

Hi and welcome to Engineering Earth. In this video we're going to review the mechanisms that create non-uniform velocity distributions that we often observe when fluids flow through conduits or channels with solid boundaries. And we're going to discuss how we can correct velocity head estimates that occur in such non-uniform flows.

So, let's start with a definition. What is a non-uniform velocity distribution? So, I'm going to answer first by showing you what a uniform velocity distribution looks like. So, let's think about an example of water that is flowing in an open channel, like I've shown you here. You can see the free surface on top um right here so that's how we know that we're working in an open channel flow. And then all around the sides these solid black lines these are solid boundaries this uh boundary at the top of course is just the interface between the air and the water that's flowing in the channel. So here I've got the same channel and the same velocity scale up here, where the blue color is going to tell us where uh the velocities are relatively slow and the red is going to be uh high velocities, or fast flows. So, on the left-hand side I'm going to draw a uniform velocity distribution. And I only need to use one color because a uniform distribution is the same throughout so I'll pick a color kind of in the middle of our velocity scale where that would be indicating kind of a moderate flow speed right. And the entire channel is going to have that same color in it because the velocity is the same everywhere in the channel, that's the definition of a uniform velocity distribution. So, on the right-hand side, now I'm going to draw a non-uniform velocity distribution and now I'm going to need more than one color, uh because a non-uniform velocity means that it's going to vary across the channel. So, I'm going to use multiple colors to indicate that variation of velocity that's happening. And how do I know where to put what color? Right, how do I know where the flow is going to be slow and where it's going to be faster? Well, here is where our knowledge of um boundary layer physics and the no slip condition can tell us that we know the slow flows are going to be happening close to the boundary and our fastest flows are going to be happening as far away from all of those solid boundaries as we can get. So, I know that my non-uniform velocity distribution is going to take the form that you see here. So now that we've compared the uniform and non-uniform distributions, let's think about what it would look like to calculate a mean velocity through this cross section. So, if I calculate a mean velocity through this cross-section that's got a flow area, capital A, I'm normally going to think about doing this, calculating an average velocity by taking the volumetric flow rate, Q , and dividing that by my cross-sectional flow area, A . And when I do this on the uniform velocity side, you know I wind up with, right the same number that corresponds to whatever this green color is, um because it's the same everywhere within the channel. Now over here on the right-hand side if I do the same thing, right I'm applying the same theory, I'm taking my volumetric flow dividing by my cross-sectional

area. But how do I know the, how do I know the value? There's so many different colors. Um so what I would have to do to know the true mean velocity is, you know if you can look beyond the colors of the distribution that I've drawn, there's that gridded area there. So, I would add up all of the area that is represented by each flow speed, and I would integrate over this uh channel cross-sectional area and that would be my true velocity. But since I don't know my true velocity, um the best I can maybe do is to compute an average velocity based on Q over A . And so, what I'm going to find out is that my average velocity is always going to be just a little bit smaller than my actual velocity, right. So over on the left-hand side my true velocity and my average velocity in the uniform distribution were the same. On my non-uniform side, my average velocity is going to underestimate the actual velocity in the channel.

Let's look at the same kind of question, but like a different example. So, in this case we are looking at an internal flow through a pipe. So, what I've done is I've turned that pipe onto its side so that we're looking again at the cross-sectional area of the flow of the pipe and uh you know this solid black line these are the walls of the pipe, and the flow is coming out from the screen towards us. So once again if I draw the uniform velocity distribution, again it's all going to be the same color, I'll use that same moderate green color. So, the whole cross-sectional flow area is going to have the same flow speed in my uniform side. And once again my average velocity, calculated as Q over A , is going to be the same thing as my actual velocity. And then, similarly, on my right-hand side where I've got my non-uniform velocity distribution, we're going to see the same thing, right. Boundary layer physics and no slip condition creating slower flow close to the pipe walls, the flow is going to speed up as we move closer and closer into the center of the pipe, further and further away from those solid boundaries, and we're going to get that same kind of high-speed core flow um as far away from the solid boundaries as we can get. And just like we saw in the open channel flow, once again we're going to have an average velocity calculated by Q over A , which is going to be less than the actual velocity through this cross-section of the pipe. So, velocity is chronically underestimated in non-uniform velocity distributions. This is a problem that we're going to run into um almost everywhere where fluids touch solids, because anywhere we have a fluid solid interface, we have boundary layer physics creating this non-uniform velocity distribution. So, you may be asking yourself at this time, why don't you just use the true velocity? Why are we calculating a mean velocity instead of measuring a true velocity through the whole cross-sectional area? Well, that's because uh measuring the true velocity in a non-uniform flow field it can be very difficult and time consuming to do that. It requires specialized instrumentation and more time than most engineers have. So, measuring volumetric discharge and cross-sectional area this is more

attainable information, so that's why we tend to approximate u_h velocity using a mean flow rather than calculating the true flow. So we may know qualitatively that our non-uniform velocity distribution looks something like what we've drawn here, because we know about boundary layer physics and you know we know that we're going to have faster flow further from the boundary slower flow close to the boundary, but that doesn't mean we can necessarily quantify it.

So, this leads us to another problem, which is, which comes in the form of estimating the energy of a flow. So, as a reminder, we know that total head, H , is the combination of our pressure head, our velocity head, and our elevation head. And we calculate our velocity head using the attainable velocity, which is the average velocity. Um, but if we calculate based on an average velocity, which we know is an underestimate, and then you know you'll notice that in calculating kinetic head we square that slightly underestimated velocity, so it compounds the error and then we systematically underestimate kinetic head. And this is a problem, right if we're systematically underestimating the energy of our flows u_h this can lead to erroneous engineering designs. And so, our answer to this issue of course is that we have introduced a coefficient a kinetic correction factor α . So α is a coefficient, it varies in u_h in value from a minimum value of one to a maximum value of two. Um so, always greater than one, you'll notice that. So that's always going to have the effect of increasing the estimate velocity head. So that's because when we calculate our average velocity in a non-uniform distribution it has that effect of chronically underestimating u_h velocity, so we always have to be bringing the, the kinetic head estimate up to account for that chronic underestimation, so that's why it's always greater than one. So, I want to point out that the α parameter modifies velocity head and not velocity. So, when you're calculating u_h kinetic head the order of operations matter. So first square the average velocity, and then we can do the multiplication and the division.

So how do we know the value of α ? So mathematically a coefficient that ranges from 1 to 2 means that it's going to have the effect of either u_h not affecting the velocity head estimate at all, when the α value is one, all the way up to um doubling the velocity head estimate when the α value is two. So that's a really big range of potential impact. In general, our α value becomes larger as the velocity profile becomes more and more strongly nonuniform. So the α value of a uniform velocity profile that we looked at in prior examples, you know the big green velocity distributions that were uniform, that's going to have an α value of one, there's no need to correct the average flow velocity because the average and the true velocity were the same in a uniform profile. When we get into the

non-uniform distributions, that's when we start to see alpha having a value that's greater than one, and as I said it's going to become larger as the velocity profile becomes more and more strongly nonuniform. And this is related to the extent of flow development that allows there to be deviation between the fastest regions of flow and the slowest. So, let's look at an example of this. So, I'm going to take that second example that we had of the pipe flow and I'm just going to turn that same pipe 90° on its side so now we're looking instead of at the cross-section, along the pipe, and so these are the pipe solid walls. So first, let's consider what a uniform velocity distribution might look like in this scenario. Right, so all of my velocity arrows have the same magnitude. Right so, my velocity profile is just like a straight line here, all of my arrows are of the same magnitude. So then let's think about uh a non-uniform velocity profile right so here I'm going to have these short little slow arrows kind of closer to the pipe walls and they are increasing in magnitude which I'm, I'm indicating with you know both the size of the arrows and the color that I'm using. So, in this example velocity profile that I've drawn, you know maybe it looks something like this. And so, this would be a fully developed nonuniform profile. And so, in this case, uh so let's back up a little bit. In my uniform distribution my actual velocity is going to be equal to my average velocity, and here my kinetic correction factor is going to be equal to one. So over here in my fully developed non-uniform distribution now my V actual is going to be greater than my average, and my alpha parameter is going to be greater than one. But how do I know how much greater than one it is? Well, let's think about one more example before I answer that question, so we're going to look at one more velocity profile. This velocity profile is also non-uniform, but what I'm drawing here is a profile that is maybe a bit more strongly non-uniform than the first one. So, this profile is also a fully developed non-uniform distribution but this time it's more strongly non-uniform, so I've written that it's a highly non-uniform. So, in this case my actual velocity is going to wind up being even more strongly greater than my average velocity. And so, we're going to have different alpha values that are applied to these two non-uniform distributions. On our top one we'll have an alpha value of maybe let's say 1.05, so a 5% increase to the kinetic head. This would be something similar to what you might apply to a turbulent flow. And then on the bottom, my strongly non-uniform profile, my alpha value is maybe going to be more similar to the two. And this might be something more similar to what you would find in a laminar flow. So how does turbulence affect the distribution of velocity? Well, if you remember a turbulent flow has all of these kind of kinetic, um momentum transfer, turbulent eddies that are happening. And these turbulent eddies and the chaos of the flow tends to um restrict the development of the flow profile, so that the fastest flow speed isn't able to increase that much higher than the slower flow speed. So, turbulence in a sense kind of inhibits the full development and constrains the non-uniformity of the velocity profile in a way that in a laminar, nice smooth parallel flow lines, um the distribution of velocity is able to attain that

much more strongly nonuniform shape that we can see in the second example. So that's why we have usually um a greater alpha value applied to laminar flows than we apply to turbulent flows.

Thank you to the National Science Foundation for supporting this work under grant number 2335802. Great job making it to the end of the video and please reward yourself with uh a moment of zen.

I study fluid mechanics because I love water and healthy aquatic ecosystems. Whatever your passion is, I hope that it motivates you to continue your study of fluid mechanics. Thanks everyone.