Fuels, Refractory and Furnaces

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Lecture No. # 32
Steady Heat flows in Furnace and Heat Exchanger

In the series of lectures on transport phenomena in furnaces, today, we will be talking on a steady heat flow in furnaces and heat exchangers. Now, in the previous lectures, we have addressed the heat transfer mechanisms and their quantifications of conduction, convection and radiation. Now, let us see, the applications of those fundamentals for heat flow in furnaces.

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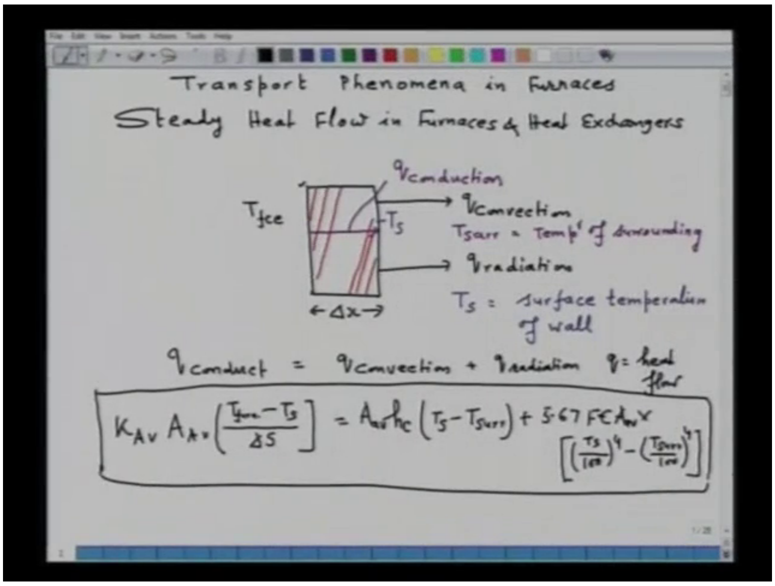

Transport Phenomena in Furnaces

Steady Heat Flow in Furnaces & Heat Exchangers

$\rightarrow q_{convection}$

T_{surr} = Temp' of surrounding

$\rightarrow q_{radiation}$

T_S : surface temperature of wall

$q_{conduct} = q_{convection} + q_{radiation}$ q = heat flow

$$\boxed{K_{Av} A_{Av} \left(\frac{T_{fce} - T_S}{\Delta S}\right] = A_{av} h_c (T_S - T_{surr}) + 5.67 F \epsilon A_{av} \times \left[\left(\frac{T_S}{100}\right)^4 - \left(\frac{T_{surr}}{100}\right)^4\right]}$$

Now, in fact, if we perform a heat balance of the furnace, then, heat balance will tell us the losses of all types; what fraction of heat is carried away by the products of combustion; the fraction of heat carried away by the product, and heat losses which is happening through the walls of the furnaces. But even then, for many situations, we do require, how the heat is flowing from combustion chamber of the furnace to the wall and accordingly, the losses which are occurring through the refractory wall of the furnace. So, it is in this context, the heat flow path from combustion chamber to the surrounding, which result into the loss of heat, is also an important, in order to optimize the lining design, the thickness of the lining design, the thermal conductivity of the lining material, whether we should go for multi layered thickness, and if multi layered thickness, what should be the thickness and what should be the thermal conductivity of the refractive lining.

So, let us consider a furnace whose wall, consider a furnace whose wall is delta x in thickness and let us say, this is the refractory lining; this is the refractory lining and through the refractory lining, the heat is flowing by the mechanism which we all know, q conduction; that means, this side, this refractory wall, this refractory wall is facing to the combustion chamber of the furnace, and let us see the temperature of the combustion chamber of the furnace; let us put it T furnace. Now, this is the wall of the furnace and from the wall, the heat is being lost by mechanism like convection, as well as, heat is also lost by radiation. Now, let us take T surrounding, that is equal to temperature of surrounding, temperature of surrounding; whereas, the surface temperature of the wall, let us take it T S; so, I will say, T S, that is equal to surface temperature of wall; surface temperature of wall. So, our heat flow path is from furnace to the wall, and through conduction, through the lining, and ultimately, heat is lost from the wall of the furnace by convection and radiation. Therefore, we can say that, q conduction, that should be equal to q convection plus q radiation, where we say q is the heat flow.

So, all that now, we have to write down the heat flow equation for conduction, that is a Fourier's law of heat conduction. So, we can write down now, say, average thermal conductivity into average area, we know this is the equation that we obtained, T furnace, T furnace minus T s upon delta S, that is equal to heat transfer coefficient; now, remember this h c is the heat transfer coefficient for free convection, because the heat is lost from the wall of the furnace by free convection mechanism; into T S minus T surrounding plus heat transfer by radiation, which we know, that is 5.67 into F which is the view factor; this is the emissivity; this is the area; this is the area, or the rather average area into T S upon 100 to the power 4 minus T surrounding upon 100 to the power 4; and, in fact, this also should be multiplied by area, A average.

So, you can see, this is the heat transfer equation, or rather the heat flow path from the combustion chamber of the furnace to the surrounding; that means, utilizing this expression, one can calculate, depending upon the parameter given, how much amount of heat is being lost, when the furnace temperature is, for example, T furnace, or one can also calculate what is the temperature of the wall of the furnace; of course, it depends upon what variables are given to us. Now, this is in the M K S system. Now, the same expression will become in F P A system, only the difference will be, instead of 5.67, you have to multiply by 0.173; that is the only difference, which you please note.

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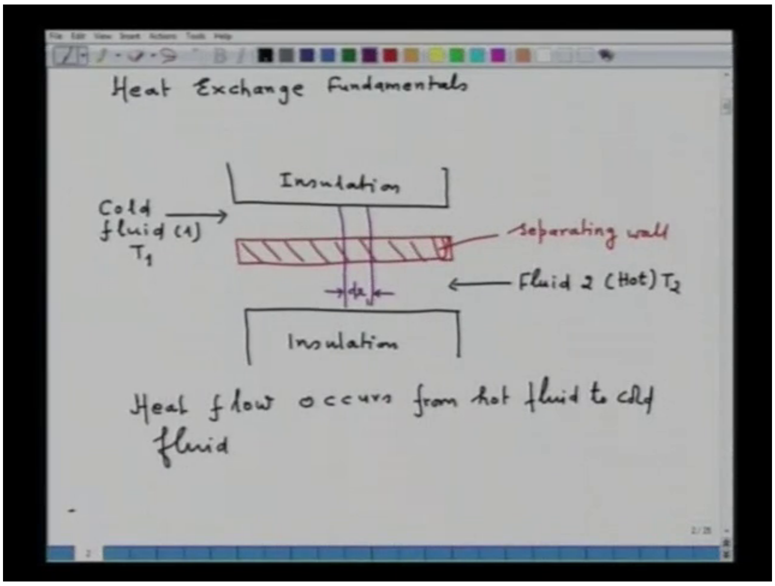

Heat Exchange Fundamentals

Heat flow occurs from hot fluid to cold fluid

Now, then, let us proceed to the next, next application, heat exchange fundamentals, fundamentals. Now, as we have seen in the last several lectures on combustion, heat transfer, we have seen that, the products of combustion carries a large amount of heat. And, it is in this context, it is essential that we try to recover the heat from products of combustion, and try to reuse it, either by heating the air or by generation of the steam, or for whatever purposes. So, it is in this context, it is important to understand, what are the fundamentals of heat exchange of the two streams, that is, hot stream and cold stream, flowing in a heat exchanger. Now, consider a heat exchanger. Let us consider a heat exchanger. So, this is a heat exchanger. Here, we have insulation; it is insulated; there also insulation and the flow of hot and cold fluid is separated by a separating wall. So, this is, this is a separating wall. This separating wall is separating the flow of cold fluid and that of hot fluid. This is the direction of flow of the cold fluid. So, this is cold fluid; let us take it fluid number 1 and we represent it by its temperature T 1; and from this direction, fluid 2, which is hot and at some temperature T 2. So, you can see that, the separating wall, it separates the cold and hot fluid. So, as the fluid flows, the heat flow occurs; heat flow occurs along the length of the exchanger, by transfer of heat from hot fluid to cold fluid. So, heat transfer occurs from hot fluid to cold fluid. And, in this picture, or in this figure, you are seeing that, cold fluid and hot fluid, both are flowing counter currently. Now, as the fluid flows in both directions, the conditions of temperature, it may, it varies from one place to another throughout the exchanger. So, let us first of all, consider the process in an infinitesimal element of length, for example, d x; let us consider very small length of the element of the heat exchanger as represented by its thickness d x.

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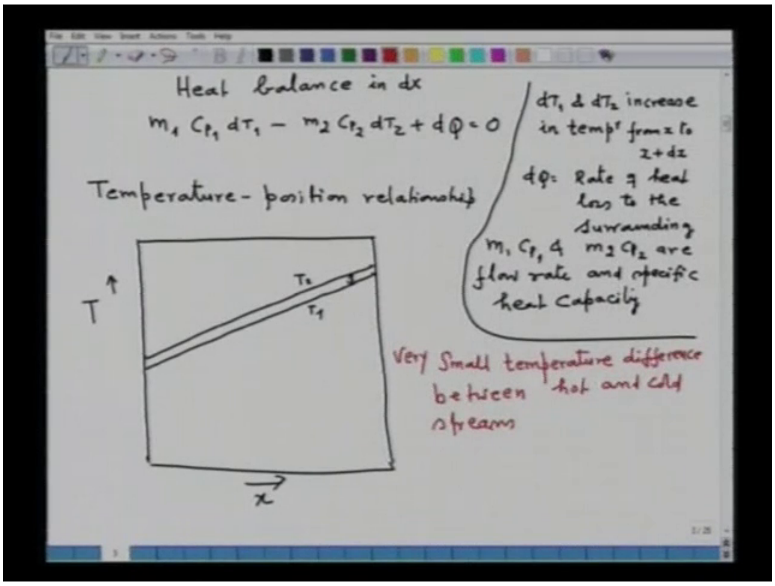

Heat balance in dx

$m_1 C_{p_1} dT_1 - m_2 C_{p_2} dT_2 + dQ = 0$

dT_1 & dT_2 increase in tempr from x to x+dx

dQ: Rate of heat loss to the surrounding

$m_1 C_{p_1}$ & $m_2 C_{p_2}$ are flow rate and specific heat capacity

Temperature-position relationship

Very Small temperature difference between hot and cold streams

So, now, we can write down heat balance. Heat balance in d x, that will be equal to m 1 C p 1 d T 1 minus m 2 C p 2 d T 2 plus d Q, that is equal to 0, where d T 1 and d T 2 are increase in temperature, are increase in temperature, as the fluid flows from x to position x plus d x; d Q is the rate of heat loss, rate of heat loss to the surrounding, to the surrounding; and, m 1 C p 1, m 1 C p 1 and m 2 C p 2 are flow rate and specific heat capacities, and specific heat capacities of fluid 1 and fluid 2. Now, as the fluid is flowing, we can, first, we can consider, let us first consider, temperature-position relationship, as the fluid is flowing from one location to another location in the exchanger. Now, we can see that, one, one condition, or one situation can occur, which can be represented by this particular figure. So, this is the temperature and here, is the distance. So, one situation that can occur is that, a very small temperature change between the two streams; this is say T 2, this is say T 1, and this is a temperature change between the two streams. So, what we see from here that, in this situation, we note that, there is a small temperature difference, a very small temperature difference, or let me put, a very small temperature difference between hot and cold stream at any value of x during the flow. So, what does it mean, this very small temperature difference, suggests that the separating wall is offering a 0 thermal resistance; that means, all the heat from the hot fluid is being transferred to the cold fluid, across the separating wall. In other way, you can also understand that, there is, all the heat which the hot fluid is containing, it transfers to the cold fluid. So, in this particular situation, the separating wall will not be offering any thermal resistance. Now, say, this particular situation can occur, when either the separating wall has 0 thermal resistance, or 0 flow rate; that means, fluid does not move; if we substitute this condition…

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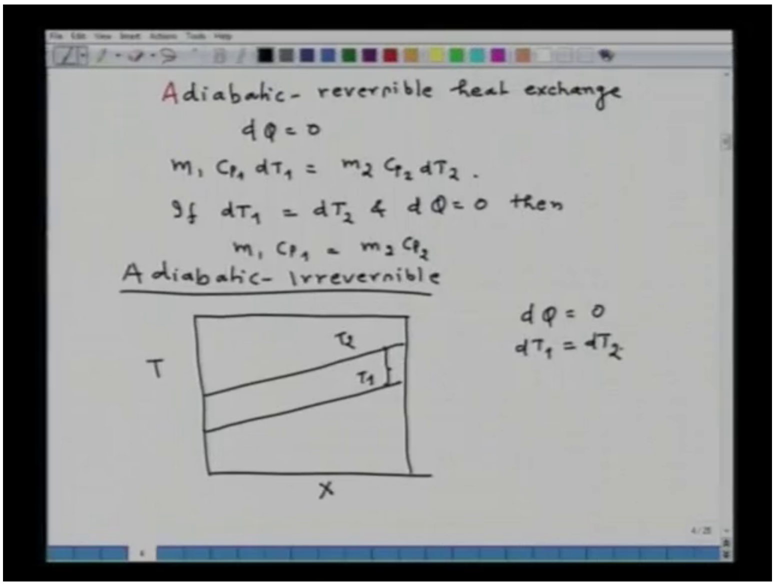
Adiabatic- reversible heat exchange

$dQ = 0$

$m_1 C_{p_1} dT_1 = m_2 C_{p_2} dT_2$.

If $dT_1 = dT_2$ & $dQ = 0$ then

$m_1 C_{p_1} = m_2 C_{p_2}$

Adiabatic- Irreversible

$dQ = 0$

$dT_1 = dT_2$

So, for example, if we consider now, an adiabatic, say, we consider an adiabatic reversible heat exchange, adiabatic reversible heat exchange. Now the, this situation which is shown in this particular figure, it is possible only, when the heat exchange process is adiabatic, as well as reversible; because in the reversible process, there are no heat losses occur, at all the point during the, in the flow passage; there is a thermal equilibrium is maintained. So, that is what, if we consider a so called adiabatic reversible heat exchange, and this adiabatic reversible heat exchange is 100 percent efficient in operation. So, for this adiabatic, we have d Q is equal to 0, d Q is equal to 0. So, from the heat balance we get m 1 C p 1 d T 1, that is equal to m 2 C p 2 into delta 2. Now, accordingly, if d T 1 is equal to d T 2, as we are seeing, there is a very infinitesimal, a small temperature difference between the two flowing stream, or adiabatic reversible heat exchange, so, if d T 1 equal to d T 2 and d Q is equal to 0, then, it follows that, m 1 into C p 1, that is equal to m 2 into C p 2; that means, it is necessary for this type of behavior of heat exchange to perceive, when the heat exchange capacity of cold and hot fluid, they are the same; that is what we are getting, if m 1 C p 1 is equal to m 2 C p 2, and if the process is adiabatic, and is also reversible, then, the flow capacity, or the heat flow capacity should be same for both the fluid; then and then, this situation can occur.

So, it suggests that, the flowing of the fluid at any finite rate against thermal resistance is an irreversible process; that means, if a separating wall offers resistance and if the flow, and if the fluid is flowing a certain rate, then, a combination of both, that is flowing of the fluid and the thermal resistance of the separating wall, it introduces irreversibility in the system and on a count of irreversibility, one can have a situation of heat exchange, something like this. Here, again T; this is, x is the distance; this is the temperature T 2 of hot fluid and this is the temperature T 1. So, this difference is due to the thermal resistance of the separating wall and because of the flow of the fluid. So, this both this things introduces an irreversibility and in both the cases, we will not be able to extract all the heat which is present in the hot stream. So, again, if we consider, this is (( )) of adiabatic, irreversible, irreversible, adiabatic irreversible condition. Now, in this, what you are seeing here that, the temperature difference which is driving the heat flow is constant over the entire length of the heat exchanger. Now, due to the irreversibility, which is caused by the flowing fluid and because of the thermal resistance, the heat exchange is not complete. You are seeing that, the temperature of the hot fluid, it remains higher and temperature of the cold fluid, it is lower than that of the hot fluid; so, that means, here, again d Q is equal to 0 and d T 1, that is equal to d T 2, only when m 1 C p 1, that is equal to m 1 C p 2; this is the another situation.

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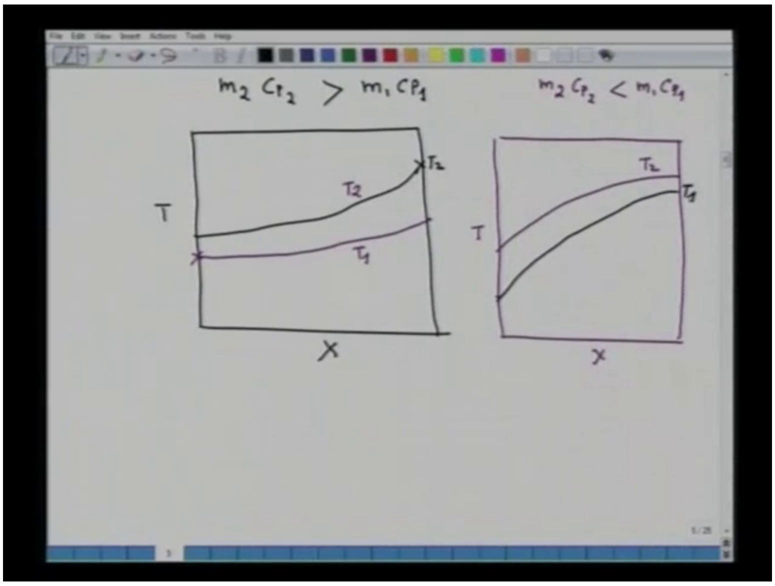

Third situation, which is more practical; say, imagine a situation when m 2 C p 2 is greater than m 1 C p 1; that is, heat capacity of the hot fluid is greater than heat capacity of the cold fluid. So, this is more or less a near practical situation. Then, how the heat exchange will look? So, if we plot again, here, temperature against position, now, hot fluid is flowing from here; so, somewhere here, we have T 2. So, T 2, its temperature will decrease; and what happened to T 1; T 1 is from here, this is say T 1; this as a cold fluid and ultimately, this is T 1 and this is the T 2. And, this difference is because, that the heat capacity of the hot fluid, if it is greater than heat capacity of the cold fluid, then, naturally, because of the differences in the heat capacity, the heat transfer from hot to cold fluid will also not commence to the full extent; and how much heat is transfer at any position, that will depend upon the ratio of the heat capacities.

Now, another situation we can have, where m 2 C p 2 is less than m 1 C p 1; then, how will it look? Again, we can plot, here; we can say T and this is x; then, this is T 2 and here, we have T 1. So, all this, it says, the difference in heat capacities does not allow the heat exchange to complete and it is in this respect, one has to optimize the flow rates of hot and cold fluid, their amount and their velocity also. We have to also optimize the length of the heat exchanger, because then, we have to allow the sufficient time for heat exchange to occur; that means, we have to optimize residence time. What we have to do, we have to optimize the residence time. We have to optimize the flow rates for a given length and cross sectional area of the heat exchanger. Also, we have to see that, we select a material which separates the cold and hot fluid which should have sufficient high thermal conductivity; that means, as far as possible, to the extent possible, or practically which is possible, it should have ideally, 0 thermal resistance; but well, 0 thermal resistance may not be possible. So, what can be said, it should have minimum thermal resistance. So, it is in this context, if you want to evaluate the performance of the heat exchanger, again I repeat, if we want to evaluate the performance of a heat exchanger, then, we can evaluate it in terms of heat transfer co-efficient, because everywhere heat is being transferring from hot fluid to the wall, from the wall to the cold fluid. So, it is again a process of heat transfer. So, if we want to understand, or if we want to compare two heat exchangers and how they are performing, now, their performance means, their capacity to extract the heat from hot fluid to the cold fluid; one, which can extract large amount of heat from hot to the cold, we will call that heat exchanger is a very good in design. So, let us see now, how to evaluate the performance of heat exchanger.

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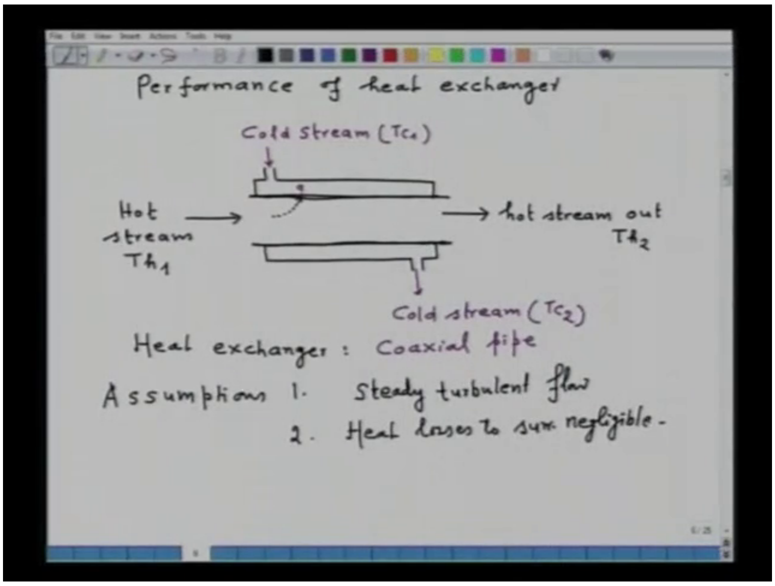

Performance of heat exchanger

Heat exchanger : Coaxial pipe

Assumptions 1. Steady turbulent flow

2. Heat losses to surr. negligible.

Now, again, as I said, the performance of heat exchanger, the performance of heat exchanger, it can be evaluated by considering the heat transfer co-efficient of two streams and thermal resistance of the pipe wall, or separating wall. That means, you have to take a co-axial pipe, where hot fluid is flowing; when cold fluid is flowing, hot fluid will transfer heat by the method of convection to the wall of the separating wall; wall gets heated up; and, depending upon the thermal resistance of the wall, the heat will be transferred to the cold fluid, and from the wall of the separating wall to the cold fluid, again by mechanism of convection. So, let us see, now, an exchanger, something like this; this is one type and here liquid is flowing. So, here, hot stream in; here, hot stream, let us say, at T h 1; here, hot stream out; hot stream out, let us take this temperature as T h 2; here, cold stream in; cold stream in, let us say at temperature T c 1; here, cold stream out, at temperature T c 2; this is what is given. So, essentially, this heat exchanger, heat exchanger is a co-axial pipe, co-axial pipe. Now, also here, this is the wall of the pipe; this is the wall of the pipe. So, hot stream will transfer its heat by convection to the wall, then, thermal resistance, because of the thickness of the wall; then again, heat will be transferred from the wall to the cold fluid. So, these are the heat transfer mechanisms. Now, in order to evaluate, let us, we have to make certain assumptions. So, assumptions; number 1, we are assuming steady, turbulent flow; steady, turbulent, this is one assumption. Second, we are assuming heat losses to surrounding is, negligible heat losses to surrounding negligible.

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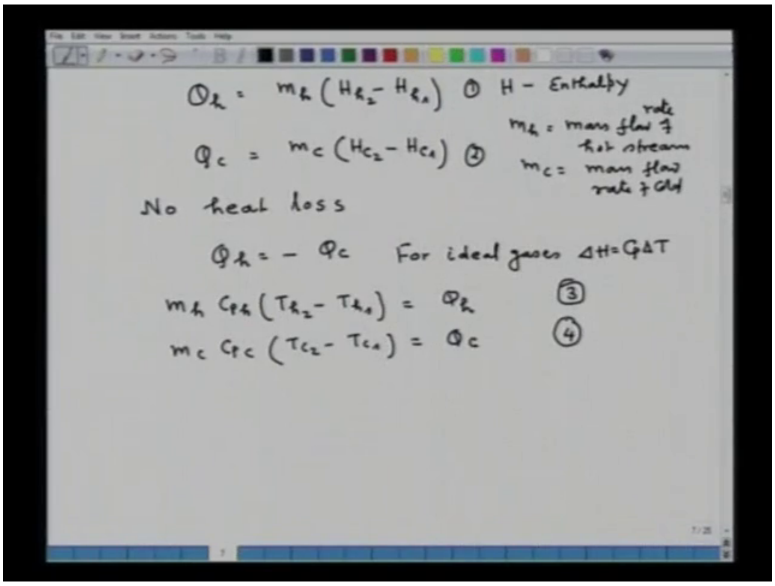

$Q_h = m_h (H_{h_2} - H_{h_1})$ ① H - Enthalpy

$Q_c = m_c (H_{c_2} - H_{c_1})$ ②

m_h = mass flow rate of hot stream

m_c = mass flow rate of cold

No heat loss

$Q_h = - Q_c$ For ideal gases $\Delta H = C_p \Delta T$

$m_h C_{ph} (T_{h_2} - T_{h_1}) = Q_h$ ③

$m_c C_{pc} (T_{c_2} - T_{c_1}) = Q_c$ ④

Then, we can write down Q h, that is the heat content in hot stream, that will be equal to m h into H h 2 minus H h 1, where H is enthalpy; enthalpy at 2, at one, that is, in the two locations. Similarly, for cold fluid, they can write down m c H c 2 minus H c 1, where m h is a mass flow rate of hot stream, mass flow rate of hot stream and m c is mass flow rate of cold stream, of cold stream. Now, let us say, this is equation number 1 and this is equation number 2. Now, since we have considered there is no heat loss to the surrounding, what does it mean?

Condition of no heat loss, condition of no heat loss, it tells us, Q h, that is equal to minus Q c. Also, for ideal gases, we know little bit from thermodynamics, we have delta H, that is equal to C p into delta T, where C p is the specific heat. So, we can write down now, m h C p h T h 2 minus T h 1, that is equal to Q h and m c C p c T c 2 minus T c 1, that is equal to Q c; let us take this equation is number 3 and this equation is number 4.

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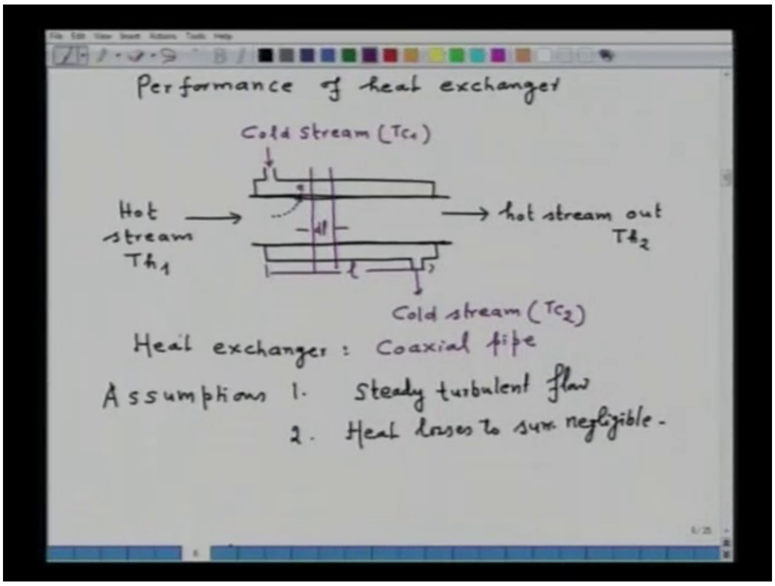

Performance of heat exchanger

Heat exchanger : Coaxial pipe

Assumptions 1. Steady turbulent flow

2. Heat losses to surr. negligible.

Now, what we have to consider is a flow path, and in the flow path, let us consider the heat balance in a small element, whose length is d l. Now, this length, it is the length of the heat exchanger, and we are considering the heat balance in a small element of length d l.

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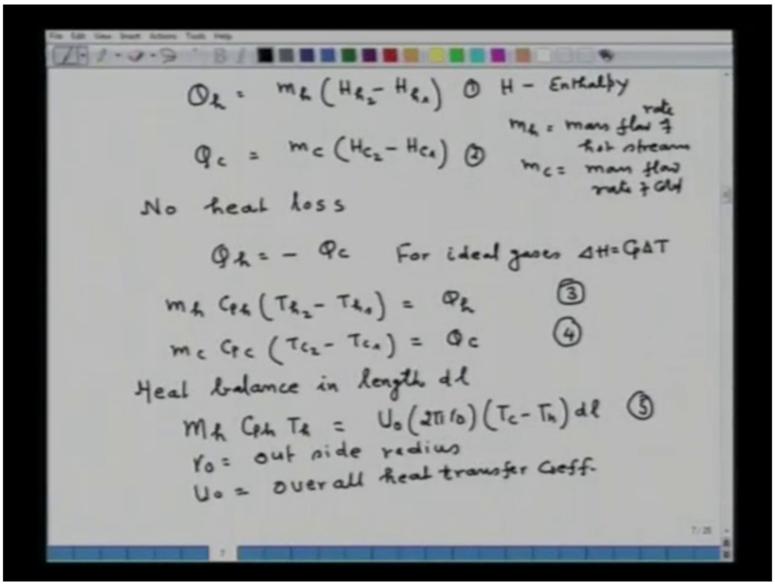

$Q_h = m_h (H_{h_2} - H_{h_1})$ ① H - Enthalpy

m_h = mass flow rate of hot stream

$Q_c = m_c (H_{c_2} - H_{c_1})$ ②

m_c = mass flow rate of cold

No heat loss

$Q_h = - Q_c$ For ideal gases $\Delta H = C_p \Delta T$

$m_h C_{ph} (T_{h_2} - T_{h_1}) = Q_h$ ③

$m_c C_{pc} (T_{c_2} - T_{c_1}) = Q_c$ ④

Heat balance in length dl

$m_h C_{ph} T_h = U_0 (2\pi r_0)(T_c - T_h) dl$ ⑤

r_0 = out side radius

U_0 = overall heat transfer Coeff.

So, you write down now…So, what we do now, we put it, say, heat balance, heat balance in length d l, you can write down now, the heat entering m h C p h into T h, that is the heat entering, by, this is the heat entering, or heat input; that should be equal to output, and output will be equal to U 0 into 2 pi r 0 into T c minus T h over the length d l and this is our equation number 5, where remember, r 0 is the outside radius of the tube; r 0 is the outside radius of the inner tube, and U 0, that is equal to overall heat transfer coefficient, overall heat transfer coefficient.

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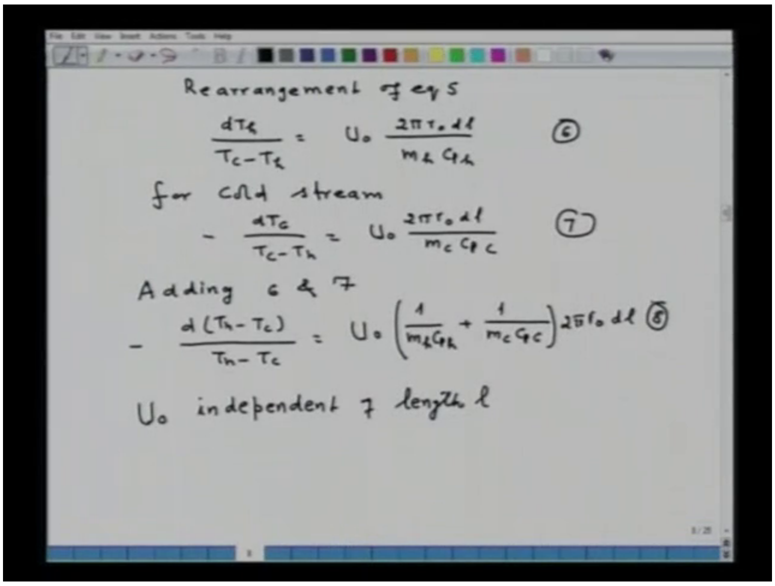

Rearrangement of eq 5

$$\frac{dT_h}{T_c - T_h} = U_0 \frac{2\pi r_0 \, dl}{m_h C_{ph}} \quad ⑥$$

for cold stream

$$-\frac{dT_c}{T_c - T_h} = U_0 \frac{2\pi r_0 \, dl}{m_c C_{pc}} \quad ⑦$$

Adding 6 & 7

$$-\frac{d(T_h - T_c)}{T_h - T_c} = U_0 \left(\frac{1}{m_h C_{ph}} + \frac{1}{m_c C_{pc}} \right) 2\pi r_0 \, dl \quad ⑧$$

U_0 independent of length l

Now, rearrangement of equation 5; rearrangement of equation 5, we can write down now, d T h upon T c minus T h, that is equal to U 0 into 2 pi r 0 d l upon m h into C p h; let us say this is 6; and similarly, for cold stream, similarly, for cold stream, equation will be minus d T C, T c minus T h, that is equal to U 0 2 pi r 0 d l, m c into C p C; let us say this is equation 7. Now, if we add, say, adding equation 6 and 7, adding 6 and 7, we get minus d T h minus T c upon T h minus T c, that is equal to U 0, 1 upon m h C p h plus 1 upon m c C p C, 2 pi r 0 in to d l; let us call this equation number 8. Now, if we assume U 0, which is the overall heat transfer coefficient, U 0 which is the overall heat transfer coefficient, we assume, it is independent of length l, independent of length l; then, we can integrate the equation number 8 from plane 1 to plane 2; plane 1 is the entry and plane 2 is the exit, as represented by the length of the heat exchanger.

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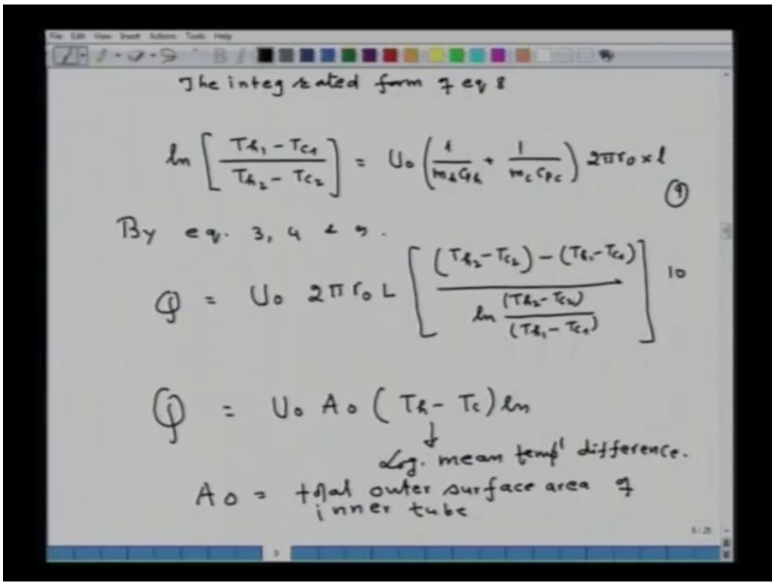

The integrated form of eq 8

$$\ln\left[\frac{T_{h_1}-T_{c_1}}{T_{h_2}-T_{c_2}}\right] = U_0\left(\frac{1}{m_h C_{ph}}+\frac{1}{m_c C_{pc}}\right)2\pi r_0 \times l \quad ⑨$$

By eq. 3, 4 & 9.

$$Q = U_0\ 2\pi r_0 L\left[\frac{(T_{h_2}-T_{c_2})-(T_{h_1}-T_{c_1})}{\ln\frac{(T_{h_2}-T_{c_2})}{(T_{h_1}-T_{c_1})}}\right] \quad 10$$

$$Q = U_0 A_0 (T_h - T_c)_{lm}$$

$\downarrow$ Log. mean temp' difference.

A_0 = total outer surface area of inner tube

So, we get the integrated form, the integrated form of equation 8, the integrated form of equation 8, you can get, ln T h 1 minus T c 1, upon T h 2 minus T c 2, that is equal to U 0, 1 upon m h into C p h plus 1 upon m c C p C, 2 pi r 0 into length of the exchanger, which is the equation number 9. Now, you can see now, this expression relates only the terminal temperatures of the heat exchanger. Now, if we see this particular equation, this equation relates only the terminal temperature of the heat exchanger, that is input temperature of the heat exchanger, not that of the stream; input temperatures of the heat exchanger and output temperatures of the heat exchangers. And also, it relates to the dimensions of the heat exchanger and hence, this expression can be used to evaluate the performance of the heat exchanger. So, by equation 3, 4 and 9, by equation 3, 4 and 9, we get Q, that is equal to U 0 2 pi r 0 l, T h 2 minus T c 2 minus T h 1 minus T c 1, upon l n T h 2 minus T c 2 upon T h 1 minus T c 1. This is let us call equation number 10, or we can write down Q, that is also equal to U 0 into A 0 into T h minus T c l n, where T h minus T c l n, this is called logarithmic mean temperature difference; A 0, remember, A 0 is the total outer surface area, total outer surface area of inner tube; remember, it is not a cross sectional area; it is 2 pi r 0 l, that is along the entire length and that area, you have to take into account.

Now, one of the most important thing in case of using these expression to calculate the heat exchanger diameter, is to note that, the temperatures which are involving in this particular expression, they are the input temperatures of the heat exchangers and output temperatures of heat exchanger; they are not the input and output temperature of these things. So, in fact, that point is to be well noted, while utilizing this expression to solve the heat exchange problems. Now, also, you have noted down in this expression that, nowhere it is involved, the method of flow of the fluid; by that I mean, in this particular example, we have considered that, the cold and hot fluid, they are flowing counter current to each other; but that counter current method, has not involved in our derivation. Towards the end of the derivation, we are getting the heat transfer, in terms of terminal temperatures. So, this expression is equally valid for co-current type of heat exchanger also. So, that point is to be noted.

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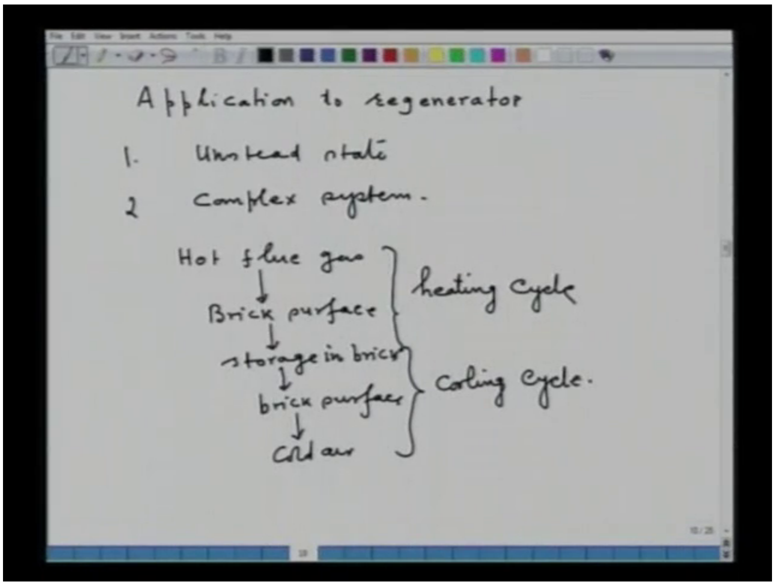

Application to regenerator

1. Unsteady state
2 Complex system.

Hot flue gas
↓
Brick surface
↓
storage in brick
↓
brick surface
↓
Cold air

heating cycle

Cooling cycle.

Now, in attempting to apply this equation to regenerator, say, application to regenerator, application to regenerator. Now, the earlier expression is applied for a recuperator. Now, let us see, how we can apply to the regenerator. Now, in fact, regenerators are unsteady state heat flow system, to which steady heat, steady state heat flow condition is not exactly available; because this particular derivation which you have done, it is valid for steady state heat flow; whereas regenerators, they are unsteady state heat flow. Condition number 1 is that, regenerators are unsteady state heat flow system. Number 2, it is a complex system, but for most of the engineering applications, we can consider regenerator as a similar to recuperator, from the point of view of heat transfer consideration; that means, how the heat is being transferred in case of regenerator, is that, say, we have hot flue gas; from hot flue gas, the heat is transferred to brick surface; and from brick surface, storage in the brick, the storage in brick; and then again, brick surface and eventually to cold air.

So, this particular cycle is the heating cycle, as all of you know from the re-generator, and this particular cycle is the cooling cycle, is the cooling cycle. Now, in this heating or cooling cycle, the heat transfer is purely by unsteady state. Here, the flow rate may vary; the temperature of the brick may vary; but in spite of this, all this unsteadiness of the re-generator, we can still consider, or we can still approximate, for our engineering calculation that, a re-generator represents a sort of a continuous recuperator, in which, say, hot flue gas is heating the brick surface; in the brick surface, the conduction is occurring and through the mechanism of conduction, heat is stored in the brick; it is on the brick surface and then, it is transferred to air. In this particular way of representing regenerator, there, we consider that, the wall is similar to that of the separating wall of the heat exchanger and we try to eliminate the actual temperature by telling that, it is a average temperature, so that, we can eliminate the time.

So, by applying this particular analogy, that is analogy is that, that hot flue gas is transferring its heat to the brick surface; the inner part of the brick is getting heated up by the conduction, similar to that of separating wall of recuperator; from the brick surface, heat is transferred by conduction to the air, which is, for example, preheating air, similar to that of recuperator. So, by considering this analogy, we assume that, the brick surfaces are at a high temperature, during flue gas cycle, than during cold gas cycle.

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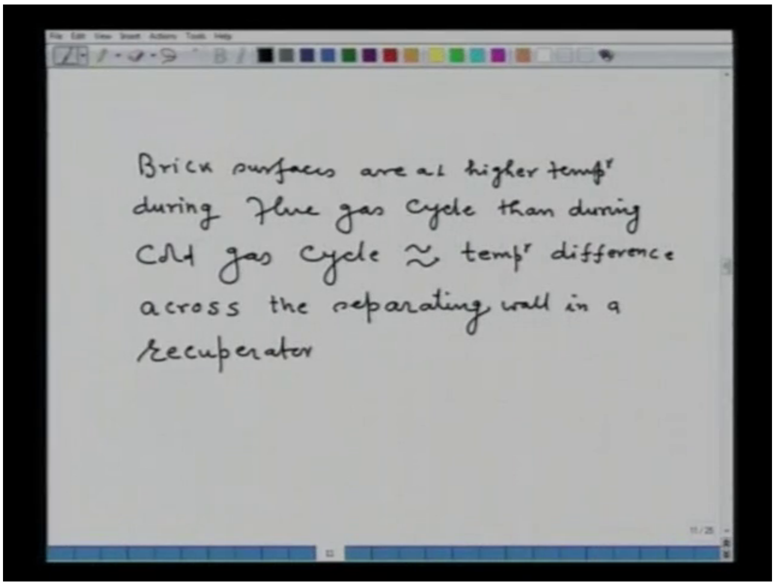

Brick surfaces are at higher temp^r during flue gas cycle than during Cold gas cycle $\approx$ temp^r difference across the separating wall in a recuperator

So, the analogy, by this analogy which I have enunciated, we will consider that, brick surfaces are at higher temperatures, are at higher temperatures during flue gas cycle, during flue gas cycle, than during cold gas cycle, during cold gas cycle; and this is approximately, the temperature difference is approximately equal to temperature difference across the separating wall, across the separating wall in a recuperator. So, with this, and with this, say, simplification, we can apply whatever we have derived for the recuperator, in case of regenerator also. Also, we can consider that, heat flow in and out of the brick is equivalent to the thermal resistance of the wall, or of the separating wall of the recuperator.

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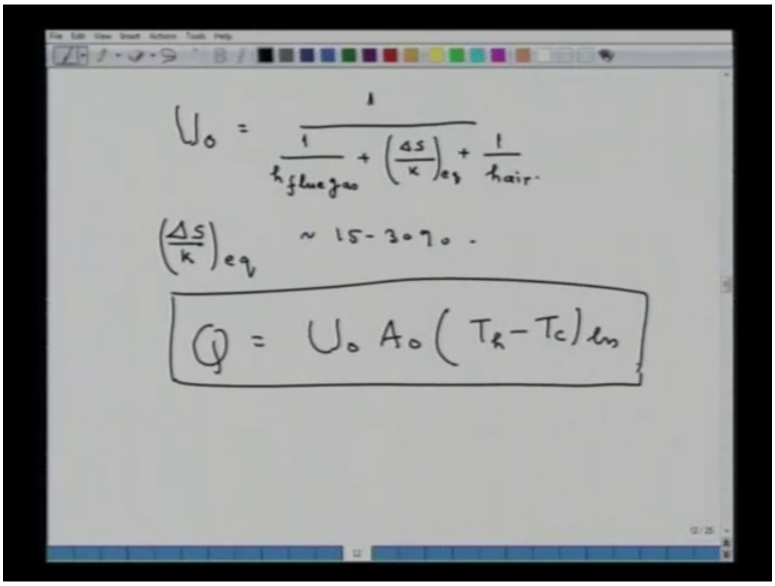

$$U_o = \frac{1}{\frac{1}{h_{flue\,gas}} + \left(\frac{\Delta s}{k}\right)_{eq} + \frac{1}{h_{air}}}$$

$$\left(\frac{\Delta s}{k}\right)_{eq} \sim 15-30\% .$$

$$\boxed{Q = U_o A_o (T_h - T_c)_{lm}}$$

Then, in that case, we can say that, U 0, which is the overall heat transfer co-efficient, that is equal to 1, 1 upon heat transfer coefficient of flue gas plus thickness of the brick upon its thermal conductivity or is equivalent plus 1 upon h air. So, this is what the definition of overall heat transfer co-efficient, where, where delta S upon K can be considered as the thermal resistance offered by the thick, by the combination of thickness of the wall and thermal conductivity, which is in equivalence to that of separating wall. So, in this particular case, several investigations have given the delta S upon K equivalent, its contribution to the total resistance of heat flow is of the order of 15 to 30 percent.

So, with this simplification, for most of the engineering application, we can write, Q, that is equal U 0 in to A 0 T h minus T c l n, that is the expression which you have derived for recuperator, can also be applied to that of regenerator also. The next lecture will see some of the problems based on these equations.