Fuel, Refractory and Furnances

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Lecture No. # 24

Macroscopic Energy Balance: Applications to Design Head Meters, Stack and Blowers, Types of Flames

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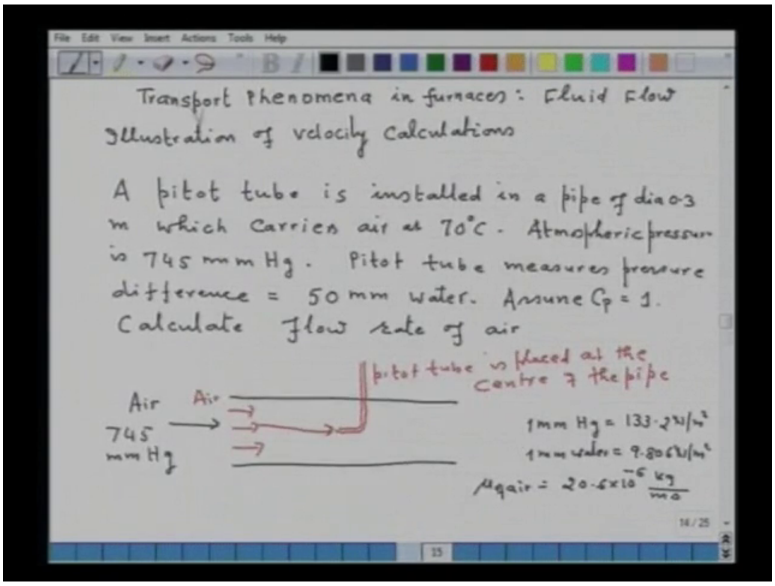

We continue our lectures on transport phenomena in furnaces and fluid flow was our topic. We have derived an equation to calculate the velocity of fluid flowing in the duct or flue or wherever in the furnace, the fluid is flowing. So, today I will be illustrating the use of the equation that first was derived to calculate the velocity through a problem.

So, I will tell the problem. So, a pitot tube is installed in a pipe or duct, whichever you want to call, of diameter 0.3 meter which carries air at 70 degree Celsius. Atmospheric pressure is 745 millimeter of mercury. Pitot tube measures pressure difference that is equal to 50 millimeter water.

Assume pitot tube coefficient, that is CP, which we have introduced in formula is equal to 1. That is, it is very well designed pitot tube. So, you are required to calculate flow rate of air passing through the pipe. Now, the problem can be illustrated in this way. If this is the pipe, air is flowing and the atmospheric pressure is 745 millimeter mercury.

So here, there is a pitot tube that is placed at the center of the pipe. It is at this position. So, the pressure difference of 50 millimeter of water, which is measured through the pitot tube, it is in fact, at this particular point. That is, at the center of the air flow. So, if the air is flowing this way, this is the flow of air and this particular streamline will impact the pitot tube. Hence, you read the pressure differential.

So, what pressure we are recording is the pressure at the center of the pipe. So, of course, what we will be determining from this pressure measurement will be the maximum velocity. From there, we have to calculate the flow rate of the air. So, this is, in fact the problem. Now something, conversion factors are also given, say 1 millimeter of mercury and that is given to be 133.2 Newton per meter square. Whereas, 1 millimeter water that is given 9.806 Newton per meter square. Now, these conversions you may be needing. Also, it is given viscosity of air at this temperature is given to you 20.6 into 10 to the power minus 6 kilogram meter per second.

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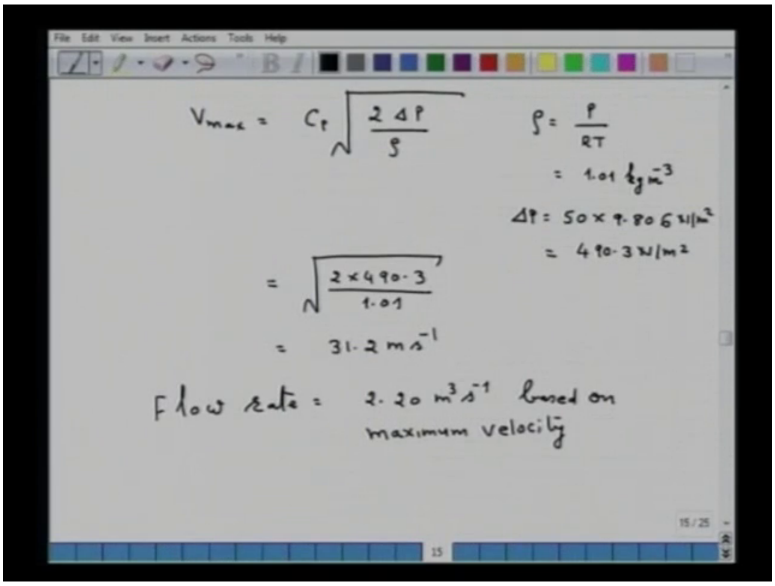

Now, we have to solve this particular problem. As we know, from the pitot tube, that is v maximum, that is equal to c p into square root of 2 into delta p upon rho. So, we have to calculate now v maximum. That is, first we calculate v maximum and from v maximum, we will calculate the flow rate.

So, we have to first of all find out the density. So, density rho, that is equal to p upon RT is 745 millimeter. So, we have to convert into Newton per meter square. The value of rho will be 1.01 kilogram per meter cube. So, this is what the value of rho. Now, we have to convert delta p, which is given in 50 millimeter of water. So, 50 into 9.806 Newton per meter square.

So, well, just multiply and that will be 490.3 Newton per meter square. Now, we know all the variables in this equation. So, v maximum, that is equal to 2 into 490.3 upon 1.01. So, that will give us 31.2 meter per second. So, this illustrates that the pitot tube can be used to measure the velocity of air or fluid in the pipe or in the dock. So, this is the maximum velocity at which the air is flowing.

Now, if we calculate the flow rate, so flow rate simply will be equal to rho UA. If we do all this substitution, then you will be getting 2.20 meter cube per second. Now, this is based on maximum velocity. As you recall, there is a velocity distribution in the pipe. So, if you want to calculate the average air flow rate; that means, you have to calculate average velocity. This average velocity may be very close to rate of the flow rate of the air, rather that we obtained from maximum velocity.

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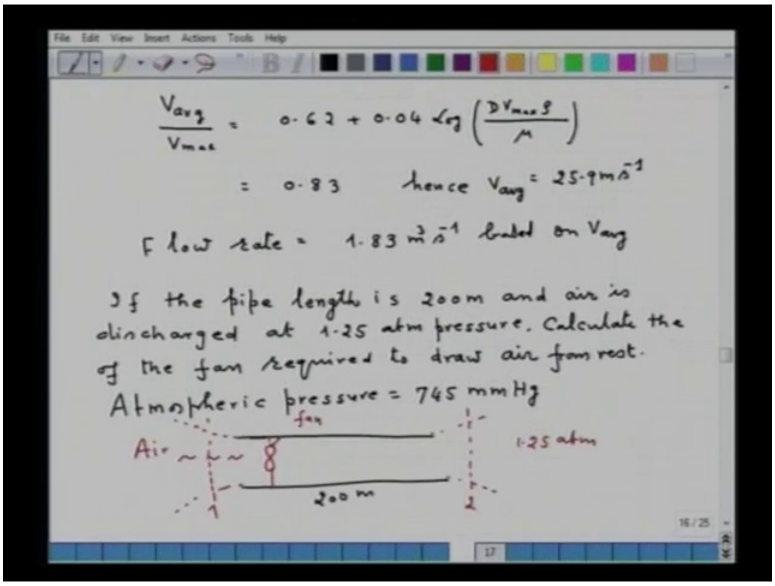

So, in this particular case, what you have to do is, you have to utilize this expression, v average upon v maximum. That is, equal to 0.62 plus 0.04 log of D v maximum upon rho into mew. We know all these variables. So, we can substitute and find out and this value will be coming to equal to 0.83. Hence, v average, that will equal to 25.9 meter per second.

Now, we can determine now the flow rate. Say, flow rate, that will come up to be equal to 1.83 meter cube per second, which is based on the average. So, that is the difference between the flow rate, when maximum velocity and average velocity are used. So, if I now want to explain this particular problem further, there I see now, if the pipe length, let us see, if the pipe length is 200 meter and air is discharged at 1.25 atmosphere pressure, then calculate the power of the fan required to draw air from rest. Atmospheric pressure is same as earlier. Atmospheric pressure is 745 millimeter mercury and that is what is given earlier.

Now, since the pipe length is involving and air is entering from rest and it is discharged at 1.25 atmospheric pressure, so now, we have to calculate the power of the fan. If I represent again through the diagram, then it looks something like this. So, this is the pipe whose length is given 200 meter and air is drawn from the rest. So, somewhere here air is entering. Somewhere here, I require to have a fan of which I have to calculate the horse power. Now, I am taking the air is discharged say at 1.25 atmosphere. That is given.

So, now if I want to solve this problem, what I have to do is, I have to first of all take, this is my section one, and this is my plain two. Literally, I have to do mechanical energy balance in order to solve this particular problem. So, now what I have done here is, I have represented plain one and plain two. Plain one is slightly up stream the entry of the pipe and plain two is slightly downstream at the exit of the pipe. It means, thereby the v 1 and v 2 will be very very small and hence they can be neglected.

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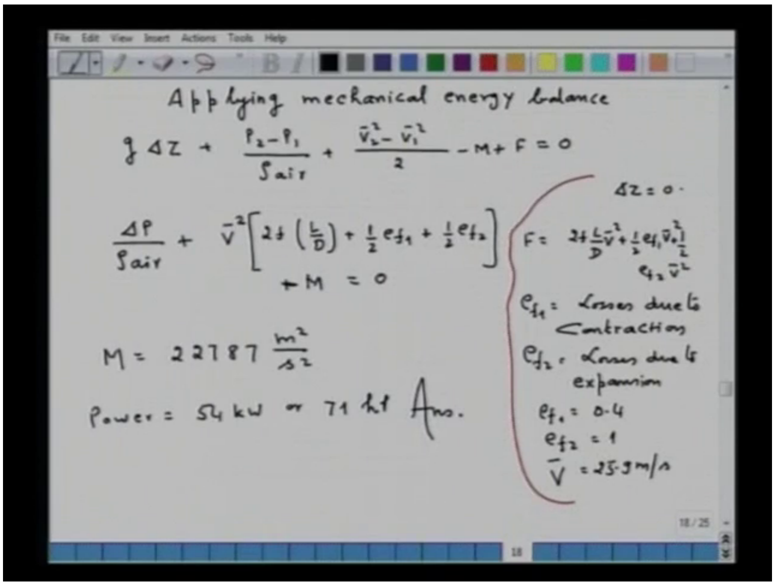

So, applying mechanical energy balance between one and two, then we get g delta z plus p 2 minus p 1 upon rho air plus v 2 bar square minus v 1 bar square upon 2 minus m plus f and that is equal to 0. That is the frictional forces. Now, since it is a horizontal pipe, so, for horizontal pipe delta z is equal to 0.

So, our equation now becomes delta p upon rho air and also v 1 is equal to v 2 because, they are very negligibly small. We can neglect it and f, you know this equation f. That is equal to 2 f l by D v bar square plus half e f 1 v bar square plus half e f 2 v bar square. So, all that we have to replace. So, that will be equal to plus v bar square 2 f l upon D half e f 1 plus half e f 2, where e f 1 is losses due to contraction and e f 2 losses due to expansion. Now, you noted that at the inlet of the pipe, the fluid enters and it contracts. At the exit, the fluid expands.

So, accordingly the values are given. Say, e f 1 that is equal to 0.4 and e f 2 that is equal to 1. Now, v bar is the average velocity in the pipe. However, if you wish to calculate by taking maximum you can do that. But, the correct would be to take the average velocity of the pipe and you know, previously you have determined average velocity was 25.9 meter per second.

So, all that, I have to substitute this values now into this equation and this, now let me just put it. This equation is a separate one. These are the values. Now, this equation is plus minus m and that is equal to 0. So, what I have to do now? I have to substitute all the values. If I do that, you can substitute and you can calculate the value of delta p, where delta p will be equal to 1.25. If I do that, then m, which is a work done, that will come to 22787 meter square upon second square. All that you substitute the values, delta p is 0.5. Convert into Newton per meter square and rho air we already determined. All these values, you have to import over here and you have to substitute and this is the work done. Now, if you multiply by the amount of air, then you get the horse power.

So, the power of fan, that is required and that is equal to 54 kilowatt or 71 horse power. So, that will be the answer. So, in fact, what I have illustrated is as follows. That, how to use the pitot tube measurement to come to the power of the fan, if the need arises to do that. Otherwise, in many cases, the velocity of fluid is important and pitot tube can be very easily used to measure the pressure and hence, to calculate the velocity. It is also very easy to manufacture the pitot tube.

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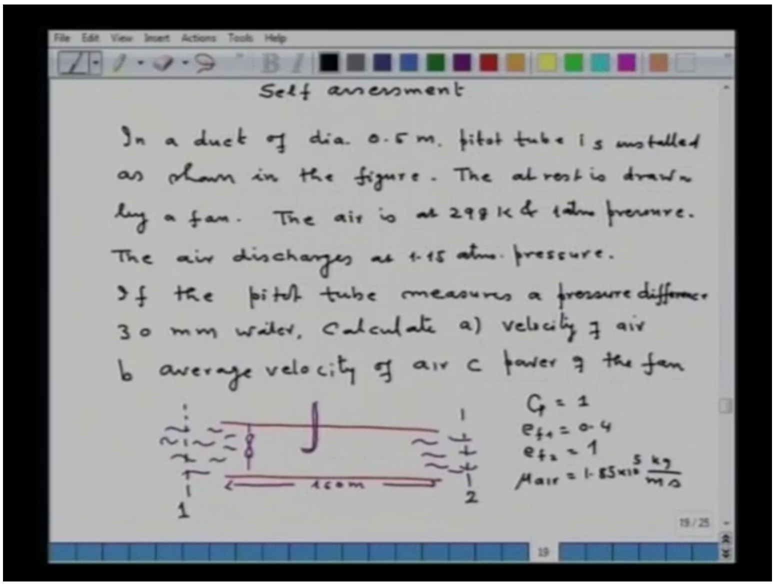

Now, I will give you a problem that you should solve yourself. So, let us put self-assessment problem. That you should solve yourself what I am writing now. In a duct of diameter 0.5 meter, pitot tube is installed as shown in the figure, which I am going to draw.

The air at rest is drawn by a fan. The air is at 298 Kelvin and 1 atmospheric pressure. The air discharges at 1.15 atmospheric pressure. If the pitot tube measures a pressure difference, say 30 millimeter water, calculate a, velocity of air, b, average velocity of air and c, power of the fan.

Now, I will draw a figure, so that you understand. So, this is the duct or pipe. So, here I have installed a pitot tube. Air is flowing, that is exiting. Somewhere here, I have put the fan of which I have to calculate what is the power required. The duct length, which I have forgotten, I can give you here. The length of the duct is 160 meter.

So, here some values you may be requiring. Take CP, that is equal to 1 and e f 1 take 0.4 and e f 2 take, this is equal to 1. Viscosity of air, you take 1.85 into 10 to the power 5 kilogram meter per second. I do not think any other value that you require. So, you can calculate these values and try that you can understand. Now, here it is important again to refer to the plain. So, somewhere here you have to put your plain 1 and somewhere here, you have to put plain 2. This will be plain 1 and this will be your plain 2. So, first of all calculate the velocity and then apply the mechanical energy balance and so on and so forth.

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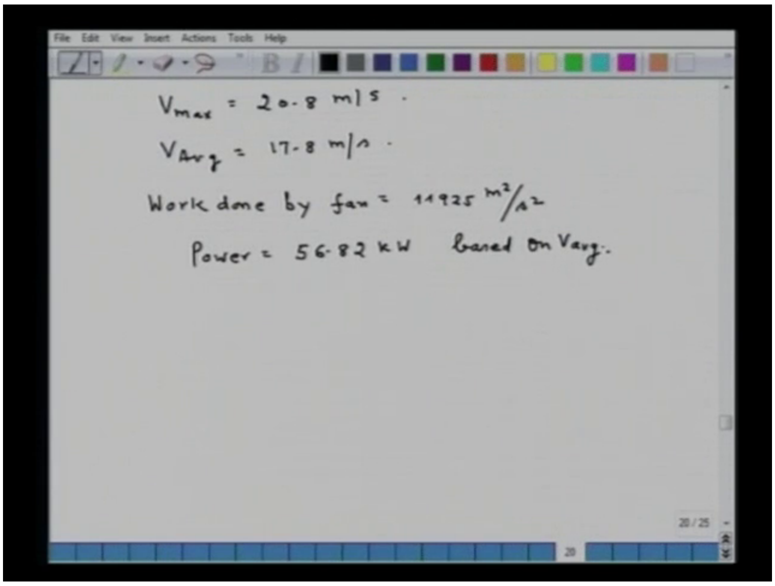

So here, v maximum, that will be equal to 20.8 meter per second and v average, that will be equal to 17.8 meter per second. If you apply mechanical energy balance, then the work done by the fan, though it is not asked, but you can also calculate, by fan, that will come up to be equal to 11925 meter square second square and power, that should come equal to 56.82 kilo watt based on v average. So, that is how you will be solving this particular problem. So, with this illustration of velocity meter is complete. Now, the next part of the fluid flow measurement is that of the head meters. Now, let us see head meters.

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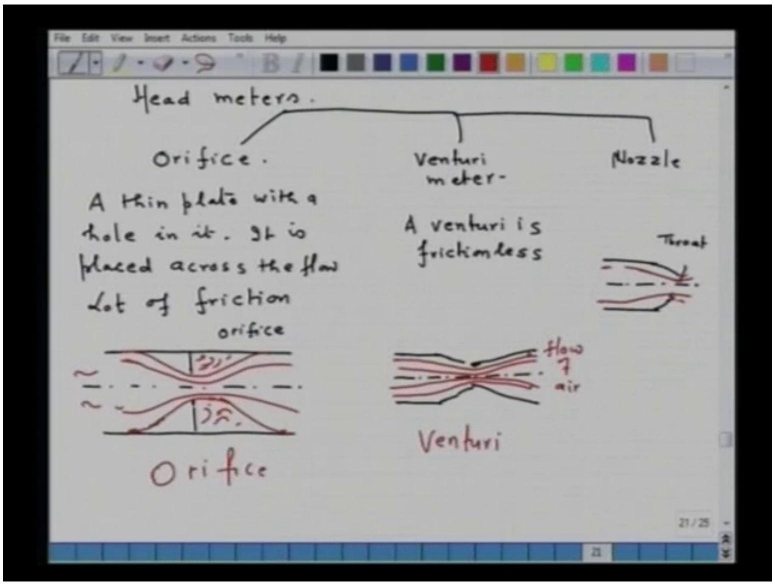

What does it mean head meter. A head meter is used to measure the pressure differential. It can be installed in a pipe or in a duct or in a flue. One can measure the pressure differential and one can co-relate this pressure differential with that of the flow rate. So, there are different types of flow head meter are used. One head meter is called orifice. An orifice is a thin plate with a hole in it and it is placed across the flow.

Another head meter is called venture. Now, venturi meter has to be decided. In the venturi meter, the flow area decreases in the direction of the flow and attains the minimum value, which is called throat of the venturi and then, again increases in the direction of flow. So, in a way a venturi is frictionless and idealistic. Third type of head meter, they are the nozzles. Nozzles, they are characterized in that. The cross sectional area decreases in the direction of flow and attains the minimum value at the exit, which is called the throat of the nozzle.

So, it is also has a friction, but, somewhere in between venturi meter and orifice. So, an orifice, it looks for example, say this is the pipe. What I do is, I just take a plate and this is the center line and then an orifice, say the plate over here of some hole. So, this is the orifice. If you want to represent the flow line, that is how the air will flow and somewhere, this is the flow direction of air.

So, air will go this way and now, the air flow. So, at this air, lot of eddies are generated. Here, the eddies are generated and because of this eddies, there is a loss of pressure. So, this is typically the flow of, say air through orifice slopes and other flow lines can also be shown. This one, that is of the orifice. Now, if I draw a venture, say let me draw a central line.

So, the flow, cross section area for the flow decreases, attains minimum value and then, it further increases in the direction of the flow. So, here the flow lines, suppose the air is flowing this way, then it will go through this way, this way, and this way. This is the flow of air. So, this is the venturi and this of the orifice. So, here the chances of eddies formation is very very minimum. Hence, very low loss of pressure to the tune that is almost a frictionless. Whereas, a nozzle, this is central line.

This is a nozzle and this portion is called flow. So, here the flow lines will go. That is, the flow discharges here and a lot of eddies will be created and there will be a loss of pressure between them. So, now let us see how we can measure the pressure differential. So, I take first of all, whether I take orifice or I take venturi or I take nozzle, the pressure measuring device will be same. The only difference will be that of the discharge coefficient.

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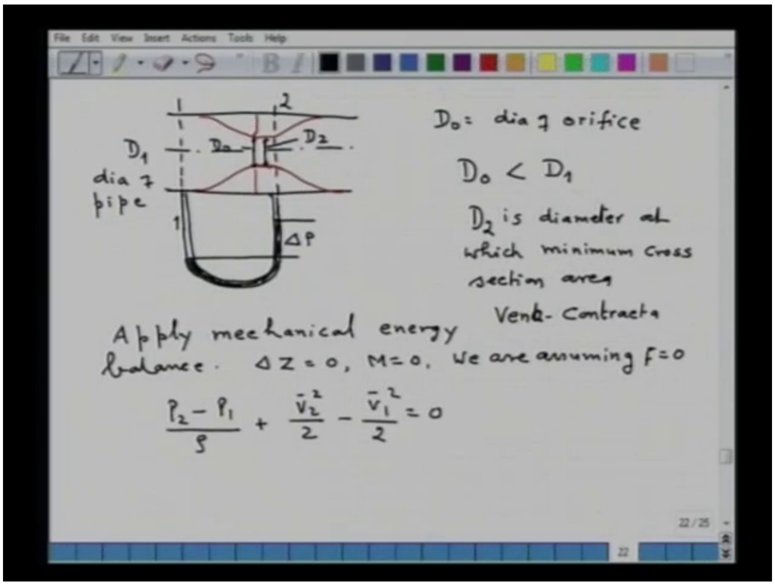

So, let us take first of all for example, the orifice. So, I represented orifice. This is central line and this is the pipe. Here, I am putting an orifice and that is a simple cross section area. So, the air flow will go this way. Let me represent, this is section one and this one is section two. This is at the entry and D 1 is the diameter of pipe. D 0, that is from here, that is, this one to this one, and D 0 is the diameter of the orifice.

Now, we have to find out and co-relate pressure difference with the velocity and also, the flow rate of the air. So, what we have done at selected section one and section two, now what we do is, we attach a pressure differential that is manometer somewhere here and between this section. This is the manometer and we will be reading this, say, this is the pressure difference that we are reading, delta p.

Now note, in order to measure the maximum pressure difference, we have to locate section two, such that the measurement give you use maximum pressure. Logistically, when we have diameter of pipe D 1 and diameter of the orifice as D 0, then naturally, D 0 is less than D 1. So, logistically, our second leg of the manometer should be at D 0. But, when the fluid flows through an orifice, the flow line contracts and the account of the contraction of flow line, a minimum cross section area for the flow results, downstream the orifice. That, I mean, that though the minimum cross section area should have been at point D 0, that is the diameter of the orifice, but, because of the fluid flow of or because of the dynamics of the flow, the minimum cross section area point, it slips downstream the orifice and this one, which is somewhat less diameter, which I will call as D 2.

So that means, this diameter is D 2 and this diameter is D 0. So, D 2 is diameter at which the minimum cross section area is there. As such, this deep U is called the formation of vena contracta. As such, the vena contracta is the formation of minimum cross section in the flow, downstream the orifice. This is a typical for the orifice, because when you locate the second leg of the manometer, if you locate at the orifice, then you will not be reading the maximum pressure. You will be reading maximum pressure downstream the orifice.

So, that is what the most important point in case of orifice. The formation of vena contracta and it is the minimum cross section somewhere downstream the orifice. It is at that vena contracta, where to put the second leg to measure the maximum pressure differential. Mind you, this is the dynamic thing. It is very difficult to locate the second pose, the vena contracta, when the fluid flows from inlet to exit. All that we know is static diameter at the inlet and the diameter of the orifice. So, that point is to be kept in mind.

Now, say we apply mechanical energy balance at one and two, its horizontal delta z equals to 0. For the time being, what we are considering, say I will put delta z is equal to 0 and there is no fan. So, m is also equal to 0. For the time being, we are assuming that frictional forces, that is the f, that is also equal to 0. Though we know, that there is a friction and there is a loss of pressure, and that will take into account some other way.

So, if we apply this balance, then we get p 2 minus p 1 upon rho plus v 2 bar square by 2 minus v 1 bar square 2 and that is equal to 0. Now, remember our one and two, one at the inlet and two, D is at the vena contracta not at the orifice diameter. Note this particular point. It is important.

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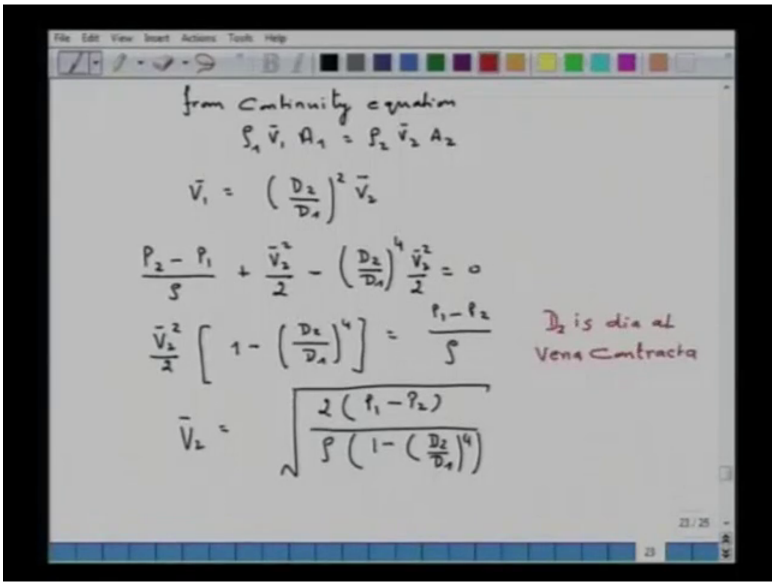

Now, say from continuity equation, we know that rho 1, v 1, a 1, that is equal to rho 2, v 2 and a 2, since fluid is incompusible, rho 1 is equal to rho 2. So, we get a very simple relationship, v 1 bar or let to average velocity, v 1 bar, and that will be equal to D 2 upon D 1 square into v 2 bar.

Now, we insert this expression into our mechanical energy balance and simplify it. Then, we get, say p 2 minus p 1 upon rho plus v 2 bar square by 2 minus D 2 upon D 1 to the power 4 into v 2 bar square upon 2 and that should be equal to 0. If I simplify this, then I will be getting, v 2 bar square by 2 1 minus D 2 upon D 1 rest to the power 4 and that is equal to p 1 minus p 2 upon rho. So, I simplify further and I will be getting, v 2 bar and that will be equal to 2 into p 1 minus p 2 upon rho 1 minus D 2 upon D 1 to the power 4 and that is closer of this all.

Now remember, I again stressed and write with a different ink that, D 2 is diameter at vena contracta. That is a important thing because, then and then, you will measure the maximum pressure differential.

We note and we know and we have done. What we have done is, we have positioned the second leg of the manometer and the vena contracta. It is very difficult to determine in practice. So, in fact, we have to use a sort of coefficient of discharge in our calculation, which account for the losses and geometrical configuration.

In other words, the shifting of the minimum cross section area, downstream the orifice, will lead to the maximum pressure. But then, we know only diameter D 1 and D 0. We do not know D 2. D 2 is the dynamic. If suppose flow rate is very high and flow rate is very low, then the vena contracta will shift. You will not be able to locate and you will not be able to do anything.

In order to locate or in order to, now use this expression for v 2 bar, in terms of known parameter, what you will do is, you will relate it to the so called diameter at the inlet and diameter at the orifice.

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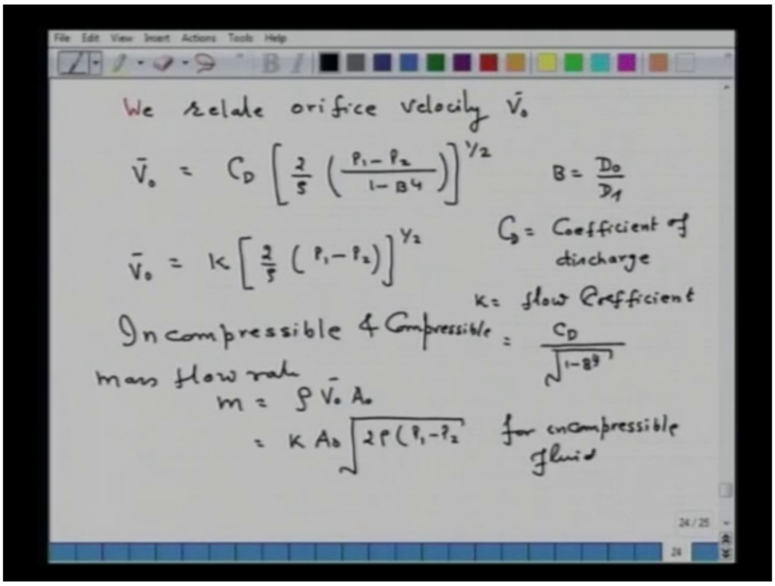

So, we relate the so called orifice velocity. Now, we relate the orifice velocity v 0 bar, that is equal to, say we write now, v 0 bar, that is equal to c D 2 upon rho p 1 minus p 2 upon 1 minus b to the power 4 and that is equal to the power 1 by half, where b, that is equal to D 0 upon D 1. C D is the coefficient of discharge.

Now, this equation is close to the known values of orifice. We know D 0 and we know D 1. All that is unknown is the coefficient of discharge. This coefficient of discharge has to be, I mean known and has to be determined. So, we further simplify the v 0 bar and write k 2 by rho p 1 minus p 2 power 1 by half. Now, k is flow coefficient and that is equal to c d upon square root of 1 minus 8 to the power 4. So, that is how, this is now the equation.

Now, if you want to, now we have a incompressible fluid and compressible. Say, for incompressible, density is constant. So, we can determine now, the mass flow rate of fluid, mass flow rate m rho velocity v 0 bar into a. So, we can substitute all these values and we can get k into a 0, a 0 is the corresponding to the area at the orifice, the root of 2 rho p 1 minus p 2 and that is for incompressible fluid.

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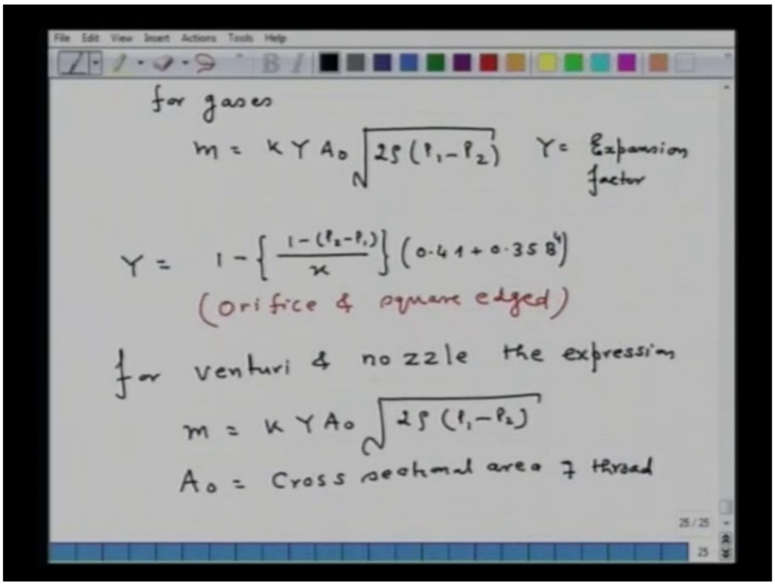

Now, for gases, this mass flow rate of air m, that will be equal to k by a 0 2 rho p 1 minus p 2, where y is an additional factor and that is called the expansion factor. Now, this y, it can be determined, say, it can be determined by y is equal to 1 minus 1 minus p 2 minus p 1 upon kappa 0.41 plus 0 .358 to the power 4. This expression holds for orifice and square edged. Orifice, we saw this is of square. From this equation, you can calculate y.

Now, the other head meter, which are venturi and nozzle, similar expression is valid. That is, m is equal k y a 0 square root of 2 rho p 1 minus p 2. So, for these expression is that, say for venturi and nozzle, the expression m is equal to k y a 0 2 rho p 1 minus p 2 is valid. Only here, the a 0, that will be equal to cross section area, a 0 correspond to cross sectional area of throat. That is, this is the minimum cross section area, because in case of venturi and nozzle, a formation of vena contracta is not there. So, the minimum cross section, which is at the throat, it can be used to determine the value of a 0.

Now, the difference will be here. You have to find out now, how to determine y for all compressible fluid. You have to find out the value of y. The value of y, it can be determined by, this is for the venture, now we have to determine the value of y.

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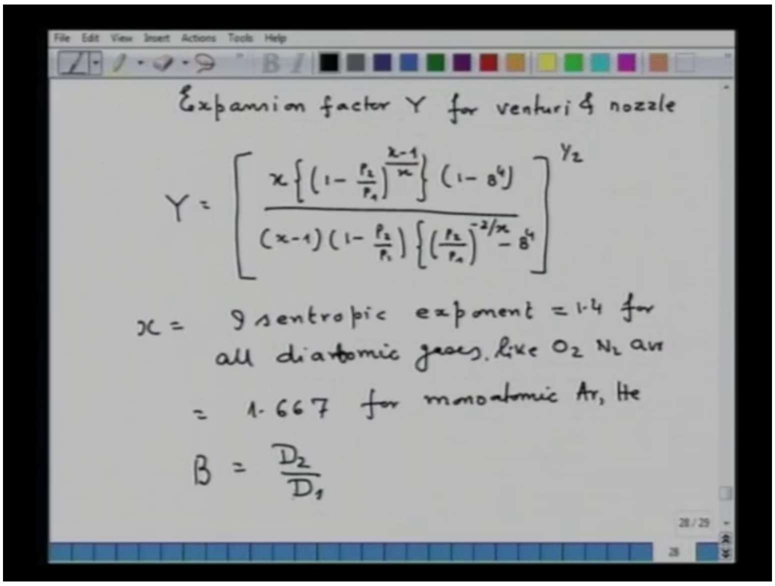

So, expansion factor for y for venturi and nozzle, it can be determined by the following expression. That is, y is equal to kappa 1 minus p 2 upon p 1 rest to the power kappa minus 1 upon kappa, bracket closed, 1 minus 8 to the power 4 divide by kappa minus 1 minus p 2 upon p 1 rest to the power minus 2 upon kappa minus 8 to the power 4 and whole rest to power 1 by 2.

Now here, kappa is an isentropic exponent and this is equal to 1.4 for all di-atomic gases and kappa is 1.667 for mono-atomic gases like, argon, helium, air, like o 2, n 2, air, this is what. So, you can determine by and rest is already we have determined. Now b, in case of venturi and nozzle, that will be equal to D 2 upon D 1, where D 2 is the diameter at throat and D 1 is the diameter of the pipe. p 2 and p 1, they are the pressures at the respective locations.

Now, we also note that the orifice plates, they also cause a loss in pressure. That means, use of orifice will also lead to a permanent losses or permanent loss of pressure. With that, if suppose the fluid is flowing in the direction, in case of frictionless, there is no loss.

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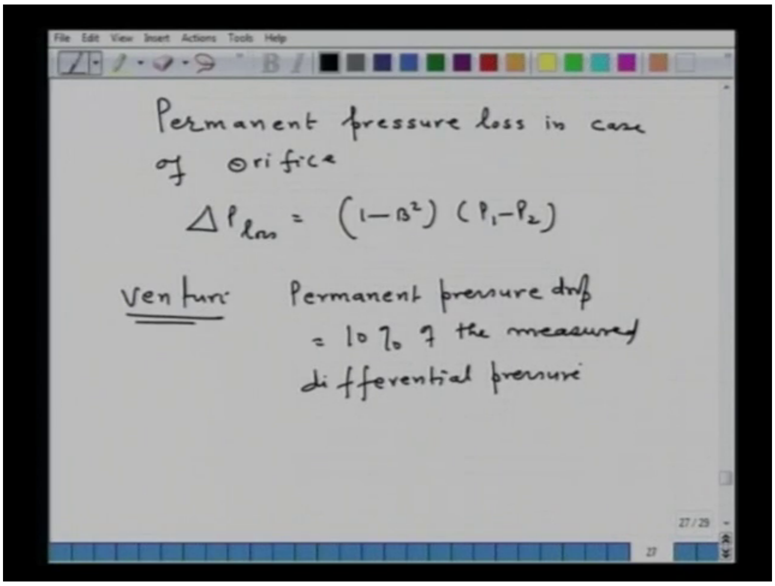

So, the permanent pressure loss in case of orifice, it can be calculated by delta p loss and that will be equal to 1 minus B square into p 1 minus p 2, whereas, for venturi, they are almost frictionless. So, their permanent pressure drop, that is equal to 10 percent of the measured differential pressure.

Now, with these, we have to derive, and calculate the velocity. In the next lecture, I will illustrate the use of these expressions to determine venturi and orifice.

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