Fuels, Refractory and Furnaces

Prof. S. C. Koria

Department of Materials Science and Engineering

Indian Institute of Technology, Kanpur

Lecture No. # 23

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

Mechanical energy balance is very useful in furnaces in several ways. A large amount of products of combustion their flow from the furnace to the flue and ultimate to stack to be discharged into the surrounding; it is required to design a blower or a fan to increase the rate of exhaust power products of combustion; also a large amount of flue for example, air is also used metering of this air from required various flow measuring devices.

So, in fact efficient utilization of fluid is very, very important for the thermal efficiency of the furnaces. So it is in this respect, the mechanical energy balance is very useful and this mechanical energy balance takes into account, the properties of the fluid at the inlet, and at the exit only. We have derived the mechanical energy balance in the form of various properties and today we will see the applications of the mechanical energy balance in order for example, to design the fans or the blowers and so on.

In fact, mechanical energy balance is also called Bernoulli equation, in the mechanical energy balance it is also called Bernoulli equation. Here must be taken that is based on per k g or per unit mass of the fuel. So, in order to get the appropriate result one has to multiply by the mass of the fluid that is going. So, let me illustrate the application of the balance by solving few problems.

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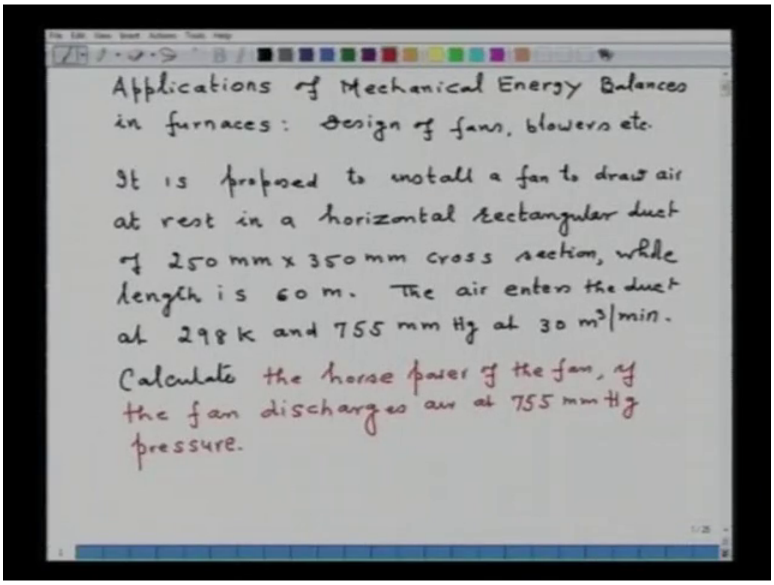

So, first of all let us take say it is proposed, it is proposed to install a fan to draw air at rest to draw air at rest in a horizontal rectangular duct, in a horizontal rectangular duct of 250 millimeter into 350 millimeter cross section, whose length that is length of the duct is 60 meter. The air enters the duct at 298 Kelvin and 755 millimeter mercury at 30 meter cube per minute.

Now, you are required to calculate, let us calculate, calculate the horsepower of the fan, calculate the horsepower of the fan if the fan discharges air at 700 and 55 millimeter mercury pressure. So, for this condition we have to find out what should be the capacity of the fan in order to meet the objective, which is there to draw air at 30 meter cube per minute. So, let us see now the, if I represent in a form of a diagram then the looks like this.

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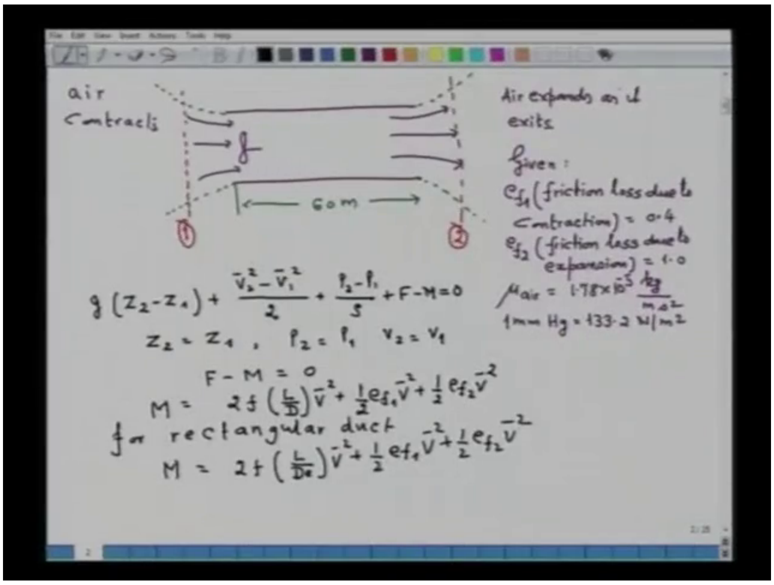

Say this is the duct of rectangular cross section, which is which is say here somewhere air is entering and somewhere here air is discharging. So, this is the extent that is this is the expansion and here when the air enters into the duct, it contracts when air exits the duct the it expands. So, this is given to us at 60 meter so, here you have install a fan so air will enter and somewhere here air will exit air will exit. So, in this is the air enters so air contracts, as it enters in the duct here as air exits the air expand as it exits.

So, as such also given to us also given to us so e f one if you recall, this is friction loss due to contraction friction loss due to contraction is given to be equal to 0.4 similarly, e f two which is the friction loss due to expansion friction loss due to expansion, that is given to us that is 1.0 also it is given to us the viscosity of air which I represent mu of air, which is the viscosity of air is given to us 1.78 into 10 to the power minus 5 kilo gram meter second square also in solving this particular problems many a times the conversion sectors are also important.

So, well it is given here say one millimeter mercury that is equal to 133.2 Newton per meter square. So, now we have to find out what should be the capacity of the fan. So, the first thing that one has to do to apply mechanical energy balance is to locate, the position one that is the inlet and position two that is the outlet. So, as such I am locating this is the position one inlet and somewhere here I am locating my position two. Now, I will write mechanical energy balance as you have derived.

So, mechanical energy balance is g Z 2 minus Z 1 plus V 2 bar square minus V 1 bar square upon two plus P 2 minus P 1 upon rho plus F minus M is equal to 0. Now, if you recall Z 2 and Z 1, they are the height to which the system is raised from the datum and as such, it will introduce potential energy into the system V 2 and V 1, they are the velocities at the exit and at entry it is precisely at location two and location one and P 2 and P 1 are the pressures F is the frictional force and M is the mechanical energy that is whichever, way the system does or surrounding does.

So, now if you apply this particular equation to the problem you see that Z 2 is equal to Z 1, Z 2 is equal to Z 1 also P 2 is equal to P 1 because air discharges at the same pressure at which it enters so that there is no pressure gradient and since, the velocity at one and two they are very, very small. So, what we will say that V 2 that is equal to V so, our mechanical energy balance if you apply this thing to this, then mechanical energy balance simply becomes F minus M equal that is equal to 0 and we know that F is the frictional forces and the so I can write down F that is equal to frictional forces, that is two f L upon D v bar square plus half e f 2 v bar square.

So, that is our frictional forces so all that we have to evaluate friction factor and we have to calculate v bar. Now, remember the v bar is different than V 1 and V 2, v bar is the velocity of air inside the duct because this particular velocity will decide the loss of loss of pressure due to frictional forces Because for frictional forces to be operative, the air should cling to the wall of the pipe. So, I will again stress that V 1 and V 2 they are different than v bar. V 1 and V 2 they are the velocities at entry and exit where v bar is the velocity of air in the duct. So, now we have evaluated this thing.

Since, now we are having a rectangular duct so we can replace D by an equivalent diameter. So, in terms of that means for rectangular duct for rectangular duct we can write down F sorry, M that is equal to two f L upon D e where, D e is the equivalent diameter v bar square plus half e f one v bar square plus half e f two v bar square now we have to calculate the various terms over here so, first of all we will evaluate D e.

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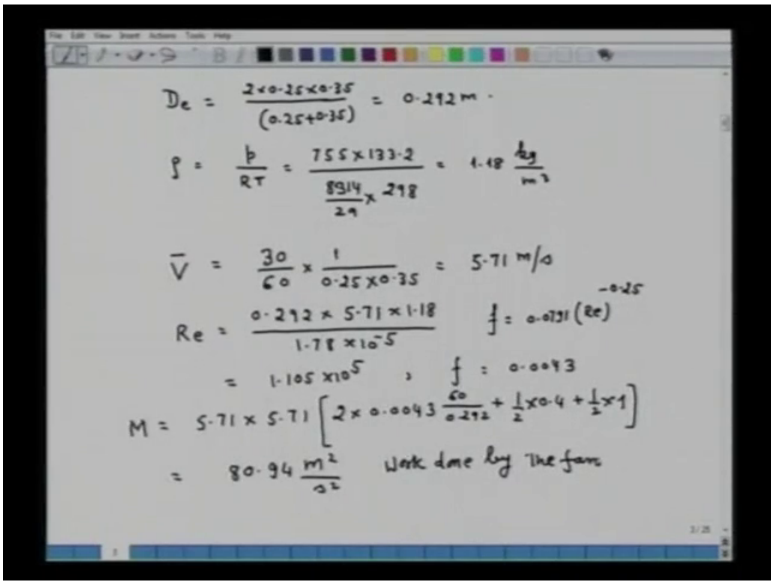

Now, D e is the equivalent diameter and you recall that is equal to two into Z 1 into Z 2 upon Z 1 plus Z 2 and that is equal to two into 0.25 into 0.35 upon 0.25 plus 0.35. So, this is you will evaluating D e and that is equal to 0.292 meter. Now, we have to evaluate the density of the air so, we can calculate rho that is equal to P upon R T and P is given to us at that is 755 millimeter of mercury into 133.2 that is because Newton per meter square that is the gross constant, 8314 divide by 29 and temperature is 200 and 9829 is molecular rate of air and it comes to 1.18 kilo gram per meter cube that is density

So, now we have to evaluate v bar so v bar they are given 30 meter cube per minute that is 30 by 60 into cross section area, that is 1 upon 0.25 into 0.35 so that is equal to 5.71 meter per second. So, now we have evaluated and also we have evaluate the value of the frictional factor M, for evaluation of friction factor you have to calculate the Reynolds number and as you recall I have given the expression that frictional force, that is equal to 0.0791 Reynolds to the power minus 0.25.

So, you calculate the Reynolds number that is V e v bar rho upon mu and for that I have given you the value of mu. So, one can calculate the Reynolds number. So, the Reynolds number would be from here Reynolds number that will be equal to 0.292 into v bar that is 5.71 into 1.18 that is the density of air divide by 1.78 into 10 to the power minus 5. So, the Reynolds number will be equal to 1.105 into 10 to the power 5 and from here I will be getting F that is equal to 0.0043.

Now, in the equation M is equal to two e f l by D e v bar square and so on, all terms are known to us F we know D e we know v bar we know e f 1 and e f 2 are given to us all that we have to substitute and get the value of M. So, now I substitute so M that will be equal to 5.71 into 5.712 into 0.0043, 60 is the length of the pipe divide by 0.292 plus half into e f 1 plus half into 1. So, that is what we will get it and if you solve then I will be getting here 8.94 meter square per square that will be the work done by a fan, that will be work done by the fan. Now, the value is plus that means an additional mechanical energy will be required by the fan.

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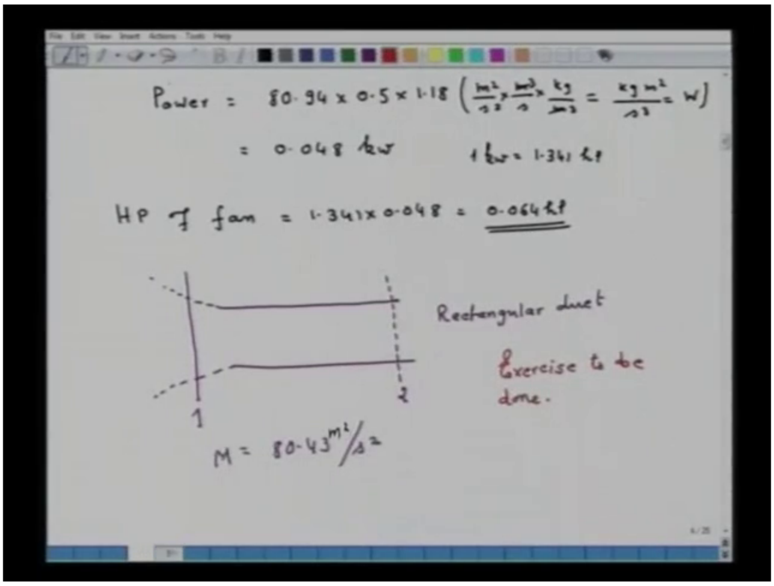

So, we can calculate now the power that is we have to calculate the power of the fan because when you go to the market to buy the fan, you have to tell him what horsepower or kilo watt capacity of the pump is needed in order to meet your objective. So, in order to calculate the power all that you have to multiply, the mass flow rate of the gas so that becomes 80.94 into 0.5 into 1.18. So, that has become the power and it want to still sure then, you have then you can do the dimensional analysis that we will be meter square upon second square into meter cube upon second into kilo gram upon meter cube. So, from here the dimension which emerges this gets cancelled so, the emerging dimension is kilo gram meter square upon second cube and all of you know this is the dimension of watt.

So, that is all we get wattage and from here we will get 0.048 kilo watt. Now, in order to calculate the horsepower say one kilo watt that is equal to 1.341 horsepower therefore, the horsepower of the fan, horsepower of fan required that will be equal to 1.341 into 0.048 and that may come to be equal to 0.064 horsepower. So, that is how you can apply the mechanical energy balance equation to calculate the capacity of the fan in many cases it is required say for example, for disposal of products of combustion you are required to create an extra pressure so, that is way you will be calculating.

Now, that is an exercise what you can do, what you can do is that you apply the mechanical energy balance for the following situation. So, I am drawing in a sketch same problem so, this is the duct and I know what I do now, the plane one I retain as it was previously, this is the plane one what I am doing now, I am shifting plane two at the exit of the pipe. This is my plane two this is my plane and this is again the same rectangular duct, all dimensions are same as what we have done just now what you have to apply. Now, the mechanical energy balance as shown in this particular diagram.

The plane two I shifted at the exit of the duct, which was in earlier problem beyond the exit of the duct. So, all that you have apply the mechanical energy balance for this particular system use all the values whatever, you require which has been just now given to solve this particular problem and calculate the work done by the pump just by shifting plane 2 to the exit of the at the exit of the duct.

So, if you that then the M value according to me coming to 80.43 meter square per second. So, this a exercise to be done as I have illustrated what is to be done. Now, in another situation say there is a melting area and the air above the melting area is often contaminated with the particulate matter. So, from the environmental point of view it is not good because then the air containing, the parcticulate containing the particulate will be inhaled and as might affect the health of the people who are working around the melting environment. So, let us no find out an arrangement where we can clean the air and for that we have to install a fan or a blower so, the situation is follows.

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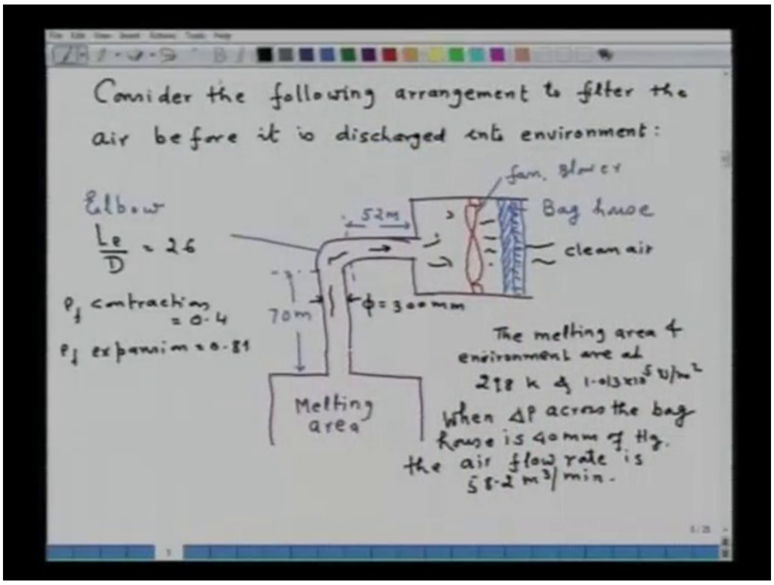

Now, consider the following arrangement consider the following arrangement to filter the air to filter, the air before it is discharged into the environment, before it is discharged into environment and the arrangement is as follows. So, we have a melting area say this is the melting area, this is melting area and here we have a arrangement for exhaust of the or the cleaning of the air.

Here is the pipe and somewhere here we have the cleaning arrangement, this is where here we are required to install a fan. So, that we can suck the air and the somewhere here we have. So, this is the bag house this is the fan. The bag house will retain the particulate and as such clean air will be discharged into the environment. So, this is the fan or you can call blower or whatever you want to call.

Now, this is 70 meter this is 50 two meter. The pipeline has one elbow this is an elbow, this pipeline has an elbow that is the vertical pipe and horizontal pipe is connected by an elbow. So, now further it is given that the melting area, melting area and environment are at 298 Kelvin and 1.013 into ten to the power five Newton per meter square pressure.

Now, it is also given that when delta P that is the pressure difference across the bag house across the bag house is 40 millimeter of mercury 40 millimeter of mercury. The air flow rate is the air flow rate is 58.2 meter cube per minute. It is also given that the elbow as shown in the diagram you can consider for the evaluation of the frictional forces, the elbow has an equivalent length that is L e upon D e that is equal to 26.

You can also consider e f for contraction that is equal to 0.4 and here e f for expansion that is equal to 0.81. So, that is what given pipe diameter is also given, this is phi that is the pipe diameter that is equal to 300 millimeter. So, what will happen? Air will flow this is the flow of air this is this, this fan or blower will suck the air and ultimately the air will pass to the bag house and here we get clean air.

Do not you think this problem is relevant for environmental cleanliness? So, what we are required? We are required to find out what should be the capacity of the fan is required. First of all you find out the work done by the blower how much amount of work will be done by the blower and from the work done, we can find out the capacity of the fan or horsepower of the fan. So, again we have to find out what is our inlet what is the plane at inlet and where is the plane outlet. So, as such for the application of the mechanical energy balance, the input and output planes are important to show because it is there you can make the mechanical energy balance.

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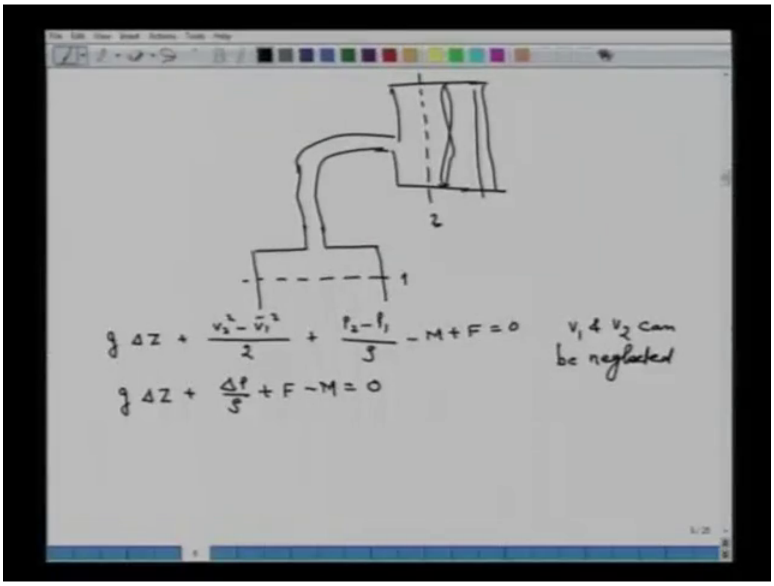

So, I will just draw the diagram to illustrate the plane 1 and plane 2. Here is the fan and this is our bag house. Now, what I will do now I am considering this is my plane 1 and somewhere here is my plane 2. So, I am applying now my mechanical energy balance between plane 1 and plane 2 so obviously, I can write down my mechanical energy balance g into delta z plus v 2 bar square minus v 1 bar square upon two plus p 2 minus p 1 upon rho minus M plus F that is equal to 0.

Now, mind you here z 1 is not equal to z 2 so accordingly we have to take here, first say v 1 and v 2 they are negligibly small and there square will be negligible small therefore, we can neglect v 1 and v 2 can be neglected because of consideration of location of plane 1 and plane 2 can be neglected. So, then our equation will become g into delta z plus delta p upon rho plus F minus M that equal to 0. So, now all that we have to apply this equation substitute the values and get the answer.

So, here again some calculation will be required because one should be very careful while substituting the dimensions of the various variable in the equation that is very, very important exercise in order to substitute the correct dimension because the result on M you will be getting in terms of meter square upon second square hence all the dimensions are to be corrected substituted.

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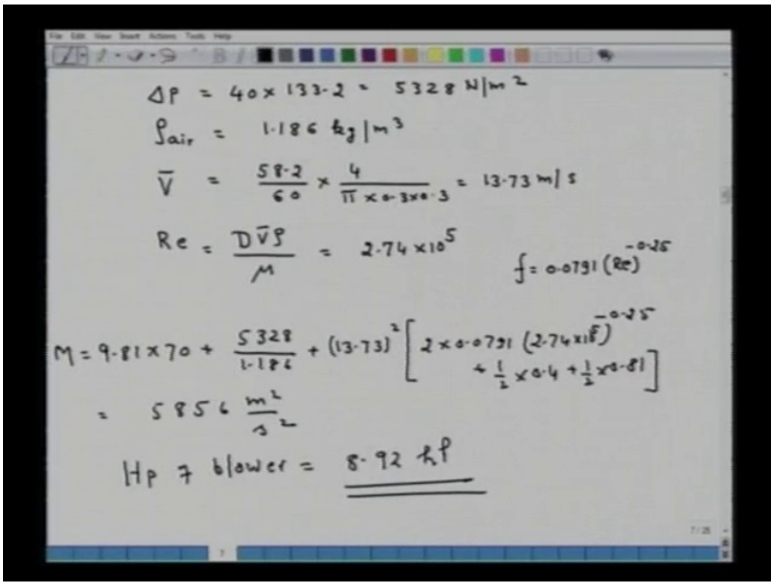

So, first all we will calculate say, let me calculate from the next figure let us calculate delta p. So, delta p is given forty millimeter we convert into Newton per meter square 100 and 33.2 that is equal to 5328 Newton per meter square. Similarly, we will calculate density of air and the density of air from the values from the formula we get 1.186 kilogram per meter cube.

We can also calculate p upon R t then we have to calculate v bar. That is equal to 58.2 upon 60 that is meter cube per second into 4 upon pi into 0.3 into 0.3. So, that is equal to13.73 meter per second that is v bar. Then we can calculate Reynolds number and

Reynolds number will be D v bar upon rho, rho into mu. So, this value will be equal to 2.74 into 10 to the power 5.

Now, I can substitute these values and I know that F that is equal to 0.0791 Reynolds number to the power minus 0.25. So, I substitute the values and these values are say 9.81 into 70 because delta z is 70 plus 5328 upon 1.186 plus 13.73 square into two into 0.0791 into 2.74 into 10 to the power 5 rest to the minus 0.25 plus half into 0.4 plus half into 0.81. So, that what you will be substituting and this value will be equal to M. So, M we can calculate from here so that will be coming equal to 5856 meter square upon second square and from here you can calculate the horsepower of the blower that will come out to be 8.92 horsepower. So, that is how one can calculate this thing.

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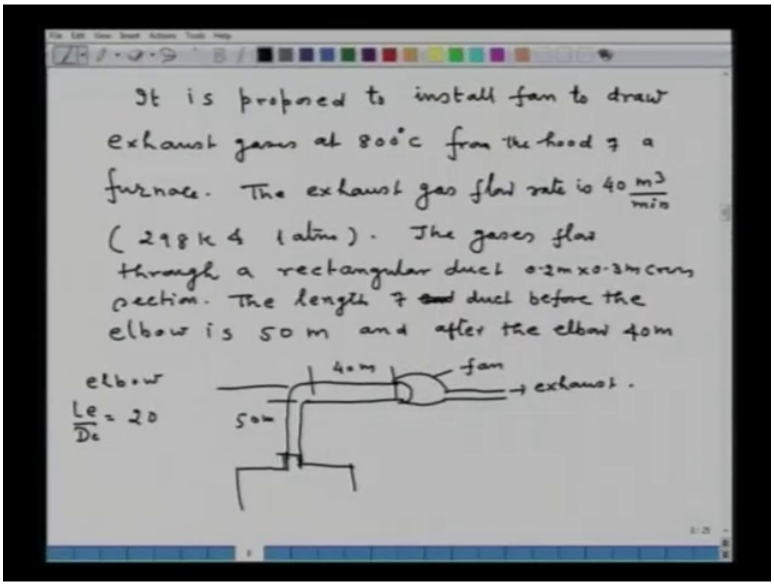

Now, I am giving you some problem for the for self calculation for example, it is proposed to install fan to draw exhaust gases at 800 degree Celsius from the hood of a furnace from the hood of a furnace. The exhaust gas flow rate, the exhaust gas flow rate is 40 meter cube per minute given at 298 Kelvin and one atmospheric pressure. The gas the gases flow through a rectangular duct, through a rectangular duct of 0.2 meter into 0.3 meter cross section.

The length of duct, the length of duct before the elbow, before the elbow is 50 meter and after the elbow 40 meter as shown in the figure say for example this is the, this is what the rectangular duct this is there here the hood and this is the fan. So, from here to here it is given as 50 meter from here to here which is given as 40 meter and this is an elbow, this is an elbow of which L e by D e that is given to equal to 20.

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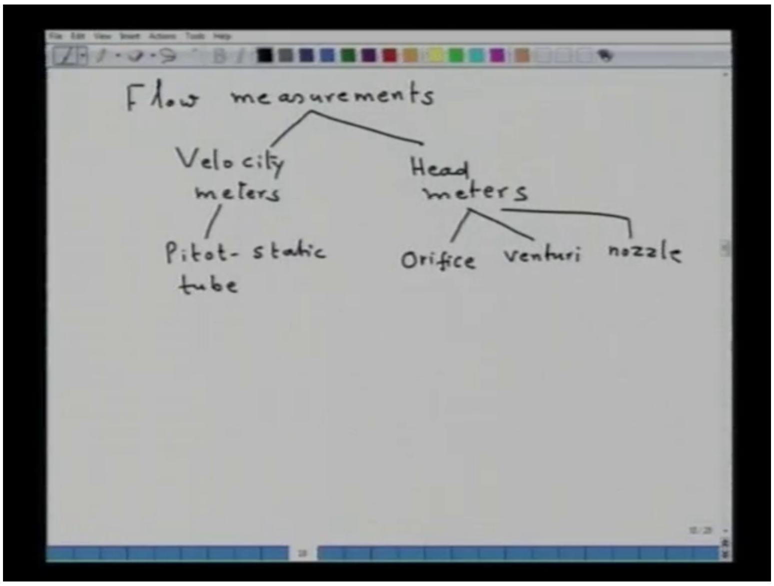

This is the fan and this is the exhaust, this is the exhaust and here given also, some values are given say given, given e f one for contraction is 0.4 e f two for expansion that is equal to 1.0 and mu by rho viscosity at 1073 Kelvin that is equal to 1.77 into 10 to the power minus 6 meter square upon second square meter square upon second.

So, you have to calculate so the you have to calculate the work done by the fan and power. So, the work done by fan is 8158 meter square upon second square and power that is equal to 8.8 horsepower. Now, this is what I wanted to illustrate for the application of the mechanical energy balance for the design of the fan blower and so on.

Now, let us look another aspect of the application of mechanical energy balance is in the flow measurement, flow measurements because often we are required to know what is the velocity of the fluid. What is the flow rate we can measure it also and we can calculate also many a times you require to measure, the pressure differential and hence we want to calculate the flow rate for design of the instruments for measuring the flow. So, as such the flow measurement they consist of there are two types one they are the velocity meters and another they are the head meters.

The velocity meters measures insect they measure the pressure and the pressure can be converted into velocity and the commonly used velocity meter is called Pitot static tube. Head meters they measure the pressure differential a cause of the flow and the head meters they are in fact orifice, venturi meter or venturi and nozzles. Mind you head meters are used to record the pressure differential during the flow, Velocity meters they are used to measure the pressure and from the pressure one can calculate the velocity.

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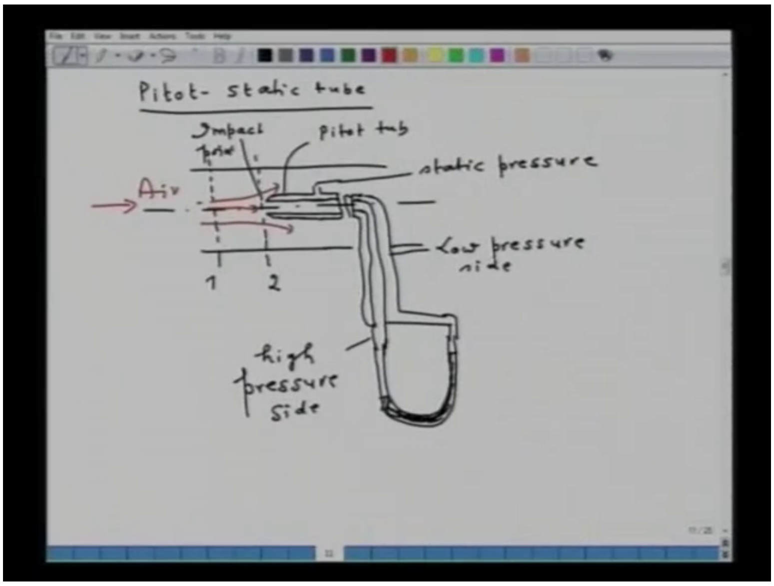

So, let us see first of all the velocity meter and in the velocity meter, the Pitot static tube is used. Pitot static tube is used to measure the pressure difference, the pressure and hence to calculate velocity. Now, this Pitot static tube it measures the difference between the static pressure and impact pressure at a given point in the flow this, Pitot static tube has an impact opening which faces directly to the flow and as the flow impacts on the Pitot tube, its velocity becomes 0 and the entire pressure is converted into the pressure and that is measured through a manometer.

So, let us consider a pipe where this is the flow, this is the center line and so here we are installing a Pitot tube, this is a Pitot tube. So, this goes to the manometer and this is a second point. This is a manometer and this records a pressure differential. So, as such this is the low pressure side and this is the high pressure side. So, let me complete the pipe. So, this is the Pitot tube, this is the impact point and this particular hole is used to measure static pressure.

So, as flow hits if I consider this is the plane 1 and the impact point is my plane 2. So, as the flow hits here these are the flow lines say, air is flowing through this way and it hits. So, here the pressure the high pressure and you record the pressure differential along this through the by the help of the manometer. So, its impact point of the Pitot tube it faces to the direction of the flow so, as the flow impacts or as the flow strikes this impact point its velocity becomes 0 and that is called the stagnation point and the pressure, which you record that is called the stagnation pressure. So, we can apply now the mechanical energy balance between point 1 and point 2.

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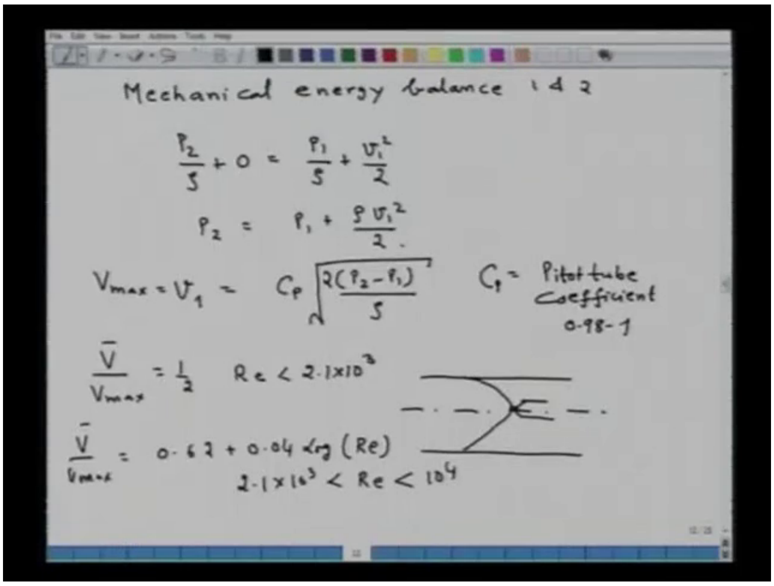

So, applying mechanical energy balance, mechanical energy balance at one and two now since, delta z is equal to 0 then we have say p 2 upon rho plus 0 that is equal to p 1 upon rho plus v 1 square by 2 where v 1 is the velocity of the fluid that we want to measure. So, at the point 2 since the air hits the impact point its velocity equal to 0 that is why p 2 upon rho plus 0 and p 1 by rho plus v 1 square by 2.

So, as such from here we can find out that p 2 that will be equal to p 1 plus rho v 1 square by 2. So, from here v 1 that is equal to p 2 minus p 1 upon rho and inside we multiply by C p and C p is the Pitot tube co efficient to take into account losses due to friction and its value for well designed Pitot tube varies between 0.98 to 1. Now, here also you should record or you should note it v 1 that is equal to v maximum because what we are measuring here, this is the center line of the flow. So, we are measuring the maximum, we are measuring velocity at the center of the air which is striking the Pitot tube.

So, therefore what we are measuring is the maximum velocity because we have directed the Pitot tube at a particular point. There could be a velocity distribution across the pipe. So, there could be there could be like this so, if I consider this is a pipe this is a center line. So, the velocity maybe distributed its distribution is like this say we have we have put our Pitot tube somewhere here; so Pitot tube measuring the velocity at the center that is the maximum velocity.

So, so this is an average velocity so from this the average velocity v bar upon v maximum that is equal to half for Reynolds number less than 2.1 into 10 to the power 3 and v bar upon v maximum that is equal to 0.62 plus 0.04 log of Reynolds number. So, that is and this is valid for 2.1 into 10 to the power 3 less than Reynolds number and less than 10 to the power 4. So, that is how an average velocity in the pipe it can be calculated.

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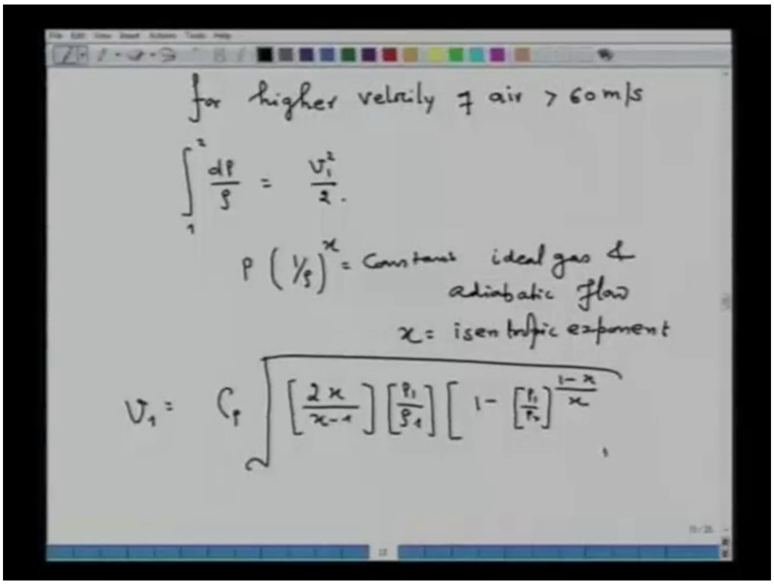

So, now this particular expression is valid for low velocities of air. Now, for higher velocities say for higher velocities, for higher velocities of air say greater than 60 meter per second. The compressive blade, compressive blade also comes into the picture, the flow becomes compressible in nature, and then one has to integrate the equation d p upon rho, because rho is no more a constant. So, that will be equal to v 1 square upon 2 for that we have to take a function say p 1 by rho to the power kappa is constant.

We consider ideal gas and adiabatic flow, ideal gas and adiabatic flow, where kappa is isentropic exponent. So, we have to evaluate this integral in order to find out the velocity through Pitot tube, pressure measurement and we evaluate this integral, then v 1 that will be equal to Pitot tube coefficient, square root of 2 kappa upon kappa minus 1, p 1 upon rho 1, 1 minus p 1 upon p 2 over 1 minus kappa upon kappa.

So, that is how you will be calculating when the air velocities are very high then the density cannot be taken as a constant, then it is called the compressible flow. So, in order to take into account the compressive related of the flow, one has to take density as a variation, and if you do that, then we get the velocity for higher air velocity through this equation and the illustration, we will see in the next class.