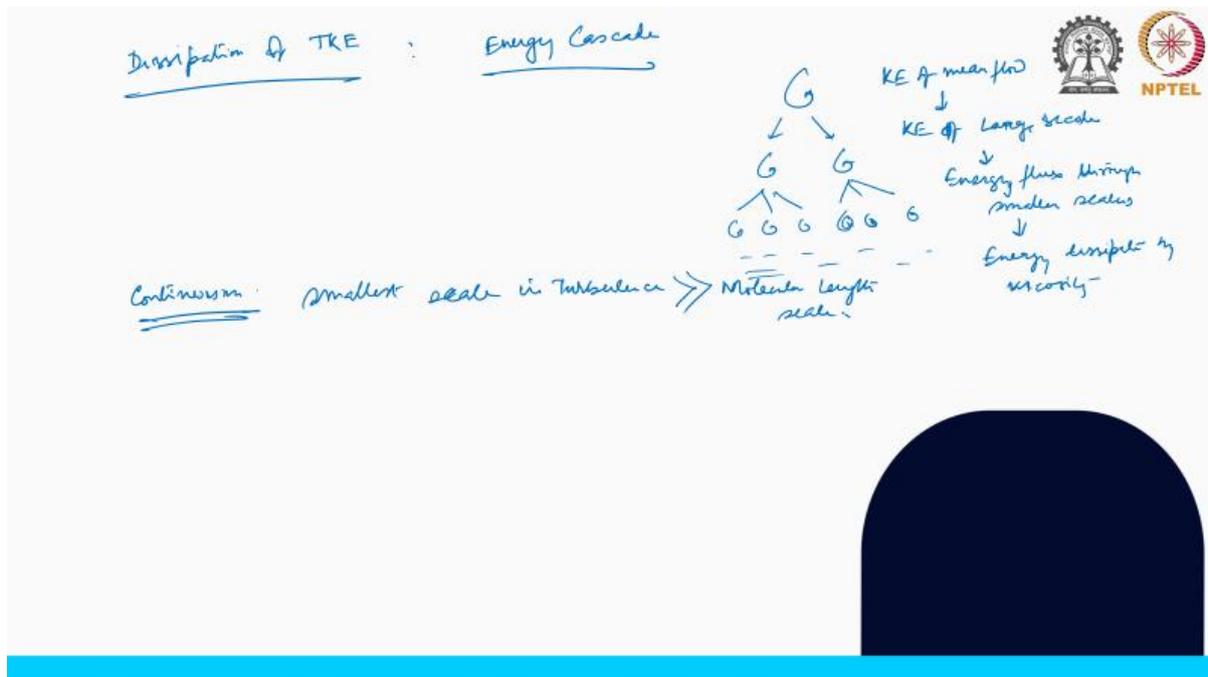
So, say if I have this transport that is going on. So these are the turbulent vortices that are there or turbulent vortices. So this is the X, this is the Y. So this is the average velocity profile, and these are the turbulent eddies. So, what happens is that even if the mean flow in the y directions or the mean velocity component of this average flow is 0 in the y directions, there would be still mixing or the transport of the species in the y directions by the turbulent HDS, which would not happen in the case of simple molecular diffusion.

And that is why we have an enhanced rate of mixing in the case of turbulence and that is why we induce turbulence when we try to mix milk with water or we try to make it hotter cup of coffee or tea cold by stirring a spoon inside it. So, the energy transfer or the mass transfer, etcetera, are enhanced in those cases; this transport of species is enhanced by the turbulent motion of the fluid. The other thing is that we have instability at higher Reynolds numbers. We will discuss this point immediately after discussing these characteristics in detail, but the point is we understand one thing that

In a pipe flow you have heard this example in a pipe flow when the turbulence happens you typically answer that when the Reynolds number of that flow goes beyond 2100 or 2200 and that kind of number and it becomes fully turbulent when that Reynolds number becomes more than 10000. Now, why does that happen? Why at higher Reynolds numbers does turbulence happen? This discussion, this region, we will talk about a bit later, but apparently what you can understand is the time scale. So, whatever the fluctuations that happen in the flow can be diminished or can be absorbed by the viscosity; that is the nature of the viscosity.

But the point is this damping the viscous damping time scale it has a time scale that once a perturbations or a fluctuations is induced the time it takes to propagate and within that time if the viscosity can absorb this perturbations then that perturbations or say that fluctuations would not propagate further. So, this difference between the time scale of viscous damping and the time scale of convective transport. So, the time scale of viscous damping and the time scale of convective transport. These two actually dictate whether there would be instability or not when the flow is happening or once the turbulence is there in the fluid.

One thing is pretty clear from my initial example: these swirling motions or the vortices, and you see their decay at the far end from the source. The point is that we say turbulence is essentially decaying in nature unless you provide a continuous source, okay? So, the point is that this is another feature of turbulence, which we call the dissipation of turbulence kinetic energy. Now, the point is, Before discussing that, let us touch on another aspect of the characteristic: the 3D nature, the 3D structures.



As I said, it is inherently 3D, intrinsically 3D in nature—the turbulence. Okay, because there is vortex stretching, vortex tilting, etcetera, which we will shortly discuss, but the point is. You have also seen, or you will also see, you yourself will also do 2D turbulence modeling, and that is completely in a statistical sense. That means turbulence can be interpreted as a 2D phenomenon if we find some statistically averaged values that are repeating in nature. So, the point is,

So, in practical applications, this 3D—that we see the fluctuations, the 3D fluctuations—In one dimension, it is averaged and statistically represented. So, this 3D fluctuations are essentially filtered out I would say and we do not resolve those fluctuations and, but we resolve. So, we although we do not resolve the 3D fluctuations not resolved, but coupling between fluctuations and mean flow field are modelled and then you represent that as the 2D turbulence modeling ok. The other feature is the energy dissipation that we briefly spoke about dissipation of turbulent kinetic energy in short I have written here TKE. So, dissipation of turbulent kinetic energy, then this means that in turbulent flow there is a flask of energy from the larger eddies to the small scales or the large scales to the small scales. Now, this large scale eddies which are in the dimension of the domain or in which it is happening. domain means if it is flowing through a pipe the diameter of the pipe.

So, at that it can have the maximum of that diameter length scale the larger eddies, but then when it flows it breaks into smaller eddies and its energy that it extra extracts from the mean flow is transferred to those smaller eddies. subsequently those smaller eddies further breaks into smaller length scale eddies further smaller length scale eddies. And this sequence goes on until there is a viscous dissipation of the from the small scale eddies. And this sequence is

called or this phenomena we call as the energy cascade. The kinetic energy that enters from the mean flow to the large scale eddies is transferred to the smaller scale and by inviscid process this energy is then transfers to the further smaller scale eddies.

And, this energy is then this happens because this larger eddies are instable or not stable in nature, unstable they breaks into smaller eddies which then transfers this energy to the smaller scale. And, those smaller scales consequently undergo the similar process and transfer the energy to further smaller scale. So, the point is this happens until this energy is dissipated into heat by viscous action. So, what happens if we try to understand schematically? So, these two smaller eddies again here can have further smaller eddies, and this sequence usually goes on.

So, at the end, the kinetic energy of the mean flow supplies the formation of these larger eddies. Then, the kinetic energy of large-scale eddies from there, the energy flux happens. So, smaller eddies or the smaller scales ultimately dissipate this energy by viscosity, as viscous dissipation into heat.

Now, how is this kinetic energy of the mean flow continuously generated? It is by pumping the fluid through the pipe. If you have a stirred tank reactor, there is a stator that continuously supplies that energy, but if those are taken out from the system or if you stop pumping it, then you would realize that this turbulent flow eventually decays and becomes laminar flow as time progresses. So, without a continuous supply of this energy, it eventually boils down to laminar flow. The other important characteristic of turbulent modeling in CFD is the consideration of continuum.

which means turbulence, although it has very small structures that it creates through the formation of eddies. The smallest scales generally considered, generated from these eddies, are much larger than the molecular length scale, okay? So, the smallest scale in turbulence is still larger than the molecular length scale. And therefore, the motion of the fluid

Then we are describing in terms of conservation equations of mass and momentum with appropriate initial and boundary conditions and we use the Navier-Stokes equation with the features of the turbulent flow in the momentum expression. Although now we understand that describing turbulence requires stochastic approach and Navier-Stokes equations is the deterministic approach, but with the averaging or with the turbulence model that we will see we eventually express this stochastic nature through the deterministic approach. The other thing that we must understand is that turbulence is the state of the flow.

Turbulent flows are flows. It is not a characteristic of a fluid. All fluids would exhibit turbulent flow at sufficiently high Reynolds numbers. All fluids would exhibit turbulent nature or turbulent flows provided there is a sufficiently high Reynolds number.

So, turbulence is not a fluid property that you must understand; it is the flow. So, on this note, I will stop here, and we will continue this discussion in the next lecture. So that we can understand what the modeling strategies are to account for these chaotic motions. Till then, thank you for your attention.