Computational Fluid Dynamics

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Module No. # 06
Dealing with complexity of physics of the flow domain
Lecture No. # 39

We have seenthe two equations model for turbulence, in terms of two quantities, k the turbulent kinetic energy, and epsilon, the rate of dissipation of the turbulent kinetic energybeing used to evaluate the turbulent viscosity or the eddy viscosity associated withturbulent flows.It is very important in turbulence modeling to consider the near wall turbulence, because that is a very important region, in terms of theproduction of turbulence and so on.

So, we have totreatthe near wall turbulence properly, so as to get solution which is appropriate.

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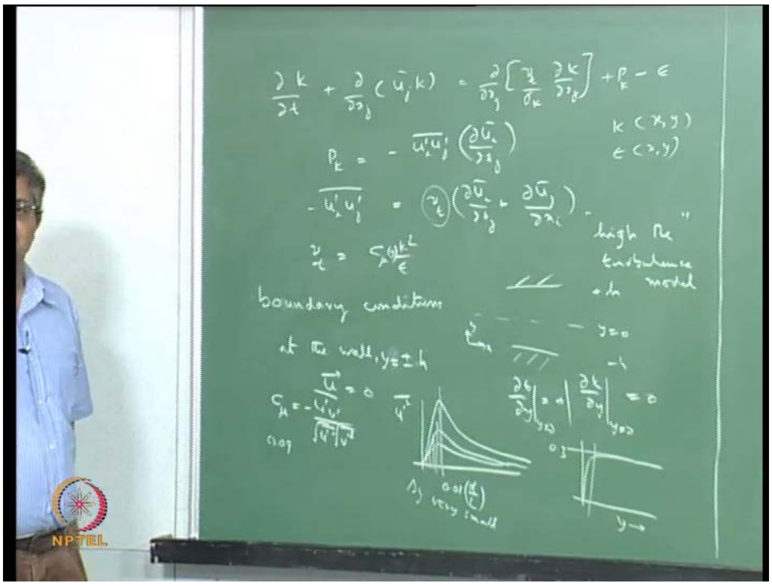

So, what we mean by near wall turbulence is, thatin our model we have written equations like; dou k by dou t plus douby dou x j ofu j k, mean this equal todou x j of nu t by sigma k, dou k by dou x j representing the turbulent diffusivity ofkinetic energy, plus a production termandrate of dissipation term, this is the epsilon and p k here, it is a production term which is minus u i prime u j prime bar, in terms like this.

So where you have large mean velocity gradients, we have a production of turbulence, which goes in to this as a source term, and this itself is represented in terms of nu t, dou u i bar by dou x jplus dou u j bar by dou x I, where nu t is given as c mu, k square by epsilon.We have a similar transport equation for epsilon and therefore, we have two standard equationsof the generic scalar transport equation representingk and epsilon, which go together to determine the turbulentviscosity, which goes on to determine the turbulent or Reynolds stresses, in terms of mean velocity gradientsand the turbulent viscosity.

Now, what about the boundary conditions, we know thatany partial differentiation equation, any differential equation cannot do withoutthe boundary conditions, and initial conditionsas appropriate. Since, we are talking about mean quantities, k and epsilon here are meantime average quantities, so wherever you have a standard boundary conditions, like asymmetry plane,plane of symmetry, andthose kinds of things are still applicable.

So, when you have plane of symmetry, like flow througha duct, which is exactly identical with respect to the center plane, then we cancalculate the flow field, either in this part or in this part,it is not necessary to go through this, in which case, along this planeonce can say that,if you say that, this is xand this is y, and this is y equal to 0, and y equal tominus h plus h; like that, one can say that dou kby dou y at y equal to 0 is 0, and similarly, one can say that dou epsilon by dou yat y equal to 0 is equal to 0.

So, these kinds of boundary conditions natural to theflow arequite valid, but what isimportant in many practical cases, is also the boundary conditions at the wall, and that is where we have to makea special distinctive characteristics of turbulent flow. Ideally, one would say that, at the wall, in this case, that is at yequal to plus or minus h. We know that the velocities has to be 0, the velocity has to be 0 by the no slip condition, in laminar flow.

Even in turbulent flow this no slip condition is valid, but we cannot use this boundary condition with this kind ofturbulence model, because this kind of turbulence model assumes that, the turbulence is fully developed, and it is strong enough that most of the diffusion andthe production terms, theseareuninfluenced by the molecular properties.For example, we have said that, u i u j prime these Reynolds stresses, are functions only of nu t which is of a function only of k and epsilon, so this is purely a turbulent quantity, and therefore, this model is appropriate only for high Reynolds numbers

So,it is a high Reynolds number turbulence model, andso 1 would expect the Reynolds number of the flow to be of the order of 20,000 or 50,000 or greater, for this flow to be valid, and also very close to the wall, we have the special feature that the turbulence is damped.

We have seen the typical plots of, for example u r m s, that is u prime square bar, it would actually go something like this, and then it would come out like this, and this maximum is very close to the wall. It may bepoint 0 1 ofthe non dimensional length. So, that is let us say that distance divided by correct length, it can be something like that

So within that, you have a very steep variation of typical turbulence quantities, andeven the other things will golike this, and towards, and they all may become, as you move away from the wall, you may have isotropy, but very close to the wall, we have severe non isotropy. And, in this model we are not considering the non isotropy of the turbulence, because we have an isotropic eddy viscosity, which is being and brought in here, and it is a function of only the scalar quantities k and epsilon, and there is no possibility of introducinganisotropy, that is very strong, very close to the wall, as you move other from the wall, then you have more ofisotropy. So, that is one reason, why we cannot make use ofthis model very close to the wall.

You also havesignificant damping of turbulence very close to the wall, and finally, we have said that C muis a constant, and we have said that this isa something like, u prime v prime bar by u prime square v prime square bar, square roots. So,it is a non dimensional variation of u prime v primebar like this, with a minus sign, and we have said that this quantity is mostly constant, like this and this has a value of a point 3 with respect to distance from the wall, distance from the wall increasing, this reachesa constant value, based on this we have put C mu value of 0.0 9. We have made this a constant, and it is not a function of a distance from the wall, but very close to the wall this changes drastically, again like here.

So, that means that when you come very close to the wall, the turbulent viscosity is no longer directly proportional to k and epsilon, but this constant of functionality itself is a function of y, the distance to the wall. And, also the k and epsilon although they are 0 at the wall, they showa very steep gradients very close to the wall, in the region very near the wall.

So, that means that if you want to resolve a very steep gradient going like this, you need to have finedelta y here, so delta y needs to be very small. In order to resolve the very rapid variation of the turbulence quantities both k and epsilon in the region close to the wall, and that means that the number of grid points, which are needed to discretisethe given cross section will become very large.

So, there are number of reasons, one is the non constancy of the constants, the non isotropy of the turbulent viscosity, and the need for very small delta y; for all these reasons we cannot take this model very close to the wall, so westart calculating variation of k and epsilon.For example, k as a function of x and y and epsilon as a function of x and y, are calculated only fromafter a small distance from the wall, within the small distance the turbulence quantities change very rapidly, but fortunately that change can be expressed in terms of local variables or what are known as inner variables, that means that the variation here

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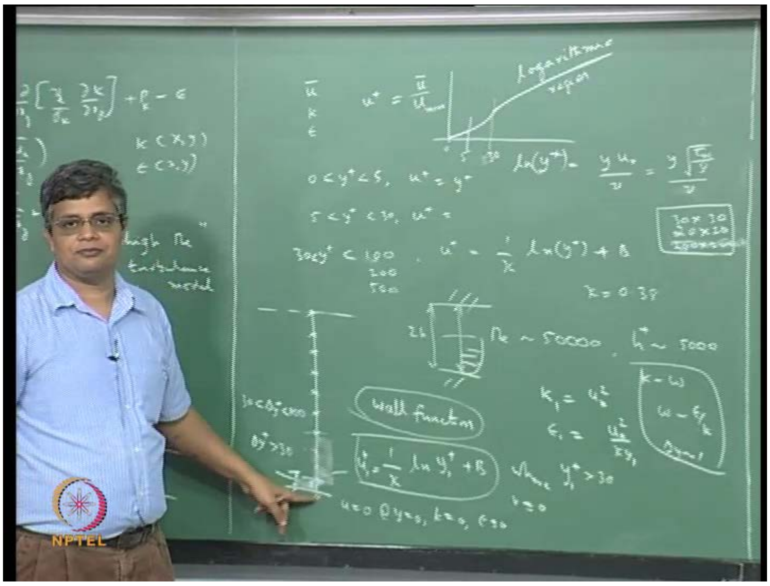

The variation of the mean velocity k and epsilon are very close to the wall, can be expressed in terms of dimensionless quantitiesy plus, which is defined asy u star divided by u; where u star is the suction velocity, and that is given as y, this is square root of wall sheer stress divided by the kinematic viscosity of the fluid. So, we are bringing in, the kinematic viscosity of the fluid here, and we are non dimentionalizing with respect to this friction velocity, which is a function of this, and now if you have to plot, this mean velocity, which is again non dimentionalized with respect to for example, u max or u mean as in the average velocity in a pipe like that.

Then, it shows a characteristic variation, it goes through like this, and then becomes a fairly constant thing on long plot, where y plus is plotted like this, and within a distance ofsay over a distance of y plus from 0 to 5, you have a linear variation between u plus and y plus, so this we call as u plus. So, we know that 0 less than y plus less than 5, this u plus varies linearly with this, and between 5 and y plus of thirty or so, u plusis afairly strong functionof y plus,it is a non-linear expression and for y plusgreater than 30, and so we can put it like this. 30 and up to well in to the flow, say of the order of, say hundred or 200 or even 500, like that depending on theflow, and what sort of pressure gradient we have and all that, there is a region in which thisu plus can be expressedas 1 by kappa, long y plus constant b, where kappa is a constant. We are familiar it is around point 4.3 8. 4 1 4 2 like that, so this has a slope of about 2.5 when plotted as u plus versus long y plus.

So, this is that this is known as the logarithmic region, and this region here, where your u plus is y plus is known as the viscous sub layer, and this is a buffer layer, so through this there is a more complicated variation here, but once you reach a distance of y plus greater than of around 30, you have almosta linear variation with log of y plus, and this is known to be valid, this logarithmica thing is valid for, it is a very universally velocity profile, this particular variation.It is universal, because it is valid for flows with pressure gradient and with adversepressure gradient, and awithfavorable pressure gradient for boundary layer flows, for flows inside pipes, andfor all this cases, this sort of thing is valid up to a certain distance.

So, in this sense very and this y plus of 30 is typically very small, because the maximum y plus,for example if you are looking atflow, between 2 plates and at a Reynolds number of the order, say 50,000, then if you say that this is 2 h, then h plus, which corresponds to the maximum distance, is of the order of 5000 or something like that.

So, this 30 which is the beginning of the logarithmic here is a small fraction of this whole thing, and we take advantage of this to say that, we know the variation of thevelocity, parallel to the wall, so in this direction you have a velocity profile like this, we know this variation in the region very close to the wall, and it is related to the local sheer stress in this particular way. So, we put, if this is our overall domain, this is the center and here, and this is wall here; so we put a first grid point here, second point, third point like this, and instead of saying that u is equal to 0, at y equal to 0, which is the no slip boundary condition. We say thatat this point, say u 1 is given by 1 by kappa long y 1 plus,plus b. So, the boundary condition that we apply here, andthis is u 1 plus.

So, this u 1 plus is the mean velocity at that point divided by the average velocity or the maximum velocity like that. So, in that sense, we specify the values of the velocity at the first grid point, taking advantage of the fact that within this point here, where in such a way y 1 plus is greater than 30, so we choose the delta y here.

We choose the delta y here, such that delta y plus is greater than 30, or let us say it is between 30 and 100 or 200 like this. So, we choose a value which is not very very close to the wall, but it is at a sufficientlylong distance fromthe wall, such that it falls in the logarithmic region, because in the logarithmic region we have an expression simple expression for u plus as a function of y plus.

So, if you know the distance when using this we can get the non dimensionalvelocity here, so this is the boundary condition that we use, so this is known as a wall function, because close to the wall, we are making use of an algebraic function, u in terms of yhere to represent the velocity, it is not given bythe momentum equation, nor is it given by the real boundary condition that at y equal to 0, u equal to 0

So, we are saying that very close to the wall, we havea velocity which is non zero and it is given by this universal velocity profile and the velocity normal to the wall, v is equal to 0 and w is equal to 0, is the standardboundary condition that we would get. What about k and epsilon, even k and epsilon are given bya similar functional values, one can show that k 1, so that is the turbulent kinetic energy at the first point, provided the first point is between 30 and 100 in terms of y plus is equal to u star square, where u star square is given in terms of this and one can showsomething like this, and epsilon 1 at this point is given in terms ofu star square by kappa y 1, something where kappa is point 38 and y 1 is the distance of the grid point from the wall. So, in that sense, we specify the values of u v w and k and epsilon at the first grid point, locating the first grid point at a sufficient distance from the wall, such that the y 1 plus lies between 30 and 100.

The reason for this is that, we do not want to get too closed to the y, because then we havesteak variation, slightly more complicated expression for this, andif you put too much, and if you take a y plus and may be 200 500 or 1000 in to that, then this first grid point will besomewhere here, and in all this region, you are not actually solving the momentum equation, you are making use of a mole function. So, in that sense, we want to make sure that the region, where we make use of where we impose the functional variation is very thin compared to the overall floor domain, we would like to make use of as much as the floor domain to be computed by the momentum equations, and it is only very close to the wall where we have deficiencies with respect to the way thatmodelingturbulence here, we make use of the wall functions.

So, this approach enables us touse,for example if you havea duct of a cross section like this, we can make use of the grid which may be a 20 by 20, grid to represent the flow through this, or may be 30 by 30, but if we do not have this wall function, and if we want to resolve this velocity profile all the way through this,right up to this, then we have to make changes to thisturbulence model, there are definitely those kind ofturbulence models which enable us to calculate right down to y equal to 0, for which the boundary condition will be u equal to be 0 at y equal to 0 and k equal to 0 and epsilon equal to 0.

So, you have the natural boundary conditions, for such models, those turbulence modelswhich make modifications to the standard high Reynolds turbulence model in such a way that you take account of the(()) trophy, that you take account ofthe damping of turbulence close to the wall and all that. So, there are such kinds of low Reynolds number turbulence models, andthere are so models whichlike k, omega type of model, where omega isrelated to epsilon by k, so instead of solving for k and epsilon like what we are solving here, we solve for k and omega and we getepsilon from this. So, these kind of approaches are more amenable to go right down to the wall, so using those models we canwe can resolve the full layer, but in such a case we cannot use only this kind of grid, we may have to havedelta y forthese kind of models, delta y close to the wall should be of the order of one.

So, that means that if you have a flow, such that the overall the maximum h plus is the order of 5000, then your grid delta y here should start with one here, and then if you have uniform spacing, you have 5000 grid points, so it should be 5000 by 5000, you probably do not need that, but overall you'd have in such a case.

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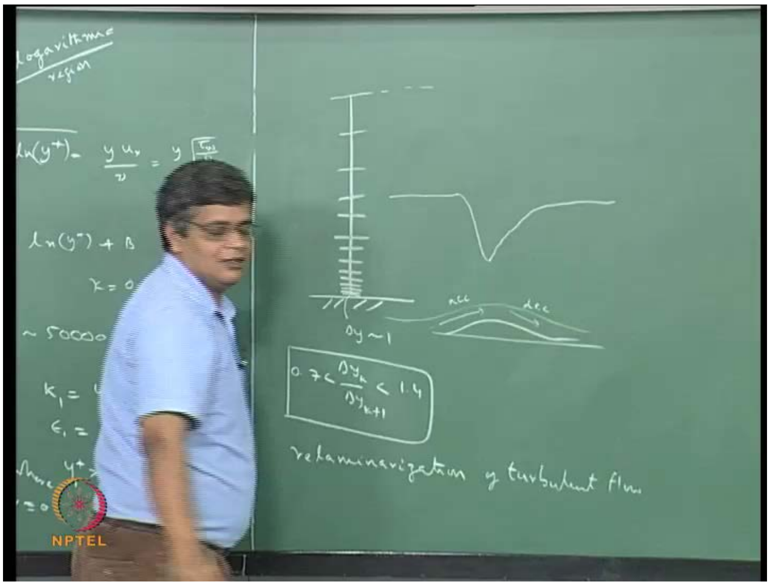

A grid which is geometrically expanding, this is the center line, and here you'llhave a grid spacing which can increasein geometric progression, but with the restriction that delta y close to the wall is of the order of 1, and also from, in order not to bring in numerical accuracies associated with a non uniform grid, you would like delta y k divided by delta yk plus 1

So, that is, this delta y divided by this delta y, so that sort of things, successive values to lie between point 7 and roughly 1.4 is a general thumb rule, so as not to lose too much accuracy ofdiscretization or approximation, finite difference approximations when we have this sort of expanding grid.

So, because of this you may not have to use 5000 or 5000 but, definitely the number of grids to representsomething like a square duct at a Reynolds number of 50,000 like this, may increase up to 200 by 200, and that means it is a hundred fold increase in the number of grid points, and the computational time will also increase much more, may be a fact of 100 squarelike that.

So,that is why in the general case, we would try to use the wall functions in order to represent the turbulence variation very close to the wall, but there are special cases where we may want tothese kinds of models which enable us to compute the flow variables all the way to y equal to 0.

For example, if you have a case ofa strongly accelerating flows, in such a case it is possible that the flow near the wall may become laminar, so that is called relaminarization of a turbulent flow, and one example is that, let us say that you have a wall here, and then you have a protuberance like this, so the flow is supposed to go through over this and come out, there's a small hill associated with this, and in this you have an accelerating regionand then you have a decelerating region. So, this acceleration of the flow, if it is strong enough, it is supposed to damp out the turbulence, and if theacceleration is sufficiently strong and sustained, the flow the flow may become laminar as it goes over the hill, and once it become laminar, the turbulent viscosity is 0.

So, that means, that your friction factor will be very different, and the heat transfer coefficient will be different and all that. So, if you were to plot,for example the Nussle number, it may be something likethis value here but, as you go over the hill, it may come down and then it may go back like this.

So, this drop in the heat transfer coefficient the Nusselt number is associated withthe relaminarization of the flow, and if you want to capture those kind of effects, then you have to resolvethe turbulenceright up to the wall, so in such a case you may have to use low Reynolds version of this, these type models or the k omega type of models like this, to getthisthesespecial effects.

Otherwise we havethis kind of fairly universal model, the k epsilon model, which can be used as a firstto investigate tocalculate the turbulent flowwithout having to fix any constants, but even though this is considered as a fairly general model, there aremodifications to this, for example strongly accelerating force for buoyant flows, andso in such cases people have come up with different set of constantsfor this, andso if we know such information, if you have such information then we can make use ofthose ad hoc fixes to the constants that going to thedetermination of k and epsilon as a function ofx y z and then the corresponding determination of theturbulent viscosity and so on.

Now, in that sense k epsilon modelcan be considered as a good enough, completely specified, self consistent andamodel whichwe can use straight away without having togive hocfixes, like we have to do for the case ofmixing length model, but this has somedeficiencies, one deficiency is the near wall treatment that we have seen, andthat is that we have to make use of wall functions, and that we cannot make use of the natural boundary conditions that at the wall we have k equal to 0 and epsilon equal to 0, but we have to assume a certainvariationor we have to impose certain variation close to the wall, somenon dimensionalvariationclose to the wall in order to get a solution.

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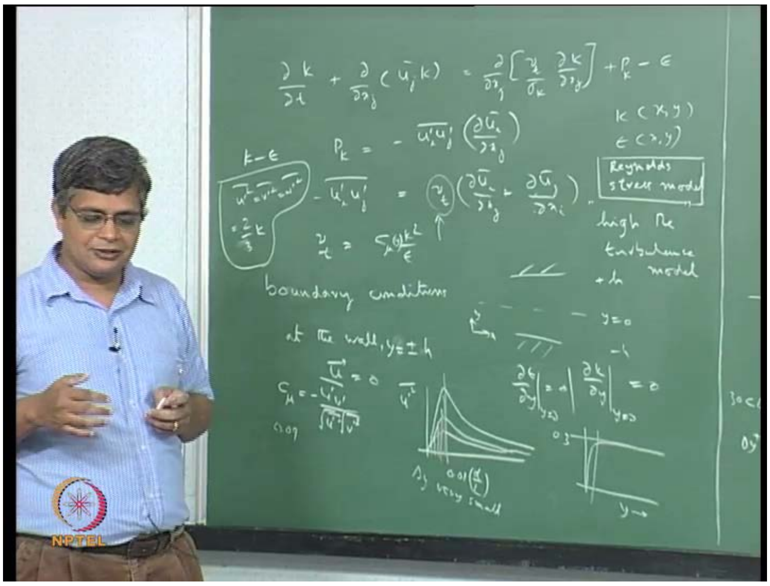

Another problem with this, is the assumption of isotropic viscosity here, the turbulence stresses hereare proportional to the mean velocity gradients through an isotropic viscosity, isotropic viscosity, because this viscosity is independent of which of the 6 stress that we areconsidering here, and this is isotropic, because this is determined only by k and epsilon, which are again scalar quantities, which are therefore, in that senseisotropic.

So, this isotropic viscosity is known to be not sogood when you are considering, for example a swirling flow, where you have flow going like this or within a flow with a strong curvature, you have flow going and then turning, so you have flow in a bend or flow in a coiled tube or flows with strong buoyancy. All, this are casesin which, the additional force field arising out of thisspecial effect, the swirling nature andthe buoyancy, these are directional, these are these are aligned only in certain components of the velocity.

So, you cansay that these bring in source terms, additional terms only in certain momentum equations, and not in others other equations, so in such a case one can expect the different turbulence stresses to respond in different ways tothe imposed external force field likebuoyancy.

So, thisassumption of isotropicviscosity, it will give usproblem in such cases, and then this model is also unable to representthedifferent levels of u prime square v prime square and w prime square at the wall, because once we know nu there, and once we know these velocities, one can calculate the different stresses here, andfor this kindof plane flow in which only du by dy is present, so that this is not present, we find thatthe turbulence stresses areconsidered to be the same, and one would say thatu prime square is equal to v prime squareis equal to w prime square is equal to two thirds of k, is the only thing that we can say about thelevelof theseturbulence quantities fluctuatingcomponents in each of the directions.

So, this equivalence of these things, isimplicit in this model,whereas experiments show that these can vary in different ways, and there are alsoexperiments, which show that, this linear relation between the turbulence stress and the strain rate, in which we havemade use of the, for example the similar linear relation between the viscous stress, and the strain rate in a fluid, if this linearity assumption is also not correct.

So, there are certain experimental data, which can be obtained, which can be explained only by a non-linear variation between the turbulence stresses, and thestrain rates, and so we have also models non-linear two equation models, and to represent the general anisotropy and responsive different turbulences from arbitrary force field, we havethe so called Reynolds stress model.

I am just writing in this box, in whichseparate transport equation is solved for each of the 6 Reynolds stresses, and in such a case you have the 4 equations representing, the time averaged continuity equation, and 3 time averaged momentum equations, and then there are 6 Reynolds stress components, so you have 6 additional transport equations for the 6

Reynolds stresses and you still havean equation forepsilon, that is dissipationrate which appears in the Reynolds stress equations.

So, you have total of eleven equations to be solved fora turbulent flow calculation, not just four, as we do in laminar flow. In the case of k epsilon model, we have to solve 4 time averaged momentum equations in the continuity equation, and then 2 equations for k and epsilon, we have 6 equations.

So, by increasing the number of equations, one can bring in more and more sophistication into calculation, and thereby we can bemore accurate in our calculations, especially for certain cases where we have sufficient data to determine fully the constants that appear in the Reynolds stress equations,but there is also theside effect oftrying to solve more and more turbulent equations, becausethe side effect is, that the number of equations that we want to solve increasesfrom 4 in laminar flow to 6 inthe two equation model to11 in the case of Reynolds stress model, this increases the computational time and it also increases thecoupling among all these equations, say therefore, the convergence of thesecoupled equations it becomescompromised so that overall solution becomes less robust.

So, that means that, if you try to solve all the equations, you may not be able to get an acceptable solution,sometimes you may get into non convergence, divergence of the (()) schemelike that. So, there is a loss of robustness as you go to, as you move away from the standard k epsilon model, towards Reynolds stress model or towards non-linear models and all that. So, we have to make a balance between theaccuracy that we want, and thekind of numerical effects that we are willing tospend in getting a solution.

If there is strong reason to believe that k epsilon model is notcorrect for a particular flow application, only then we should venture out into thespecial effects, either for better treatment of the turbulence close to the wall, in terms ofthe k omega type of models, which require more number of grid points or the Reynolds stress type of models which do not depend on the isotropic nature of the turbulence viscosity asmodeled in this or the non-linear models whichalso do not make this relation linear. So, all those special effects should be considered in, if we know, if we anticipate a problemwith the k epsilon model.

Now, we have said enough about the flow equations to especially the solution of the navier stokesequations in case of turbulent flow, but typically we not only have the flow, but we also have theheat transfer, the mass transfer and the chemical reactions associated with the flow. What about those things, how are those equations modified, when we consider turbulent flow.

The simple answer is that, the approach that we have used for thenavier stokesequations, for the momentum equations in terms of Reynolds averaging, and thentrying to come up witha simplified form ofan equation, representingthe turbulence effecton the overalltime averaged variation of the quantity.

So, that approach isextendable readily to the energy equation for no isothermal flows, and to the species conservation equation for the mass transfer and also chemical reactions. So, we can come up with time averaged energy equation, which look very similar and in such case instead of having a term like u i prime,u j prime.

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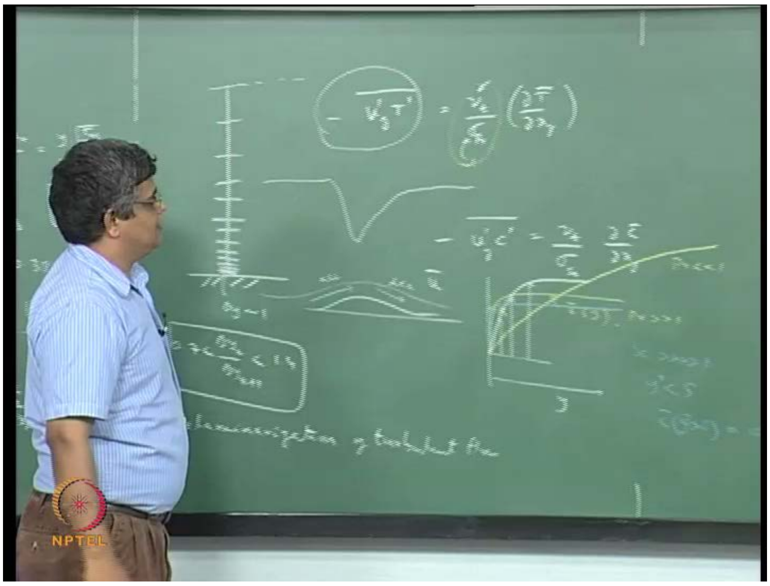

We will have a term like u j prime, T prime, minus u j prime T prime as the equivalentfluctuating energy flux, temperature flux, time c v will give us the energy flux, associated with turbulence and this is modeled in very similar way, like this is represented as nu t by something like the turbulent prandtl number,we will just put it as prandtl number here, subscript prandtl number, times dou t by dou x j, dou t bar by dou x j.

So, this is how we can do, this is already calculated as part of the solution of the momentum equations, andthis value here is roughly the order of 1, t bar is calculated from thetime averagedenergy equation. So, this is one way ofclosing this particular equation.

So, this is the additional term, that appears inthe time average energy equation, and that can be solved like this.Similarly, when we are looking atthe species conservation equation, when they come up with u j prime, say c prime, where c represents concentration species, and this again can be represented as u t by sigmaSchmidt number or something like that, representing the mass transfer, timesdou c bar by dou x j.

So, in that sense, when we time average the corresponding conservation equation, we do get into terms which are similarto the turbulence stresses that we have obtained by time averaging the navier stokesequations. We can extend a similar kind of modeling of this turbulence fluxes in terms of the turbulent viscosity, and turbulent prandtl number, turbulent Schmidt number and the mean gradients of thetemperature, and of the concentrationgradientlike this, and thereby come up withtime averagedscalar transport equationsfor the energy. And, when we come to thewall variation,variation of the temperature andconcentration flows to the wall, we have to come up with equivalent wall functions. As long as, the prandtl number of the fluid, andthe Schmidt number of the fluid for the energy flux, andthemass flux are around 1, we can make use of very similar kind ofvariationswall functions for this, but typically when we considerheat transfer, the prandtl number of the fluid need not be equal to 1, for many gases it is of the order of point 7, so it is fairly close to 1, but if you considersome organic liquids, it can be very high, of the order of 100, and if you consider liquid metals, prandtl number can be very low of the order of point 0 1.

So, you can have wide variation of the prandtl number, and in such cases when prandtl number deviates significantly from 1, you have to be very careful about the correctness of the wall functions that we use to represent theturbulent fluxes close to the wall.

Similarly, when we consider mass transfer, we havethe Schmidt numberwhich represents mass diffusivity to themomentum diffusivity, so that can be very large and for someorganic fluids it can be of the order of 10000 even 50000 like that.

So, again in such a case you havea variation of the concentration profile which is very different from the variation of thevelocity profile, in turbulent flow, and especially when the prandtl number is much much greater than 1, or when the Schmidt number is much much greater than 1, you have the strange casethat, if you are looking at a velocity profile which is going like this.

So, this is thevelocity, and this is the distance from the wall, so this is y here, and this is the average velocity, so this is thetypical let us say that this is the turbulenttypical turbulent velocity profile, the prandtl numbervariation can be like this, it is most of the variation of the temperature, so this ist bar as a function of y. It can be like this, if the prandtl numberis much much greater than 1, and it can be like this, if prandtl number is much much less than 1, and what does it mean here, your first grid point in the wall functions may be such that, your first grid point is here, this is yourthis is the region in which you have assumeda certainvariation of velocity, and you see that, for when prandtl number is much muchgreater than 1, most of the variation in the temperature, mean temperature profile is already over within that region.

So, you are imposing an uncalculated turbulenceprofileon the heat transfer here, and there may be somediscrepancy coming from that, and when you are considering this, when you use a wall function which is standard wall function, that again may be quite wrong here.

If we consider a Schmidt number, which can be much much higher than 1, so Schmidt number much muchgreater than 1,let us saya 10,000, then the variation of the concentration profile, it may be like this, that means that typically for these values, the even for y plus, within y plus of greater than 1 itself, that is within the viscous sub layer itself. So, mean concentration for y greater than y plus greater than 5,it may become constant.

So, the variation ofthe concentration with y will be within the viscous sub layer, and what is importance of that, generally when we talk about viscous sub layer here, we say that k is equal 0, that is, it is purely viscous dominated thing, there is no turbulence within that viscous sub layer. So, there’sa general thingthat we normally ascribe doing this.

So, that means that in the case of turbulent diffusivity of thespecies for a Schmidt number, which is much much greater than 1. In reality there may be some effect ofturbulence, but you are imposingno effect of turbulence here. So, this is something that we have to consider here.

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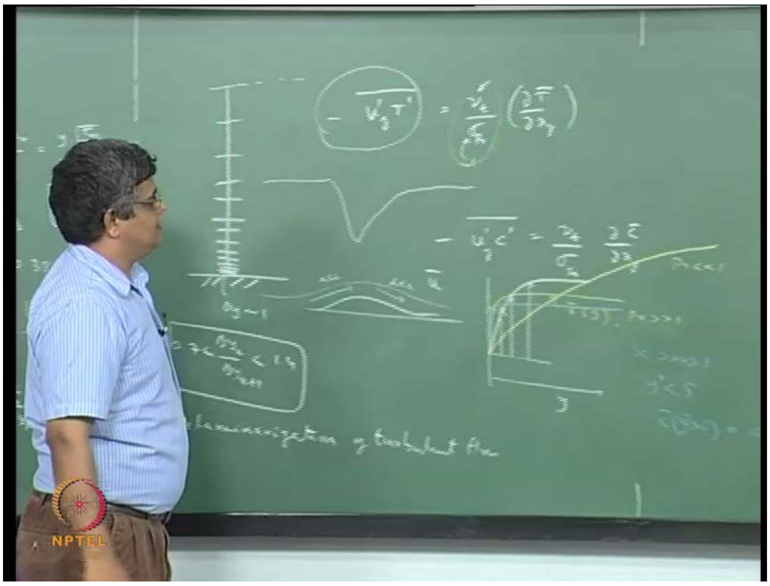

So, as per yourwall function which is somewhere here, there is no further variation ofconcentration profile within this region. So, this leads to some discrepancy, one has to be careful about evaluation ofthe temperature profiles and the concentration profiles for fluids which have a prandtl number or a Schmidt number much greater than 1.

One has to pay special attention to the near wall treatment ofthese quantities in turbulent flows. So, if necessary one may have to go to models like this, which can take us right up to y equal to 0; in which case, they can bring infaithfully, the effect ofmolecular viscosity and molecular diffusivity in the flux ofmass flux, species mass flux andenergy flux close to the wall. So,that is one thing or we have to alter the standard wall functionsthat we usefor the energy andspeciesconcentration.

So, we have to be careful, otherwise we cannot expect to get good agreementbetween the measured heat transfer coefficients or measured mass transfer coefficients and the computed completed one,all not because of the discretization errors, and all computation errors, because you have made wrong assumptions about the influence of turbulence close to the wall for these cases. So, there you have wall dominated heat transfer, wall dominated mass transfer, it is important to look carefully at the near wall treatment oftheturbulent diffusion of these quantities, in case of turbulent flow.

In case of laminar flow, we do not have any such problem, but turbulent flow we have problem, because we are solving only the approximate form of the equations with assumedmodel for the turbulent transportofthese quantities. So, if this is accurate, if this is appropriate, we get good profiles for temperature and concentration. If, this is not accurate, then we can get wrong values of the profiles, and therefore wrong values ofthe heat transfer and mass transfer coefficients.

So, this is about turbulencemodeling, one can see that in the general case we have to use some sort of Reynoldstime averaging of the governing equations, so that we do not have to worry about very fineturbulencefluctuations, temporal fluctuations, and spatial fluctuations, but in the process we are coming up with additional unknown quantities like the Reynolds stresses, and these are only approximately modeled inusinga vast array of models like this, and therefore, the equations that we are solving for turbulent flow are no longer, fundamental equations which have to be (()), these are only approximate form of equations.

So therefore, we have to be varying of the errors introduced in modeling, when we are looking for tumbling flows, and there is an array of modelsfrom which, we can choose that model which is appropriate for our flow. Although, thestandard k epsilon model has proved to a robust model, it may not always give thecorrect values, and if so we have to anticipate what kind of problems we have, what kind ofphenomenon we are looking at, flow phenomenon we are looking at, and choose to either go for a Reynolds stress model, in case we are looking at strong curvature effects, strong buoyancy effects playing a partin this or if you are looking atstrong wall influence, we may have to go for these type of modelsor we may have to take careful look at the wall functions that we are using.

So, one has to judiciously selectturbulence model, so that we cansolve for the variables of interest, that is velocities pressure, temperature and concentration and so on.

Finally, when we are looking at chemical reactions, we have to specify the mean rate of reaction and that isvery verycontentious issue, and there is a vast array of models, when we have a largeset of chemical reactions which are happening together, because usually this chemical reaction rates are dependent exponentially on the temperature, and temperature fluctuations may causea wide range in terms of the chemical reaction rates.

So, there is an entirelydifferent set of models developed for that, one has to consider those things, before one attempts a seriouscalculation of turbulent reacting flows. So, we have to be informed to make good choices and I hope this particular discussion has helped in highlighting some of the aspects.