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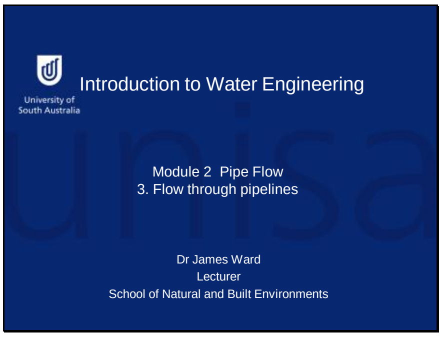
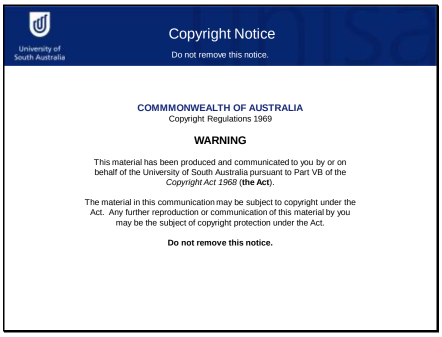


Welcome to the third presentation in Module 2

Slide 2



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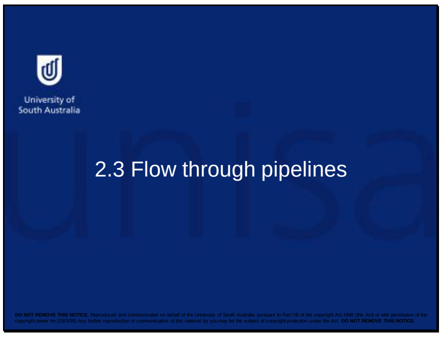
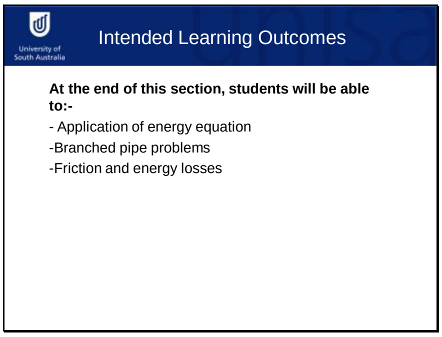


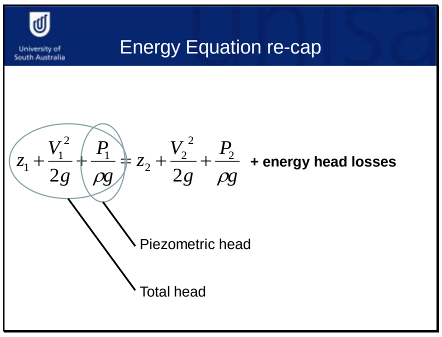
Okay, let's look at flow through pipelines.

Slide 4



The learning outcomes are presented here – we'll look at the applications of energy equations to pipe flow, including flow through branching pipe lines and we'll look at energy losses due to friction.

Slide 5



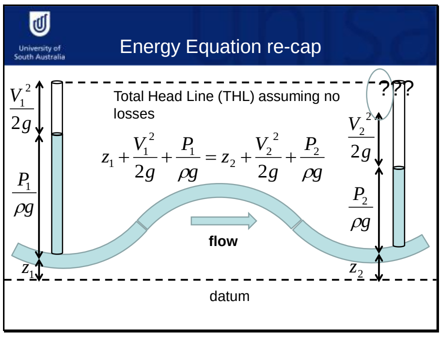
In the last two lectures we used the energy equation. We briefly touched on the fact that when we move between two points,

there's some energy that gets lost because of friction. This time, we're going to focus on those energy head losses and look at ways to predict them.

So just recapping – the energy equation includes pressure head or piezometric head

Which forms part of the total head. The elevation head, Z, and velocity head, V squared on 2 g, tend to be fixed by the geometry of the system, so the friction head losses manifest themselves as a loss of pressure energy from one point to the next.

Slide 6



This figure shows flow in an arbitrary pipe. There are two piezometers to measure piezometric heads.

At the upstream point we've got elevation head, Z1

Plus the pressure head, P1 on rho g

And of course the velocity head. Downstream, after the water's gone through some length of pipe,

let's say we've ended up at the same elevation Z2,

And now we've got a smaller pressure head

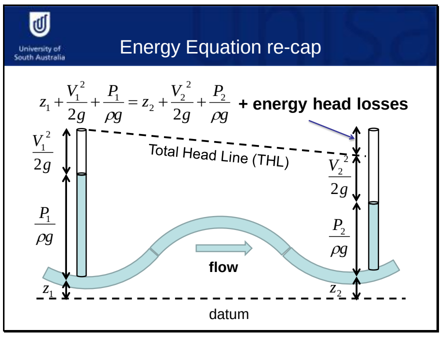
And the same velocity head as before, because the pipe's the same diameter.

Now if we plotted a total head line from the two points

assuming no head losses in the energy equation

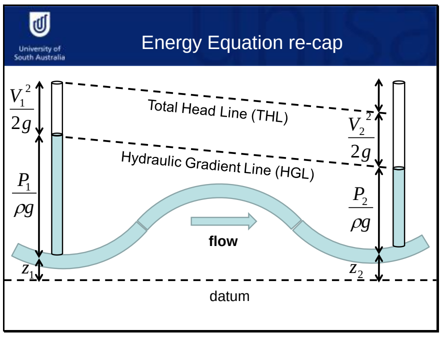
Then we'd end up with a gap at the downstream end.

Slide 7



The true total head line's going to slope down, because there's energy head losses due to friction in the pipe. This is why the downstream pressure P2 is smaller than P1.

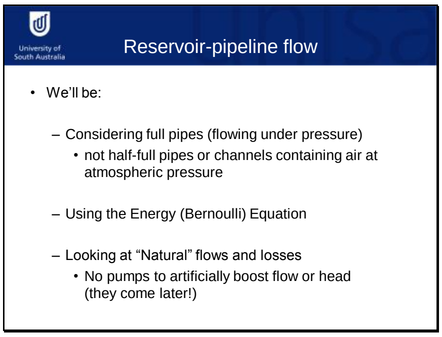
Slide 8



Now, assuming we're dealing with a uniform diameter pipe, the velocities are going to be the same.

So we can just draw a line connecting the piezometric levels, which we call the hydraulic gradient line.

Slide 9



For this Introductory course of Water Engineering, we'll

look at full pipes under pressure.

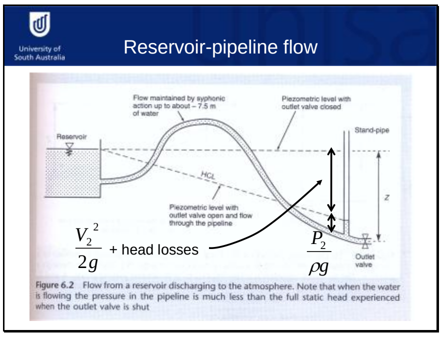
In later hydraulics courses you'll look at stormwater and sewer pipes which tend to run only partly full and contain air at atmospheric pressure.

The equation we're going to use over and over again is the energy or Bernoulli equation we introduced in the previous lecture

Importantly, for now we're just considering gravity-driven flow

Later we'll look at pumps which are used to add energy to a system.

Slide 10



Here we've got a basic reservoir with water flowing through a syphon to a discharge point somewhere below. If we take the discharge elevation to be zero, then at the downstream end we've got

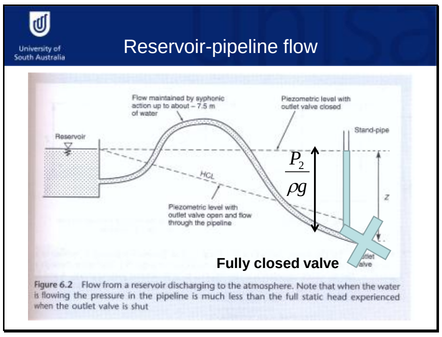
Pressure head, P2 on rho g

And here we've got a big gap to get up to the total head line. The gap has got to be a combination of

Velocity head plus whatever head losses happened along the pipe

Image source- Les Hamill 2011, Understanding hydraulics.

Slide 11



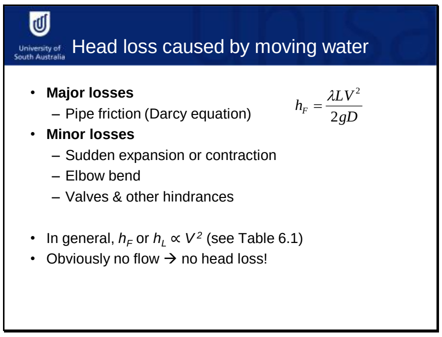
Now imagine we close a valve at the end of the pipe.

Now watch what's happening to the pressure in the piezometer here. It's rising up and up until when the valve's fully closed,

P2 on rho G is effectively equal to the upstream elevation in the reservoir. There aren't any head losses in this system because the water isn't moving.

Image source- Les Hamill 2011, Understanding hydraulics.

Slide 12



Head loss is only caused by moving fluid.

We tend to divide losses into two types. Major losses refer to the friction due to the water rubbing along the pipe surface, and we use an equation called the Darcy Equation for this.

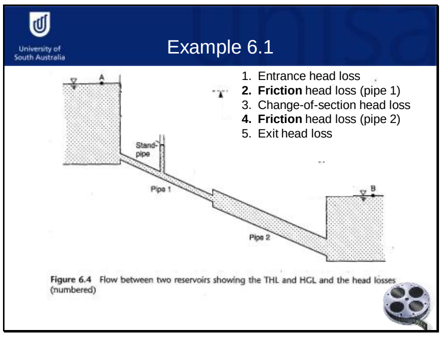
The key thing in the Darcy equation is the lambda term, which is the Darcy friction factor. L and D just refer to the length and diameter of the pipe. So you can see that the things that contribute to high friction head loss are long pipes, and small diameters.

Then when we talk about Minor losses, we're talking about friction as the water goes through a sudden expansion or contraction in the pipe, or goes round a sharp bend, passes through a valves or basically just encounters anything that disrupts the flow. You might remember last time we looked at flow measurement devices and some of those were more disruptive to the flow than others, which meant we had to introduce a coefficient of discharge to account for the friction head losses.

In general, major and minor losses are both proportional to the velocity squared, which is why

We don't get any head loss in a pipe with no water flowing through it. It's important to note that just because we call these things Major and Minor losses, it doesn't necessarily mean Major losses are always bigger. For a short pipe system with lots of bends, valves, junctions and so on, the minor losses might actually dominate. But for a long pipe without many interruptions, it'll be dominated by major losses. Table 6.1 in the text book shows some calculations for head loss in a couple of common situations.

Slide 13



Here's a qualitative example of what happens to the energy head line in a pipe connecting two reservoirs. We start at the water surface in the upper reservoir,

and the first thing that happens is we lose a bit of energy due to friction as the water enters the pipe.

This is called entrance head loss.

Then as we move along the pipe we lose more and more energy. This is because of friction in the pipe, which keeps sucking energy out of the system all the way. Because it's a constant diameter pipe for this bit, the velocity's constant and that means the friction head loss is constant – so it's a linear decrease in energy as we go along.

Then the total energy takes another hit due to friction in the join between the two pipes as the water enters a larger-diameter pipe,

Which we call a "change of section" head loss.

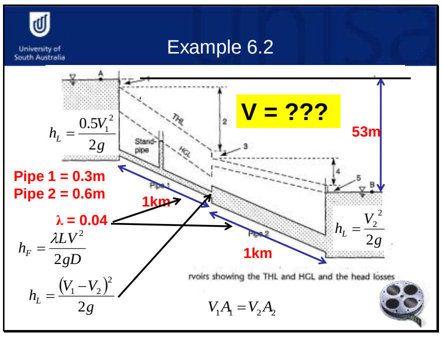
Then it continues losing energy due to the friction in the bigger pipe. What you'll notice though is that the rate of energy loss is less, or in other words the slope of the energy line isn't as steep. What's happening here is that the velocity's now less, because we're in a bigger pipe, and since friction head loss is proportional to velocity, there's not as much loss.

The final energy level has to be the water level in the lower tank, but the last thing you'll notice right at the end of the energy line is that the energy drops off suddenly – what's happening here is that we've got a little loss of energy,

called an exit head loss, a bit like the entrance head loss at the start. The exit loss in this case is actually just considered to equal the velocity head because all the velocity gets dissipated in the reservoir. So that's what we might expect our total energy line to look like from one water level to the next. The hydraulic gradient line, which is the line that doesn't include the velocity head, is doing similar things to the total energy line, except it's got a strange little gain at the change of section, which is different to what happens in the total energy line. Why do you think this might be? If you can't work it out, look at the example in the textbook.

Image source- Les Hamill 2011, Understanding hydraulics.

Slide 14



Now let's throw some sort of realistic numbers on this example and see what it looks like. We want to know what the flow's going to be in this system. This is tricky because we've got two velocities – water's running at a higher velocity in the first pipe and then it goes into a bigger pipe and slows down.

We've been told the smaller pipe diameter is 30 centimetres and it feeds into a 60 centimetre diameter pipe.

So you can use the continuity equation to get one of the two velocities as a function of the other one, which means you'll only have the one velocity to solve.

Then we've been given a physical elevation difference of 53 metres between the two water surfaces.

The pipes are each 1 kilometre long,

which we'll use in the Darcy equation to calculate the Major losses, given a Darcy friction factor of 0.04

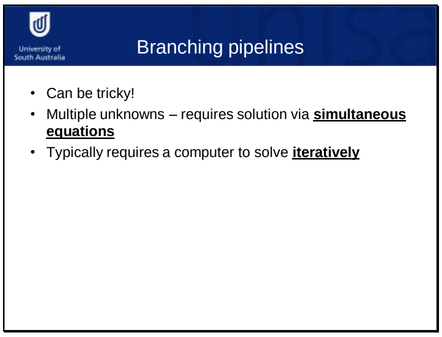
We'll take the entrance head loss to be 0.5 V1 squared on 2 G,

We've been told the minor head loss due to the junction's equal to this equation from Table 6.1

And the exit loss is just the velocity head as it comes out of the second pipe. Okay, so you want to evaluate the energy equation between the two water surfaces labelled A and B here, so your pressure and velocity terms are zero. Then you've got the elevation difference, 53 metres, equals the sum of all these head losses. Have a go at it yourself, and if you need some help check out the example in the textbook.

Image source- Les Hamill 2011, Understanding hydraulics.

Slide 15



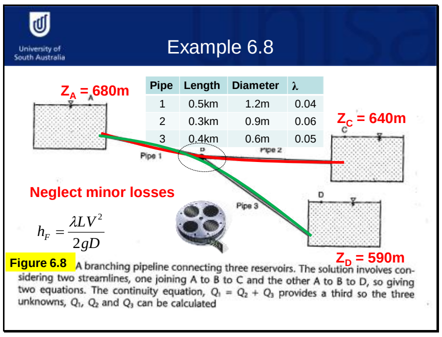
Alright, believe it or not, that was a simple example. In reality we have to consider branching pipelines,

Which can be a lot harder to cope with.

For branching of pipelines, typically we've got a number of unknowns, like the velocities in several different pipes.

We typically use simultaneous equations to solve sets of multiple unknowns. Depending on the equations we get, we might be able to solve them directly or we might have to use a computer to solve them iteratively.

Slide 16



Here's an example of a branched pipe system.

First of all we've been given a whole lot of information about the pipes – their length, diameter and lambda value for the friction calculation.

We've been told in this case we can neglect the minor losses

so all we need to work out is the Darcy equation.

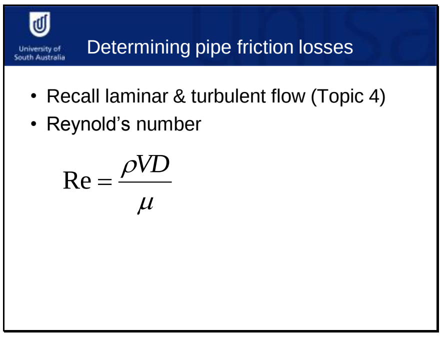
In this case we've got water flowing from one reservoir to two different reservoirs, each with a different surface water level. So we've got the elevations of the water surfaces which are going to drive the flow in each pipe.

You've got three unknowns, which are the three pipe velocities. The trick here is to divide and conquer. As long as you can build up three equations, you should be able to solve them somehow to get your three velocities. So first, you set up an equation for the flow just in pipes 1 and 2 and you ignore pipe 3. Then it's just like the previous example, where you've got an elevation difference equal to a head loss, and actually it's easier because you can neglect minor losses.

Next up we ignore pipe 2, and just consider flow through pipes 1 and 3 using exactly the same procedure. So we should end up with two equations, one containing the unknown velocities in pipe 1 and pipe 2, and the other containing the velocities from pipes 1 and 3. We still need a third equation if we want to solve the three unknowns.

The third equation is simple – just apply the continuity equation at the junction and this'll bring together all three velocities as a function of the respective pipe diameters. Now you'll have 3 equations and 3 unknowns and one way or another you should be able to solve it. As usual you can consult the textbook for help if you need to.
Image source- Les Hamill 2011, Understanding hydraulics.

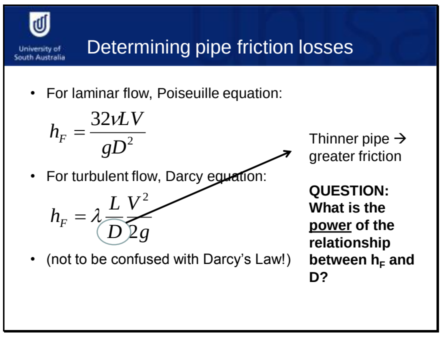
Slide 17



Okay, so in the last example we had lambda given to us for each pipe, so it was easy to work out the friction loss using the Darcy equation. Now we want to look at how to estimate friction losses when you don't know lambda. First of all we need to know what sort of flow's going through the pipe. Hopefully you remember learning about laminar versus turbulent flow when we first looked at fluids in motion.

We use the Reynolds number to determine whether the flow is laminar, turbulent or transitional. Remember that the Reynolds number is density times velocity times diameter of the pipe divided by viscosity.

Slide 18



Once we know whether we've got laminar or turbulent flow, we can work out the friction loss.

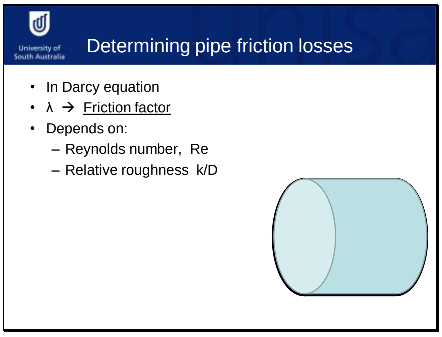
We only actually use the Darcy equation when we've got turbulent flow. Friction loss in laminar flow conditions can be determined using a different equation, called the Poiseuille equation.

Pay attention to the use of kinematic viscosity in the numerator term in this equation. For turbulent flow, this is where we use the Darcy equation.

If you go on to study geotechnical engineering or groundwater hydrology, you'll come across something called Darcy's law, which is a different equation – don't confuse the two!

It's important to recognise the significance of the diameter term in pipe flow. The thinner the pipe, the greater the friction loss. You should also think about the relationship between hF and D for a given flow rate, remembering that a given flow rate passing through a smaller diameter pipe leads to a much larger velocity than a large diameter pipe. So the pipe diameter has a very significant influence on friction loss.

Slide 19



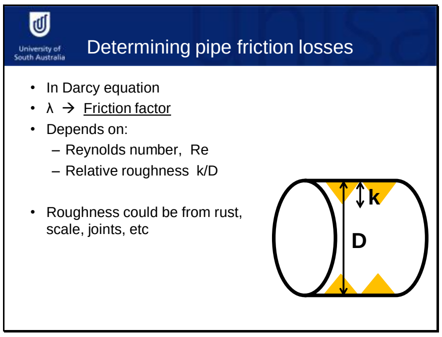
Okay, so we've got a simple equation for friction losses in laminar flow but turbulent flow's a lot more common and we still don't know where the friction factor, or lambda, comes from.

Lambda depends on a couple of important terms.

Firstly, it's related to the Reynolds number, so we don't just use Reynolds number to work out whether we've got laminar or turbulent flow, we also use it to work out essentially how turbulent the flow is, so we can estimate what's happening with the friction.

The other parameter influencing lambda is the "relative roughness".

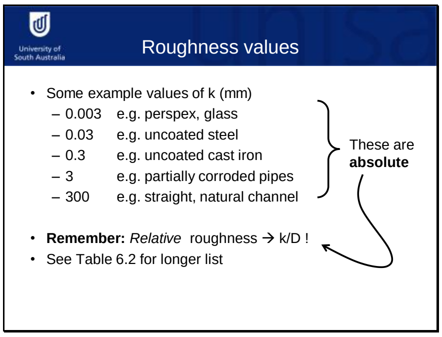
Slide 20



When we talk about relative roughness, we mean the size of any bumps or protrusions on the inside of the pipe wall, relative to the pipe diameter. Big bumps in a small pipe leads to a large k/D term, and vice versa. So this is really another way that the pipe diameter influences friction.

Typically protrusions are from a combination of the pipe material and the joins. In old steel pipes there might be rust, or depending on the water quality there might be mineral deposits called scale. Some pipe joins are relatively smooth on the inside of the pipe, and some are more intrusive.

Slide 21



Here are some values of k, which means we're talking about the physical bump size in millimetres.

Smooth materials like perspex and glass have extremely small bumps, less than a hundredth of a millimetre.

Uncoated steel's typically about an order of magnitude higher,

Going to cast iron takes us up by another order of magnitude

And again for partially corroded pipes with significant rust – so here we're talking about protrusions averaging about 3 millimetres in size

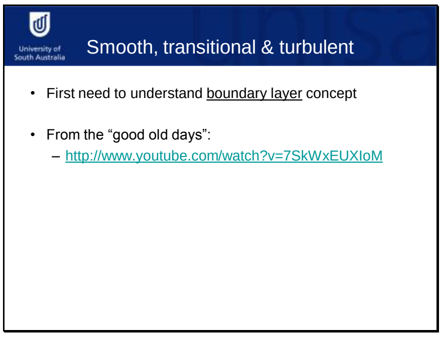
We wouldn't be using Darcy's equation in channel flow but for the sake of interest the roughness you might encounter in a relatively straight channel with some natural protrusions would be on the order of hundreds of millimetres.

Now, you have to remember that these are absolute values, because we're just looking at k measured in millimetres.

When we go on to calculate lambda, the thing we need to know is relative roughness, which relates these absolute values back to the physical size of the pipe. So an absolute k of 0.3 millimetres, as an example for uncoated cast iron, might not actually generate much friction if it's in a large pipe 1 metre in diameter.

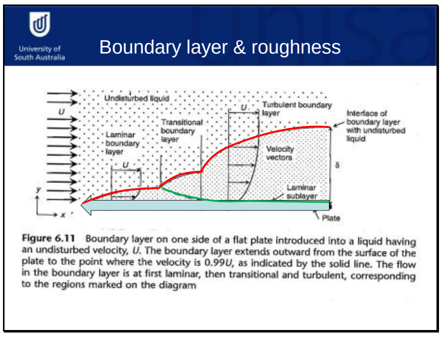
A longer list of k values is available in Table 6.2 in the text book.

Slide 22



Before we get into calculating lambda, we need to briefly touch on the concept of boundary layers. Here's a YouTube video showing the fundamentals.

Slide 23



As you might guess, friction's mostly about what's happening at the interface between the moving fluid and the solid pipe wall.

In this picture we've got just a simple flat plate that's been pushed into an oncoming stream of fluid and we're looking at what's happening to the fluid as it flows over the plate. This'd be happening on both side of the fluid but we're just focusing on the top side for simplicity. Without the plate there, the fluid would have been moving at a uniform velocity, U, but by introducing this plate we're disturbing the flow field. Let's look at what happens.

Near the front, where the fluid first encounters the solid plate, there's a fairly thin layer of laminar flow right near the plate. So what's actually happening here is that a thin layer of fluid's being forced to move really slowly, and right up at the plate the fluid's virtually stopped. You can see the distribution of velocities as you move away from the plate through this boundary layer, the velocity increases to the background flow velocity of U.

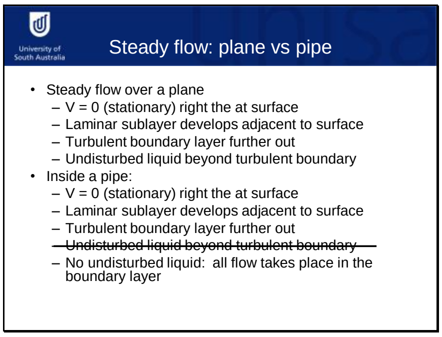
Okay, so that thin laminar boundary layer actually continues along the whole plate,

but as we move along we find the plate's causing more and more disturbance to the flow field. So this next little bit's a transitional layer, which extends out a bit further than the original laminar boundary layer and it's got slightly more turbulent flow in it. So what's happening is the fluid right near the plate's being slowed right down by friction, which is causing a nice little layer of slow-moving laminar flow along the surface and as we move further out it's causing more turbulence. But the turbulence only persists out a certain distance from the boundary, and this is why we're calling it a boundary layer.

Now, if the plate's long enough, this effect can cause fully turbulent flow conditions to develop in the boundary layer, causing the boundary layer to be really quite thick compared to the laminar sublayer.

Image source- Les Hamill 2011, Understanding hydraulics.

Slide 24



So to summarise what we understand about boundary layers,

When you've got steady flow over a planar surface,

Right at the surface the velocity's effectively zero,

Then you've got a skinny little laminar layer, called the sublayer

And assuming the plane is reasonably long there'll be a turbulent boundary layer outside the laminar sublayer

Then moving out beyond the turbulent boundary layer you're back in the original steady fluid.

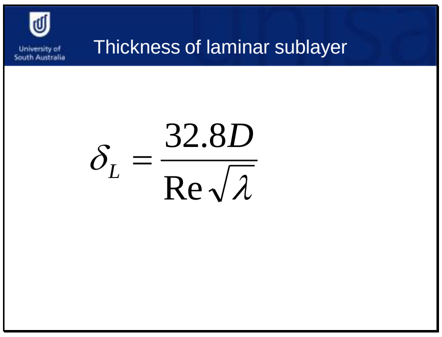
Alright, that's all well and good, but what does it mean for pipe flow?

Well, essentially the physics in a pipe are all the same as a plane

Except because a pipe's got a surface on the other side, and all around, the boundary layers join up and there's no opportunity to transition back into the undisturbed flowfield.

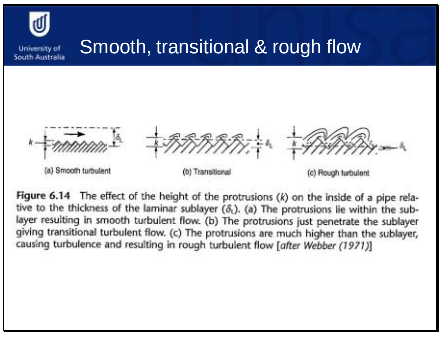
So flow in a pipe's considered to be effectively all taking place in the turbulent boundary layer.

Slide 25



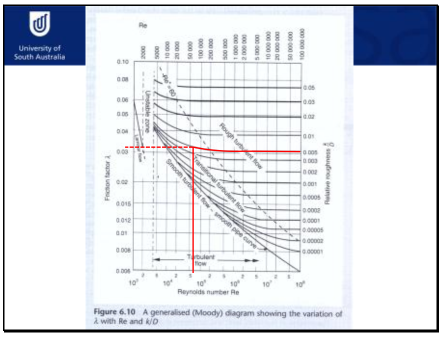
Right, so we know we've got a little laminar sublayer going along the pipe wall, and the rest of the flow's going to be the turbulent stuff. Here's an equation to estimate thickness of the laminar sublayer, "delta L". It's a function of pipe diameter, Reynolds number and the friction factor lambda. Because it depends on Reynolds number, the thickness of the laminar sublayer also depends indirectly on the velocity of the fluid.

Slide 26



Believe it or not, it's not enough to just say we've got turbulent flow in the pipe – we need to be able to characterise it into smooth turbulent, transitional turbulent or rough turbulent. The way we do that is to look at the thickness of the laminar sublayer relative to the size of the protrusions in the pipe. In smooth turbulent flow, the bumps are smaller than the thickness of laminar boundary layer, so all of the turbulent flow happens away from the actual bumps – it's a bit like the laminar sublayer's acting as a shock absorber for the main flow; if the bumps are bigger than the thickness of laminar boundary later, the turbulent flow ends up bouncing around on the bumps and we've got what we call rough turbulent flow. In between these, when the bumps are just protruding out a little way past the sublayer, we call it transitional flow.

Slide 27



These concepts all come together in a relationship called the Colebrook-White equation, which is commonly simplified and plotted up in what we call the Moody diagram.

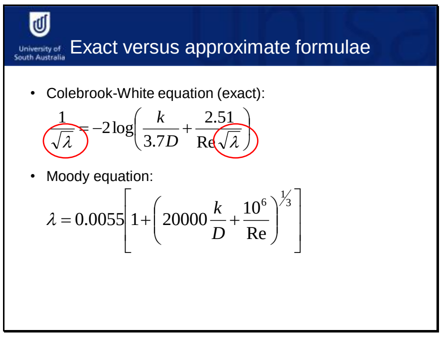
This diagram lets you take a given Reynolds number,

Combined with relative roughness,

And the intersection of these lets you read off the friction factor, lambda. As you can see there are regions on the graph corresponding to smooth turbulent flow, transitional turbulent flow and rough turbulent flow, but actually all you really need to know is the Reynolds number and the relative roughness.

Image source- Les Hamill 2011, Understanding hydraulics.

Slide 28



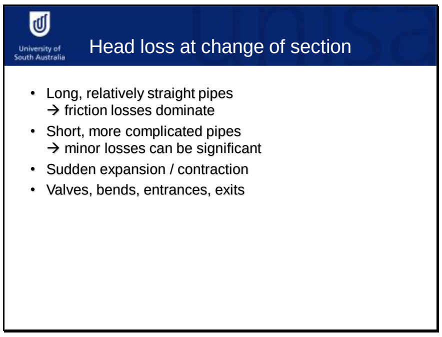
If you need a really accurate value of lambda,

you'll need to use the Colebrook-White equation. As you can see it's complicated to solve,

because lambda's on both sides. This means you need to use an iterative procedure, in other words solving by trial-and-error. It's actually really easy to solve these sorts of equations now using standard spreadsheet software but historically an equation like this was a real pain.

So to avoid the trial-and-error bit, historically people have tended to come up with approximate equations that give answers that are pretty close, and that have the advantage that they can be solved directly. In this case we've got the Moody equation, which is obviously where the Moody diagram comes from. You can get a reasonably accurate value of lambda from this equation, or even just by reading off the chart, and for lots of applications this'll be as accurate as you need it to be. But, if you need extra precision, you can use the Moody value of lambda as a starting point, then use the Colebrook-White equation and trial and error to refine it.

Slide 29



Back at the start of this lecture we said that head losses are divided into major losses and minor losses. All of the pipe friction calculations we've just been looking at with lambda and the Darcy equation are to do with major losses,

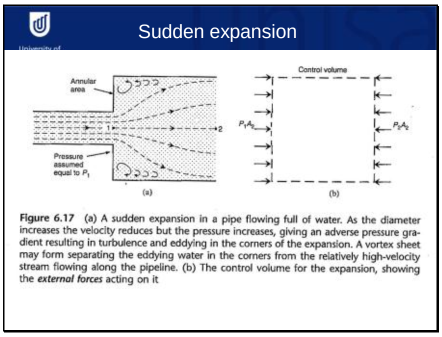
which tend to dominate in long pipes without too many bends or interruptions.

But in shorter pipes or pipes with a relatively large number of bends, junctions, changes of diameter and so on, the so-called minor losses can be significant – in some cases maybe even more than the friction losses. They should generally be considered in the analysis in any case.

A typical change of section is the sudden expansion that happens when a smaller pipe feeds into a larger pipe, or vice versa.

More generally, these minor losses include valves, bends, entrances and exits to tanks, and so on. Really anything that interrupts the normal flow of the pipe and results in a loss of energy.

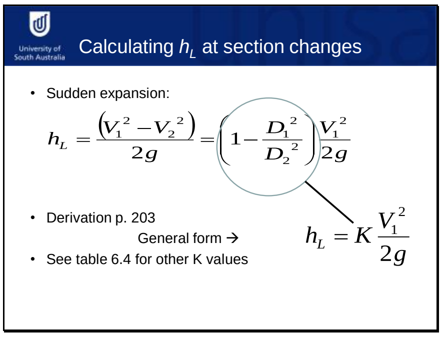
Slide 30



If you remember when we looked at the momentum equation and the control volume concept, this diagram should be familiar. We're not going to go into the calculations here, but you can read more in the textbook if you like. Essentially the point here is that you can derive equations for the energy head losses in a change of section by using a combination of the momentum equation and the energy equation. The energy loss is to do with the extra turbulence caused by the change in flow conditions; it's not to do with the friction between the fluid and the pipe walls. That means to find the total head loss across a change in section you'd need to add on the friction loss for the short length of pipe too.

Image source- Les Hamill 2011, Understanding hydraulics.

Slide 31



The derivation of head loss for a sudden expansion from the previous slide

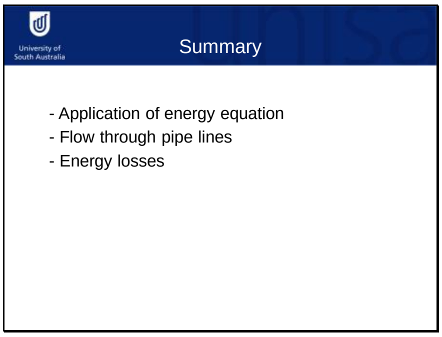
is given on Page 203 in the text book.

This is just one particular type of minor loss but the general form of minor losses, whether for expansions, contractions, bends, valves, whatever, is the headloss is equal to a coefficient K times the velocity head.

In the case of a sudden expansion, K is found through the derivation, but in other situations like complex valve arrangements it might only be possible to find K by physical experimentation – actually running a series of flows through the device and determining the pressure head loss. You'll be looking at this in your practical.

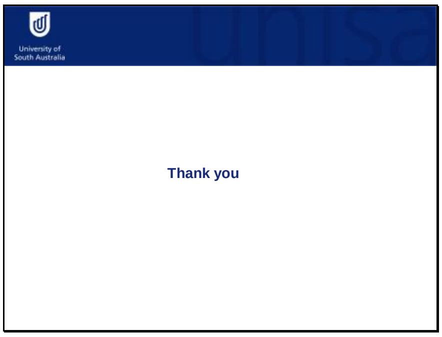
The values of K for a number of common flow situations are also available in Table 6.4 in the text book.

Slide 32



So in summary, we've looked at applications of the energy equation as it applies to flow through pipe lines with energy head losses due to friction and other minor losses.

Slide 33



If you've got any questions or need further clarification, please post a question or comment on the Discussion Forum.