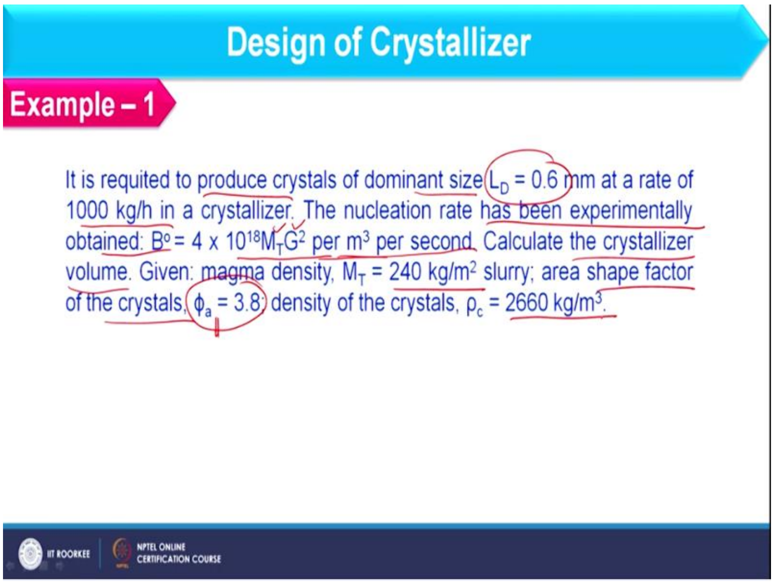
Process Equipment Design
Prof. Shabina Khanam
Department of Chemical Engineering
Indian Institute of Technology – Roorkee

Lecture –41
Design of Crystallizer: Examples

Hello everyone. This is 41th lecture of the course Process Equipment Design and here we are in 9th week of this course. And in this lecture, we are going to design the crystallizer and I welcome you all in this lecture. So, as far as crystallizer design is concerned if you remember the last lecture of the last week that is 40th lecture of this course where we have consider steps which are involved in design of crystallizer.

And each step will be illustrated over here with the help of examples. So, let us start with first example for design of crystallizer.

(Refer Slide Time: 01:05)

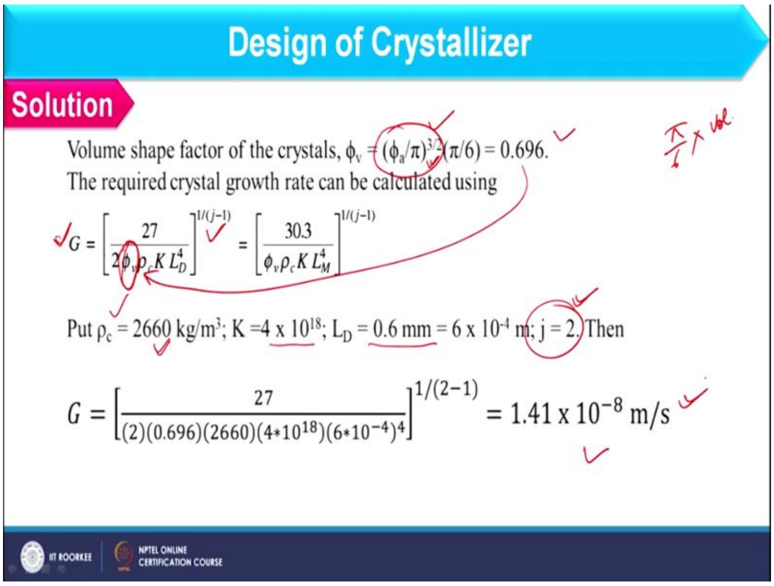


So, as far as this example is concerned we have example 1 as so in this example we need to produce the crystal of dominant size that is LD which is equal to 0.6 mm at the rate of 1,000 kg per hour in the crystallizer. So, 0.6 mm crystals are formed with the rate of 1,000 kg per hour. So, as far as nucleation rate is concerned that data we can obtain experimentally and experimental data is given to us as B 0 which is equal to 4 into 10 is to the power 18 MT G square.

So, MT is basically the magma density and G is the growth rate and that B value is per meter cube per second. What we have to calculate is the crystallizer volume. Magma density is given to us as 250 kg per meter square slurry, area shape factor of the crystal is given as 3.8 so that is basically psi a, density of the crystal is given as 2,660 kg per meter cube. So, in this way we are given different parameters and here shape of the crystal is given.

So, based on these parameters we should calculate the volume of the crystallizer. So, let us discuss that.

(Refer Slide Time: 02:36)



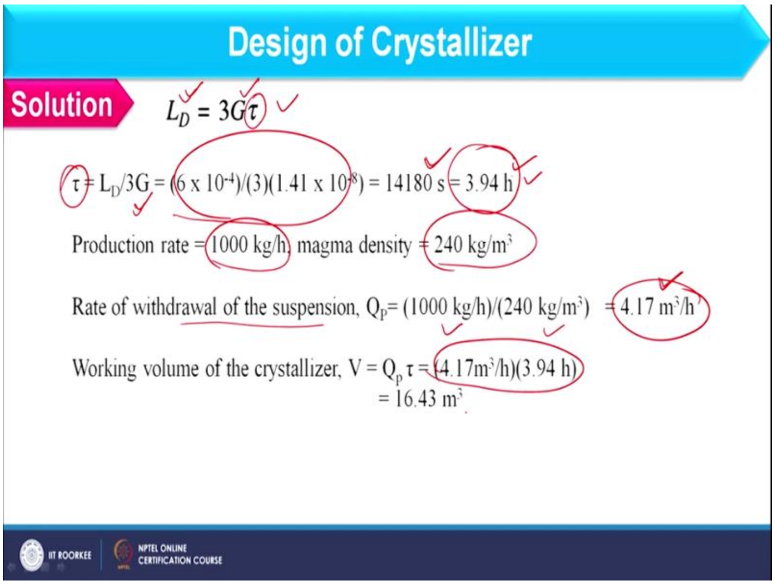
So, to decide the volume of the crystallizer we should calculate the growth rate and growth rate is basically required volume shape factor as so the expression of G is like 27 divided by 2 phi v rho c K L D power 4 and whole expression power 1 / j – 1. So, if you see this phi v this is basically the volume shape factor which we can find as it is equal to phi a divided by pi 3 / 2 pi / 6.

So, volume shape factor is basically pi / 6 into volume of the particle. So, that volume of the particle we can find out by this because area shape factor is given to us divided by pi and 3 / 2 we can consider. So, the volume shape factor of the crystal is obtained as 0.696. So, that value we can consider over here and further rho c that is basically the density of the crystal it is given as 2,660 kg per meter cube K value is 4 into 10 is to the power 18.

L D 0.6 it is given and j is 2. How this j = 2 we can obtain. If you focus on this B 0 expression j is basically this factor. So, in that case j is 2. So, here I am having two value of j.

So, considering all these parameters we can find out G value as 1.41 into 10 is to the power – 8 meter per second. So, that is basically the growth rate of the crystal.

(Refer Slide Time: 04:46)



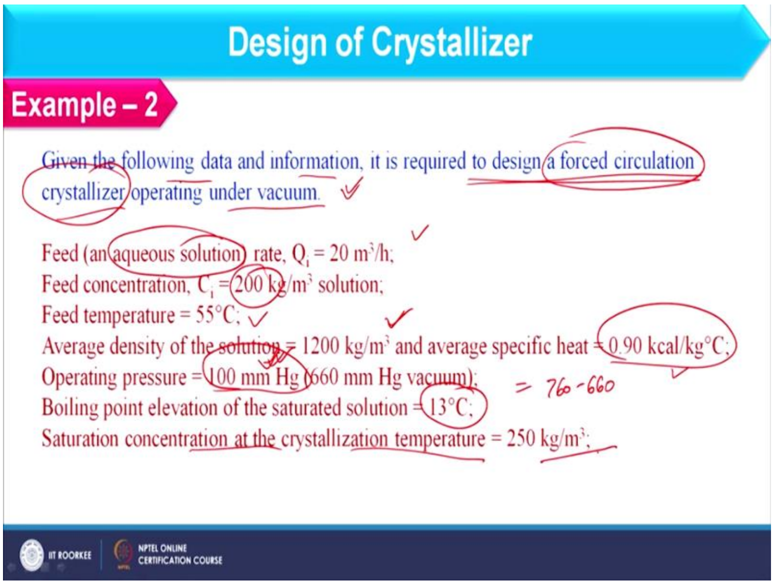
Now, once I am having the growth rate we can relate growth rate residence time with the size of the crystal using the expression as this where L D is equal to 3 G tau. So, L D is basically the size of the crystal that is 0.6 mm and G growth rate we have already obtained tau is basically the residence time. So, we can calculate the residence time by L D divided by 3 into G.

So, all values are known to me and I can find the tau value as 14180 second which is equal to 3.94 hour. So, you see the total residence time of the solution in the crystallizer is 3.94 hour. So, production rate is basically 1,000 kg per hour that is given in the problem only, magma density 240 kg per meter cube it is also given and we have to find out rate of withdrawal of the suspension that how much slurry is taken out from the system.

So, that is basically 1,000 into 240 kg per meter cube. So, it gives total output from the crystallizer as 4.17 meter cube per hour. And this much output we can obtain when it will available in the crystallizer for this much time. So, therefore the total volume of the crystallizer is multiplication of these two which is 16.43 meter cube. So, if you see here I am having volume of the crystallizer as working volume.

So, what is working volume? Working volume is basically the volume of the solution not the total volume of the crystallizer. So, in that way we can find out the working volume of the crystallizer, for total volume we should add some more factors which we will discuss in next example.

(Refer Slide Time: 07:09)



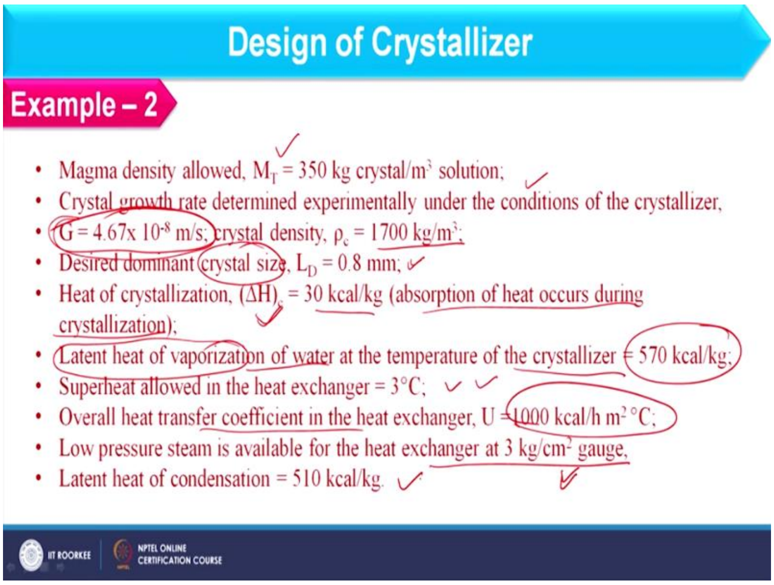
So, let us focus on example number 2. So, here we are given the following data and information which is required to design a forced circulation crystallizer operating under vacuum because crystallizers are usually operated under vacuum. And what is this forced circulation crystallize? In detail, we will discuss the working of this in next lecture. So, let us focus on the information available to us.

The first is the feed rate and that must be an aqueous solution. So, the feed rate is 20 meter cube per hour, feed concentration is given as 200 kg per meter cube of solution. So, 200 kg solute is available per meter cube of solution. Feed temperature 55 degree Celsius, average density of the solution is 1,200 kg per meter cube. So, that you can consider as density of the solution.

Average specific heat of the solution is given as 0.9 kilocalorie per kg degree Celsius, operating pressure is 100 mm Hg. So, that is basically the absolute value so vacuum should be 660 mm Hg. So, the absolute pressure is basically 760 – 660 so 100 mm is given like this. And next we have the boiling point elevation of the saturated solution which is 13 degree Celsius.

So, you can see this temperature is considered within the crystallizer and after that we are given with the saturated concentration at crystallization temperature and that is 250 kg per meter cube. So, you see at crystallization temperature the saturation condition is already given to us and that the concentration is 250 kg per meter cube and for that data we have to design the crystallizer.

(Refer Slide Time: 09:17)



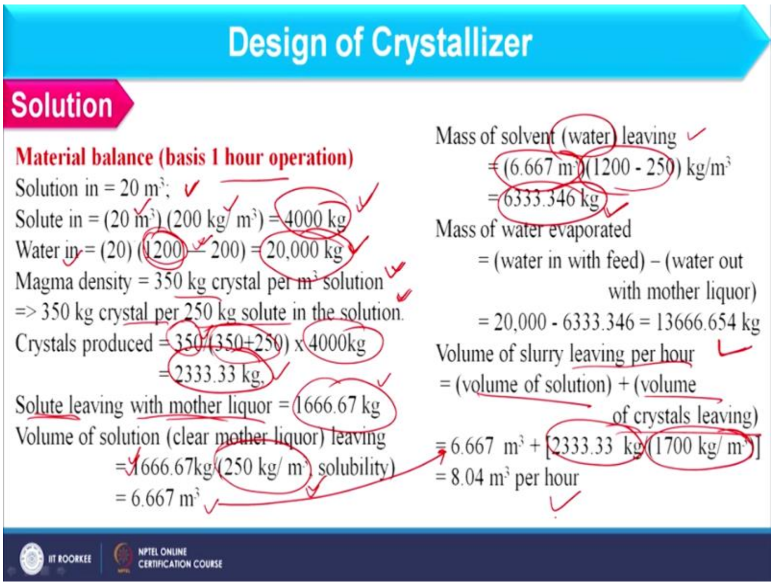
Along with this we need much more data and the data given as the magma density allowed is 350 kg crystal per meter cube of solution, crystal growth rate determine experimentally under the conditions of the crystallizer and G value is given to us crystal density is given as 1,700 kg per meter cube. Now, the crystal size is basically dominant crystal size and that we consider as L D and that is 0.8 mm.

Heat of crystallization because it is required to make the energy balance and that is 30 kilocalorie per kg and it is basically the absorption of heat occurs during crystallization. So, crystal takes this heat and further we have latent heat of vaporization of water at temperature of crystallizer which is 570 kilocalorie per kg. So, this heat is required for the water to be converted into vapour form inside the crystallizer when evaporation will take place.

And further we have superheat allowed in the heat exchanger and that is 3 degree. So, all these parameters will be used and where it will be used that will be clear to you when we solve this problem. And further we have overall heat transfer coefficient in a heat exchanger which is equal to 1,000 kilocalorie per hour meter square degree Celsius. Low pressure steam is available in a heat exchanger at 3 kg per centimeter square gauge.

And latent heat of condensation is 510 kilocalorie per kg. So, you see number of parameters are given to us and based on that let us start the design of crystallizer.

(Refer Slide Time: 11:21)



So, first of all we have to make the material balance and to make the balance we consider the basis and that basis is 1 hour operation. So, let us discuss that. So, here you see we have solution in. Solution in means whatever solution is entering into crystallizer and that is 20 meter cube. If you see this is basically the feed and for one hour basis we consider 20 meter cube.

How much solute should be entered because feed concentration is given as 200 kg per meter cube. So, in 20 meter cube total this much solute will be entered and that should be 4,000 kg. How much water should enter that is basically 20 meter cube and 1,200 is basically the density of the solution minus 200 that is the solute concentration at the inlet condition. So, when we deduct this we can find how much water is entering and that comes out as 20,000 kg.

Further, we consider magma density which is 350 kg crystal per meter cube of solution. So, this value is given to you. So, what we can consider further? So, when solution will enter in the crystallizer that will be at saturation condition. So, at saturation condition what we can consider that 350 kg crystal per 250 kg solute in the solution. So, what will happen? We have 350 kg crystal and 250 kg solute.

So, if I consider how much crystal should be form so that we can calculate as 350 that is crystal density divided by total solute which is available in magma, which is available in feed. So, that is basically 350 + 250 per meter cube and we have total 4,000 kg solute. So how much crystal we can obtain as 2333.33. So, further we have to find out the solute which is leaving with the mother liquor.

And that should be 166.67 because 4,000 is entering this much crystal are formed so remaining is available with mother liquor. So, next we have to find out volume of the solution which is leaving with the mother liquor. So, that we can obtain with the solid which is leaving with mother liquor that is 1666.67 divided by 250 kg per meter cube which is the concentration at saturation condition.

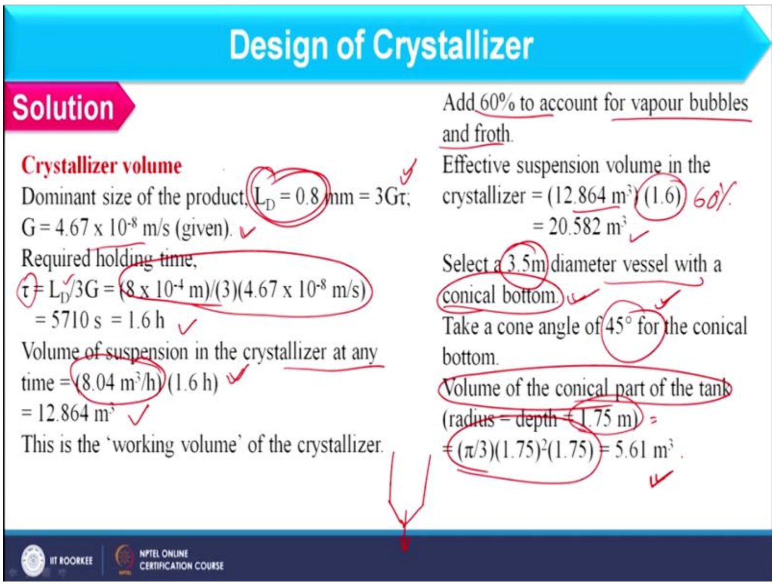
So, total volume of the solution is 6.667 meter cube which is leaving the crystallizer and further we have to make the balance on solvent side. So, mass of the solvent which is water and that mass of the solvent leaving the crystallizer is total volume which is leaving that is 6.667 and that should 1,200 – 250. So, 1,200 is the density of the solution minus 250 which is at saturation condition.

So, total water which is leaving is 6333.346. So, this much water is available with mother liquor. So, how much water should be evaporated is basically difference of this as well as this. So, total vapour formed are basically 13666.654 kg. So, further we can find out how much volume of the slurry leaving per hour that is volume of the solution and the volume of the crystal leaving.

So, volume of the solution we have already calculated here so that I can consider here as well and volume of the crystal because total crystal are formed as 2333.33 kg divided by density of the crystal. So, we can consider 8.04 meter cube per hour of slurry which is leaving per hour. So, in this way we can find out how much volume which is leaving the crystallizer in a given time and that is per hour.

And now we have to calculate the volume of the crystallizer. For that purpose we have to find out the residence time. It means for how long the solution is remaining in the crystallizer. So, whatever solution is leaving into the residence time will give the total volume of the liquid which is available in the crystallizer at a given time.

(Refer Slide Time: 16:53)



So, to find out we have to consider the L D which is basically the size of the product and that is 0.8 mm. And that should be equal to 3 G tau and this expression we have already discussed in the last example and here we are given the growth rate as 4.67 into 10 is to the power – 8 meter second and we need to calculate the holdup time or that is basically the residence time so that tau value we can obtain as L D / 3 G.

And when I am putting all these value in this expression we can find the total tau is 1.6 hour. So, let us focus on the total volume of the suspension in the crystallizer. This much volume per hour is leaving the crystallizer in a given time and this much time is required for processing in the crystallizer. So, the multiplication of these will give the total volume of the liquid which is available in crystallizer.

So, that is basically the working volume we have to find out total volume. So, up to working volume we have already seen the solution last example. Let us further discuss what we should consider more to find out crystallizer volume. In that case you should also include the volume where vapour is formed and that volume should be more than the volume which we consider as the working volume.

So, usually the volume of space in crystallizer where vapour is formed and forth is created is usually 60% of the total. So, we need to add 60% to account the vapour bubbles and the forth and the total volume of the crystallizer so we can obtain as 12.864 meter cube into 1.6

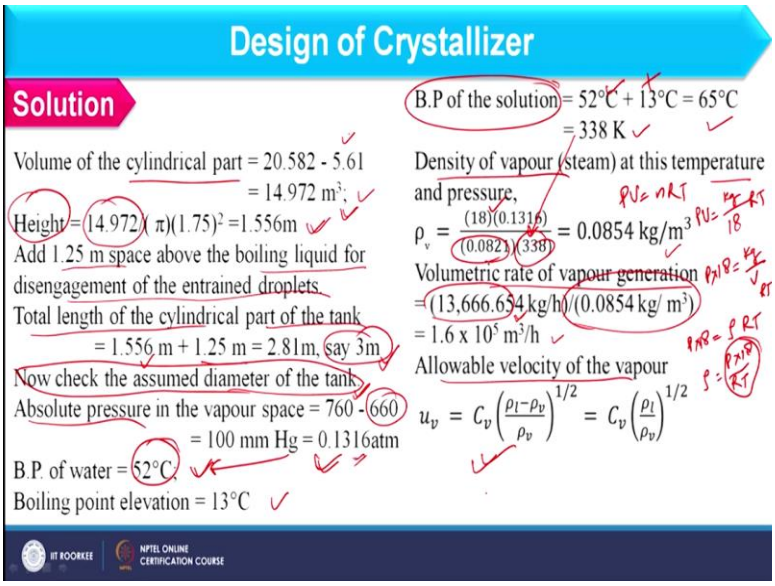
because 60% extra we are considering. So, total volume of crystallizer we can obtain as 20.582 meter cube.

Further, if you recall the last lecture of last week there we have consider that diameter should be assumed and then that diameter should be verified further. So, let us assume the diameter and as far as assumption is concerned we consider a random value and that is basically 3.5 meter diameter of the vessel with conical bottom because that is an important structure because crystallizer without conical section faces difficulty to discharge the solid.

So, in this way we can consider crystallizer body as the vessel having conical bottom. How much conical bottom is 45 degree angle. So, cone is available at 45 degree. So, volume of the conical part is how much? If I consider that radius should be equal to depth because that is corresponding to 45 degree. So, depth is basically 1.75 and so the radius and pi / 3 r square h is the volume of the conical part.

And considering these values we can find the volume of conical section of the crystallizer as 5.61 meter cube. So, in this way you can find the total volume of the crystallizer and volume of the conical section. Deduction of this will give the volume of the crystallizer when I am considering the cylindrical section of the crystallizer only.

(Refer Slide Time: 20:58)



So, let us see that volume of the crystallizer part is 20.582 – 5.61 so 14.972 meter cube we consider as volume of the cylindrical part of the crystallizer. Now you know the diameter. So, I know the volume of the cylindrical part so I can calculate height of the cylindrical section or height of the shell. So, further we need to add 1.25 meter space above the boiling liquid for disengagement of the entrained droplets.

So, that is basically the added height and so the total length of the cylindrical part of the tank is 1.556 which is the height of the shell plus 1.25 which is the additional height. So, total 2.81 meter we can consider as height of the cylinder which is equivalent to 3 meter. So, we can consider 3 meter as height of the cylindrical part of the crystallizer and further we have to check the diameter because we have assumed the value of diameter as 3.5 meter.

So, for that we have to focus on absolute pressure and then the volume and so the volumetric flow and the velocity. So, let us start that calculation. So, as far as pressure is concerned we have pressure as 100 mm Hg which is the absolute pressure 660 vacuum is given so that we can deduct from 760 because that is the atmospheric pressure at Hg scale. So, we can consider 100 mm Hg which is equivalent to 0.1316 atmosphere.

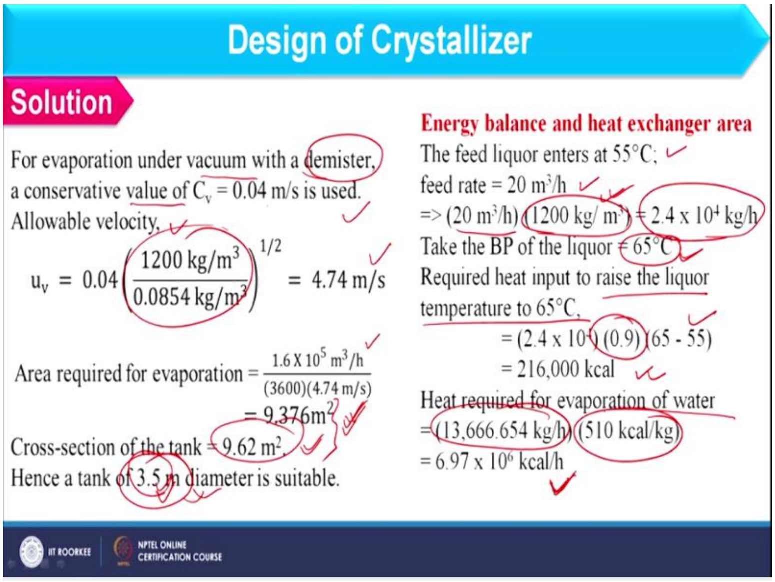
Boiling point of the water is given as 52 degree Celsius corresponding to this pressure so that we can obtain from the steam table and further boiling point elevation is given to us at 13 degree Celsius. So, the volume of the solution we can obtain as addition of boiling point plus BPR and that should be 65 degree Celsius which is 338 Kelvin. And now we have to find out density of the vapour that is the steam at given temperature and pressure.

So, how we can obtain that? Now, we consider steam as ideal gas. So, ideal gas we have the correlation as Pv = nRT. So, if we consider this here we can write this equation as Pv is equal to total mass that is kg per molecular weight and that molecular weight is of water which is 18 into RT. So, we can further resolve this as P into 18 which is equal to kg per volume into RT.

So, this we can find as P into 18 = density into RT. So, density should be P into 18 / RT. So, this expression we can consider over here. So, 18 is the molecular weight, pressure we can obtain as 0.1316, 0.0821 is the value of gas constant that is R and 338 is basically the temperature. So, solving this equation we can find density of the vapour which is steam and that should be equal to 0.0854 kg per meter cube.

Now, once I am having this we can find out volumetric rate. Next, we have to calculate the volumetric flow of vapour generation and that should be 1366.654 that is how much water which is leaving as vapour that we have already calculated previously and that should be divided by the density of the vapour and so we can obtain volumetric flow rate of the vapour as 1.6 into 10 is to the power 5 meter cube per hour. And further we can obtain allowable velocity of the vapour using this expression.

(Refer Slide Time: 25:52)



Where evaporation under vacuum with demister that is basically the pad in which liquid droplet is captured, a conservative value of C v is consider which is basically 0.04 meter per second. So, considering this value we can obtain the allowable velocity of the vapour and that is basically 4.74 meter per second. Other parameters are given to you so you can calculate this vapour velocity.

And once I am having this we can divide the volumetric flow divided by the vapour velocity and we can find the total cross sectional area of evaporation section and that is the section in crystallizer also. So that comes out as 9.376 meter square. So, considering this cross sectional area you can find out the diameter which will be close to 3.5. So, further I am considering that 3.5 diameter is suitable.

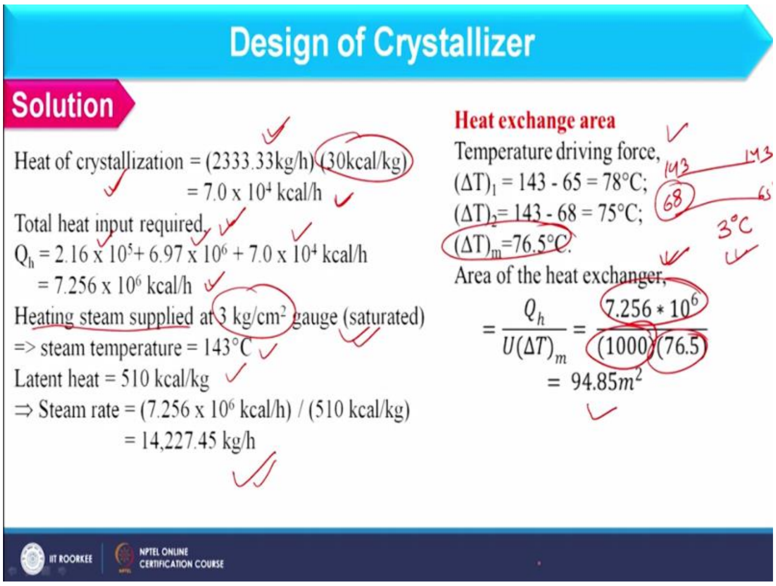
Now, if you are checking the diameter and if diameter whatever you have calculated is not close to the assumed value you can find this diameter and restart the calculation from previous slide where you have to obtain the height depending upon these diameter. So, in that way you have to iterate it again, but here we are stopping here because I am getting the diameter which is close to the assumed value.

However, value I have obtained that will be slightly lesser than this. So, I have to find out revised cross sectional area corresponding to this diameter and it is coming as 9.62 which is close to this. Now, we have to carry out the heat balance and find out the heat transfer area. So, let us start the calculation for heat exchanger. Till now, we have only focused on the crystallizer side now we should discuss the heat exchanger side also.

So, as far as feed which is entering into the heat exchanger is at 55 degree Celsius and feed rate is 20 meter cube per hour. So, you can calculate total mass flow rate of feed that is 20 meter cube per hour into 1,200 kg per meter cube that is the density of the solution. So, total mass flow rate is 2.4 into 10 is to the power 4 kg per hour including BPR of the liquid we can find boiling point of the solution as 65 degree Celsius which you can find in previous slides also.

So, required heat input to raise the liquor up to 65 degree from 55 considering the Cp of the solution which is already given in the problem you can find total heat input as 2.16 into 10 is to the power 5 kilocalorie. And further we have to find out the heat required for evaporation of the water, heat of vaporization is already given to us, total vapour which is generated is given to us. So, this much is the total heat which is required for evaporation of water.

(Refer Slide Time: 29:18)



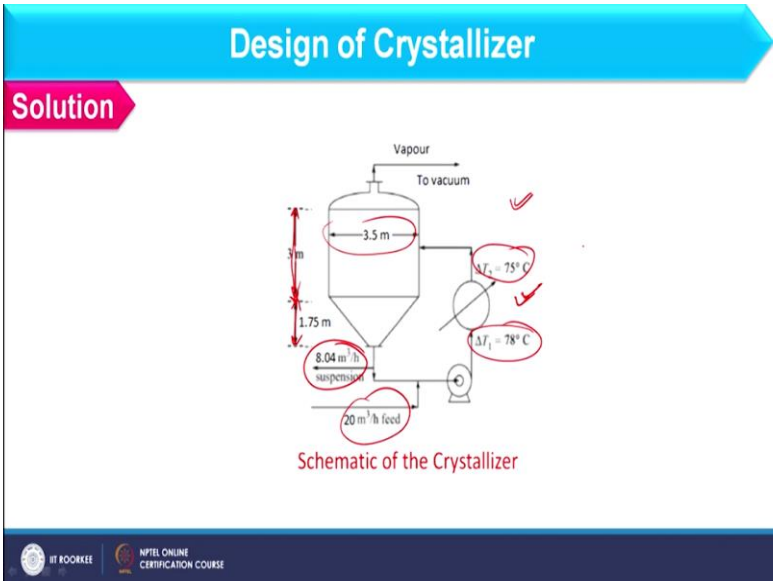
So, further we can find out the heat which is required for crystallization because heat of crystallization is also given to us and how much crystals are formed per hour it is also given to us. So, we can calculate the heat of crystallization accordingly. So, total heat input is whatever is required for heating purpose, whatever is required for vapourization and whatever is required for crystallization.

Addition of all these three values will give the total heat input in the system and we are providing this heat with the help of steam which is available at 3 kg per centimeter square. If you consider the steam table corresponding temperature you can find out as 143 degree Celsius considering saturated steam and latent heat is already given to us so we can simply calculate steam rate.

Now, once I am having the steam rate and total heat we can find out the heat transfer area and for that we have to find out log mean temperature difference. So, here you see 143 is available at saturation condition and feed is heated up in 65 degree to 68 degree and how this 68 is obtained because this 3 degree is basically the superheat which is required and which is given in the problem only.

So, LMTD you can obtain as 76.5 degree Celsius. So, how much area you can obtain? Total heat duty divided by overall heat transfer coefficient which is also given and divided by LMTD. So, 94.85 meter square is the total area of heat transfer. So, considering all these value we can design the crystallizer and that will be like here we have.

(Refer Slide Time: 31:20)



This is the schematic of crystallizer where 3.5 is the diameter, 3 meter is the height of the cylindrical section and 1.75 meter is the height of (()) (31:33) section. Total slurry which is coming out from the system is given as this, total feed is 20 meter cube per hour and in the heat exchanger we consider delta T as 75 and 78 at two terminal conditions and so in this way we can design the crystallizer.

And we can make the geometry of crystallizer as shown in this slide. So, in this lecture we have discussed two example to illustrate the design of crystallizer in details. So, that is all for now. Thank you.