Fuel, Refractory and Furnaces

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Lecture No. # 21

Transport Phenomena in Furnaces: Fluid Flow

Transport Phenomena in Furnaces; in fact, transport phenomena is a very important subject in metallurgical engineering curriculum. Transport phenomena involve, transport of heat, momentum and mass in any process. When the reactants are converted into product or when the material is heated at high temperature, then there occurs either flow of the fluids or flow of the heat or flow of the mass.

Now, this flow occurs for example, flow of the fluid occur, because of the momentum transfer which sakes of velocity gradient. Flow of heat occurs, because of temperature gradient, and which sakes thermal gradient in the process or in the reacting chamber. The flow of mass is due to the concentration gradient. So, velocity gradient, temperature gradient and concentration gradient, they are the mechanism of momentum, heat and mass transfer respectively in any process. In fact, from the kinetic point of view, it is important that during conversion of reactant into product or during heating of an object to a thermo-mechanical processing (( )) or heat treating temperature. The gradient of velocity it affects the flow of heat, because velocity gradient and temperature gradient are interrelated.

And similarly, the velocity gradient also affects the concentration gradient. Knowledge of all the gradients and their quantification to the fluid flow, heat flow and mass flow is very important from the consideration of the design point of view. I will be restricting myself to the application of this wide subject transport phenomena as applied to furnaces only. As you recall a furnace is a thermal enclosure and essentially, it is used to heat the reactant to the desire temperature.

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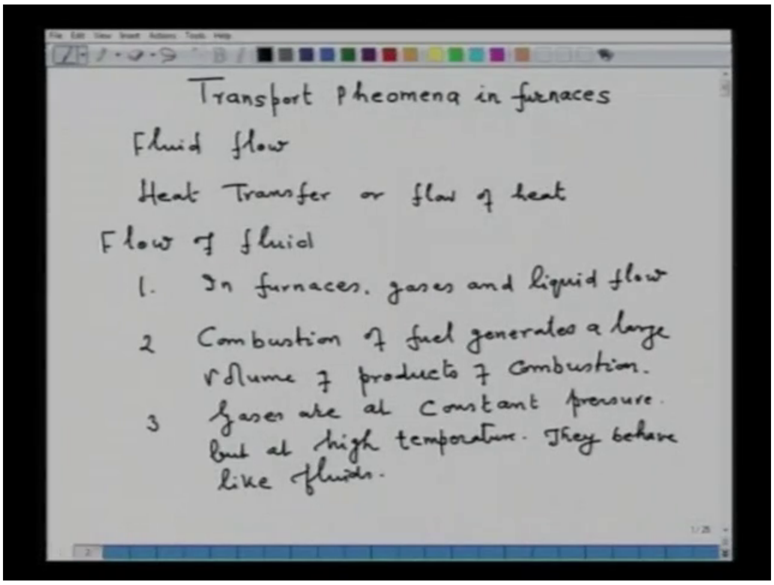

So, with reference to the application of transport phenomena in furnaces, we are mainly concerned on fluid flow and heat transfer or flow of heat. In furnaces, hardly there is a mass transfer, when these are used for heating purposes only. So, we will be restricting ourselves to the application of transport phenomena fundamentals to fluid flow and heat transfer.

Now, if we consider the importance of both these phenomena that is fluid flow in heat transfer, then the flow of fluid is important in several aspects. First say in furnaces, gases and liquid flow, gases and liquid flow gases of the air is used for combustion purposes. So, there involves the flow of the gases and always and also involve flow of liquid, because they use the cooling of the furnaces through water.

Second, the combustion of fuel as all of you know, combustion of fuel it generates a large volume of products of combustion a large volume of products of combustion in a reaction chamber of constant area. As you recall, product of combustion are the main mechanism of transfer of energy from the combustion of fossil fuel.

In fact, the flow of the product of combustion inside the reaction chamber is important to attain a uniform furnace temperature; that means all part of the furnace should be heat by uniform velocity of the products of combustion. So, that the temperature of furnace can be attained a constant value, there should not be any overheating or under heating areas in the furnace.

The overheating means excess temperature, under heating means lower temperature in order to attain minimum consumption of the fuel. Also the velocity or the movement of product of combustion inside the reaction chamber is also important from the point of view of the heat (( )) it by the product of combustion at the temperature of product of combustion.

Over heating or under heating in both cases, the POC may have the higher temperature or lower temperature and in that case, the efficient utilization of fuel will not occur. What I wanted to say from this, that it is the pattern of flow of product of combustion in the furnace is important that is there should not be dead region, there should be uniform velocity, and all these things are important when we consider the design of reaction chamber for a particular volume of product of combustion.

So, it is here the movement of the products of the combustion inside the furnace chamber is an important issue. Third thing is that say, gases are most of the time at constant pressure, they flow I mean gases flow inside the reaction chamber are most of the time at constant pressure, but at high temperature, at high temperature they behave like fluids they behave like fluids.

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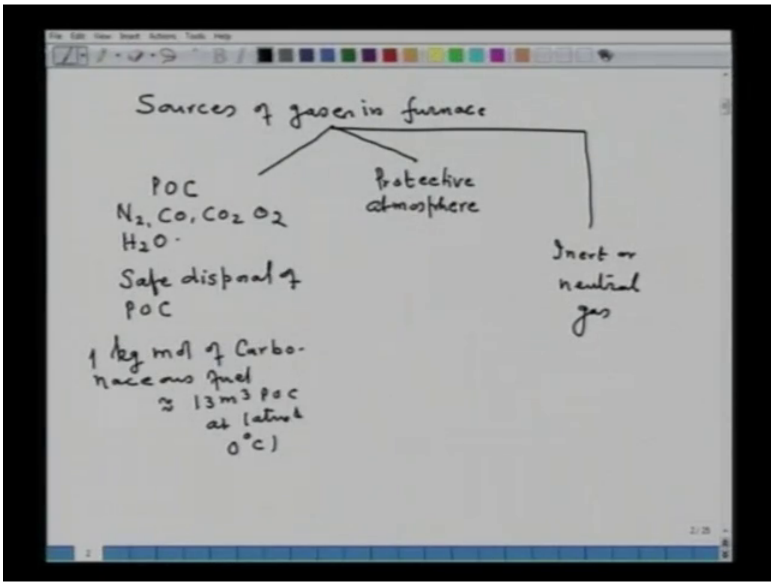

Now, let us look what are the resources of gases in the furnace. A source of gases in furnace, one such source is product of combustion. Now, product of combustion comprises of nitrogen, C O, C O 2, O 2 and H 2 O, the velocity of their flow is important, velocity at the exit of the product of combustion is important. And what is more important is the safe disposal is the safe disposal of products of combustion, so that the environmental hazards are minimized.

So, that is an important to design the flow passage, so that the products of combustion are discharge into the atmosphere at greater height in order to eliminate the hazard of influences of products of combustion. So, design of (()) and design of flow passage is again a fluid flow issue that has to be addressed.

You must know that for example, if we take 1 kg mole of carbo-naceous fuel of carbo-naceous fuel approximately it generates 13 meter cube POC at 1 atmosphere and 0 degree Celsius. If you want to understand please follow lecture 9 to 12, where we have calculated all these thing.

8000 degree Celsius, this volume will be 7 to 8 times larger. Those things are also to be considered while designing reaction chamber and flow passage to the velocity and the pattern flow is important. Another source of gases in the furnace is the protective atmosphere protective atmosphere. Now, the protective atmosphere is used for heat treating purposes or to avoid oxidation in various cases, the nitrogen, inert gas like organs are use as protective atmosphere, and their safe disposal is important.

In some cases, ammonia is used to prepare the atmosphere, so in that case the safe disposal is also important. Third is the inert or neutral gas inert or neutral gas. Now, the inert or neutral gas atmosphere is important to the extent that, this should be conserved, their flow velocity should be (( )). So, that you have a neutral or inert atmosphere in the furnace.

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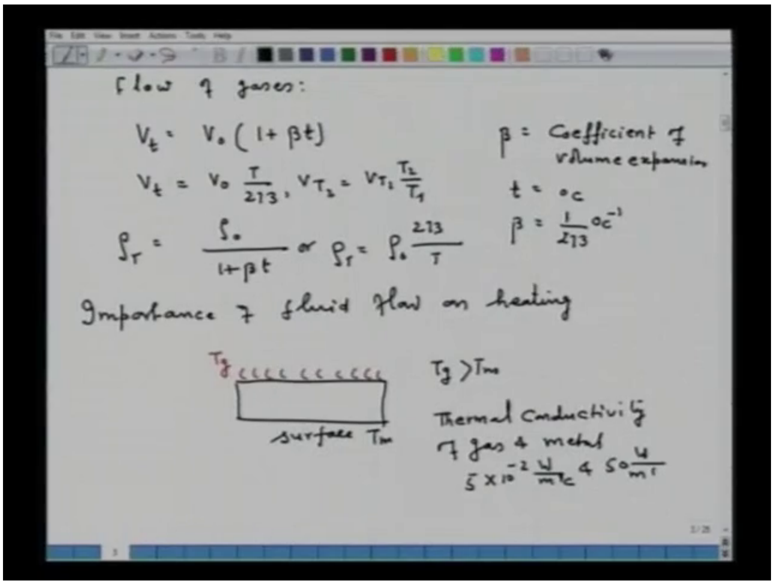

Now, say flow of gases if we consider what the issues are when we consider flow of the fluid. Say flow of gases, now as all of you know from your basic science that gases expand on heating, volume increases and density decreases. So, at constant pressure, volume at temperature is proportional to temperature, whereas density is inversely proportional to the temperature.

We can write down for example, volume at temperature t that would be equal to V 0 1 plus beta t, where beta is coefficient of volume expansion, coefficient of volume expansion t is degree Celsius. A coefficient of volume expansion say, beta that is equal to 1 upon 273 degree C has to the power minus 1; or you have also know that, V t that is equal to V 0 into t upon 273 or V T 2 that is equal to V T 1 into T 2 by T 1 that are simple relationship.

Similarly, density at temperature T, that is equal to rho 0 upon 1 plus beta t or rho T that is equal to rho 0 273 by T, where T is in degree centigrade. Now, say let us see the importance of say importance of fluid flow on heating fluid flow on heating. You may thinking that why should I study fluid flow, because I am I am studying only the furnaces. Let us see what is the importance of fluid flow in heating.

Now, for example, you are heating a surface. So, this surface is a temperature T m and which is having (( )) layer of gas, which is at temperature T g. Now, the T g has to be greater than T m. So, if there is a (( )) gas on the top surface, (( )) surface of the say metal, then the transfer will occur by conduction from bulk of the gas to the surface and from the surface to the inside of the metal. So here, the thermal conductivity of gas and metal they are important.

Normally, thermal conductivity of gas thermal conductivity of gas and typically for metal, they are 5 into 10 to the power minus 2 for gas watt per meter per degree Celsius. And for metal, it is 50 watt meter Celsius, so you can see that, the thermal conductivity of gas is very very small as compare to that of the metal. And hence, there be very very slow heat transfer, if there is a quiescent layer of hot gas on the top surface of the metal.

So, for this purpose a motion in the gaseous phase is important. Therefore, if you allow the gas to flow, the heat transfer will be faster or surface will be heated faster. So, heat transfer in a system with fluid in motion it depends on the velocity of fluid, higher is the velocity of the fluid, higher is the transfer of heat. So, what is important here is to know what is the velocity at which the fluid should flow.

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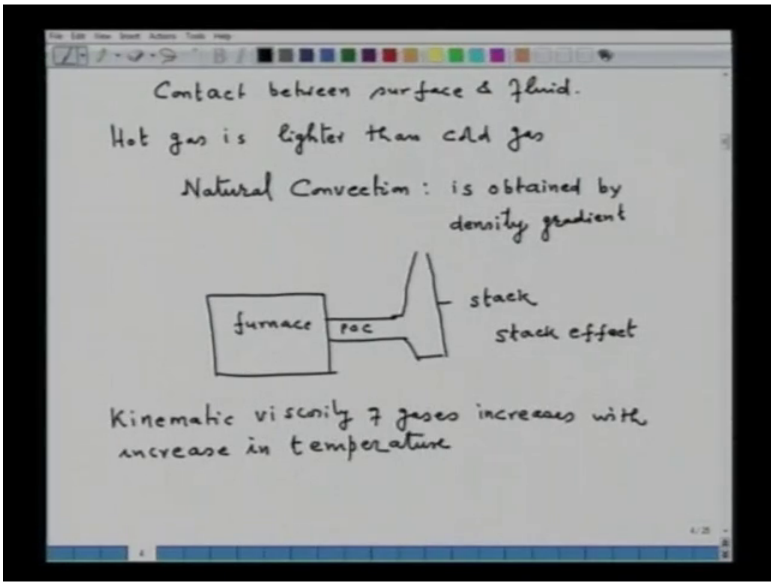

Another important thing is also the contact the contact between surface and fluid. Heating will occur only wherever the fluid makes contact with the surface, no contact no heating will be there. Also important to know that, near this surface, the heat flow will occur will always occur by conduction. And also to know that a uniform velocity of the gas will give you a uniform heating. Therefore, the velocity of gas moving velocity of gas is an important issue.

Also we know that, hot gases say hot gas is lighter than cold gas is lighter than cold gas. So, what will happen? Under gravity, hot gases move up and cold gas will move down. So, this is called natural convection, this called natural convection. And natural convection is obtained by density gradient by density gradient or you can also call rebinds the forces.

Now, in furnace this natural convection is very important. Now, this differencing density between the hot fuel gas and cold fuel gas can be used to dry out a product of combustion from the furnace to the atmosphere. So, for example, if we have this is a furnace (Refer Slide Time: 19:11), this is the flow passage, here the product of combustion of flowing at higher temperature.

Now, if I have to design say, this is the stack then, I can make use of the height of the stack in order to regulate the flow of POC from the furnace to the atmosphere. So, this is the furnace, this is the POC and this is called the stack effect. So, this is again a very important in the design of the furnace to know, what should be the height of the chimney, so that the products of combustion are discharged into the atmosphere at a greater height, so that their harmful effects are minimized.

So, one should be able to calculate the density gradient, and from that one should be able to know what should be the height of the furnace. Now, another thing is also if we recall the kinematic viscosity the kinematic viscosity of gases it increases with increase in temperature increase in temperature. What does it mean for that we have to see what is the kinematic viscosity.

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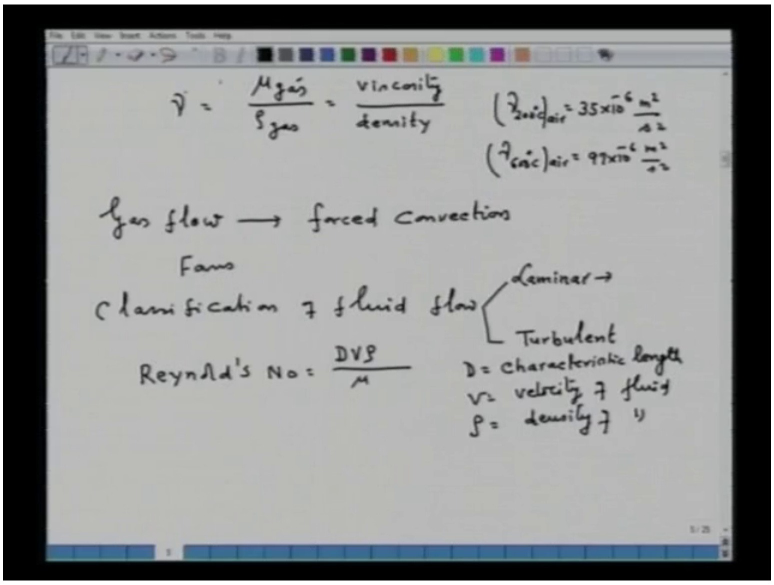

Now, kinematic viscosity of a gas that is equal to viscosity of gas upon density of gas, I will write down in words for you that is a viscosity of gas upon density of gas. So, if kinematic viscosity of gas increases with the temperature that means viscosity of the gas increases with the increase in temperature.

Now for example, if I take air, a kinematic viscosity at 200 degree Celsius of air that is equal to 35 into 10 to the power minus 6 meter square per second. And this kinematic viscosity at 600 degree Celsius of air that is equal to 97 into 10 to the power minus 6 meter square per second.

Now, what this figure indicates, the increase in kinematic viscosity, because of the increase in the viscosity of the gas. So, when the viscosity of gas increases, the movement of the gas is very sluggish. As a consequence of it, the conductive heat transfer is very very slow, so there (( )) heat transfer is important.

So, what we can use that, gas flow it can be induced by force convection. So, in fact the velocity of the gases can be affected either by the density gradient or by imposing some some type of force from outside. So, that the gases are forced to move, so that the heating related function it enhances. Now, this force convection is also important.

Now, imagine the fuel and air they are combusting, and on combustion the flame is created. Now, the flame it constantly pushes fuel air and product of combustion outward. So, therefore, the knowledge of the velocity of the flame and (( )) extend, it can induce the motion of the product of combustion in the chamber that is an important issue.

Sometimes, in order to induce force convection fans are used, blowers are used. Now, this fans and blower what they do? They push the gas flow inside and create the condition force convection. So, we should know, what should be the capacity of the fan, what should be the capacity of the blower, because we have to integrate with the furnace, these are the important issue.

Now, let us know about the background let us see what are the classification of the fluid flow, say classification of fluid flow. Now in general, the flow is either laminar flow or a turbulent flow. In the laminar flow, stream lines they are straight, in turbulent flow stream lines are zigzag. A turbulent flow is characterized by highly fluctuating velocity component in the flow.

So, the distinguish feature of laminar and turbulent flow can be done by Reynolds's number. So, Reynolds's number it characterizes whether the fluid flow is laminar or turbulent, and that is equal to D V rho upon mu, where D is the characteristic dimension, which is length characteristic length, V is the velocity of the fluid, rho is the density of fluid and viscosity I have already said it is the mu.

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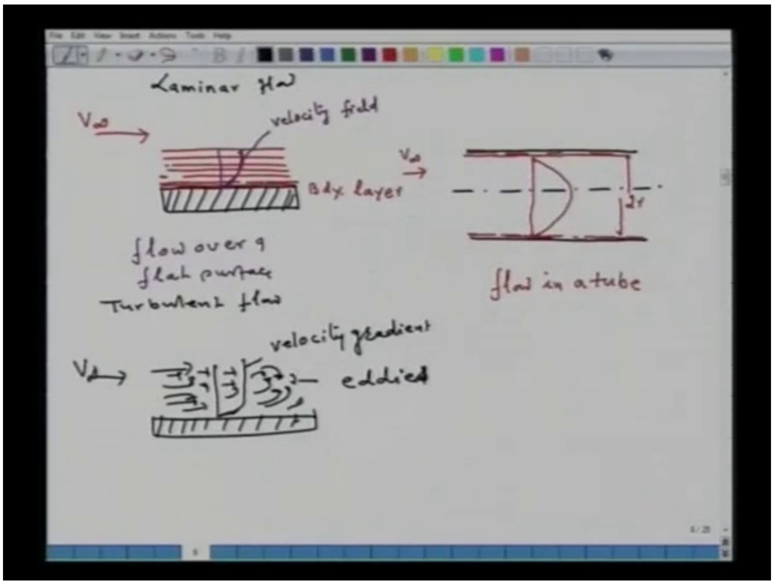

So, depending on the flow, the various type of flow pattern can be seen. For example, we consider the flow a laminar flow of (( )) on a flat plate, if I consider this is a flat plate this is the flat plate and imagine the flow is occurring perpendicular to the plate. So, this is the direction of flow of velocity V infinity. So, as the flow comes in contact with the surface immediately one has so called a retarding influence that is the induction of the so called boundary layer.

And outside the boundary layer, the flow the velocity in fact, it increases and attains a constant value, which is equal to V infinity at some distance perpendicular to the direction of flow. So, if you want to show the velocity gradient, then the velocity profile will look this is the one and here, this is a short of a parabolic profile and so, this one is the increase in velocity and then, it attains a constant velocity that of the V infinity of the fluid. So, this is what the flow over a flat surface, and this is the velocity field or velocity variation with the distance perpendicular to the direction of flow.

Now, if we consider it same thing we consider in a tube. Say for example, this is the tube (Refer Slide Time: 28:17), this is the center line same thing, the flow is in this direction V infinity. So, what will happen, as the flow comes in contact with the (( )) immediately its velocity will be equal to 0, because of the friction and (( )). So, if this is 2 r, and if I want to show the velocity gradient in the direction of r then look something like this (Refer Slide Time: 28:59), that means you have here flow in tube.

So, there is maximum velocity at the center and it decreases, as the flow occurs near the (( )) of the tube. Now, if we consider for example, a turbulent flow. So, in a turbulent flow this case is for laminar flow. Say, if we consider now turbulent flow, now in turbulent flow the flow is highly zigzag, the eddies of difference scale in different velocities will be generated on a count of which the flow is fast. So, if I want to represent (( )) this is the direction of V infinity. So, you have say, this is the velocity gradient.

We know the difference between laminar flow and and the turbulent flow is that, there is very I mean immediately there is a similarity in velocity, that of the approach velocity that is V infinity, whereas in laminar flow it goes it take a little longer distance perpendicular to the direction of flow.

So here, the eddies of all dimension in all the flow, this is the surface. So, this eddies of different lengths and dimensions they are in fact responsible for faster movement of the liquid in turbulent flow. So, what is what I wanted to convey from here is that, when the velocity fluid is important for the flow of the liquid, for the heat transfer of the liquid then one has to distinguish whether the flow is laminar or the flow is turbulent.

Turbulent flow occurs at high velocity, laminar flow occurs at low velocity. In laminar flow there are gradients, in turbulent flow there are no gradients, there are localized gradient, but overall the velocity is very high. So, heat transfer rate will be very high.

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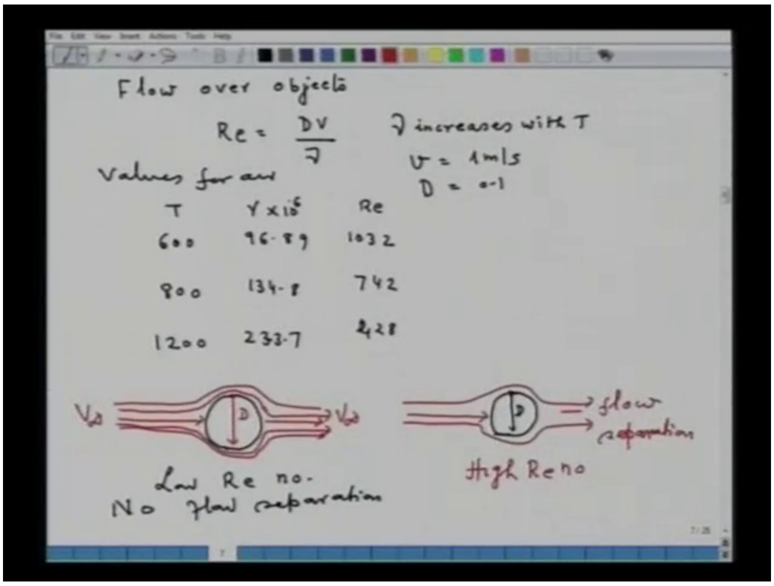

Now, if we consider for example, flow over objects say, flow over some objects, now here as I said Reynolds's number we define D V rho by mu I can take as kinematic viscosity. Now, when this is implied in furnace then now since, this gamma, this kappa it increases with temperature I mean this is the kinematic viscosity.

Now, for example, if I take say V I take 1 meter per second, D I take 0.1 meter and I take for example, a temperature here I take value of kinematic viscosity. And here, I calculate temperature calculate a Reynolds's number say, temperature if I take 600 degree Celsius, 800 degree Celsius and 1200 degree Celsius. This value is 96.89, 134.8, 233.7 and Reynolds's number is 1032, 742 and 428, so these are the values for air.

Now, what I wanted to say from here is that, as a temperature in the furnace increases, the Reynolds's number decreases. And the decrease in Reynolds's number means the flow is a transitional. At low temperature the flow is turbulent, then at high temperature, the flow may be somewhere between laminar and turbulent flow, so because the Reynolds's is decreasing.

So, in furnace (( )) or in furnaces, the flow could be transient in nature. Now, say for example, if we consider a flow pattern over the cylinder. Say, if I consider this is a cylinder and let us see the approach velocity of V infinity. Then for ideal case, this velocity it should cover the entire surface, this is a sort of a (( )) pattern, this is the diameter D of the cylinder and this is an again V infinity. So, this thing will occur for very low Reynolds's number.

Now, the characteristic feature of this, there is no flow separation there is no flow separation. And if the flow separates that is the flow of the liquid separates from that of the object, then there be (( )) then there will be non-uniform heating. Now, for example, if we take if increase the Reynolds's number the same object whose diameter is D, if we take this is the approach velocity, now here high Reynolds's number.

So, the flow is turbulent. So, in that case it might happen that, the flow it may not touch the rare part of cylinder, so this is the, so called flow separation. This is the flow separation. So, in this two it is important that, from laminar to transition, from laminar to turbulent flow, this is the somewhat mechanism. If we still go the higher the Reynolds's number, then (( )) and eddies will be created and that will be adding to the heat transfer mechanism.

So, a perfect contact between the fluid and the product or the body is important, there should be no separation of flow. If there is a separation of flow, then that particular part of the object will not be heated up, so that is an important and require consideration of fundamentals of fluid flow.

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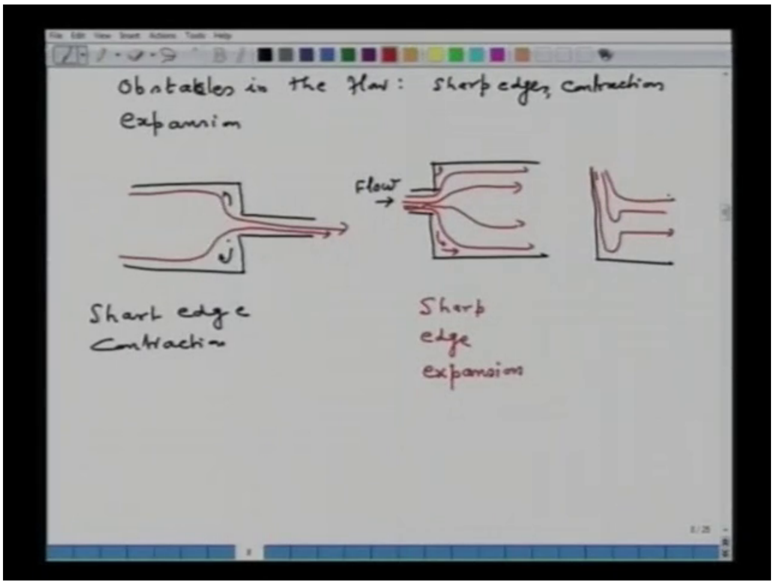

Now, let us say there will be some obstacles in the flow some obstacles in the flow flow like sharp edges, contraction, expansion, because when you want to design a pipeline, all these things can happen and at all places, there is a loss of (( )) or loss of pressure occurs. So, you should be able to quantify, what is the loss of pressure.

Now, for example, if we consider a contraction say let us see, this is a flow passage, so here the liquid is flowing and it gets contracted over here while going out, similarly here there is a contraction. So, this is called sharp edge contraction sharp edge contraction. So, in the sharp edge contraction, what happens? There will be the eddies will be created in these particular edges. So, accordingly there is a loss of pressure or another you can consider that, this is the flow direction. So, in the flow direction, as the liquid flow what will happen it will go and it will expand as it is passing through an expansion here, here, here and as a result of it, eddies might be created over here.

So, this is a sharp edge expansion or one may have a sort of a rectangle channel. So here, the fluid is flowing and is possible that coming this liquid going this and then, at this way and then, this way and ultimately we have. So, what is what is being said over here that this is, these obstacles due to the flow of fluids through these obstacles.

There will be loss of pressure and this pressure must be accounted in order to design flow passage that means flow separation should be avoided, sharp edges should be avoided, expander or contraction if it is there, then one should taken into account the loss of pressure to this.

Now, also it is important the arrangement of load in the furnace. How the load is arranged that will also govern, how the fluid is flowing into the load, because ultimately the heating will be occur by the velocity of the by the flow of the fluid; and hence the velocity filed, which is set up under the action of forces that is an important here.

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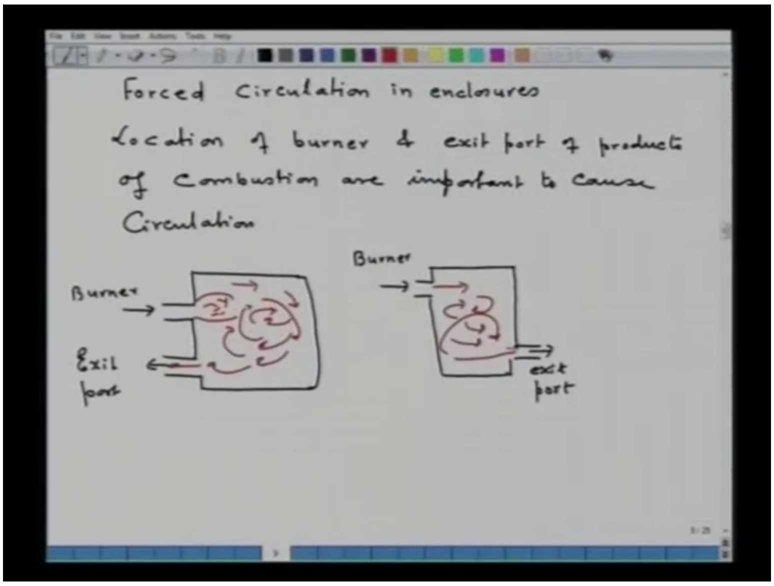

Now similarly, if we consider for example, force circulation in enclosure force circulation in enclosure, now this is often important while considering a location of the burner in the furnace and the exit port. Also in furnaces, we do not use one burner, very often more than one flame or more than one burner is required. So, the location of the burner and the exit port is important to cause the circulation of POC inside the furnace chamber.

Now, for example, if we consider the following say, what I wanted to say is a location of burner and exit ports of products of combustion are important to cause circulation. Now, why this is important because you know that, the thermal energy of the fuel is released by product of combustion. And the product of combustion, circulate uniformly in the reaction chamber, and the location is very important this is again a fluid flow problem.

So, for example, if I take a furnace enclosure, this is a furnace enclosure, here I put burner and this is the exit port this is the exit port. In another situation, what I do, I take this furnace, here is my burner and here is the exit port. So, the burner will produce a flame the products of combustion because, hotter, lighter will go up, but it is force to move downward. So, a sort of flow pattern, which is a re-circulatory in nature, will be created.

You know how it will be created, because the hot gases tend to move upward, but they cannot move upward, they are force to move downward. So, in this downward motion, a sort of circulatory loop in the combustion chamber will be created and that is a very very important way of releasing heat from product of combustion.

So, the location of burner in exit port, there will be important. In this particular case, a good circulation loop in the center of the furnace will be created. Now, if I locate my burner over here and exit port over here, then though loop will be created, but it will not be of that intense as an ultimately the gas will go out.

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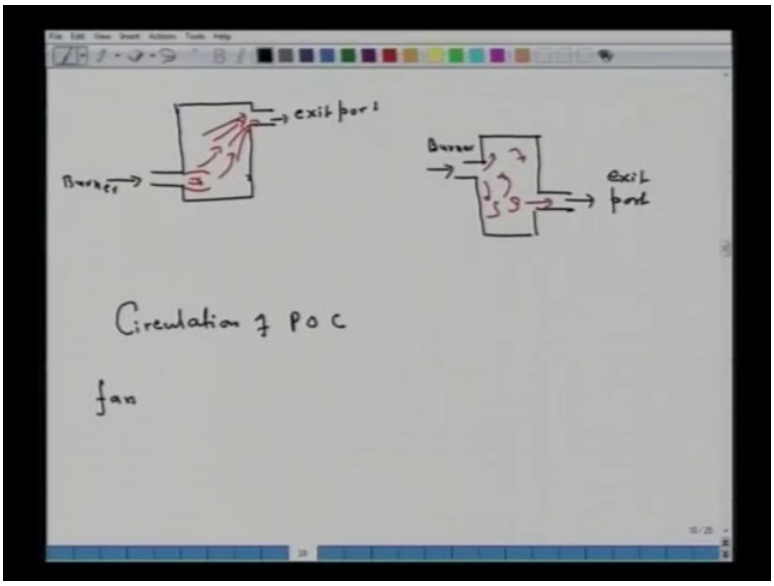

Now, in the third situation say if I put (No audio from 45:10 to 45:20), say this is my burner and this is the exit port and in the (( )) case what I can do is, that is I can put (No audio from 45:38 to 45:46). So, these are the different location this is again burner and this is again port exit port rather, this is a burner location.

Now, this particular location is not very good, because the flame which is being created over here, it is very high temperature gases will move upward and gases have directly path to the exit. So, as such no re-circulating type of movement will be produced in this case well the burner port slightly in the middle, gases will move up down, down, down, down and ultimately it will go out.

So, what is important in the location or fixing the location of burner in the exit port is that, the circulation should be the circulation of POC is important. That is the location of burner and exit port, it determines the circulation of POC inside the furnace chamber or (( )) the work piece. And circulation of POC it creates vertices, vertex flow and the work piece which is placed in the vertex, they will be heated faster.

So, this also again a problem or issue related with fluid flow phenomena to understand the circulation cause by the location of the ports, burner and the exit and the creation of vertices. Similar in this similar, we have to locate the fan say sometime we have also use fan to create a force convection. So, fan of speed 200 RPM, 300 RPM, 400 RPM are blower, they are also important to create force convection.

So, what I have today illustrated is as follows is that, in furnaces which work at high temperature the thermal energy of the fuel is derived from combustion of fuel in the form of products of combustion. So, it is the velocity of product of combustion, it is the circulation of the product of combustion, it is the important.

So there, the laminar flow and turbulent flow have their own advantages and disadvantages in connection with the flow. Similarly, the free convection and force convection, there are also the mechanism of heat transfer, they are also important, both these mechanism are governed by the velocity of the fluid. So, what is in fact involves when we say we want to study the fluid flow.

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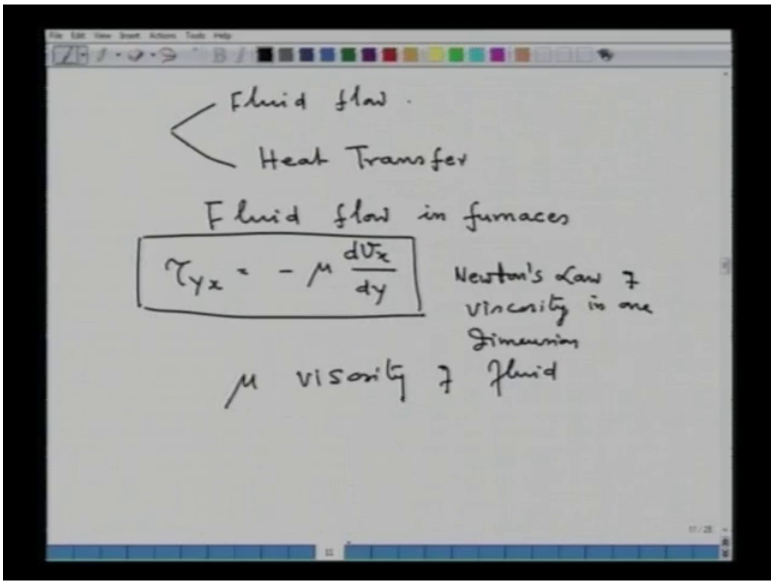

So, in essentially say transfer phenomena in furnace, it comprises of fluid flow and heat transfer. As such, first part we will be taking fluid flow in furnaces fluid flow in furnaces. Now, the basic objective of fluid flow is to determine the velocity. Once you know the velocity, then we can calculate all other parameter for example, the loss of pressure due to sharp corner, due to contraction, due to expansion, due to obstacle and (( )).

So, in all such fluid flow studies as all of you know, the Newton law of viscosity is an important. And Newton law of viscosity can be very easily perceived is that, if the liquid is flowing in x direction, then x direction momentum is m into p. Now, this x direction momentum is transferred in the y direction.

So, therefore, the transfer of momentum from x direction to y direction as represented by the shear (( )), which is tau y x that is related by mu D V x upon d y, this is the basic Newton's law of viscosity in one dimension Newton's law of viscosity in one dimension. That is, the liquid is flowing in x direction and x direction momentum is transferred in the y direction; so at steady state, the velocity V, x will be a function of y only in the beginning, it will be a function of y and t at steady state, it will be a function of y only. And the Newton's law of viscosity it connects the transfer of momentum with the velocity of gradient and mu is the viscosity of fluid viscosity of fluid.

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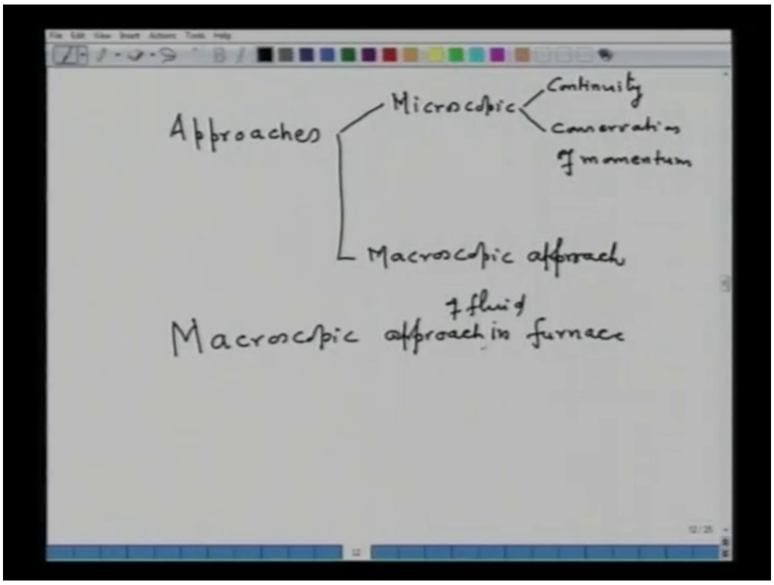

Now here, onwards two approaches are there in order to study the fluid flow. So, the approaches one is a microscopic approach. In the microscopic differential volume elements of delta x, delta y and delta z are selected, the fluid is allowed to flow in all these three direction. And the differential equations are obtained and these differential equation are solved by a numerical method or by computer (( )).

So, this microscopic balance is very accurate one, but it involves tremendous amount of competition. The microscopic balance in terms involves the concept of continuity that is conservation of mass and conservation of momentum and conservation of momentum. For very accurate and precise calculation, the microscopic approach is very, very useful, it gives us the differential equations and these differential equations can be solved, it cannot be solved without the numerical method.

However, there is another approach which is a macroscopic approach. In the macroscopic approach, this is more or less, we consider only the inputs and outputs, we do not consider what is happening inside the flow or inside the chamber. We define the properties at the inlet, we define properties at the outlet outlet and then we work upon.

So, this sort of approach is used is so called algebraic equation, they can be very easily integrated and this macroscopic approach found to be very, very useful in case of furnaces. And as such, our further I will continue with the macroscopic approach macroscopic approach in that is macroscopic approach of fluid flow in furnaces.