Process Integration
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Module - 2
Fundamental Concepts
Lecture - 1
Fundamental Concepts Related to Heat Integration - Part 01

Welcome to the course on Process Integration of the lecture series. This is module two lecture one fundamental concepts related to heat integration. Now while we go for heat integration using the concepts of process integration, a lot of fundamental concepts of heat transfer are being used. Now in this lecture series, we will see what are those fundamental concept, so that while doing the heat integration the students may not get any difficulty to conduct it. Now the process integration specially the heat integration uses the laws of thermo dynamics.

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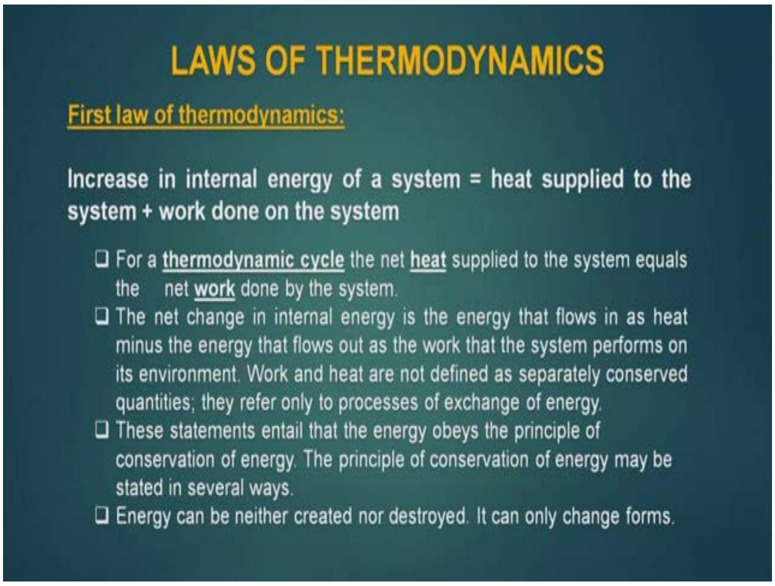

LAWS OF THERMODYNAMICS

First law of thermodynamics:

Increase in internal energy of a system = heat supplied to the system + work done on the system

- For a thermodynamic cycle the net heat supplied to the system equals the net work done by the system.
- The net change in internal energy is the energy that flows in as heat minus the energy that flows out as the work that the system performs on its environment. Work and heat are not defined as separately conserved quantities; they refer only to processes of exchange of energy.
- These statements entail that the energy obeys the principle of conservation of energy. The principle of conservation of energy may be stated in several ways.
- Energy can be neither created nor destroyed. It can only change forms.

So, let us see reverse it, the first law of thermal dynamics, it is says that increase in internal energy of a system is equal to the heat supplied to the system plus work done on the system. For a thermodynamic cycle, the net heat supplied to the system equals the net work done by the system. The net change in internal energy is the energy that close in as heat minus the energy that close out as the work that the system performs on its environment. Work and heat are not defined as separately conserved quantities in the first law. They refer only to processes of exchange of energy these statements entail that the energy obeys the principle of conservation of energy. The principle of conservation of energy may be stated in several ways. Energy can be neither be created nor destroyed. It can only change forms.

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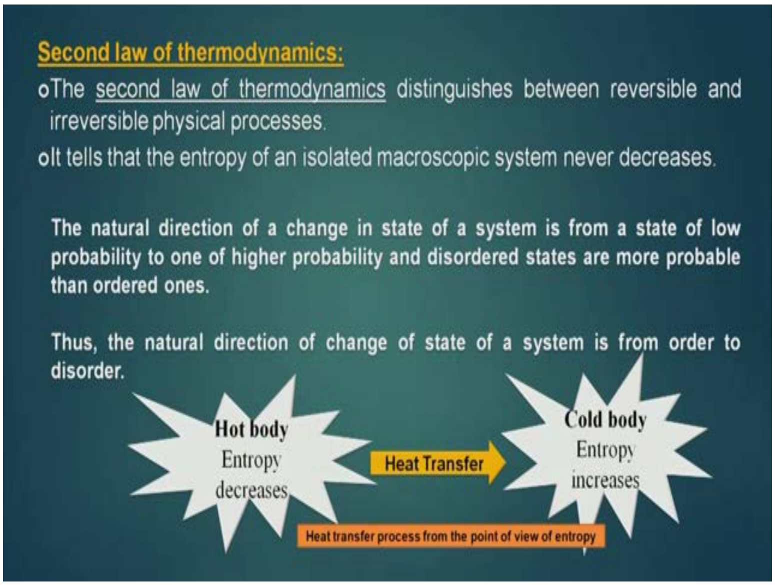

Second law of thermodynamics:

- The second law of thermodynamics distinguishes between reversible and irreversible physical processes.
- It tells that the entropy of an isolated macroscopic system never decreases.

The natural direction of a change in state of a system is from a state of low probability to one of higher probability and disordered states are more probable than ordered ones.

Thus, the natural direction of change of state of a system is from order to disorder.

Hot body Entropy decreases

Heat Transfer

Cold body Entropy increases

Heat transfer process from the point of view of entropy

The second law of thermo dynamics. The second law of thermo dynamics distinguishes between reversible and irreversible physical processes. It tells that the entropy of a isolated macroscopic system never decreases. The natural direction of a change in state of a system is from a state of low probability to one of higher probability and disordered states are more probable then order ones. Thus, the natural direction of change of sate of a system is from order to disorder. So, we see here the hot body, the entropies decreases, so the heat transfer takes place from hot body to cold body, because for a cold body the entropy increases. So, this is the natural way of transfer of heat.

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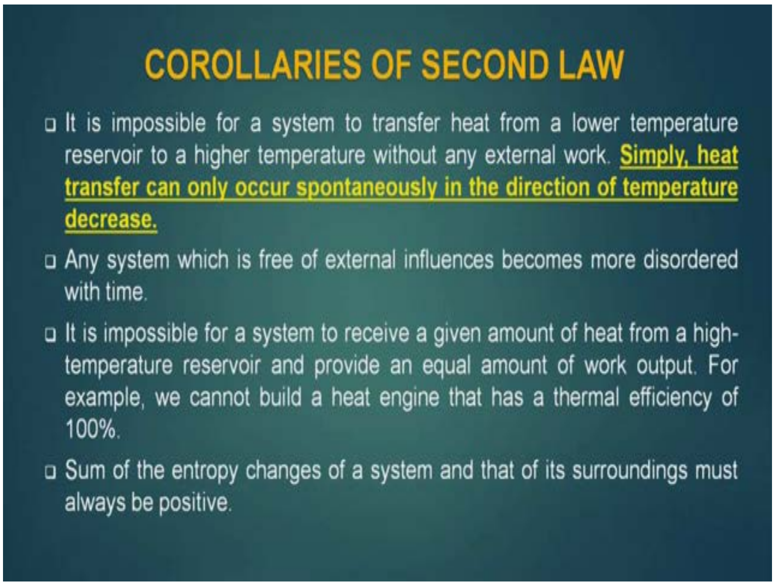

COROLLARIES OF SECOND LAW

- It is impossible for a system to transfer heat from a lower temperature reservoir to a higher temperature without any external work. Simply, heat transfer can only occur spontaneously in the direction of temperature decrease.
- Any system which is free of external influences becomes more disordered with time.
- It is impossible for a system to receive a given amount of heat from a high-temperature reservoir and provide an equal amount of work output. For example, we cannot build a heat engine that has a thermal efficiency of 100%.
- Sum of the entropy changes of a system and that of its surroundings must always be positive.

Now, the corollaries of second law. It is impossible for a system to transfer heat from a lower temperature reservoir to a higher temperature without any external work. What does it mean, simply, heat transfer can occur spontaneously in the direction of temperature decrease. Any system which is free of external influences becomes more disordered with time. It is impossible for a system to receive a given amount of heat from a high temperature reservoir and provide an equal amount of work output. For example, we cannot build a heat engine that has a thermal efficiency of 100 percent. Sum of the entropy changes of a system and that of its surroundings must always be positive. These are the corollaries of the second law we have seen.

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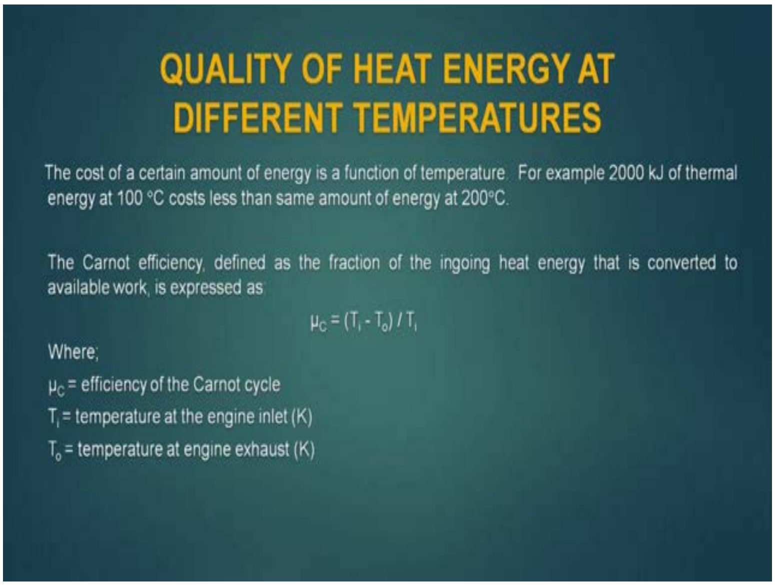

QUALITY OF HEAT ENERGY AT DIFFERENT TEMPERATURES

The cost of a certain amount of energy is a function of temperature. For example 2000 kJ of thermal energy at 100 °C costs less than same amount of energy at 200°C.

The Carnot efficiency, defined as the fraction of the ingoing heat energy that is converted to available work, is expressed as:

$$\mu_C = (T_i - T_o) / T_i$$

Where;

μ_C = efficiency of the Carnot cycle

T_i = temperature at the engine inlet (K)

T_o = temperature at engine exhaust (K)

Now, let us see what is the quality of heat energy at different temperatures why this is necessary because in the process integration where possible we will try to substitute low temperature heat energy sorry we would like to substitute the high temperature heat energy with low temperature heat energy why it is. So, because the low temperature heat energy as less cost than the high temperature heat energy. So, in this lecture, we will try to find out the scientific fundamentals behind this argument the cost of a certain amount of energy is a function of temperature. For example, a 2000 kilo joule of thermal energy at 100 degree centigrade cost less than the same amount of energy at 200 degree centigrade lets prove it through the Carnot efficiency. Let us define what is the Carnot efficiency. The Carnot efficiency defined as the fraction of the in going heat energy that is converted to available one and is expressed at mu C is equal T i minus T 0 divided by T I; mu C is the efficiency of the Carnot cycle; T i is the temperature at the engine inlet, and T 0 is the temperature of the engine exhaust.

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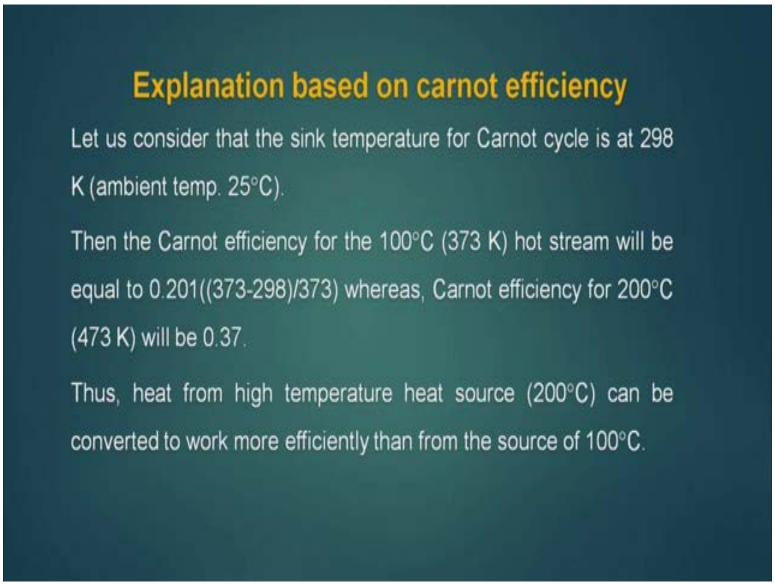

Explanation based on carnot efficiency

Let us consider that the sink temperature for Carnot cycle is at 298 K (ambient temp. 25°C).

Then the Carnot efficiency for the 100°C (373 K) hot stream will be equal to 0.201((373-298)/373) whereas, Carnot efficiency for 200°C (473 K) will be 0.37.

Thus, heat from high temperature heat source (200°C) can be converted to work more efficiently than from the source of 100°C.

Now, let us explain the heat based on this Carnot efficiency let us consider that this sync temperature for Carnot cycle is 298 that is ambient temperature at 25 degree centigrade then the Carnot efficiency for the 100 degree centigrade that is 373 Kelvin hot stream will be equal to 0.201 which can be computed based on the fact that 373 minus 298 divided by 373 which comes out to be 0.201. Whereas the Carnot efficiency for 200 degree centigrade that is heat available at 200 degree centigrade will be 0.37, So, one term we see that the Carnot efficiency increases once the temperature is increases; that means, the T i is more. Thus, the heat from high temperature heat source that is 200 degree centigrade can be converted to work more efficiently than the source of 100 degree centigrade and that is why the heat which is available at 200 degree centigrade is costlier than the heat the same heat which is available at 100 degree centigrade.

Now, the same thing, we will like to explain on the bases of entropy and what we want to explain that if the heat 2000 kilo joule is available at 200 degree centigrade. And then the same heat that is 2000 kilo joule is available at 100 degree centigrade, the cost of the heat that is 2000 kilo joule at 200 degree centigrade will be more than at 100 degree centigrade.

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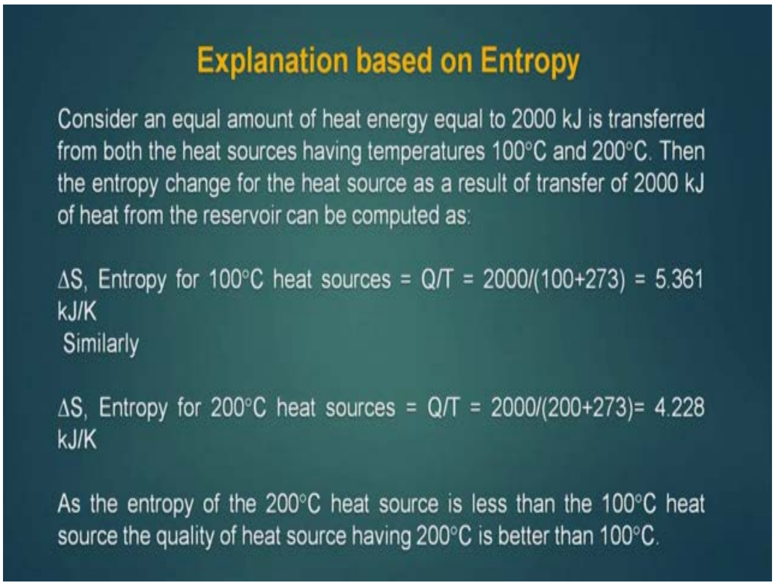

Explanation based on Entropy

Consider an equal amount of heat energy equal to 2000 kJ is transferred from both the heat sources having temperatures 100°C and 200°C. Then the entropy change for the heat source as a result of transfer of 2000 kJ of heat from the reservoir can be computed as:

ΔS, Entropy for 100°C heat sources = $Q/T = 2000/(100+273) = 5.361$ kJ/K

Similarly

ΔS, Entropy for 200°C heat sources = $Q/T = 2000/(200+273) = 4.228$ kJ/K

As the entropy of the 200°C heat source is less than the 100°C heat source the quality of heat source having 200°C is better than 100°C.

So, let us explain it based on the entropy consider an equal amount of heat energy equal to 2000 kilo joule is transferred from both. The heat sources having temperature 100 degree centigrade as well as 200 degree centigrade then the entropy change for the heat source as a result of the transfer of 2000 kilo joule of heat from the reservoir can be computed as delta S at 100 degree centigrade is equal to Q by T is equal to 2000 divided by 100 plus 273 comes out to be 5.361 kilo joule per kg. Similarly, the same value at 200 degree centigrade comes out to be 4.228 as the entropy of 200 degree centigrade. Heat source is less than the 100 degree, heat source the quality of heat source having degree centigrade is better than 100 degree centigrade. So, through entropy also we have prove that the quality of heat which is available at 200 degree centigrade is better than what is available at 100 degree centigrade. Let us explain it on the bases of more potential the same thing, I will explain on the bases of work potential.

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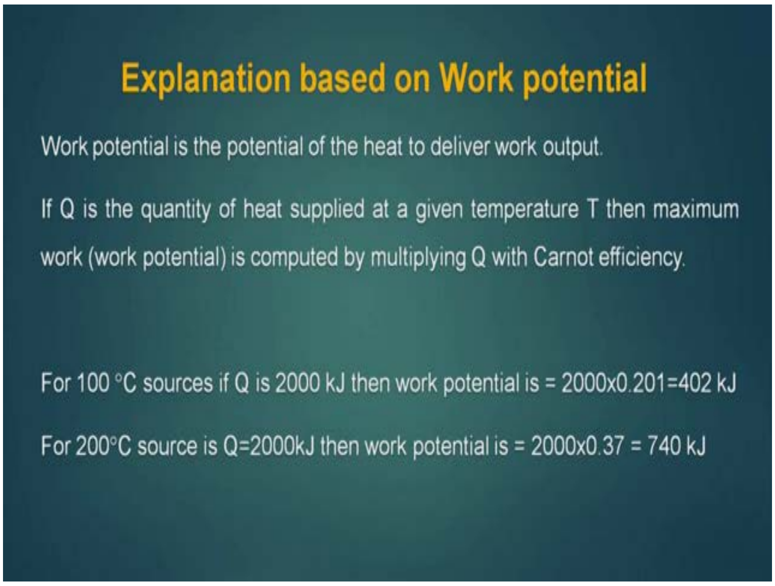

Explanation based on Work potential

Work potential is the potential of the heat to deliver work output.

If Q is the quantity of heat supplied at a given temperature T then maximum work (work potential) is computed by multiplying Q with Carnot efficiency.

For 100 °C sources if Q is 2000 kJ then work potential is = 2000x0.201=402 kJ

For 200°C source is Q=2000kJ then work potential is = 2000x0.37 = 740 kJ

The work potential is the potential of the heat to deliver work output. If Q is the quantity of heat supplied at a given temperature T then maximum work that is work potential that is computed by multiplying Q with Carnot efficiency. So, for 100 degree centigrade source, if Q is 2000 kilo joule then the work potential is 2000 into 0.201 which we have computed in the case of the Carnot efficiency, so it comes out to be 402 kilo joule. Whereas the same for the 200 degree centigrade source comes out to be 740 kilo joule. So, here also we see that the work potential of 200 degree centigrade source is more than the 100 degree centigrade source and that is why the quality of heat which is available at 200 degree centigrade is better than 100 degree centigrade and that is cost is more

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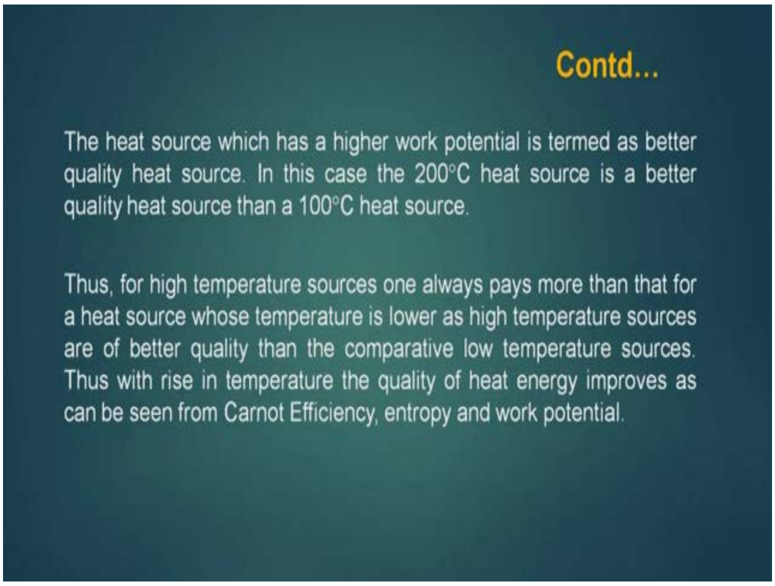

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The heat source which has a higher work potential is termed as better quality heat source. In this case the 200°C heat source is a better quality heat source than a 100°C heat source.

Thus, for high temperature sources one always pays more than that for a heat source whose temperature is lower as high temperature sources are of better quality than the comparative low temperature sources. Thus with rise in temperature the quality of heat energy improves as can be seen from Carnot Efficiency, entropy and work potential.

So, the heat source which has a high work potential is turned as better quality heat source. In this case, the 200 degree heat source is a better quality heat source than 100 degree heat source. Thus for high temperature sources one always pays more than that for a heat source whose temperature is lower as high temperature sources are of better quality than the comparative low temperature sources. Thus with the rising temperature the quality of heat energy improves as can be seen from Carnot efficiency entropy and work potential this is our conclusion, but when we talking of refrigeration. Then how to define the quality of a refrigeration system or the refrigeration temperature, because we have seen that if the temperature in the positive scale increases the quality increases. So, whether the reverse is true here or the same is true here for the refrigeration’s system.

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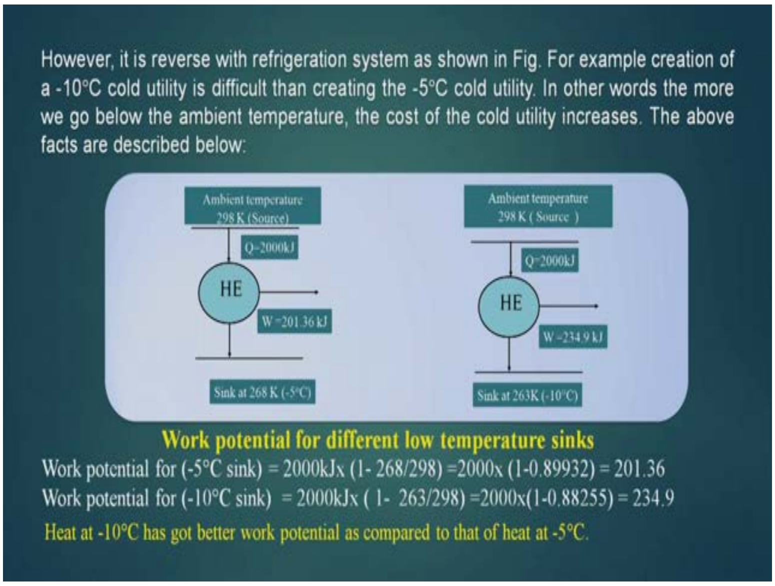

However, it is reverse with refrigeration system as shown in Fig. For example creation of a -10°C cold utility is difficult than creating the -5°C cold utility. In other words the more we go below the ambient temperature, the cost of the cold utility increases. The above facts are described below:

Work potential for different low temperature sinks

Work potential for (-5°C sink) = 2000kJx (1- 268/298) =2000x (1-0.89932) = 201.36

Work potential for (-10°C sink) = 2000kJx (1- 263/298) =2000x(1-0.88255) = 234.9

Heat at -10°C has got better work potential as compared to that of heat at -5°C.

Let us see how it is reverse with refrigeration system as shown in the figure. For example, creation of a minus ten degree centigrade cold utility is difficult than creating a minus 5 degree centigrade cold utility. In other words, the more we below the ambient temperature the cost of the cold utility increases. The above fact can be described by this. We see this figure there is the ambient temperature and Q equal to 2000 is passed from ambient temperature to the sync temperature which is at minus 5 degree centigrade and then in the right most figure it is at minus 10 degree centigrade and the left minus 5 degree centigrade. If I calculate the work potential for minus 5 degree centigrade sync, it comes out to be 201.36 and the work potential for the minus 10 degree sync it comes out to be 234.9. So, the heat at minus 10 degree centigrade has got better work potential as compared to that it have 5 minus 5 degree centigrade. And hence the cost of refrigeration system has minus 10 degree centigrade for the same quantity of heat will be more than that of minus 5 degree centigrade.

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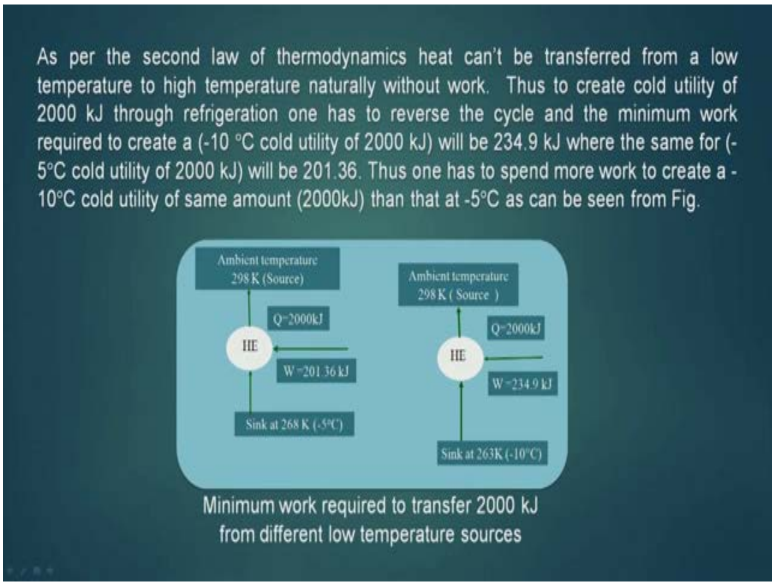

As per the second law of thermodynamics heat can't be transferred from a low temperature to high temperature naturally without work. Thus to create cold utility of 2000 kJ through refrigeration one has to reverse the cycle and the minimum work required to create a (-10 °C cold utility of 2000 kJ) will be 234.9 kJ where the same for (-5°C cold utility of 2000 kJ) will be 201.36. Thus one has to spend more work to create a -10°C cold utility of same amount (2000kJ) than that at -5°C as can be seen from Fig.

Minimum work required to transfer 2000 kJ from different low temperature sources

Now, if we analyses this as per this second law of thermodynamic. So, the second law say the heat cannot be transferred from a low temperature to a high temperature naturally without work. Thus to create cold utility of 2000 kilo joule through refrigeration one has to reverse the cycle and the minimum work required to create minus ten degree centigrade cold utility of 1000 kilo joule will be two thirty four point nine kilo joule; that means, if I want to create a refrigeration or a cold utility at minus ten degree centigrade. I have to invest 234.9 kilo joule to create it. Whereas, if I calculate the same for the minus 5 degree centigrade then it comes out to be 201.36 kilo joule. Thus one has to spend more work to create a minus 10 degree centigrade cold utility of the same amount that is 2000 kilo joule than at minus 5 degree centigrade and this can been seen from the figure below.

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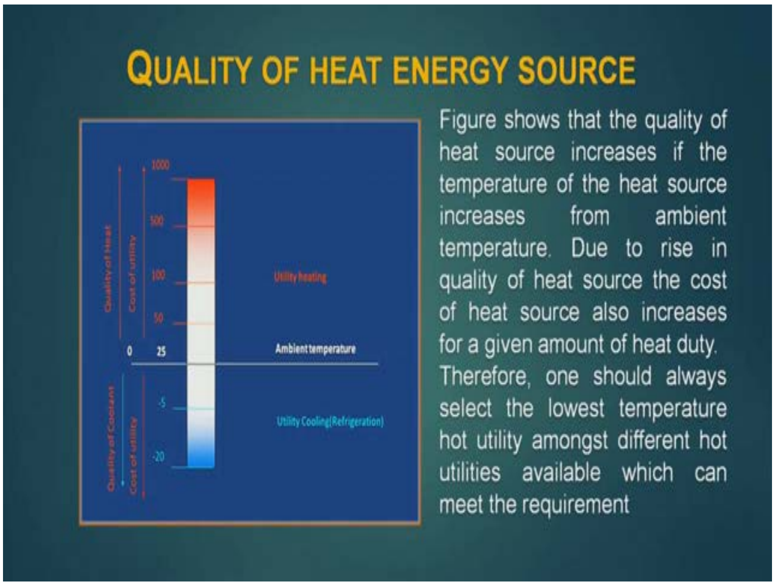

QUALITY OF HEAT ENERGY SOURCE

Figure shows that the quality of heat source increases if the temperature of the heat source increases from ambient temperature. Due to rise in quality of heat source the cost of heat source also increases for a given amount of heat duty. Therefore, one should always select the lowest temperature hot utility amongst different hot utilities available which can meet the requirement

So, the conclusion is this if you take the ambient temperature than the quality of the heat increases when we go for a higher temperature where as for refrigeration system. If I go towards below the ambient temperature then its cost increases, and this clearly shows that the quality of heat source increases, if the temperature of the heat source increases from ambient temperature. Due to rising quality of heat source the cost of heat source also increases for a given amount of heat duty. Therefore, one should always select the lowest temperature hot utility amongst different hot utility available which can meet the requirement. Now this concept will be extensively used in heat integration when we will go for different temperature utility that is multiple utility available, and what utility we should select for our heat exchange network, so this thinking will help them.

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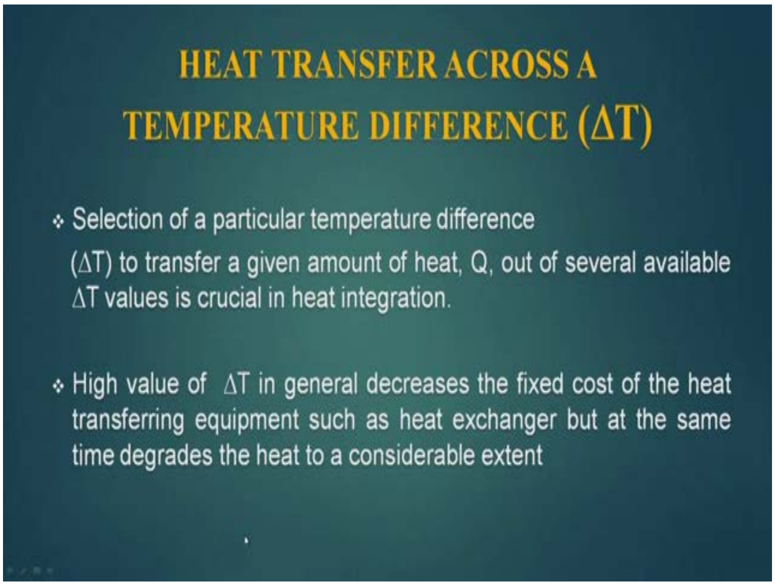

HEAT TRANSFER ACROSS A TEMPERATURE DIFFERENCE (ΔT)

- Selection of a particular temperature difference (ΔT) to transfer a given amount of heat, Q, out of several available ΔT values is crucial in heat integration.
- High value of ΔT in general decreases the fixed cost of the heat transferring equipment such as heat exchanger but at the same time degrades the heat to a considerable extent

Now let us examine the heat transfer across the temperature difference delta T. This is also important, why, because if we are operating at a very high delta T which is not required. Then we are unnecessarily degrading the heat we should select that much of delta T which is required for a system. And in fact, in the passes integration all the heat integration the distribution of delta T for different work is very important and the saving which it claims is due to this selection of a particular temperature difference that is delta T to transfer a given amount of heat Q out of several available delta T value is crucial in heat integration high value of delta T. In generally in general decrease the fixed cost of the heat transfer in equipment such as heat exchanger, but at the same time degrades the heat to considerable extent and this will prove through different means.

Now, let us take an example that if we are operating at different delta T levels then all the detraction of heat take place for this two exemplifies. This we have taken a heat source at 800 Kelvin and the amount of heat is 2000 kilo joule and there are two sync one at 500 Kelvin and other at 750 Kelvin and this heat transfer is taking place through a conductor that is metal one as in the case of heat exchanger now the question is to determine which heat transfer passes is more irreversible in other words in each process the energy is degraded plus.

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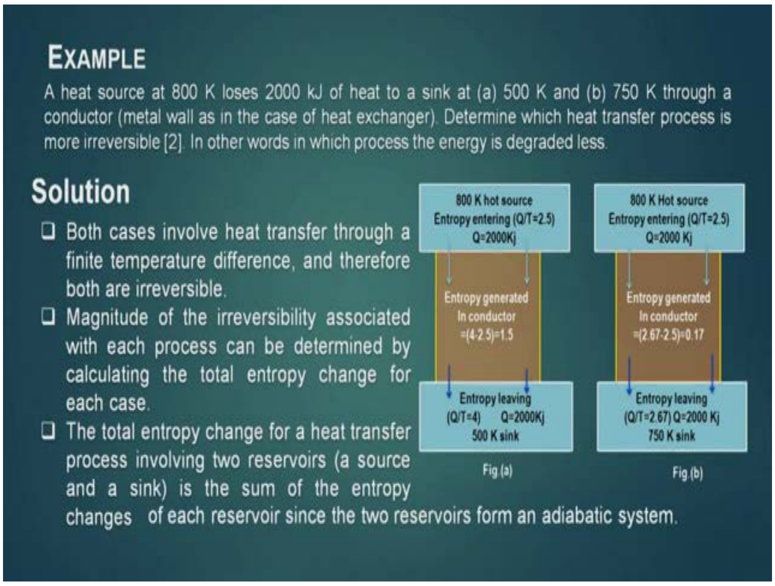

EXAMPLE

A heat source at 800 K loses 2000 kJ of heat to a sink at (a) 500 K and (b) 750 K through a conductor (metal wall as in the case of heat exchanger). Determine which heat transfer process is more irreversible [2]. In other words in which process the energy is degraded less.

Solution

- ❑ Both cases involve heat transfer through a finite temperature difference, and therefore both are irreversible.
- ❑ Magnitude of the irreversibility associated with each process can be determined by calculating the total entropy change for each case.
- ❑ The total entropy change for a heat transfer process involving two reservoirs (a source and a sink) is the sum of the entropy changes of each reservoir since the two reservoirs form an adiabatic system.

800 K hot source
Entropy entering (Q/T=2.5)
Q=2000Kj

Entropy generated
In conductor
=(4-2.5)=1.5

Entropy leaving
(Q/T=4) Q=2000Kj
500 K sink

Fig (a)

800 K Hot source
Entropy entering (Q/T=2.5)
Q=2000 Kj

Entropy generated
In conductor
=(2.67-2.5)=0.17

Entropy leaving
(Q/T=2.67) Q=2000 Kj
750 K sink

Fig (b)

Now, if you see the solution both cases involve heat transfer through a finite temperature difference and therefore, both are irreversible magnitude of the irreversibility associated with each process can be determine by calculating the total entropy change for each case. The total entropy change for a heat transfer passes involving two reservoir a source and a sync if the some of the entropy changes of each reservoir since the two reservoir for m adiabatic system. So, if you see the were the sync is 500 k then the entropy generated in the conductor is 1.5 and if the sync is at 750 k the entropy generated in the conductor is 0.17 and hence when the sync is 750 k; that means, when the delta T is less then entropy generated in the conductor is less and hence the degradation is less. So, this is the conclusion we derive.

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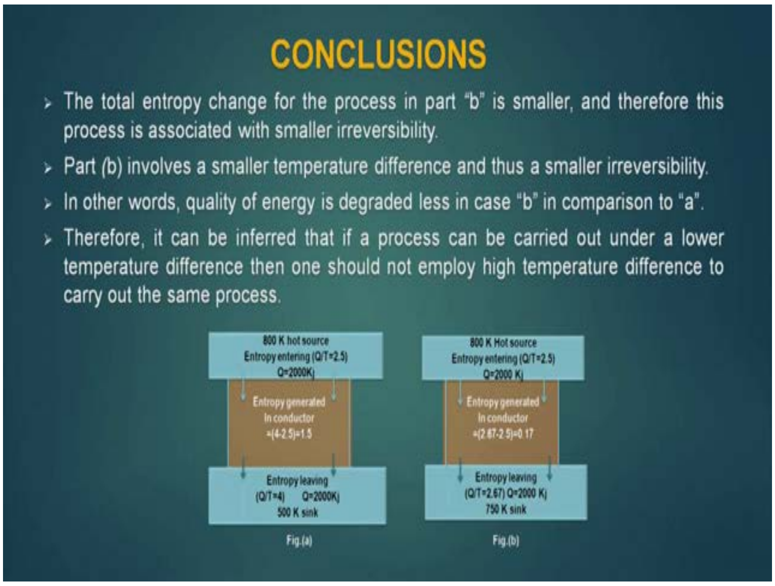

CONCLUSIONS

- The total entropy change for the process in part "b" is smaller, and therefore this process is associated with smaller irreversibility.
- Part (b) involves a smaller temperature difference and thus a smaller irreversibility.
- In other words, quality of energy is degraded less in case "b" in comparison to "a".
- Therefore, it can be inferred that if a process can be carried out under a lower temperature difference then one should not employ high temperature difference to carry out the same process.

800 K hot source
Entropy entering (Q/T=2.5)
Q=2000KJ

Entropy generated
In conductor
=(4-2.5)=1.5

Entropy leaving
(Q/T=4) Q=2000KJ
500 K sink

Fig.(a)

800 K Hot source
Entropy entering (Q/T=2.5)
Q=2000 KJ

Entropy generated
In conductor
=(2.67-2.5)=0.17

Entropy leaving
(Q/T=2.67) Q=2000 KJ
750 K sink

Fig.(b)

So, the slides tell the same thing, total entropy change for the process in part b is smaller. And therefore, this process is associated with smaller irreversibility part b involves that is figure b involves a smaller temperature difference and thus smaller irreversibility. In other words, the quality of energy is degraded less in case of b in compression to a. Therefore, it can be in ford that if the process can be carried out under a lower temperature difference then one should not employ high temperature difference to carry out the same process and this will see in the process heat integration.

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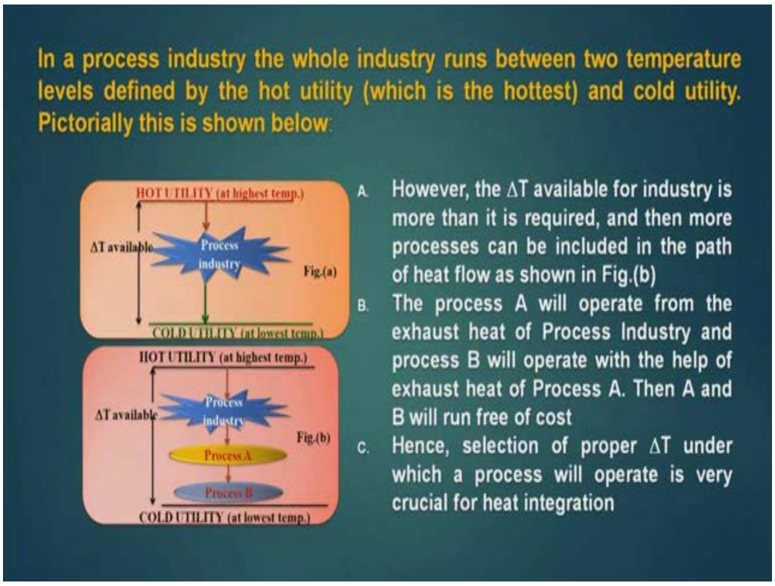

In a process industry the whole industry runs between two temperature levels defined by the hot utility (which is the hottest) and cold utility. Pictorially this is shown below:

HOT UTILITY (at highest temp.)
ΔT available
Process industry
Fig.(a)
COLD UTILITY (at lowest temp.)

HOT UTILITY (at highest temp.)
ΔT available
Process industry
Process A
Process B
Fig.(b)
COLD UTILITY (at lowest temp.)

A. However, the ΔT available for industry is more than it is required, and then more processes can be included in the path of heat flow as shown in Fig.(b)

B. The process A will operate from the exhaust heat of Process Industry and process B will operate with the help of exhaust heat of Process A. Then A and B will run free of cost

C. Hence, selection of proper ΔT under which a process will operate is very crucial for heat integration

This concept will be fully used on the same concept which we have just discuss is shown in the figure. In a process industry, the whole industry runs between two temperature level defined by the hot utility and the cold utility. So, hot utility is at the hottest temperature and the cold utility at the coolest temperature this is shown in the in pictorial figure a. So, the process industry is working under this two temperature level at delta T how are the delta T available for industries more than it is required if it is. So, and then more process can be included in the path of the heat flow as shown in figure b.

If it so, if more delta T is available then we can include more processes in the path of heat flow. So, the process a will operate form the exhaust heat of process industry and process B will operate with help of exhaust of heat of process A. If you are able to introduce two more process within the same delta T available then process A and B will run free of cost hence the selection of property delta T under which a process will operate is very crucial for heat integration. And if it is more than we should plan to introduce some more process within that delta T and run the process free of cost. Now, let us go for convective heat transfer because the convective heat transfer is extensively used in the heat integration.

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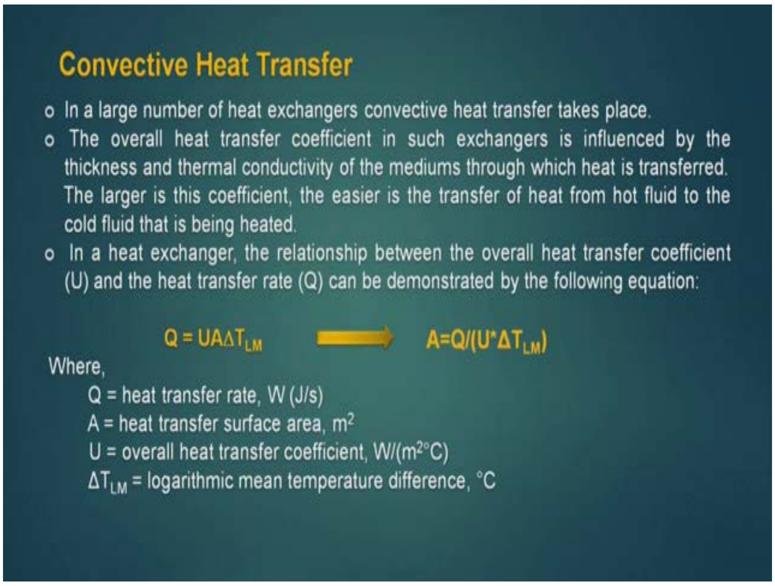

Convective Heat Transfer

- In a large number of heat exchangers convective heat transfer takes place.
- The overall heat transfer coefficient in such exchangers is influenced by the thickness and thermal conductivity of the mediums through which heat is transferred. The larger is this coefficient, the easier is the transfer of heat from hot fluid to the cold fluid that is being heated.
- In a heat exchanger, the relationship between the overall heat transfer coefficient (U) and the heat transfer rate (Q) can be demonstrated by the following equation:

$$Q = UA\Delta T_{LM} \longrightarrow A=Q/(U^{*}\Delta T_{LM})$$

Where,

Q = heat transfer rate, W (J/s)
A = heat transfer surface area, m^2
U = overall heat transfer coefficient, $W/(m^{2}\,°C)$
ΔT_{LM} = logarithmic mean temperature difference, °C

Because most of the heat exchangers work under convective heat transfer. In a large number of heat exchangers, convictive heat transfer take place. The overall heat transfer convergent much exchanger is influence by the thickness and thermal conductivity of medium through which heat is transferred the large is this coefficient the easier is the transfer heat from hot fluid to the cold fluid that is been heated in a heat exchanger the relation between the overall heat transfer coefficient Q. The heat transfer at Q can be demonstrated by the following equation the equation is q is equal to u a delta T l m or you can write down that a is equal to q divided by u into delta T L M. Here Q is heat transferred rate, A is the heat transfer surface area, and U is the overall heat transfer coefficient and delta T L M is the log mean logarithmic mean temperature differences.

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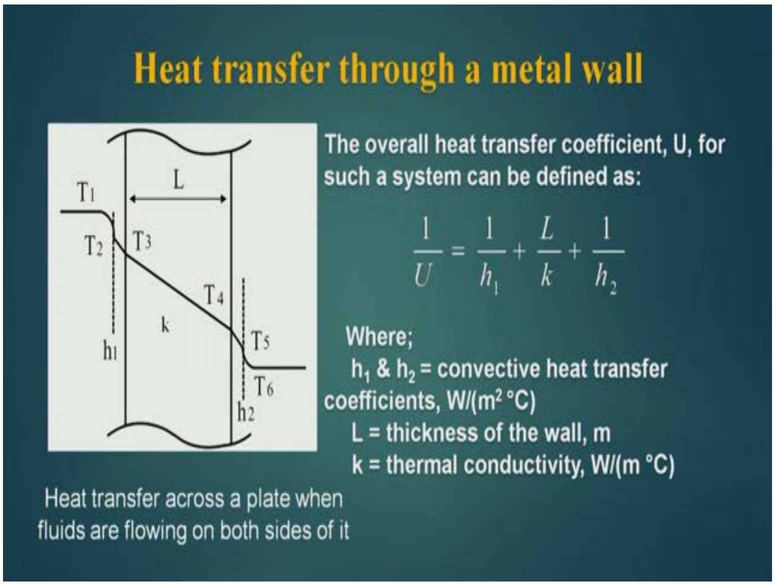

Heat transfer through a metal wall

The overall heat transfer coefficient, U, for such a system can be defined as:

$$\frac{1}{U} = \frac{1}{h_1} + \frac{L}{k} + \frac{1}{h_2}$$

Where;

h_1 & h_2 = convective heat transfer coefficients, W/(m^2 °C)

L = thickness of the wall, m

k = thermal conductivity, W/(m °C)

Heat transfer across a plate when fluids are flowing on both sides of it

Let me see the heat transfer through a metal wall then the overall heat transfer co efficient can be written as 1 by h 2 plus l by k plus 1 by h 2. Here there are fluids in both the sides of the wall. So, the convective heat transfer is taking place one spin coefficient h 1 and other spin coefficient is h 2 and conductive heat transfer is taking place across the wall were h 1 and h 2 are convective heat transfer co efficient; l is the thickness of the wall and k is the thermal conductivity of the wall.

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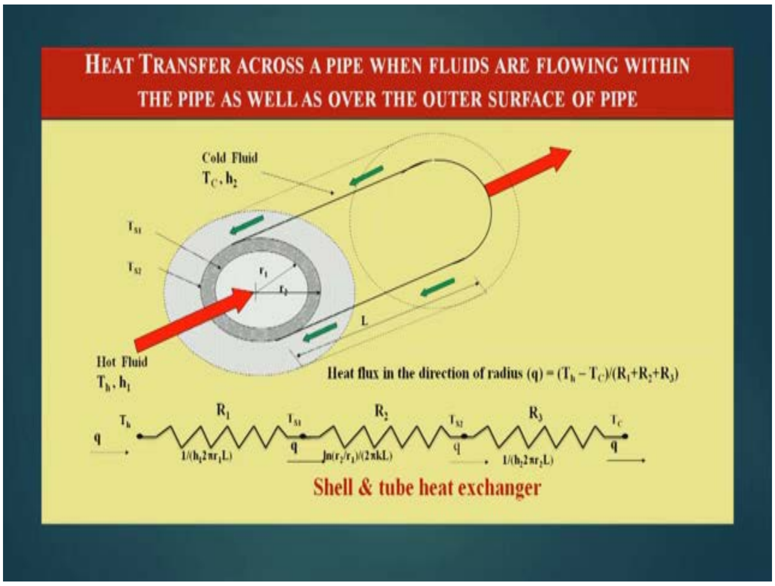

HEAT TRANSFER ACROSS A PIPE WHEN FLUIDS ARE FLOWING WITHIN THE PIPE AS WELL AS OVER THE OUTER SURFACE OF PIPE

Heat flux in the direction of radius $(q) = (T_h - T_C)/(R_1+R_2+R_3)$

Shell & tube heat exchanger

Now, if it is a tube and the heat transfer is taking place then the hot fluid which is entering has the temperature of T h and the convective heat transfer coefficient is h 1. The cold fluid which is in the analyze as the temperature of T c and heat transfer coefficient T 2. Now if you try to analyze the heat transfer then we see that there are three resistances available when heat is transferring from hot fluid to the cold fluid. The first resistance is r 1 which is offered by the hot fluid. The second resistance is from the wall of the heat exchanger or the tube and the third fluid is third resistant is offered by the cold fluid which is around this tube. So, the amount of the resistance is given here in the figure and the heat plugs can be calculated out by the driving force and resistance value.

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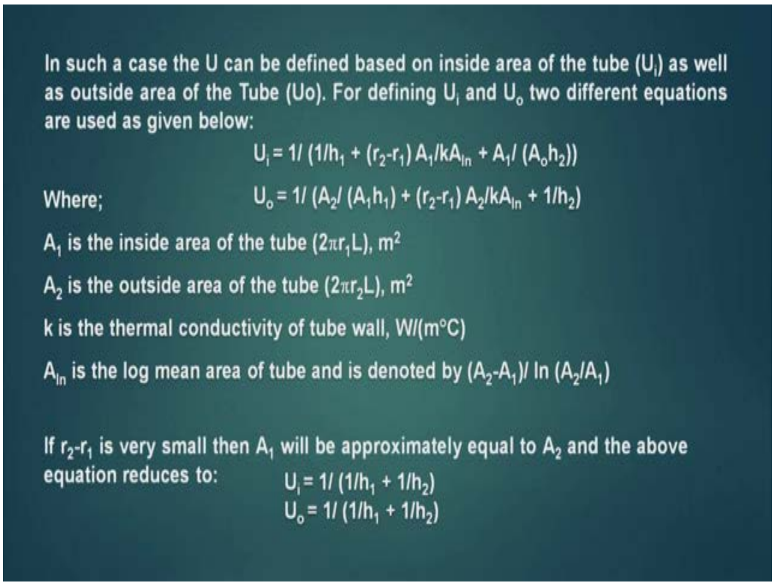

In such a case the U can be defined based on inside area of the tube (U_i) as well as outside area of the Tube (Uo). For defining U_i and U_o two different equations are used as given below:

$$U_i = 1/\,(1/h_1 + (r_2 - r_1)\,A_1/kA_{ln} + A_1/\,(A_o h_2))$$

Where;

$$U_o = 1/\,(A_2/\,(A_1 h_1) + (r_2 - r_1)\,A_2/kA_{ln} + 1/h_2)$$

A_1 is the inside area of the tube ($2\pi r_1 L$), m^2

A_2 is the outside area of the tube ($2\pi r_2 L$), m^2

k is the thermal conductivity of tube wall, W/(m°C)

A_{ln} is the log mean area of tube and is denoted by $(A_2 - A_1)/\ln(A_2/A_1)$

If $r_2 - r_1$ is very small then A_1 will be approximately equal to A_2 and the above equation reduces to:

$$U_i = 1/\,(1/h_1 + 1/h_2)$$
$$U_o = 1/\,(1/h_1 + 1/h_2)$$

In such a case U can be defined based on the inside area of the tube U i as well as outside area of the tube U o. For defining U i and U o two different equation are used as given below. So, these are the two equation which are used to define the overall heat transfer coefficient based on the inside area and based on the outside area. Where A 1 is the inside area of the tube, A 2 is the outside area of the tube, A is the thermal conductivity of tube and A l is the log mean area of the tube, and its denoted by A 2 minus A 1 divided ln A 2 by A 1. If r 2 minus r 1 is very small then A i will be approximately equal to a two and the above equation reduces to U i is equal to one divided by 1 by h 1 plus one by h 2. So, if the r 2 minus r 1 is very small then U i becomes equal to U o. Now you see the thermal diving force in a heat exchanger.

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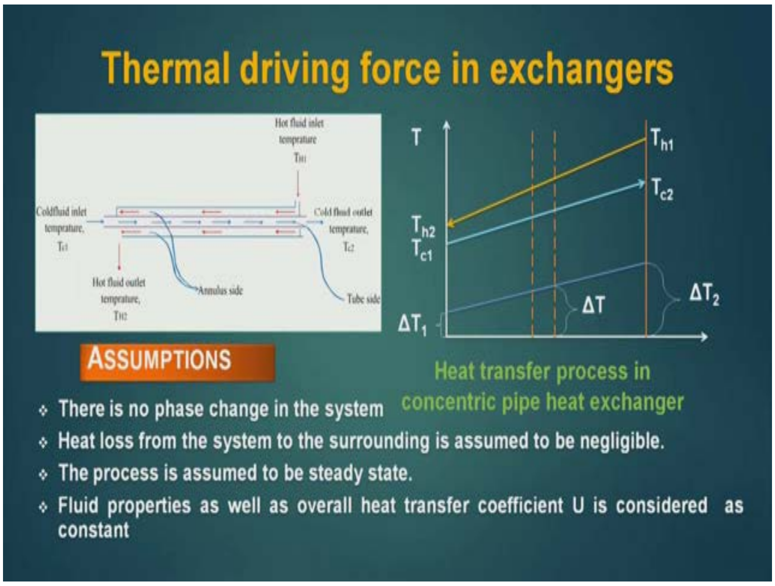

Thermal driving force in exchangers

Heat transfer process in concentric pipe heat exchanger

ASSUMPTIONS

- There is no phase change in the system
- Heat loss from the system to the surrounding is assumed to be negligible.
- The process is assumed to be steady state.
- Fluid properties as well as overall heat transfer coefficient U is considered as constant

And if you consider there is no phase changes taking place heat loss from the system to the surrounding is assume to be negligible then we can draw this. So, this is the hot stream which is entering at P h 1 and going out at P h 2. This is the cold stream which is entering at T C 1 and going out at T C 2 and this is along the length we are plotting this we can plot this along the length or along the heat picked up. So, this is the value of the delta T. So, at one end, we have delta T 1 and other end it is delta T 2. Now if the delta T is changing along the length or along the heat picked up then what delta T we should take for the whole system and that is why everything process as to be generated. And this average delta T is given by delta T L M, which is log in temperature difference. Now we see the derivation of log in temperature difference.

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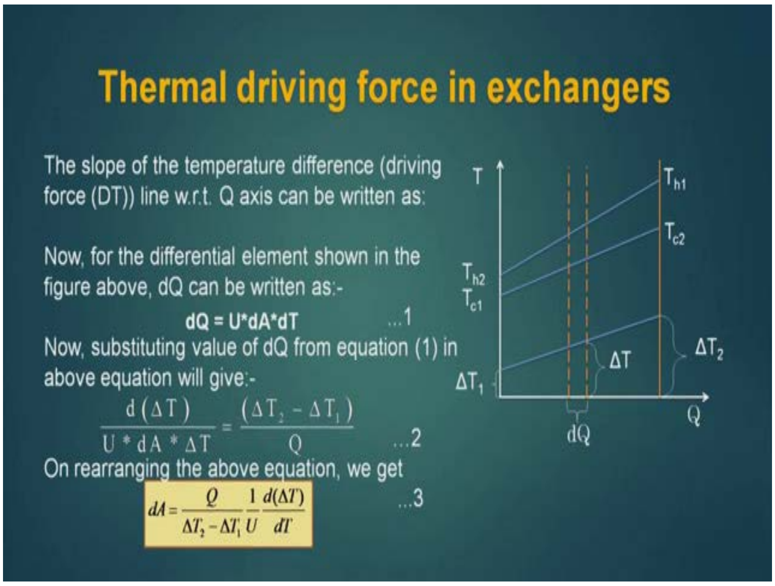

Thermal driving force in exchangers

The slope of the temperature difference (driving force (DT)) line w.r.t. Q axis can be written as:

Now, for the differential element shown in the figure above, dQ can be written as:-

$$dQ = U*dA*dT \quad ...1$$

Now, substituting value of dQ from equation (1) in above equation will give:-

$$\frac{d(\Delta T)}{U*dA*\Delta T} = \frac{(\Delta T_2 - \Delta T_1)}{Q} \quad ...2$$

On rearranging the above equation, we get

$$\boxed{dA = \frac{Q}{\Delta T_2 - \Delta T_1}\frac{1}{U}\frac{d(\Delta T)}{dT}} \quad ...3$$

So, we are computing here how to find out a average driving force for the heat exchanger and here we are considering a counter current heat exchanger the slope of the temperature difference driving force that is delta T line with respect to q axis can be written as v q is equal to u into d a into d t now the substituting value that is d q from the equation one we have this equation differentiation of delta T divided by u d a d t is equal to delta T d 2 minus delta T 1 divided by Q and here we find the equation delta d a is equal to q divided by delta T 2 minus t one into one by u into del delta T divided by d t.

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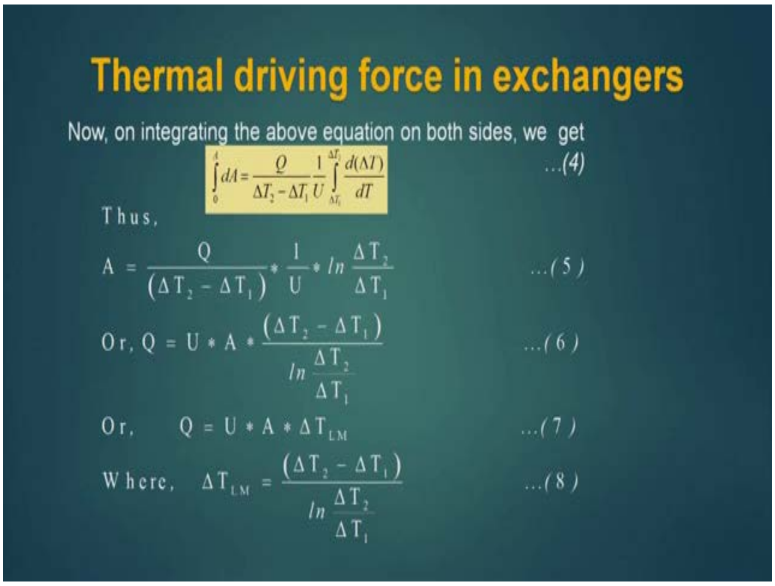

Thermal driving force in exchangers

Now, on integrating the above equation on both sides, we get

$$\boxed{\int_0^A dA = \frac{Q}{\Delta T_2 - \Delta T_1}\frac{1}{U}\int_{\Delta T_1}^{\Delta T_2}\frac{d(\Delta T)}{dT}} \quad ...(4)$$

Thus,

$$A = \frac{Q}{(\Delta T_2 - \Delta T_1)} * \frac{1}{U} * ln\frac{\Delta T_2}{\Delta T_1} \quad ...(5)$$

$$Or,\ Q = U * A * \frac{(\Delta T_2 - \Delta T_1)}{ln\frac{\Delta T_2}{\Delta T_1}} \quad ...(6)$$

$$Or,\quad Q = U * A * \Delta T_{LM} \quad ...(7)$$

$$Where,\quad \Delta T_{LM} = \frac{(\Delta T_2 - \Delta T_1)}{ln\frac{\Delta T_2}{\Delta T_1}} \quad ...(8)$$

And this equation when integrated between zero to a which is area of the heat exchanger and from delta T one to delta T two which are the inlet and exist delta T is of the exchanger then v get a average delta Theta which is called delta T l m is equal to delta T two minus delta T one l and delta T two divided by delta T one. So, this delta T which is called delta T l m is basically a average delta T for the whole system.

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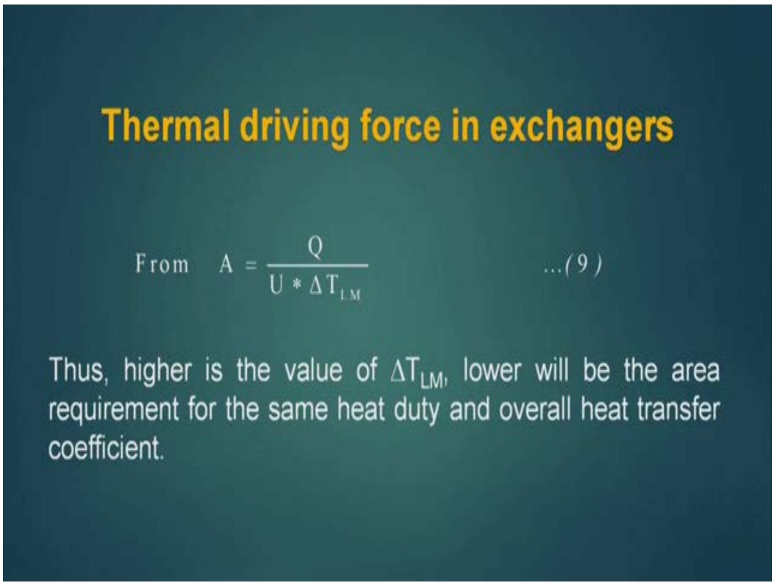

Thermal driving force in exchangers

From $A = \frac{Q}{U * \Delta T_{LM}}$ ...(9)

Thus, higher is the value of ΔT_{LM}, lower will be the area requirement for the same heat duty and overall heat transfer coefficient.

And from here, we can calculate a. Now this relationship very clearly tells that if the delta T L M value is high then area of the heat exchanger will be low for a fixed value of Q. And if delta T L M will be low then area of the heat exchanger will be high for a fixed value of Q. As U are U is the function of flow rate physical property of the liquid generally once the configuration of heat exchanger fixed u does not change much.

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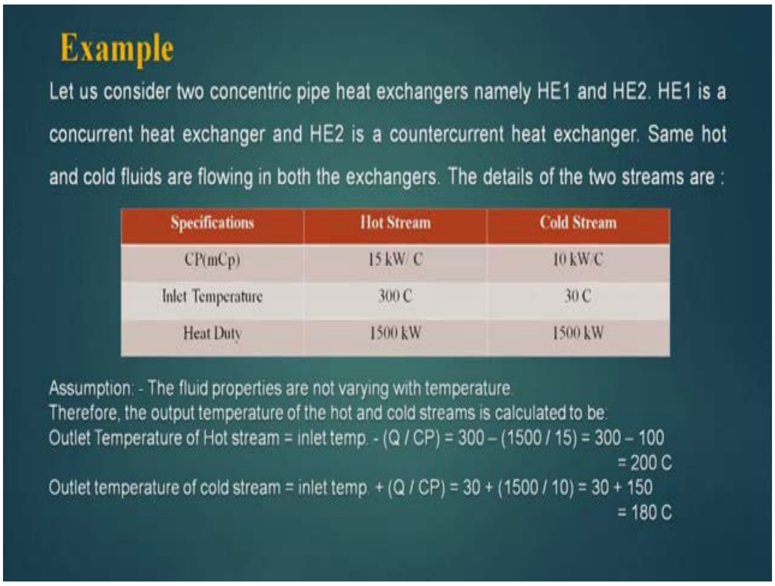

Example

Let us consider two concentric pipe heat exchangers namely HE1 and HE2. HE1 is a concurrent heat exchanger and HE2 is a countercurrent heat exchanger. Same hot and cold fluids are flowing in both the exchangers. The details of the two streams are :

Specifications	Hot Stream	Cold Stream
CP(mCp)	15 kW/ C	10 kW/C
Inlet Temperature	300 C	30 C
Heat Duty	1500 kW	1500 kW

Assumption: - The fluid properties are not varying with temperature.
Therefore, the output temperature of the hot and cold streams is calculated to be:
Outlet Temperature of Hot stream = inlet temp. - (Q / CP) = 300 – (1500 / 15) = 300 – 100
= 200 C
Outlet temperature of cold stream = inlet temp. + (Q / CP) = 30 + (1500 / 10) = 30 + 150
= 180 C

Let us take an example. Let us consider the concentric pipe heat exchanger namely H E 1 and H E 2. H E 1 is the co-current heat exchanger and H E 2 is a counter current heat exchanger. Same hot and cold fluid are flowing in both the heat exchangers. The details of two streams are given here, the C p value that is m C p values of the both the streams are given hot streams and cold streams. Inlet temperature of the hot stream is 300 degree centigrade and cold stream is 30 degree centigrade, the heat duty is 1500 and 1500 because whatever heat what is giving cold is taking that heat.

Now, if we calculate, we take the assumption that the fluid property are not varying with the temperature and there is no heat loss. Therefore, the outlet temperature of the hot and cold streams can be calculated as the outlet temperature of the hot stream is equal to the inlet temperature minus Q by capital C p comes out to be 200 degree centigrade. So, the hot stream, the inlet temperature is 300 degree centigrade and the outlet temperature is 200 degree centigrade, and the outlet temperature of the cold stream is 180 degree centigrade.

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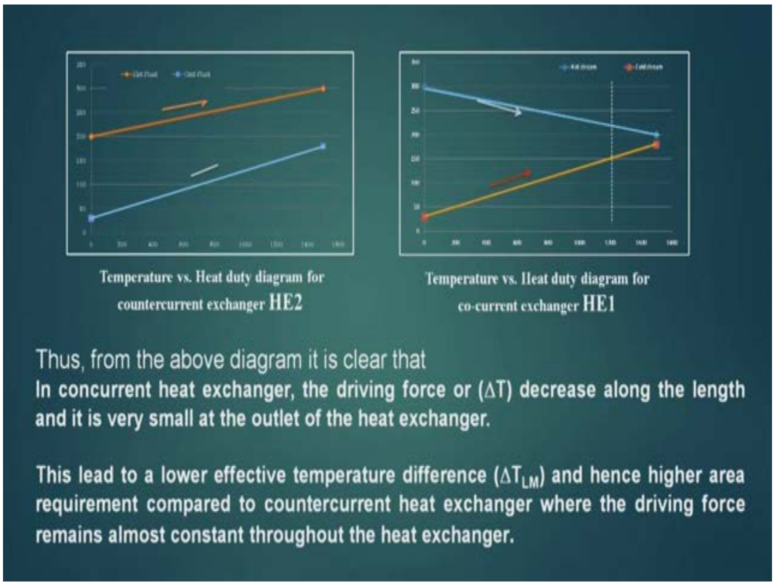

Temperature vs. Heat duty diagram for countercurrent exchanger HE2

Temperature vs. Heat duty diagram for co-current exchanger HE1

Thus, from the above diagram it is clear that

In concurrent heat exchanger, the driving force or (ΔT) decrease along the length and it is very small at the outlet of the heat exchanger.

This lead to a lower effective temperature difference (ΔT_{LM}) and hence higher area requirement compared to countercurrent heat exchanger where the driving force remains almost constant throughout the heat exchanger.

So, if I plot the delta T values or the temperature values of both the streams of co-current heat exchanger and counter current heat exchangers, we see that the delta T value are quite different. While in a counter current heat exchanger, the delta T value along the length or along the heat duty is remaining almost constant, but here it is not that. So, the conclusion is thus for the above diagram, it is clear that the co-current heat exchanger the driving force or the delta T decreases along the length, and it is very small at the outlet of the heat exchanger. This leads to a lower effective temperature difference, and hence higher area requirements compared to the counter current heat exchangers, while the driving force remains the almost constant throughout the heat exchanger. And that is why in the heat transfer in almost all the cases, we prefer counter current heat exchanger. Only in few specific cases, where heating is required vigorously in the inlet, because at the inlet the delta T is very high. So, if I want a very quick heating at the inlet we go for co-current heat exchanger.

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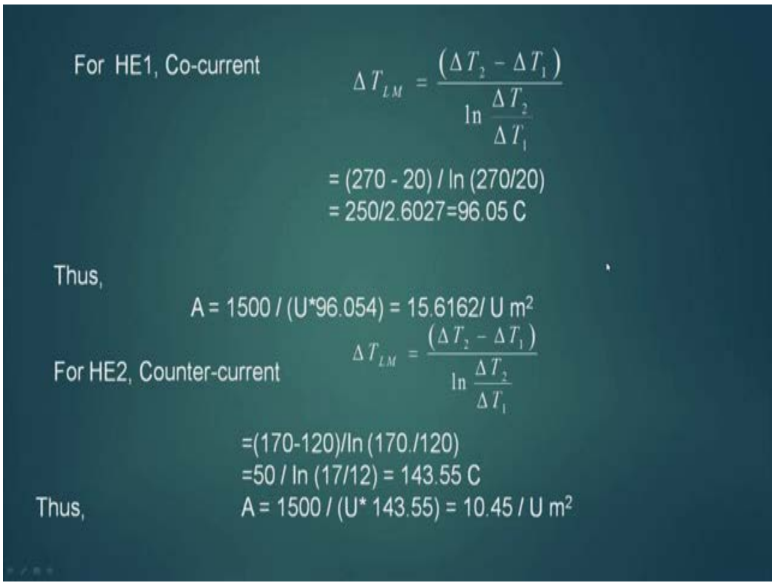

For HE1, Co-current

$$\Delta T_{LM} = \frac{(\Delta T_2 - \Delta T_1)}{\ln \frac{\Delta T_2}{\Delta T_1}}$$

= (270 - 20) / ln (270/20)

= 250/2.6027=96.05 C

Thus,

A = 1500 / (U*96.054) = 15.6162/ U m^2

For HE2, Counter-current

$$\Delta T_{LM} = \frac{(\Delta T_2 - \Delta T_1)}{\ln \frac{\Delta T_2}{\Delta T_1}}$$

=(170-120)/ln (170./120)

=50 / ln (17/12) = 143.55 C

Thus, A = 1500 / (U* 143.55) = 10.45 / U m^2

For co-current heat exchanger, we see that this is comes out to be 96.05; and for counter current heat exchangers, we find that the L M T d is 143.55 degree centigrade, and area for the co-current heat exchanger is 15.6162 divided by U. And whereas for the counter current heat exchanger, the area is 10.5 divided by U. So, what we see that as the delta T l m is less in the counter current, the co-current heat exchanger will require more area than the counter current heat exchanger.

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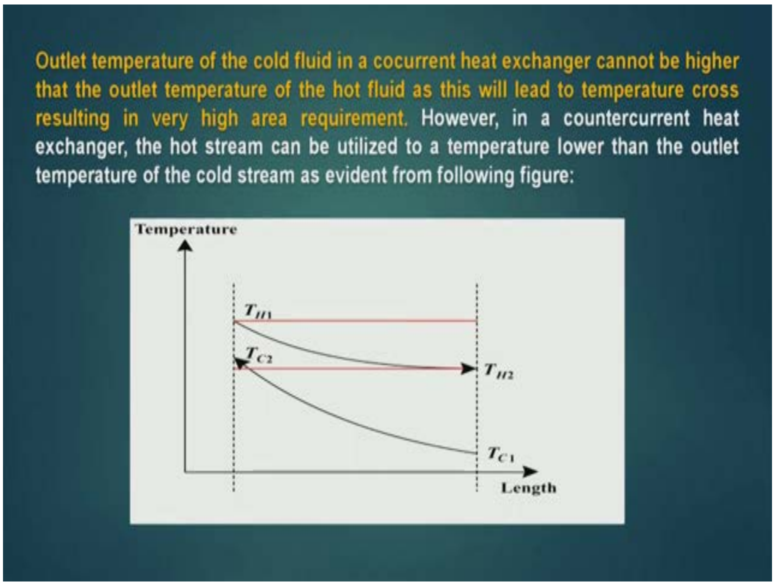

Outlet temperature of the cold fluid in a cocurrent heat exchanger cannot be higher that the outlet temperature of the hot fluid as this will lead to temperature cross resulting in very high area requirement. However, in a countercurrent heat exchanger, the hot stream can be utilized to a temperature lower than the outlet temperature of the cold stream as evident from following figure:

Let us further develop this the outlet temperature of cold fluid in a co-current heat exchanger cannot be higher than the outlet temperature of the hot fluid, as this will lead to temperature cross resulting in very high area requirement. However, in the co-current heat exchanger the hot stream can be utilized to a temperature lower than the outlet temperature of the cold stream as evident from the following figure. So, here we see counter current heat exchanger, and what we see here the outlet temperature of the hot fluid that is T H 2 is lower than the outlet temperature of the cold fluid. This is possible in a counter current heat exchanger. Though we do not like temperature cross to take place in the heat exchanger, but this is somewhat temperature cross can be accommodated in a counter current heat exchanger. Whereas, in co-current heat exchanger, it will require a lot of area if there is a temperature cross and in the due to this temperature cross, there will be reverse flow of heat.

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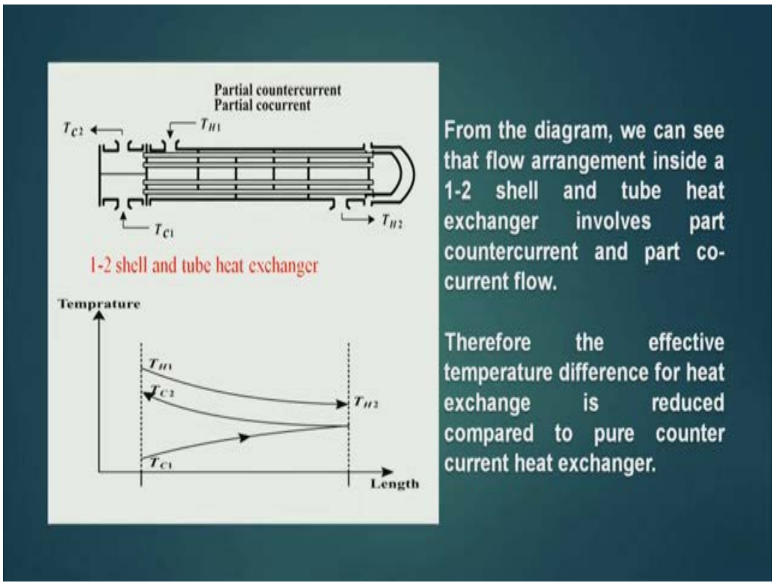

From the diagram, we can see that flow arrangement inside a 1-2 shell and tube heat exchanger involves part countercurrent and part co-current flow.

Therefore the effective temperature difference for heat exchange is reduced compared to pure counter current heat exchanger.

Now it is a 1-2 shell and tube heat exchanger the tube site temperature profile will be like this. This is counter current and this is co-current. This is counter current and this is co-current. Now in such case to account for this type of changes we generally go for a F t factor. From the diagram, we see that the flow arrangement inside 1-2 shell and tube heat exchanger one to make one shell and two tube pass it heat exchanger involves part counter current and part co-current flow. Therefore, the effective temperature difference for heat exchange is reduce compared to the pure counter current heat exchanger.

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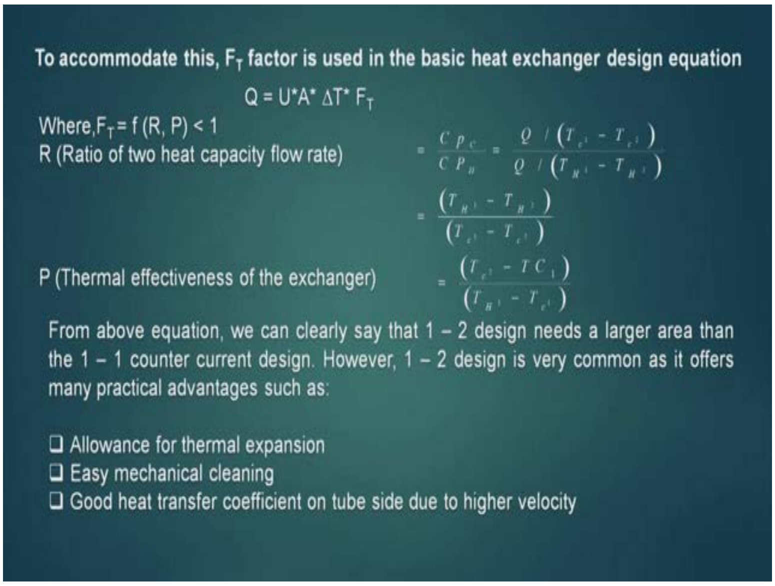

To accommodate this, F_T factor is used in the basic heat exchanger design equation

$$Q = U^*A^*\,\Delta T^*\,F_T$$

Where, $F_T = f(R, P) < 1$

R (Ratio of two heat capacity flow rate) $= \dfrac{Cp_c}{Cp_H} = \dfrac{Q\,/\,(T_{c2} - T_{c1})}{Q\,/\,(T_{H1} - T_{H2})}$

$= \dfrac{(T_{H1} - T_{H2})}{(T_{c2} - T_{c1})}$

P (Thermal effectiveness of the exchanger) $= \dfrac{(T_{c2} - TC_1)}{(T_{H1} - T_{c1})}$

From above equation, we can clearly say that 1 – 2 design needs a larger area than the 1 – 1 counter current design. However, 1 – 2 design is very common as it offers many practical advantages such as:

- ☐ Allowance for thermal expansion
- ☐ Easy mechanical cleaning
- ☐ Good heat transfer coefficient on tube side due to higher velocity

Now, to accommodate this a F t factor is used in the basic heat design equation. So, for a multi tube, for a multi shell heat exchangers, we have this equation Q is equal to U A delta T into F t. And this F t factor is going to take in to account this type of mix flows. Where F t is the function of r and p and is always less than one; where R is defined as the ratio of two heat capacity flow rate C p c divide by C p h and come out to be T H 1 minus T H 2 divided by T C 1 minus T C 2. And P is the thermal effectiveness of the heat exchanger, and this is given by T C 2 minus T C 1 divided by T H 1 minus T C 1. From above equation, we can clearly say that 1-2 design needs a larger area then 1-1 counter currently design. However, 1-2 design is very common as it offers many practical advantage such as along for thermal expansions, easy mechanical cleaning, good heat transfer coefficient on tube side due to high velocities.

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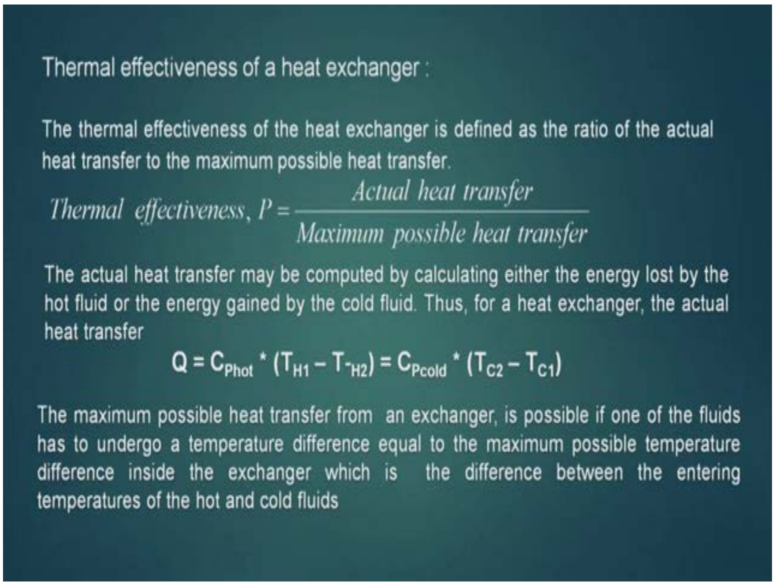

Thermal effectiveness of a heat exchanger :

The thermal effectiveness of the heat exchanger is defined as the ratio of the actual heat transfer to the maximum possible heat transfer.

$$\text{Thermal effectiveness, } P = \frac{\text{Actual heat transfer}}{\text{Maximum possible heat transfer}}$$

The actual heat transfer may be computed by calculating either the energy lost by the hot fluid or the energy gained by the cold fluid. Thus, for a heat exchanger, the actual heat transfer

$$Q = C_{Phot} * (T_{H1} - T_{-H2}) = C_{Pcold} * (T_{C2} - T_{C1})$$

The maximum possible heat transfer from an exchanger, is possible if one of the fluids has to undergo a temperature difference equal to the maximum possible temperature difference inside the exchanger which is the difference between the entering temperatures of the hot and cold fluids

Now, let us see what is the thermal effectiveness of a heat exchanger. The thermal effectiveness of a heat exchanger is defined as the ratio of the actual heat transfer to the maximum possible heat transfer. So, the thermal effectiveness P is equal to actual heat transfer divided by maximum possible heat transfer, and we have seen that the F t factor is a function of this P value. The actual heat transfer may be computed by calculating either the energy lost by the hot fluid or the energy gain by the cold fluid. Thus for a heat exchanger, the actual heat transfer Q is equal to C p hard into T H 1 minus T H 2 or C p cold into T C 2 minus T C 1. This is basically the heat picked by the cold flow or heat given by the hot flow when it is moving from T H 1 to T H 2 temperature. However, the maximum possible heat transfer from an exchanger, is possible only one if one of the fluid has to undergoes, it temperature difference equal to the maximum possible temperature difference inside the heat exchanger, which is the difference between the entering temperature of the hot and the cold fluids.

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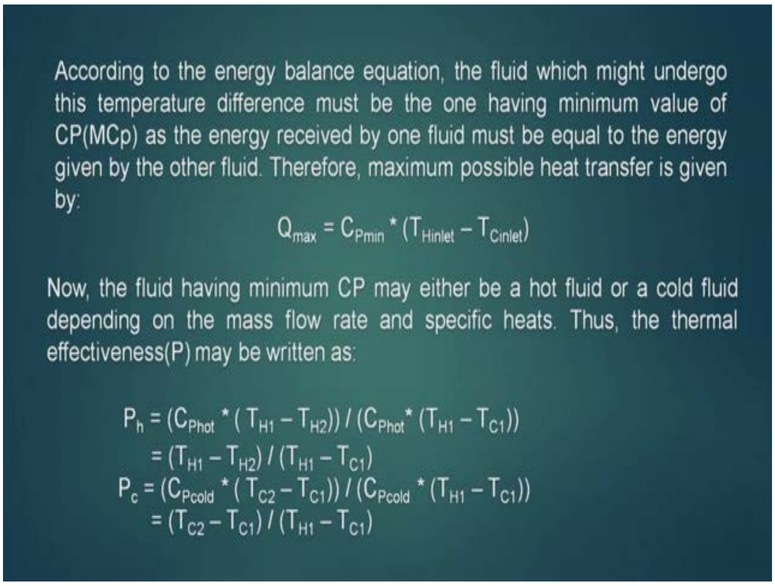

According to the energy balance equation, the fluid which might undergo this temperature difference must be the one having minimum value of CP(MCp) as the energy received by one fluid must be equal to the energy given by the other fluid. Therefore, maximum possible heat transfer is given by:

$$Q_{max} = C_{Pmin} * (T_{Hinlet} - T_{Cinlet})$$

Now, the fluid having minimum CP may either be a hot fluid or a cold fluid depending on the mass flow rate and specific heats. Thus, the thermal effectiveness(P) may be written as:

$$P_h = (C_{Phot} * (T_{H1} - T_{H2})) / (C_{Phot} * (T_{H1} - T_{C1}))$$
$$= (T_{H1} - T_{H2}) / (T_{H1} - T_{C1})$$
$$P_c = (C_{Pcold} * (T_{C2} - T_{C1})) / (C_{Pcold} * (T_{H1} - T_{C1}))$$
$$= (T_{C2} - T_{C1}) / (T_{H1} - T_{C1})$$

Now, if it is so, so according to the energy balance equation the fluid which might undergo this temperature difference must be the one having minimum value of C p that is m C p mass into specific heat - that is mass flow rate into the specific heat. As the energy receive by one fluid must be equal to the energy given by the other fluid, therefore, maximum possible heat transfer is given by Q max is equal to C p minimum into T H in let minus T C inlet. Now the fluid having minimum C p may be either be hot fluid or a cold fluid, depending on the mass flow rate and specific heat. Thus the thermal effectiveness P may be written as P for hot is equal to C p hot into T H 1 minus T H 2 divided by C p hot T H 1 minus T C 1 or T H 1 minus T H 2 divide by T H 1 minus T C 1. And for cold, if the cold food gives you the minimum then P c is equal to cold C p cold into T C 2 minus T C 1 divided by C p cold T H 1 minus T C 1, so comes out to be T C 2 minus T C 1 divided by T H 1 minus T C 1.

Thank you.