Nature and Properties of Materials
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Lecture 36
Material Selection for Heat Exchanger

In this lecture we are going to now see a practical application of our knowledge of material properties for material selection for the heat exchanger okay, so this is what we are going to see in this particular lecture. So let us see how some of the thermal properties that we have learned earlier can come into picture in terms of material selection for a very important practical system called heat exchanger.

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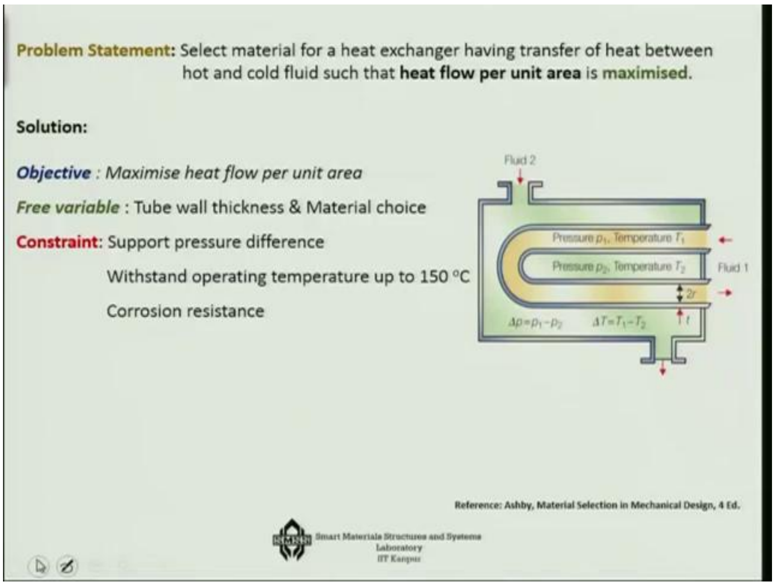

Problem Statement: Select material for a heat exchanger having transfer of heat between hot and cold fluid such that **heat flow per unit area** is maximised.

Solution:

Objective : *Maximise heat flow per unit area*

Free variable : Tube wall thickness & Material choice

Constraint: Support pressure difference
Withstand operating temperature up to 150 °C
Corrosion resistance

Reference: Ashby, Material Selection in Mechanical Design, 4 Ed.

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Now that why a heat exchanger is required because it helps in terms of exchanging the heat between hot and cold fluid such that the heat flow per unit area is maximise. There are many applications for example, in automobiles or even in simple room heaters okay, in many cases you need to actually either cool the system very fast or you need to heat it up very fast. In both the cases, you need to design a suitable heat exchanger to do this particular work. So our objective here is to maximise the heat flow per unit area.

And what are our free variables? The tube wall thickness and the material choice. What are the constraints that we may actually come across? One of them is the support pressure difference, maximum pressure difference Delta p between the net fluid and the fluid outside. And this is important, up to what temperature it can withstand let us say in this particular example, we will keep it to be sufficiently high 150 degrees centigrade, and also corrosion resistance can be another important point, we will keep that point in mind when we will finally select the material, so let us go to the board and use the Ashby criteria to do this same exercise.

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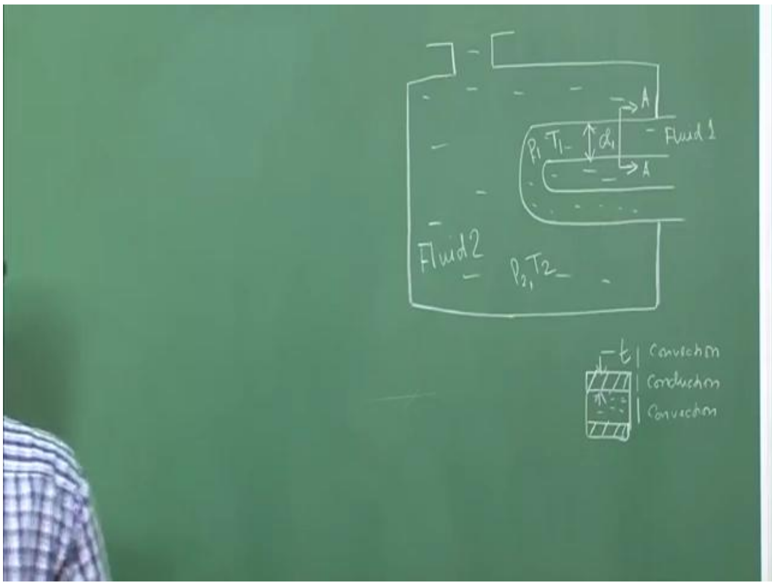

So we have a heat exchanger, let us first draw the exchanger. Suppose, this is the surrounding fluid and on the surrounding fluid we have a heat exchanger coming in and which has a uniform diameter and suppose this part is our boundary, so this is what is our fluid 2 boundary, this is our fluid 2. And we have the fluid 1 inside, this is fluid 1 and we have the temperature here is T 1, the pressure here is P 1, the temperature here is T 2, pressure here is P 2, so the same fluid is here all around the fluid 2 okay. And we also have this one with a uniform say diameter all-around say suppose d 1.

And if we cut across this tube here A, what we are going to see is that it has a finite thickness, uniform thickness and this thickness is t of the that is the wall thickness, right because that thickness will become important for us when we will analyze the system. Now, then there are 3 things that we will be basically analyzing in it, one is that there is fluid 1 inside here right, so the first thing is the heat that is getting convicted from this fluid 1 to this solid.

Then it is conducted so this conduction and again there is a convection, so there are the 3 elements that will come into the picture, so conduction, convection at the 2 other sides, so there are these combinations of convective and conductive heat transfer that is going to take place in the system. Now let us assume steady-state heat flow okay, let us just put our objective of course at the top, which is maximise heat flow per unit area okay.

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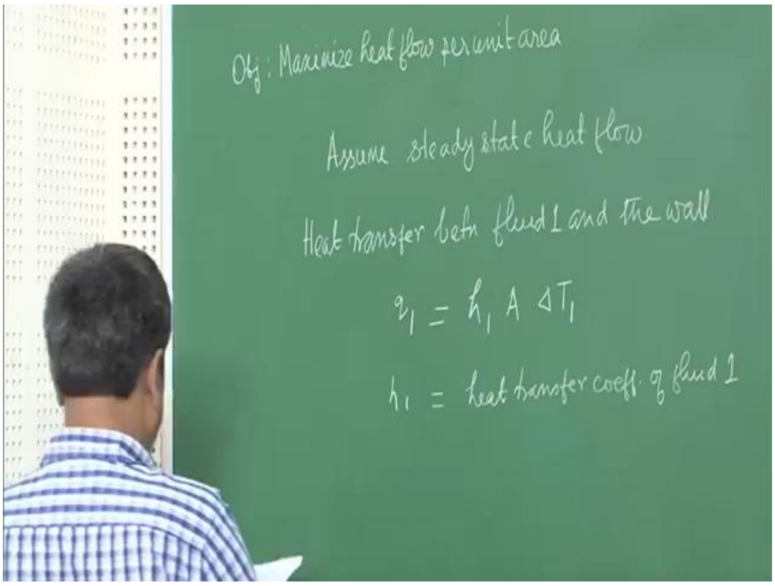

Obj: Maximize heat flow per unit area

Assume steady state heat flow

Heat transfer betn fluid 1 and the wall

$q_1 = h_1 A \Delta T_1$

h_1 = heat transfer coeff. of fluid 1

And let us now assume the steady-state heat flow, now the heat transfer between fluid 1 and the wall okay, so let this be denoted as q 1 which is h 1 A times Delta T 1, where h 1 is the heat transfer coefficient of fluid 1 and then so we should be able to find out, Delta T 1 is of course the temperature difference between the fluid and surface 1 that is the internal surface of the fluid, the temperature difference is going to actually is Delta T 1, so that is what is my 1st part A that is the heat transfer between fluid 1 and the wall which is happening here.

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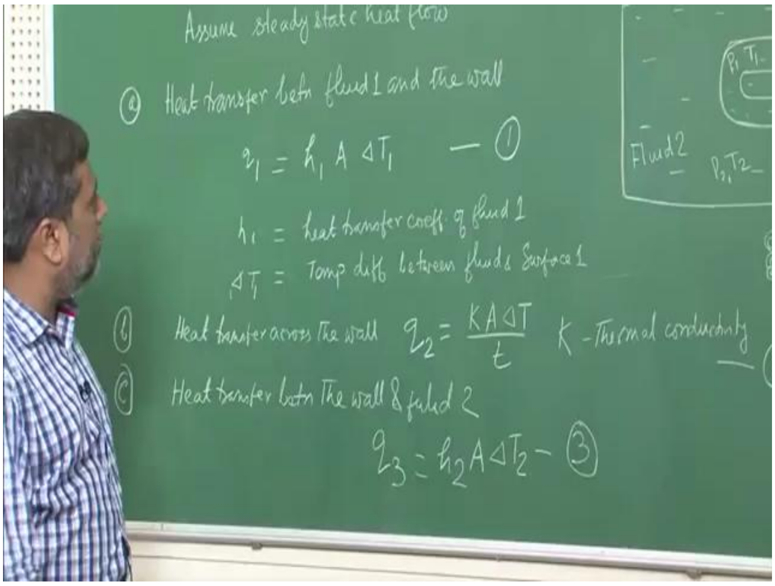

Assume steady state heat flow

ⓐ Heat transfer betn fluid 1 and the wall

$q_1 = h_1 A \Delta T_1$ — ①

h_1 = heat transfer coeff. of fluid 1

ΔT_1 = Temp diff between fluid & Surface 1

ⓑ Heat transfer across the wall $q_2 = \frac{KA\Delta T}{t}$ K - Thermal conductivity

ⓒ Heat transfer betn the wall & fluid 2

$q_3 = h_2 A \Delta T_2$ — ③

Next will be the B that is the heat conduction and next will be C, so let us look at the conduction. So heat transfer across the wall, this can be written as so this is our 1st equation, now the 2nd equation is q 2 = k A Delta T over T, where we know that A is the surface area, k

Delta T is known to us T is the thickness as I have shown here, the T is the thickness of the wall and k is the thermal conductivity, now the last part C, so this is my 2nd part.

Now last part C which is heat transfer between the wall and fluid 2, in that case q 3 is very similar is h 2 A Delta T 2, this is my 3rd equation, so we have to basically get an equivalent expression of heat transfer on the basis of these 3 equations that come into the picture. So if we will keep this particular equation in our mind then we can go for this equivalent heat transfer now. So let us try to erase this part now and try to get a formulation for the equivalent one, which takes care of all these 3 things together.

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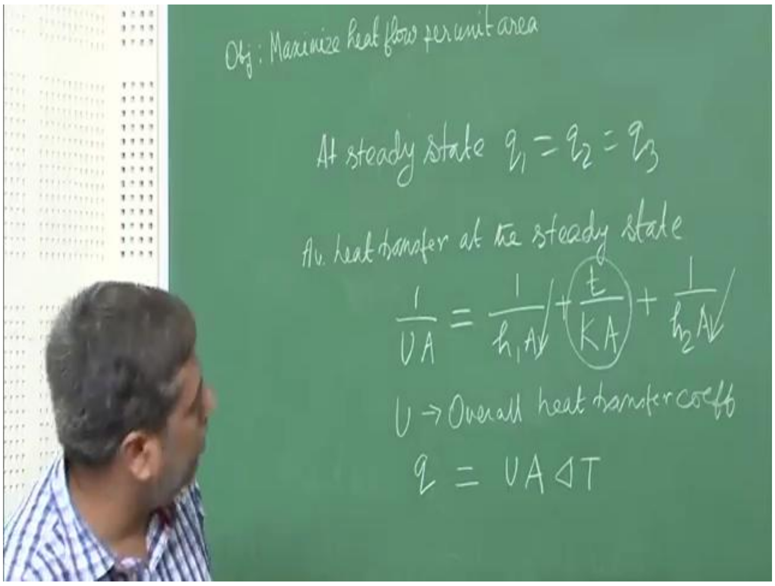

Obj: Maximize heat flow per unit area

At steady state $q_1 = q_2 = q_3$

Av. heat transfer at the steady state

$$\frac{1}{UA} = \frac{1}{h_1 A} + \frac{t}{KA} + \frac{1}{h_2 A}$$

$U \rightarrow$ Overall heat transfer coeff

$$q = UA\Delta T$$

Now, one point we have to keep in our mind here that at steady state these 3, at the steady-state q 1 = q 2 = q 3, so that has been achieved and hence at that stage the heat transfer the average heat transfer at the steady-state is 1 over U A = 1 over h 1 A + t over k A + 1 over h 2 A okay. So it is like you have 3 resistive systems and all 1st order and all of them are together that is the giving you the equivalent total resistance to the system, so U here is the overall heat transfer coefficient.

And it can be also written that the q in the steady states this q = U A delta T. Now, what happens is that in most of the cases this actually dominates the heat transfer, the t over k A, and in comparison to that we can actually neglect these 2. So suppose in any particular case it is possible for us to do that, in that case what we can write is that we can further simplify this expression now and we can write it as for the domination of heat conduction across the tube wall over convections.

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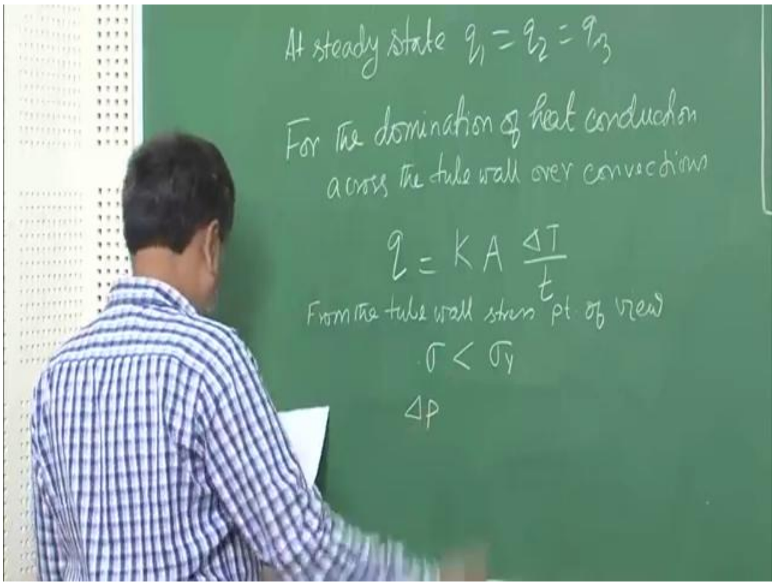

At steady state $q_1 = q_2 = q_3$

For the domination of heat conduction across the tube wall over convections

$$q = K A \frac{\Delta T}{t}$$

From the tube wall stress pt of view

$$\sigma < \sigma_y$$

$$\Delta P$$

We can write that simply q = k A Delta T over t, right. So this we can say is the steady-state overall heat conduction when everything else is actually neglected. Now, during this transfer of the fluid at pressure P 1, this wall is also subjected to some stress which is something like a Hooke’s stress that is happening in the wall, so it is expanding trying to expand the wall. So from the mechanical point of view, it has to withstand that pressure also, so the stress that will come from the tube wall stress point of view, we can write that Sigma has to be less than Sigma y.

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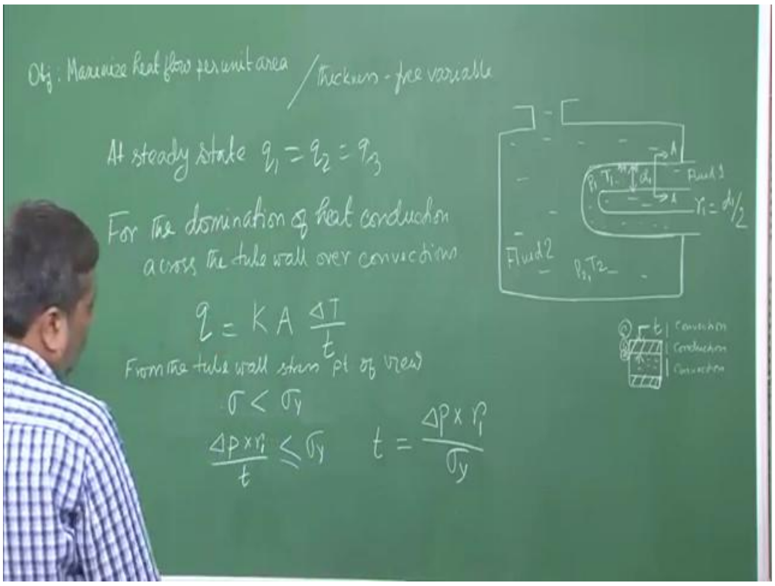

Obj: Maximize heat flow per unit area / thickness - free variable

At steady state $q_1 = q_2 = q_3$

For the domination of heat conduction across the tube wall over convections

$$q = K A \frac{\Delta T}{t}$$

From the tube wall stress pt of view

$$\sigma < \sigma_y$$

$$\frac{\Delta P \times r_i}{t} \leq \sigma_y \qquad t = \frac{\Delta P \times r_i}{\sigma_y}$$

And what is the stress here, that is Delta P, the pressure difference times r, the radius of the tube divided by t that has to be less than or equal to Sigma y. In fact, by keeping thickness as the free variable here, so thickness is here as a free variable, so I can write that t = Delta p times r okay let us call it as r 1, r 1 = our d 1 by 2, so Delta P times r 1 divided by Sigma y. Now I can substitute this in this equation of overall heat transfer so that means I can write here that q = k A Delta T times Sigma y divided by Delta P times r 1, right.

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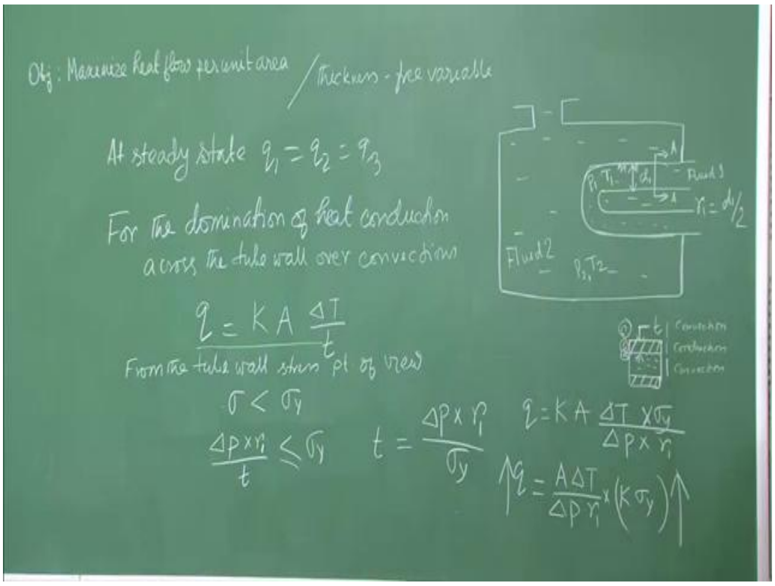

Obj: Maximize heat flow per unit area / Thickness - free variable

At steady state $q_1 = q_2 = q_3$

For the domination of heat conduction across the tube wall over convections

$$q = KA\frac{\Delta T}{t}$$

From the tube wall stress pt of view

$$\sigma < \sigma_y$$

$$\frac{\Delta p \times r_1}{t} \leq \sigma_y \qquad t = \frac{\Delta p \times r_1}{\sigma_y}$$

$$q = KA\frac{\Delta T \times \sigma_y}{\Delta p \times r_1}$$

$$\uparrow q = \frac{A\Delta T}{\Delta p\, r_1} \times (K\sigma_y)\uparrow$$

So I can write also as q equals to, let us keep all the other parameters separate that is A Delta T over Delta P r 1 and k Sigma y. So in a heat exchanger, if I want to increase the heat exchange rate. more heat to transfer from fluid 1 to fluid 2 so that either I can heat up fast or I can cool fast, I must increase this k times Sigma y that is both k and the yield strength has to be increased, so that it can sustain the pressure, at the same time the higher thermal conductivity allows us to take more temperature to take more heat from fluid 1 to fluid 2. Now let us look into that what are the possibilities that are there for us for this particular system.

So now if you look into the Ashby chart, we will see that in this particular case because we have k over k Sigma I, so if you take a logarithm of the 2 that means if k Sigma y is a constant, then log of k would become - log of Sigma y + log of C, so that means there is a negative slope and that negative slope considering the 150 degree temperature difference will bring us in this particular light, okay.

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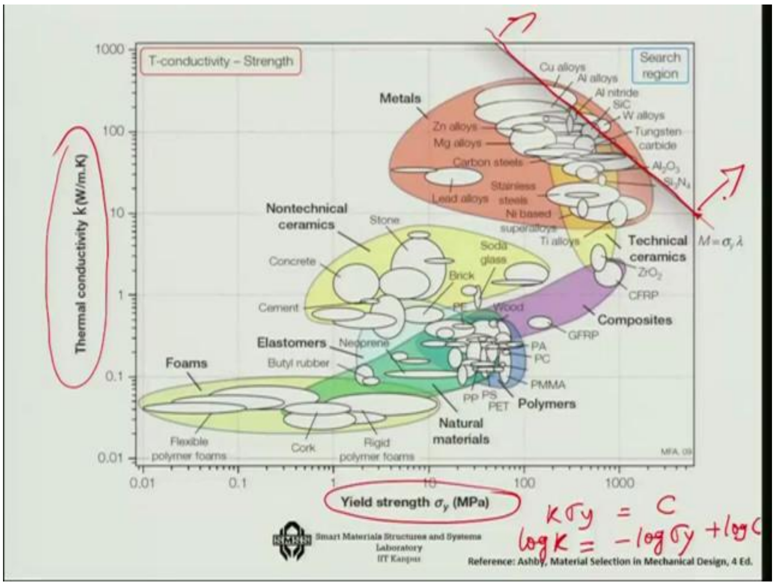

$K\sigma_y = C$

$\log K = -\log \sigma_y + \log C$

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Reference: Ashby, Material Selection in Mechanical Design, 4 Ed.

This is a line with negative slope and if this particular line now we actually look at it, so this is a curve this is relationship between thermal conductivity and Sigma y. With this negative relationship all I have to see is actually see everything beyond this point because everything below this point are not suitable for the heat exchanger design here up to 150 degree centigrade, so if I magnify this part what are the possibilities for us that is coming?

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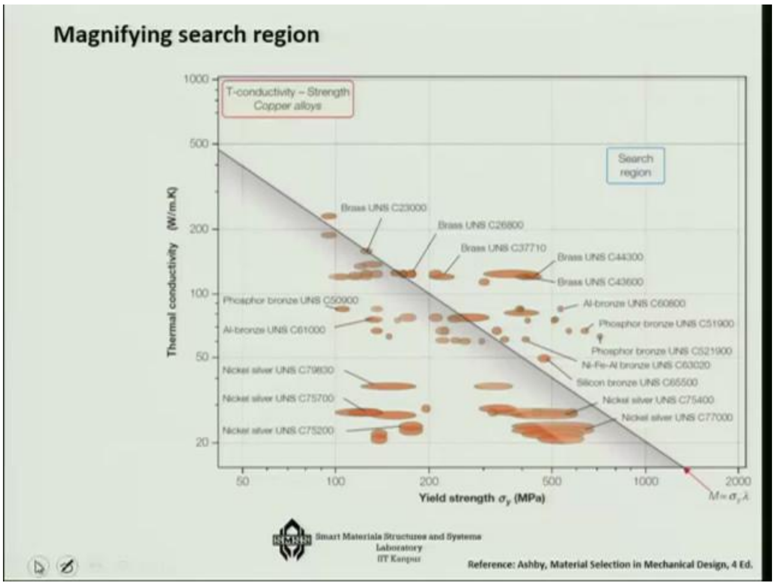
Magnifying search region

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Reference: Ashby, Material Selection in Mechanical Design, 4 Ed.

You can have the brass UNS alloys; we can have aluminium bronze alloys, phosphor bronze alloys, nickel base alloys, silicon bronze alloys, so these are the possibilities that come in our particular slide area. So if I look at it further, you will see that the brass is like naval brass here the k Sigma y index is the highest 5 into 10 to the power 4, the only problem is for naval application that is a dezincification that means it is susceptible to the environmental pollution, so that is why the corrosion point of view this is not a good idea.

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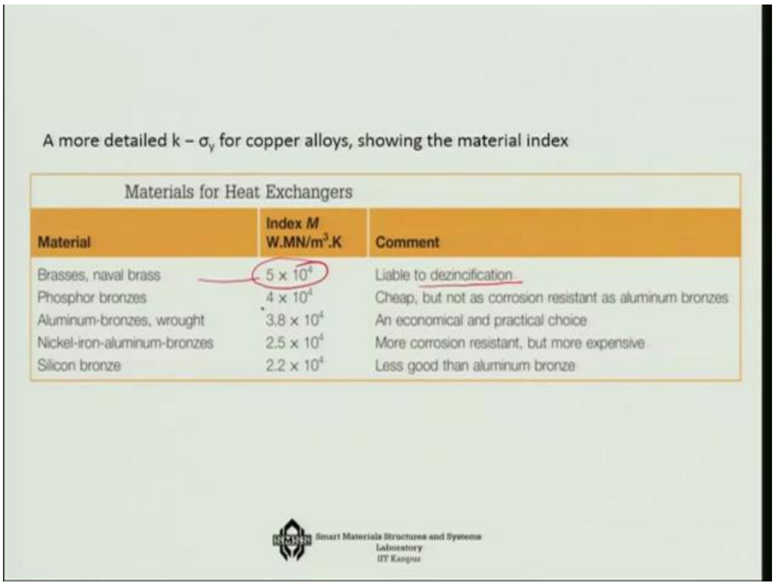

A more detailed k – σ_y for copper alloys, showing the material index

Materials for Heat Exchangers

Material	Index *M* W.MN/m^3.K	Comment
Brasses, naval brass	5×10^4	Liable to dezincification
Phosphor bronzes	4×10^4	Cheap, but not as corrosion resistant as aluminum bronzes
Aluminum-bronzes, wrought	3.8×10^4	An economical and practical choice
Nickel-iron-aluminum-bronzes	2.5×10^4	More corrosion resistant, but more expensive
Silicon bronze	2.2×10^4	Less good than aluminum bronze

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Phosphor bronze, 4 into 10 to the power 4 which is cheap, but not as corrosion resistant as the next one that is the aluminium bronze, which is slightly lower 3 burger 8 into 10 to the power 4, but it is economical, it is corrosion resistant and this comes out to be a more practical choice than the brass or the phosphor bronze from the corrosion point of view. Nickel iron aluminium bronze is actually more corrosion resistant, but it is more expensive and this also is little less. Similarly, silicon bronze is less good because its index is less.

So out of all the choices as we can see that the 1st 3 are better choices from the material index point of view, but if we put corrosion as the constraint and also economy as the constraint, then aluminium bronze wrought is coming out to be the best choice and that is what is generally used in the heat exchanger design. In the next lecture, we will learn about the electrical properties of the system, thank you.