Basic Principles and Calculations in Chemical Engineering
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Lecture - 22
Energy Balance with Multiple Streams without Reaction

Welcome to massive open online course on basic principles and calculations in chemical engineering. So we are discussing about the energy balances on nonreactive processes under module seven. Now in this lecture of this module we will discuss about again that energy balance with some examples where multiple streams will be involving without reactions.

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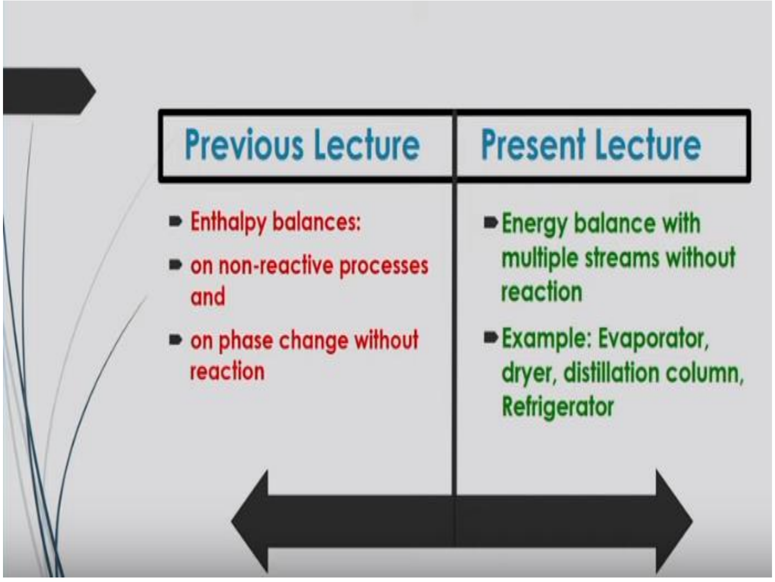

Previous Lecture

- Enthalpy balances:
- on non-reactive processes and
- on phase change without reaction

Present Lecture

- Energy balance with multiple streams without reaction
- Example: Evaporator, dryer, distillation column, Refrigerator

In the previous slides, we have described that enthalpy balances on nonreactive processes and also how enthalpy can be calculated based on the phase change. So here again, we will discuss that enthalpy balances or heat balances there with nonreactive systems where there will be more than one you know, streams will be there in the process like evaporation process, drying process, distillation process, even refrigeration process, how this you know, heat energy can be calculated during the process.

Now, before going to that, you know calculation based on that, you know principle of energy conservation equation we should know that what is that energy conservation equation.

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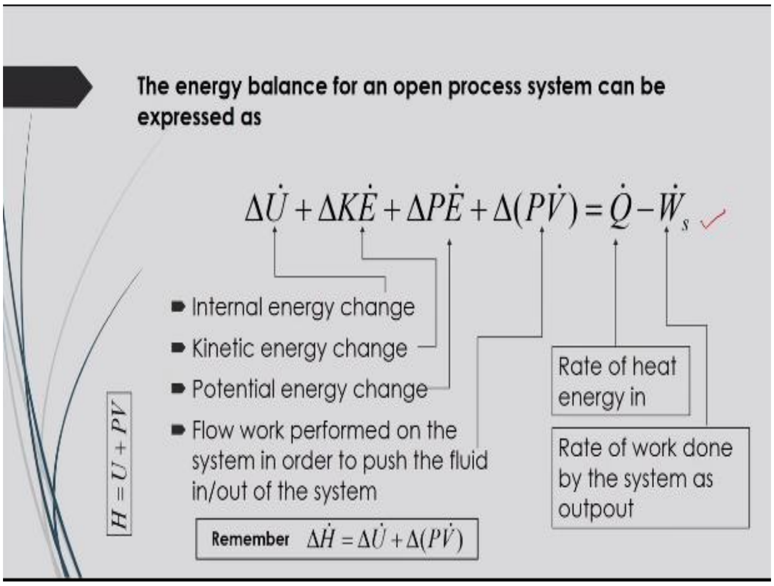

The energy balance for an open process system can be expressed as

$$\Delta\dot{U} + \Delta\dot{KE} + \Delta\dot{PE} + \Delta(P\dot{V}) = \dot{Q} - \dot{W}_s$$ ✓

- Internal energy change
- Kinetic energy change
- Potential energy change
- Flow work performed on the system in order to push the fluid in/out of the system

Rate of heat energy in

Rate of work done by the system as outpout

$H = U + PV$

Remember $\Delta\dot{H} = \Delta\dot{U} + \Delta(P\dot{V})$

We have already described all those equations and derivation in our previous lectures. So still we are actually let us having this look of that equation here. Here this you know general energy balance for an open process systems can be expressed by this equation where delta U is the internal energy change. Delta KE is the kinetic energy change. Delta PE is the potential energy change and delta PV is the you know flow work that is performed on the system in order to push the fluid in or out of the system.

And Q dot the rate of heat energy that is into the system and W s dot, this is the rate of work done by the system as the output. So this energy balance is to be used for the calculation of different you know, processes where multiple streams are involved in there. So as we know that the summation of this internal energy change and also flow work performed on the system that will give you that you know enthalpy change of the you know system there.

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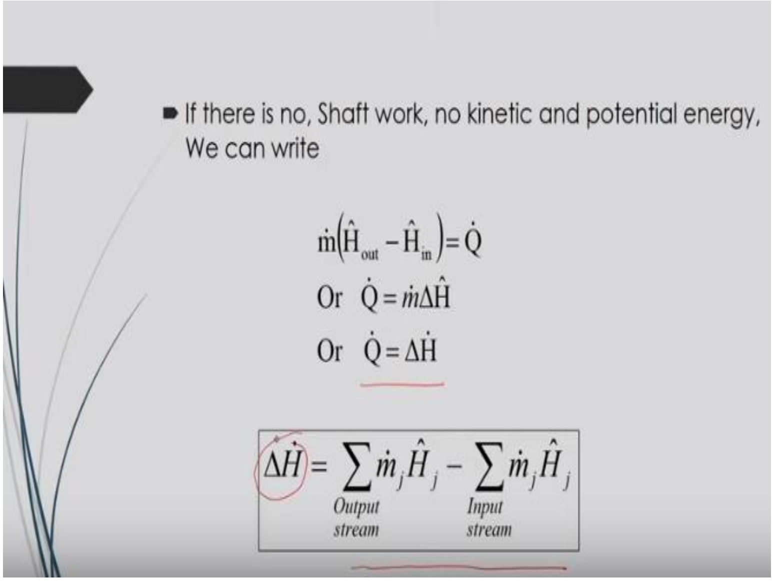

- If there is no, Shaft work, no kinetic and potential energy, We can write

$$\dot{m}\left(\hat{H}_{out} - \hat{H}_{in}\right) = \dot{Q}$$

$$\text{Or} \quad \dot{Q} = \dot{m}\Delta\hat{H}$$

$$\text{Or} \quad \dot{Q} = \Delta\dot{H}$$

$$\boxed{\Delta\dot{H} = \underset{\substack{Output\\stream}}{\sum \dot{m}_j \hat{H}_j} - \underset{\substack{Input\\stream}}{\sum \dot{m}_j \hat{H}_j}}$$

So if there is no shaft work, no kinetic and potential energy you know will be there, then we can say that canceling all those you know shaft work know that is kinetic energy, potential energy, we can have this simplified form of this, you know energy balance equation as Q dot will be is equal to delta H dot. Here, remember that this delta H dot is basically the rate of enthalpy change for that particular systems.

Now, if there are more than one, you know streams there in the process, then you have to calculate what will be the enthalpy for all components in the output streams and also what should be the enthalpy in you know, enthalpy of that components in the inlet stream. And from those, you know that total enthalpy of those components in the inlet and output streams, we can calculate that enthalpy change there by this equation.

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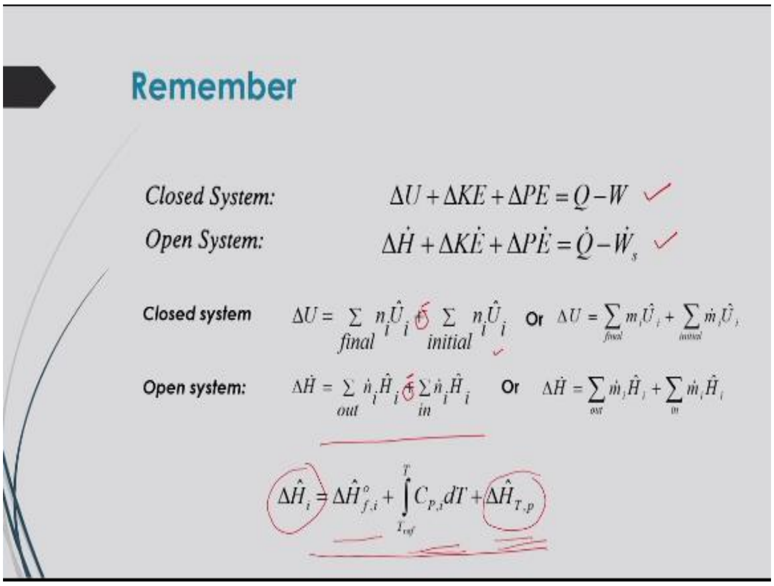

Remember

Closed System: $\Delta U + \Delta KE + \Delta PE = Q - W$ ✓

Open System: $\Delta\dot{H} + \Delta K\dot{E} + \Delta P\dot{E} = \dot{Q} - \dot{W}_s$ ✓

Closed system $\Delta U = \sum_{final} n_i \hat{U}_i + \sum_{initial} n_i \hat{U}_i$ Or $\Delta U = \sum_{final} m_i \hat{U}_i + \sum_{initial} \dot{m}_i \hat{U}_i$

Open system: $\Delta\dot{H} = \sum_{out} \dot{n}_i \hat{H}_i + \sum_{in} \dot{n}_i \hat{H}_i$ Or $\Delta\dot{H} = \sum_{out} \dot{m}_i \hat{H}_i + \sum_{in} \dot{m}_i \hat{H}_i$

$$\Delta\hat{H}_i = \Delta\hat{H}^o_{f,i} + \int_{T_{ref}}^{T} C_{P,i}\,dT + \Delta\hat{H}_{T,p}$$

Now in this case, remember that for the closed system, this equation to be used where the rate of the energy is not being considered. Whereas open system you will see that this the same equation, but in terms of rate, at a continuous process we can say that this equation will be you know considered.

And in terms of internal energy for multiple streams based you know processes you will see that, that for closed system that internal energy change will be again that summation of internal energy of all components in the final and initial states and from which you can get the total you know that internal energy change there. And similarly for open system that we can have this you know that enthalpy change of this on the inlet and outlet streams.

So here it will be, there may be you know that our final or initial here that we will see you have to subtract this. So here instead of plus it will be negative here it will be negative there. Whereas for all you know that if there are, you know, that multiple inlets there, then you have to sum it up in inlet there all that components for each systems there.

So in this way you have to you know, calculate this enthalpy for particular you know component what should be that specific enthalpy there that is specific enthalpy will be calculated based on that what will be the enthalpy change of formation of that components and also if there is a change of temperature from reference to other temperature, then you have to calculate the sensible heat.

And also if there is a enthalpy change due to the phase change, then you have to add up all those you know, that enthalpy change due to that you know, change of you know phases. So in that case, the summation of all this you know enthalpy change due to formation, enthalpy change due to the sensibly heat change and also enthalpy change due to the phase transition then you have to get this you know enthalpy change for that individual components in the you know system.

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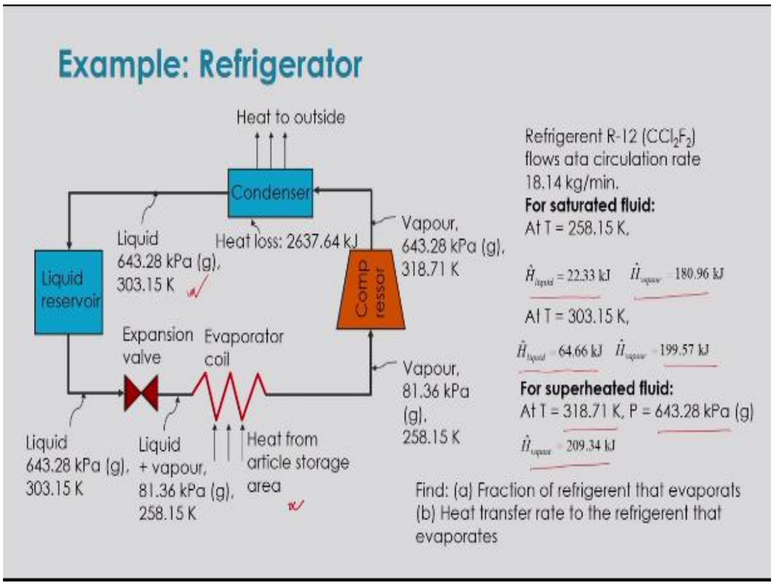

Example: Refrigerator

Refrigerent R-12 (CCl_2F_2) flows ata circulation rate 18.14 kg/min.

For saturated fluid:

At T = 258.15 K,

$\hat{H}_{liquid} = 22.33$ kJ $\hat{H}_{vapour} = 180.96$ kJ

At T = 303.15 K,

$\hat{H}_{liquid} = 64.66$ kJ $\hat{H}_{vapour} = 199.57$ kJ

For superheated fluid:

At T = 318.71 K, P = 643.28 kPa (g)

$\hat{H}_{vapour} = 209.34$ kJ

Find: (a) Fraction of refrigerent that evaporats
(b) Heat transfer rate to the refrigerent that evaporates

Now let us do an example for refrigeration process. We know that we are using refrigerator in our daily use. Even for air condition we are using that you know air conditioner like this how those things are actually working where we seek principle like show here that you know that there are some components like here different units like liquid reservoirs, expansion valve, evaporator coil, compressor and condenser.

These are the you know, several units are generally used for that refrigeration process. In this case, you will see that in the liquid reservoir some you know refrigerant to be you know kept there. So from that reservoir that refrigerant like you know that refrigerant R-12 it is called carbon dichloride difluoride. So there you can use that refrigerant there are generally being used.

So liquid reservoir of that refrigerant as a liquid it will be there and from that it is sent to sent through the expansion valve and whenever it is coming from that expansion valve at a certain you know that pressure, maybe you know that the pressure will be lower than that, you know, that inlet stream of this expansion valve. And you will see that this liquid will be you know coming out from that expansion valve as a liquid and vapor.

And after that it will be coming through the evaporator where this you know liquid will be evaporated and in that case by this evaporator heat from the certain article that is stored in refrigerator area that will be you know coming into that you know evaporator.

And after that the vapor of that you know refrigerator will be you know passing through that compressor where the pressure will be you know again increased from increased by this you know compressor there at higher temperature of this vapor. And then it will go through the condenser where heat loss will be there and this heat loss will be going that outside there, so that heat will be going to that outside by this condenser.

And then that vapor that refrigerant again it will become that liquid refrigerant and it will be stored in the liquid reservoir. Again from that liquid reservoir it will go through that expansion valve and then evaporator and then compressor and then condenser and it will be you know that continuously cycle will be going on.

So in this operation you will see that whenever liquid is coming from the liquid reservoir and passing through that expansion valve, the pressure will be you know reduced and temperature will be you know reduced to a certain temperature. And then it will go through that evaporator where heat will be sucked from that you know, substances or material which is kept in that refrigerator.

And by that heat you will see that it will be evaporated and then it will go to the compressor and by this compressor there again that pressure will be you know increased by increasing the temperature also there. So and it will go through that condenser to condense it that you know refrigerator by releasing that heat to the atmosphere. So in this way this refrigerator generally works.

So based on this you know principle and in the slides that if we use this refrigerant and flows at a circulation rate of you know 18.14 kg per minute. In that case, you will see that for saturated fluid at T you know that 258.15 Kelvin this enthalpy change, it will be for that liquid it will be 22.33. And enthalpy of the vapor for that superheated fluid it will be 180.96 kilojoule.

Whereas, at 303.15 K that is Kelvin this enthalpy of the liquid it will be you know 64.66 kilojoule and then enthalpy of this vapor it will be 199.57 kilojoule and for superheated fluid at temperature 318.71 K this pressure is that is 643.28 kilopascal, there the enthalpy of that vapor it will be 209.34 kilo joule.

So here in this slide in this you know schematic diagram of this regeneration process, you will see that there are several you know that operating conditions or several conditions like temperature and pressure are given in the inlet and outlet of this you know several you know equipments which are being used there.

So if we consider that you know expansion valve there at inlet condition of this expansion valve, it will be liquid flowing at that you know circulation rate and the pressure is 643.28 kilopascal that is in gas pressure, where temperature is 303.15 Kelvin and after this expansion valve, the mixture of liquid and vapor will be there at a pressure of 81.36 kilopascal and temperature of 258.15 K.

Here this is basically less than 0 degrees Celsius we can say. So here this know it will be you know vapor form here this you know this refrigerant and then it will go through that evaporator coil where that heat will be supplied to that evaporator and this liquid and vapor will be you know superheated and at a temperature at a pressure of 81.36 kilopascal and temperature at 258.15 K.

And it goes through that compressor where compressor outlet will have the component of vapor of that refrigerant and pressure of 643.28 kilopascal. But temperature will be higher than this you know that inlet temperature that is 318 point you know 71 Kelvin and after that it will go to the condenser where inlet condition of that condenser it will be that you know vapor and also outlet condition it will be liquid of that you know pressure and temperature is shown here in the slides.

So in this condenser some heat will be lost that is to the you know that atmosphere and based on which you have to calculate that fraction of refrigerant that evaporates there and heat transfer rate to the refrigerant that evaporates there. So in this case what should be the heat transfer rate in this evaporator coil and also you have to calculate that fraction of the refrigerant that evaporates you have to calculate there.

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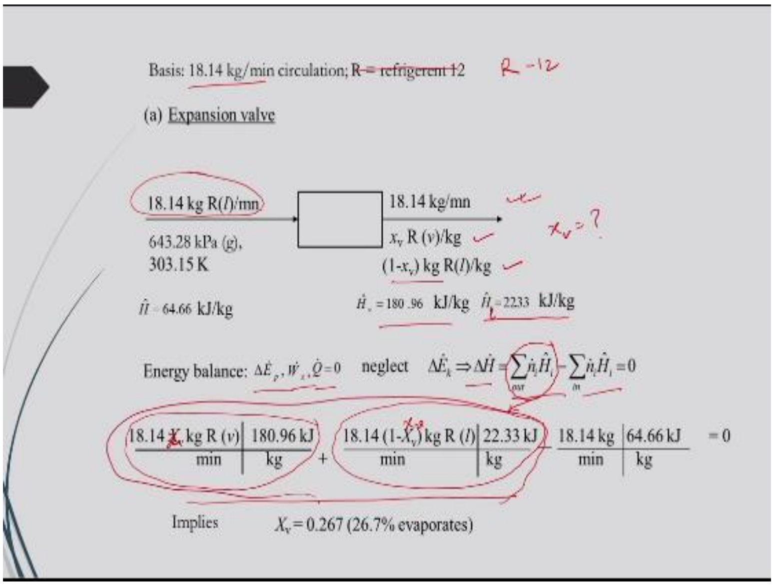

Basis: 18.14 kg/min circulation; ~~R = refrigerant 12~~ R-12

(a) Expansion valve

18.14 kg R(*l*)/mn

643.28 kPa (g),
303.15 K

$\hat{H} = 64.66$ kJ/kg

18.14 kg/mn
x_v R (*v*)/kg
$(1-x_v)$ kg R(*l*)/kg

$x_v = ?$

$\hat{H}_v = 180.96$ kJ/kg $\hat{H}_l = 22.33$ kJ/kg

Energy balance: $\Delta\dot{E}_p, \dot{W}_s, \dot{Q} = 0$ neglect $\Delta\dot{E}_k \Rightarrow \Delta\dot{H} = \sum_{out}\dot{n}_i\hat{H}_i - \sum_{in}\dot{n}_i\hat{H}_i = 0$

$$\frac{18.14\, X_v \text{ kg R}(v)}{\text{min}}\Big|\frac{180.96 \text{ kJ}}{\text{kg}} + \frac{18.14(1-X_v)\text{ kg R}(l)}{\text{min}}\Big|\frac{22.33\text{ kJ}}{\text{kg}} - \frac{18.14 \text{ kg}}{\text{min}}\Big|\frac{64.66\text{ kJ}}{\text{kg}} = 0$$

Implies $X_v = 0.267$ (26.7% evaporates)

Now in this case let us solve this problem. First here basis is that what is the circulation rate of you know refrigerant, refrigerant here in this case it is basically R-12 as refrigerant. This is R-12 as refrigerant. So circulation rate is 18.14 kg per minute and if we consider first that expansion valve we can say that inlet is you know liquid flow rate is 18.15 kg that is liquid refrigerant, R means refrigerant here.

And here pressure is 643.28 kilopascal and temperature 303.15 K and in the outlet condition that the same circulation rate is there since it will be of 18.14 kg per minute, but fraction of that you know refrigerant will be converting into vapor. So that will be you know regarded as x v and 1 – x v that will remain as a liquid. Then this x v you have to calculate here that is fraction of the refrigerant, which will be evaporates.

And in this case the heat of vaporization it is given that 180.96 kilojoule whereas heat of you know enthalpy of that liquid is given as you know this 22.33 kilojoule per kg. Now, if we do the energy balance over this you know expansion valve, we can see that here, potential energy will be equals to 0. You know shaft work will be equals to 0. Heat supply to this system that will be equals to 0.

And then we can have only you know that kinetic energy change there. So that will be is equal to you know enthalpy change there but this enthalpy change will be because of that what will be the enthalpy in the outlet stream of this you know expansion valve and total enthalpy in the you know inlet streams there. Now according to these, we can say that if we do this material balance of this you know inlet and outlet streams, we can see that at the outlet streams what are the components are there.

So it will be 18.14 into x v. This is basically a vapor of that refrigerant and this is x v vapor and into 180 point you know 96 you know kilojoule since, this you know specific heat, specific enthalpy of that you know vapor is 180.96. So we can say that this amount of you know enthalpy is there for this vapor. And similarly, for other components for that liquid component here that is 1 – x v, this is x v small x v.

So 18.14 into 1 – x v into kg this amount of you know liquid will be there of that refrigerant. And here enthalpy for that liquid is 22.33 kilojoules. You have to multiply it. So ultimately this amount will give you that you know enthalpy of that liquid in that outlet streams. Now, summation of these two you know enthalpy will give you that total enthalpy in that you know outlet streams.

Basically from this equation this component will come as here okay, summation of these two.

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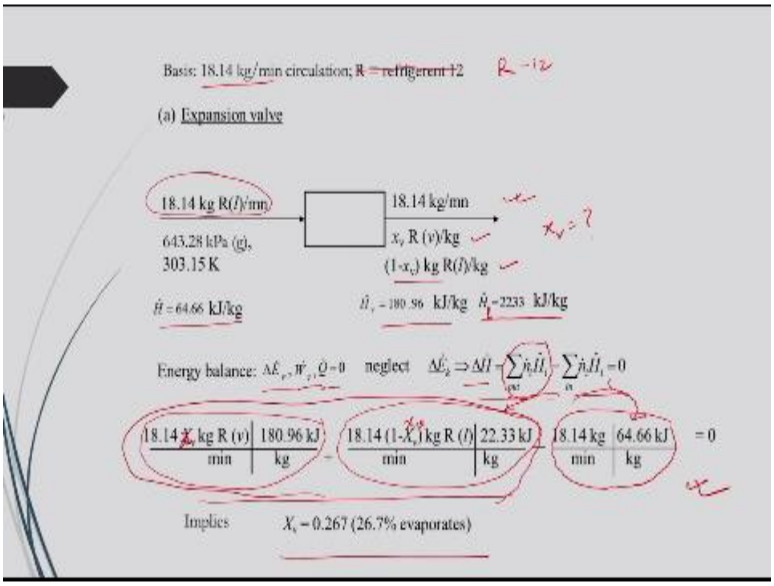

Basis: 18.14 kg/min circulation; ~~R = refrigerent 12~~ R-12

(a) Expansion valve

$\hat{H} = 64.66$ kJ/kg

$\hat{H}_v = 180.96$ kJ/kg $\hat{H}_l = 22.33$ kJ/kg

Energy balance: $\Delta \dot{E}_p, \dot{W}_s, \dot{Q} = 0$ neglect $\Delta \dot{E}_k \Rightarrow \Delta \dot{H} = \sum_{out} \dot{n}_i \hat{H}_i - \sum_{in} \dot{n}_i \hat{H}_i = 0$

$$\frac{18.14\, x_v \text{ kg R}(v)}{\text{min}} \bigg| \frac{180.96 \text{ kJ}}{\text{kg}} + \frac{18.14(1-x_v)\text{ kg R}(l)}{\text{min}} \bigg| \frac{22.33 \text{ kJ}}{\text{kg}} - \frac{18.14 \text{ kg}}{\text{min}} \bigg| \frac{64.66 \text{ kJ}}{\text{kg}} = 0$$

Implies $X_v = 0.267$ (26.7% evaporates)

Now similarly, we can say that other components in the inlet stream since here only one stream is here. So we can have this you know, liquid refrigerant, what it is know enthalpy it is given 64.66 and amount is 18.14 kg of that liquid refrigerant. So we have to multiply this 18.14 by 64.11 64.66 kilojoule per kg. Then you can have this you know summation of this component here, we can represent this things here.

So according to this equation, we can write this you know, equation here. So from this if you solve this problem for x v you can get this xv will be equal to 0.267 that is 26.7% evaporators there, evaporates there. So 26.7% of liquid refrigerant will be evaporates in this refrigeration process.

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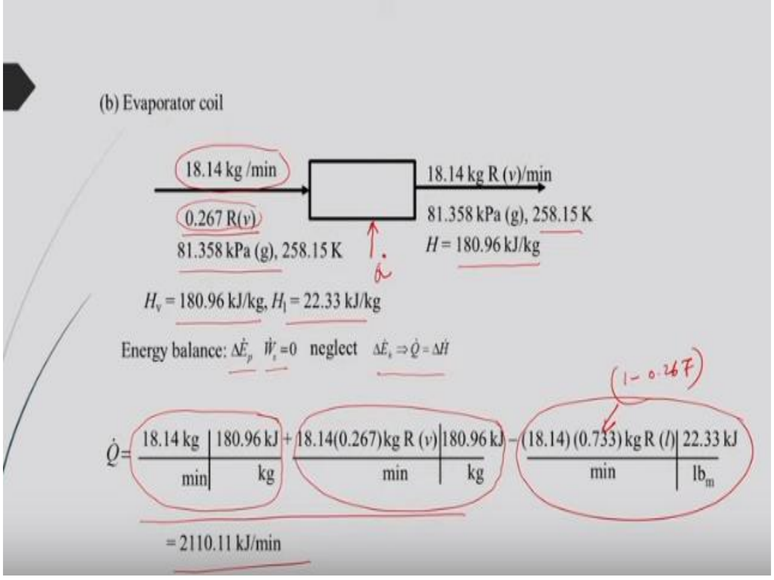

(b) Evaporator coil

18.14 kg /min

0.267 R(*v*)

81.358 kPa (g), 258.15 K

18.14 kg R (*v*)/min

81.358 kPa (g), 258.15 K

$H = 180.96$ kJ/kg

$\dot{Q}$

$H_v = 180.96$ kJ/kg, $H_l = 22.33$ kJ/kg

Energy balance: $\Delta\dot{E}_p$, $\dot{W}_s = 0$ neglect $\Delta\dot{E}_k \Rightarrow \dot{Q} = \Delta\dot{H}$

$$\dot{Q} = \frac{18.14\ \text{kg}}{\text{min}}\Big|\frac{180.96\ \text{kJ}}{\text{kg}} + \frac{18.14(0.267)\ \text{kg R}(v)}{\text{min}}\Big|\frac{180.96\ \text{kJ}}{\text{kg}} - \frac{(18.14)\overset{(1-0.267)}{(0.733)}\ \text{kg R}(l)}{\text{min}}\Big|\frac{22.33\ \text{kJ}}{\text{lb}_m}$$

$$= 2110.11\ \text{kJ/min}$$

Now, next question is that what will be the, you know that heat transfer rate to the refrigerant that evaporates. Now, if we do that again evaporator coil energy balance there, we can say that in the inlet streams, the flow rate of that refrigerant is 18.14 kg per minute and the fraction of vapor in the coil it will be basically what is coming out from the expansion valve, it is basically 0.267 you know vapor refrigerant.

And this vapor refrigerant will go to this evaporator coil and you will see that it will be you know, again going out from this evaporation coil after getting heat, that heat is not known to you. So that heat will be supplied here so that heat rate to be you know, calculated. But you will see that enthalpy of that vapor which is coming out from that evaporator is 180.96 kilojoule per kg and at a pressure of 81.358 kilopascal and temperature of 258.15 K.

Whereas, at the inlet condition this you know enthalpy of this vapor is 180.96 kilojoules per kg whereas liquid enthalpy is 22.33 kilojoule per kg. So here this you know fraction of that vapor will be coming to that evaporation coil as well as other part of that refrigerant that will be 1 - 0.267 that fraction of refrigerant as a liquid it will go to that evaporator coil.

Now in that case, we can say that here what will be the amount of you know energy that is supplied. So accordingly again if you do that energy balance, so we can get that you know, potential energy even shaft valve will be neglected. So we can have this you know that Q dot will be is equal to delta H dot. Now Q dot from this we can then have that from the enthalpy change.

So what is the enthalpy in that inlet condition of this you know evaporator coil, this will be there. Again but in the vapor component which is here simply this. Whereas in the outlet streams that vapor you know this is your, you know outlet conditions whereas inlet conditions this you know this will be your liquid you know that refrigerant.

So we can say that here, this is basically this liquid components is 0.733 this is you know 1 - 0.267 we can say. So this you know fractions of liquid will be entering to that evaporator valve which will be you know evaporated along with that, you know vapor which is coming out from that expansion valve, so that also will be there.

So adding up all those you know enthalpy change and after you know balancing that finally you can have this value of Q dot will be is equal 2110.11 kilojoule per minute. So in this way we can calculate what will be the you know heat energy to be supplied to the evaporator coil to you know evaporate that liquid refrigerant and passing through that you know compressor at a certain pressure there, that will be calculated in this way.

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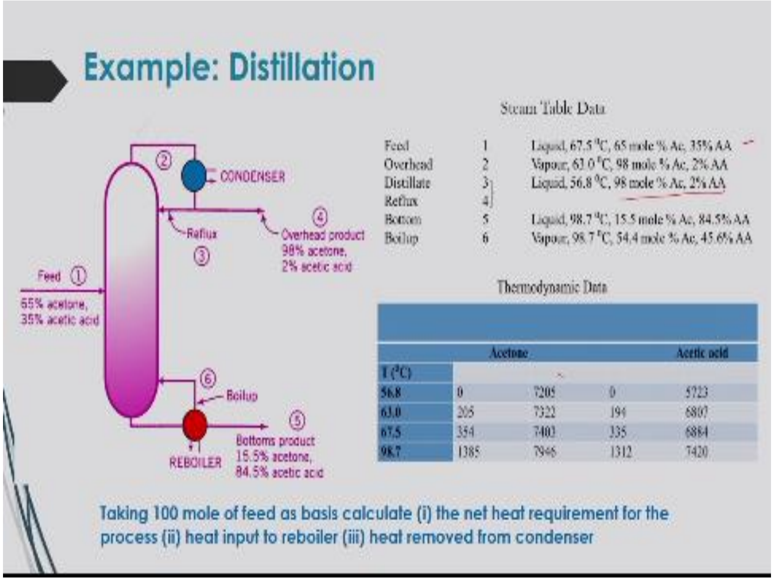

Example: Distillation

Steam Table Data

Feed	1	Liquid, 67.5 °C, 65 mole % Ac, 35% AA
Overhead	2	Vapour, 63.0 °C, 98 mole % Ac, 2% AA
Distillate	3	Liquid, 56.8 °C, 98 mole % Ac, 2% AA
Reflux	4	
Bottom	5	Liquid, 98.7 °C, 15.5 mole % Ac, 84.5% AA
Boilup	6	Vapour, 98.7 °C, 54.4 mole % Ac, 45.6% AA

Thermodynamic Data

	Acetone		Acetic acid	
T (°C)				
56.8	0	7205	0	5723
63.0	205	7322	194	6807
67.5	354	7403	335	6884
98.7	1385	7946	1312	7420

Taking 100 mole of feed as basis calculate (i) the net heat requirement for the process (ii) heat input to reboiler (iii) heat removed from condenser

Let us do another example of you know distillation process where you will see that several you know output from that distillation column will be there whereas one inlet of that feed streams will be there to the distillation column. There you know as an example here like let it be you know, acetone and acetic acid mixture. It will be you know, passed through that you know, distillation column where it will be evaporated based on that boiling point temperature.

And in this case, you know from the bottom of that distillation the product will be coming as you know bottom products of you know certain percentage of acetone and acetic acid and it will be you know recycled to that you know distillation column certain amount that will be as boil up.

Whereas from the top portions, you know that evaporates or you can say vapor phase it will be coming out from the top and then through the condenser it will be sent and so that after condensing that vapor components it will be coming you know liquid and some amount of that liquid will be you know sent back to the you know distillation column as a reflux.

Whereas, other portions will be taken out as a you know, overhead product like some percentage of acetone and acetic acid. So in the overhead product since the acetone has you know, lower boiling point, than acetic acid So we can say that maximum portion of acetic acid will be in the overhead product whereas, you know that small amount of you know acetone will be there in the bottom product.

Whereas, maximum portion will be acetic acid as a liquid in the you know, bottom part of the distillation. And from this bottom part one reboiler to be used to send back to the distillation column certain amount of that you know product for again distillation process. So in this way it will be you know that you know continuously you know operated this distillation column.

And in this case you have to calculate that what will be the net heat required for the process and also heat input to the reboiler and heat removed from the condenser that you have to you know, calculate. Based on that you know certain amount of heat like here 100 mol of heat as basis if you consider then what should be the net heat required for the process that you have to calculate.

So for this you need some data. So from the steam table, you can you know have this data like this for feed if you represent it as one and for you know that feed liquid at 67.5 degree Celsius of the mixture of 65 mol percent of you know acetone and 35% of acetic acid there. And in the overhead as a stream two we can have this you know, that vapor of 63.0 degrees Celsius, where 98 mol percent of you know acetone and 2% of acetic acid will be there.

And in stream three, you will see some amount of you know liquid overhead product will be sent back to the distillation column there and there you will see that it will be sent as a reflux. So we can have this under reflux and that will be as a liquid and it will be sent to the distillation column at temperature 56.8 degrees Celsius. Whereas, the composition will be the same as that it is coming from the, you know overhead product there.

Similarly, you can say that the overhead product from that stream four that will have the same composition and temperature there what is sent back to the you know, distillation column as a reflux. And bottom product we can say that in the stream pipe here, temperature will be 98.7 degree Celsius and mol fraction of that components will be 15.5% of acetone and 84.5% of acetic acid.

And you can say that after reboiling of those you know liquid components by that reboiler as a boil up to be sent to the distillation column at a temperature of 98.7 degrees Celsius. Whereas, mol fraction of that you know acetic or acetone, it would be 54.4 mol percent and acetic acid will be 45.6% of that.

So in this case, you have to find out at a different temperature of this different streams, what will be the you know thermodynamic data like this here what will be the enthalpy change there that you can get from it is a steam table here it is given in this table here. So from this we can of course calculate that you know different, we can say that we can do that energy balance to find out that you know, net heat requirement for the process.

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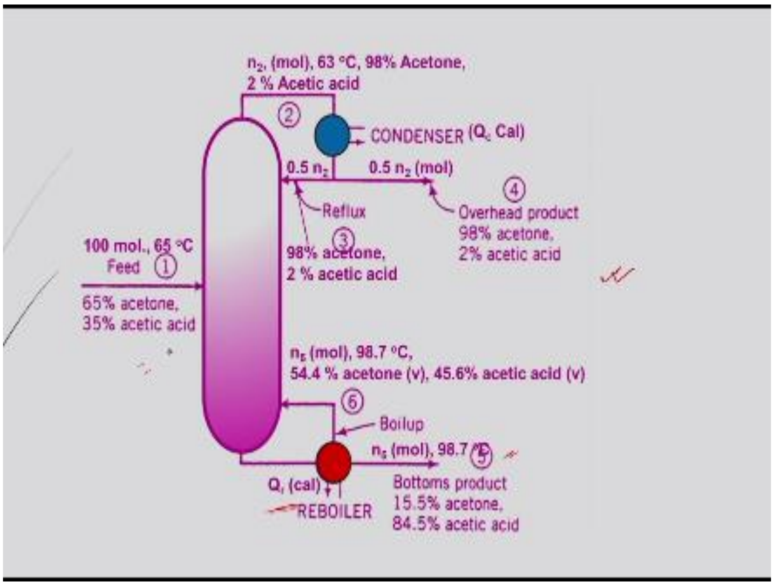

Now, we can actually you know, outline this whole, you know schematic diagram with the different you know, temperature and mol fractions all those things here in this picture as shown in the slide. So please go through this what will be that, you know fraction of that components it is coming out from the top of this distillation column as overhead and what would be the fractions of that components that is going into that distillation column and it is coming as bottom products there.

What will be the Q r that is heat is required for the reboiler and also what is the temperature So all these actually mentions here in this you know, this distillation column.

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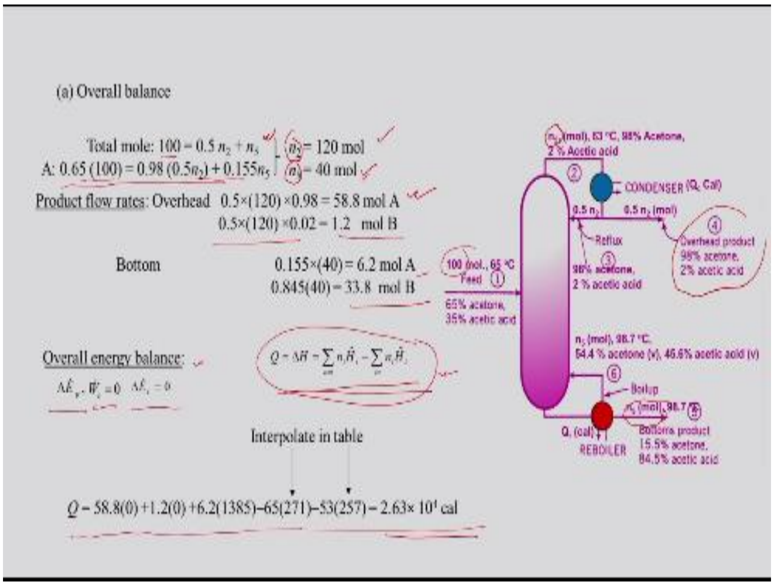

(a) Overall balance

Total mole: $100 = 0.5\,n_2 + n_5$; $n_2 = 120$ mol

A: $0.65\,(100) = 0.98\,(0.5n_2) + 0.155n_5$; $n_5 = 40$ mol

Product flow rates: Overhead $0.5\times(120)\times0.98 = 58.8$ mol A

$0.5\times(120)\times0.02 = 1.2$ mol B

Bottom $0.155\times(40) = 6.2$ mol A

$0.845(40) = 33.8$ mol B

Overall energy balance:

$\Delta\dot{E}_k, \dot{W}_s = 0$ $\Delta\dot{E}_p = 0$

$$Q = \Delta H = \sum_{out} n_i\hat{H}_i - \sum_{in} n_i\hat{H}_i$$

Interpolate in table

$$Q = 58.8(0) + 1.2(0) + 6.2(1385) - 65(271) - 53(257) = 2.63\times 10^4 \text{ cal}$$

Now, if we do the you know, balance now this balance may be first of all you have to do that material balance how much you know that overhead product is coming, how much you know bottom products is coming also to be you know calculated based on that material balance here. Material balance and energy balance simultaneously will be considered.

So at a you know that certain rate of that you know feed will be you know distillate and it will be coming out from the overhead product and it will be coming out as a bottom product. Now what will be that amount, that is not known to you. If we do the material balance you can find it out there. Now, if we do that overall balance as a total mol there, so we can say that here the inlet is 100 that is 100.

And what will be the outlet, that you know that outlet is here. It is given as per this diagram. It will be you know that 0.5 into as mentioned in the diagram and you plus here n 5, n 5 is here, what is that? This is your n 5 that is bottom product. So in this case, we can do this overall material balance here by this equation and then if we do the you know material balance for you know acetone here in this case, we can say that 0.65 into 100 then it will be is equal to 0.98 into 0.5 into plus 0.155 n 5.

According to this you know, this material balance there so acetone for acetone if you do this component material balance and solving this two equation we can get this n 2 will be is equal to what 120 mol and n 5 will be is equal to 40 mol. What does it mean that the moles of you know total moles coming out from that you know distillation column as a vapor it will be 120.

Whereas as a, you know bottom product this amount is coming out as n 5, it is 40 mol. So we can see this here that product flow rates at the overhead stream here. So it will be as 0.5 into 120 into 0.98. So this will be is equal to simply 58.8 mol A and B will be is equal to 0.5 into 120 into 0.02. It will be 1.2 mol B. And at the bottom what will be that amount of mol A and mol B here.

Here mol A means here we will see that here basically that acetone and mol B is basically that acetic acid. So we can say here, this amount of acetone and this amount of, you know acetic acid will be coming out from the bottom. Now, if you do the overall energy balance here in this case again that potential energy just to be neglected and shaft work to be neglected and also you know that delta E s some you know that other you know phase change energy will be you know negligible.

So overall we can say that this is you know kinetic energy you can say that will be also neglected. So overall we can say that this Q will be is equal to delta H. Then here it will be summation of n i H i – n i H i there. In this case what will be the inlet and outlet streams based on which we can do that energy balance here. Now, from this energy balance we can then write directly that Q will be is equal to here.

And after substitution of this value in this inlet and outlet conditions then we can have finally this value of 2.63 into 10 to the power of 4 calorie. Now in this case incorporate you know the value in the table whatever it is given at different temperature that this values are there.

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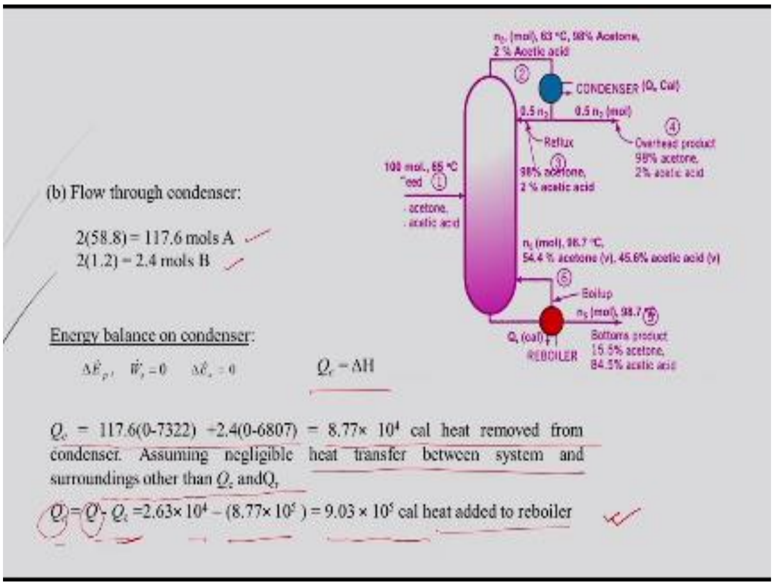

(b) Flow through condenser:

2(58.8) = 117.6 mols A

2(1.2) = 2.4 mols B

Energy balance on condenser:

$\Delta \dot{E}_p, \ \dot{W}_s = 0 \quad \Delta \dot{E}_k = 0 \qquad Q_c = \Delta H$

Q_c = 117.6(0-7322) +2.4(0-6807) = 8.77× 10^4 cal heat removed from condenser. Assuming negligible heat transfer between system and surroundings other than Q_c and Q_r

$Q_r = Q - Q_c = 2.63\times 10^4 - (8.77\times 10^5) = 9.03\times 10^5$ cal heat added to reboiler

And after that you know you have to find out what will be the you know heat you know loss in the condenser that also calculate by you know material balance what will be the amount of you know that moles of acetone in you know flowing through that condenser and also what will be the moles of that acetic acid is flowing through the condenser.

So accordingly you can do again that you know energy balance for that condenser. Now, accordingly, if you substitute that value of enthalpy there, you can get this you know enthalpy change as here 8.77 into 10 to the power 4 calorie that will be heat removed from the condenser. Now in this case assuming negligible heat transfer between system and the surroundings other than Q c and Q r, so we can have this Q r will be is equal to Q – Q c.

That will be is equal to here we can say 2.63 into 10 to the power of 4 minus 8.77 into 10 to the power of 5 here from which we can say that this 9.03 into 10 to the power 5 calorie heat to be added to the reboiler because this Q r is the you know that reboiler heat energy supplied to that you know reboiler.

And Q is the here total you know, energy that already we have calculated by this equation here, total you know heat required for the process. And if you subtract that, you know, condenser heat what is coming out from that condenser, then you can get this what will be the heat is actually supplied to the reboiler there. So in this way you can you know do the energy balance for the distillation column.

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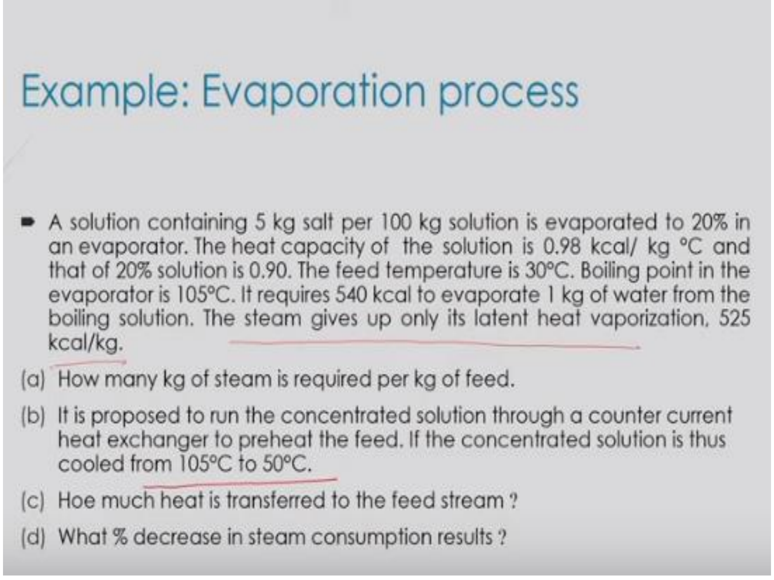

Example: Evaporation process

- A solution containing 5 kg salt per 100 kg solution is evaporated to 20% in an evaporator. The heat capacity of the solution is 0.98 kcal/ kg °C and that of 20% solution is 0.90. The feed temperature is 30°C. Boiling point in the evaporator is 105°C. It requires 540 kcal to evaporate 1 kg of water from the boiling solution. The steam gives up only its latent heat vaporization, 525 kcal/kg.

(a) How many kg of steam is required per kg of feed.

(b) It is proposed to run the concentrated solution through a counter current heat exchanger to preheat the feed. If the concentrated solution is thus cooled from 105°C to 50°C.

(c) Hoe much heat is transferred to the feed stream ?

(d) What % decrease in steam consumption results ?

Now, let us do another example of evaporation process based on this you know energy balance equation. So in this case, if we consider that a solution that contains 5 kg salt per 100 kg solution is evaporated to 20% in an evaporator. The heat capacity of the solution is 0.98 kilo calorie per kg degree Celsius and that of 20% solution is 0.90. Now, the feed temperature is you know that 30 degrees Celsius.

Whereas boiling point in the evaporator is 105 degrees Celsius. It requires 540 kilocalorie to evaporate 1 kg of water from the boiling solution. Now, the steam gives up only its latent heat of vaporization as 525 kilocalorie per kg. Now, based on this principle, you have to calculate how many kg of steam is required per kg of feed. And also it is proposed to run that concentrated solution through a counter current, you know heat exchanger to you know preheat the feed.

If the concentration solution, concentrated solution you can say is thus cooled from 105 to 50 degrees Celsius. In that case, how much heat is to be transferred to the feed stream there you have to calculate and what percentage decrease in the steam consumption results as per this problem.

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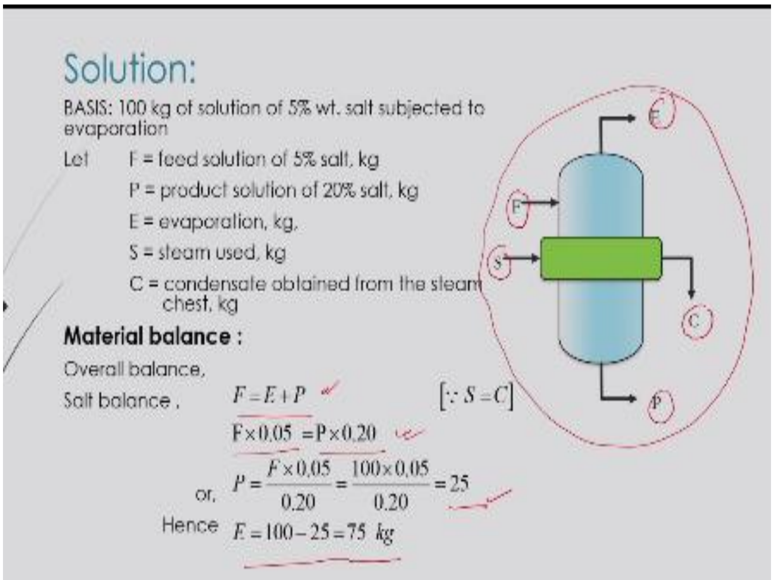

Solution:

BASIS: 100 kg of solution of 5% wt. salt subjected to evaporation

Let F = feed solution of 5% salt, kg
P = product solution of 20% salt, kg
E = evaporation, kg,
S = steam used, kg
C = condensate obtained from the steam chest, kg

Material balance :

Overall balance, $F = E + P$ $[\because S = C]$

Salt balance , $F \times 0.05 = P \times 0.20$

or, $P = \frac{F \times 0.05}{0.20} = \frac{100 \times 0.05}{0.20} = 25$

Hence $E = 100 - 25 = 75\ kg$

So let us do this calculation here for this you know evaporation process. As a basis we can take 100 kg of solution where 5% in weight percent you can say salt will be there subjective to that evaporation. And in this case as per figure here, this is one evaporator as shown here in the slide. F is representing here as you know that feed solution of 5% salt which will be entering to that evaporator which is to be evaporated.

And P is the product solution of 20% of salt and E is the you know, evaporation amount that is in kg. S is you know steam that is used for that evaporation and C is the condensate that is obtained from the steam chest in kg. Now, if we do the material balance to find out all those you know, stream amount which is coming in and coming out based on which we can get that E will be is equal to here 75 kg.

And P that is product solution of 20% salt will be coming as 25. So in this case, we have to do the overall balance like this F will be is equal to E + P overall balance here for the you know solution and salt balance if you do that, in this feed stream the salt amount is 5% whereas products in salt amount is you know only 20%.

So according to that you know salt balance we can simply you know calculate this you know what will be the product that will be coming out from that evaporation, that amount is equal to 25 in kg. And hence if you substitute this product value in this overall balance, you can get what should be the you know evaporation amount there as E and that is 75 kg according to this calculation.

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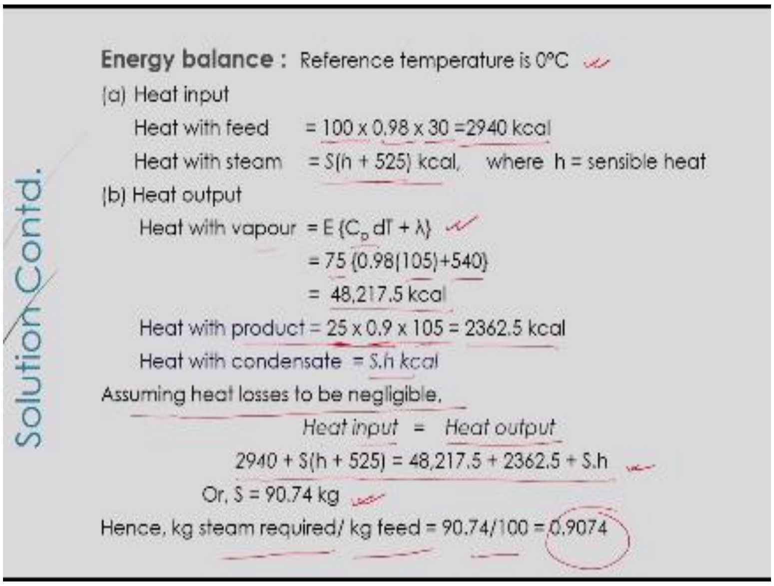

Solution Contd.

Energy balance : Reference temperature is 0°C

(a) Heat input

Heat with feed = 100 x 0.98 x 30 =2940 kcal

Heat with steam = S(h + 525) kcal, where h = sensible heat

(b) Heat output

Heat with vapour $= E\{C_p\,dT + \lambda\}$

$= 75\{0.98(105)+540\}$

$= 48{,}217.5$ kcal

Heat with product = 25 x 0.9 x 105 = 2362.5 kcal

Heat with condensate = *S.h kcal*

Assuming heat losses to be negligible,

Heat input = *Heat output*

2940 + S(h + 525) = 48,217.5 + 2362.5 + S.h

Or, S = 90.74 kg

Hence, kg steam required/ kg feed = 90.74/100 = 0.9074

Now, you have to do the energy balance there. Now, for that energy balance you have to consider some reference temperature. In this case we are considering that reference temperature is zero degree Celsius. Now, we have to first calculate what are the heat input there. Now heat with feed that will be is equal to since feed amount is 100 kg.

And you know that specific heat of that feed stream is 0.98 and temperature difference is you know that 30 degrees Celsius. So we can say that this amount of that is 2940 kilocalorie of heat will be with the feed. Similarly, heat with the steam that is entering to that evaporator as here S into h plus 525 kilocalorie. Where in this case h is sensible heat we are considering. S is the you know that amount of steam.

So we can simply that calculate the S into h, this is enthalpy that is sensible heat change for that S amount of steam there and you know that also there will be certain amount of that you know latent heat that will be is equal to S into 525 there also. So this amount of heat will be you know supplied to that evaporator. And heat output that will be come out heat with vapor and it will be simply that E into C p dT plus lambda.

Again this lambda is the latent heat of you know vaporization. So here after substitution of that C p value and temperature difference is 105 and E amount is 75 and that latent heat of vaporization is 540 kilo calorie. Then we can have this you know that 48217.5 kilo calorie there that is heat with vapor. Similarly, heat with product that will be is equal to 25 into you know 0.9 into 105.

This is the you know amount supplied, that is amount is coming out as a product and 0.9 is that specific heat capacity and 105 is the temperature difference and based on which you can say that this is simply that sensible heat of that product. So it is coming out as a 2362.5 kilo calorie. Similarly, what should be the heat with condensate, that also to be calculated.

Here condensate here in this case only simply that is to convert that vapor into condensing form. So for that you need some you know heat of condensation. That will be is equal to h here. So S dot h will be the total amount of heat with condensate there. So assuming heat losses to be negligible here, all the heat will be utilized there. So in this case heat input will be is equal to heat output there.

So here we can say as per that balance of that heat we can write simply this equation and from which after substitution of this you know sensible heat and also you can say that other components they and then you can get what should be the amount of steam is supplied to that evaporator there. So it is coming out as 90.74 kg that is you know supplied as a steam to that, you know evaporator to you know evaporate those solution there inside the evaporator.

Hence kg of steam required per kg of feed it will be simply that is 90.74 divided by feed amount. That will come around 90% there. So in this way you can calculate what should be the you know, fraction of you know feed stream as a steam that will be supplied to the evaporator to you know evaporate those solution there.

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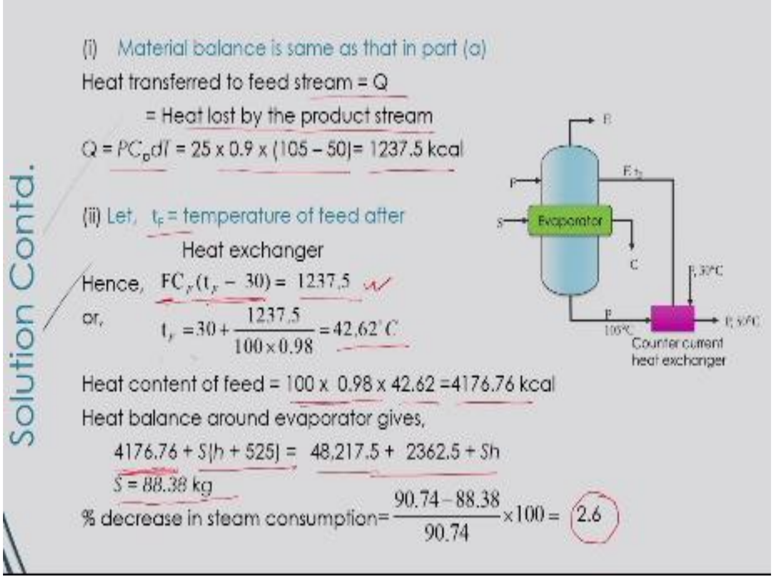

Solution Contd.

(i) Material balance is same as that in part (a)

Heat transferred to feed stream = Q

= Heat lost by the product stream

$Q = PC_p dT = 25 \times 0.9 \times (105 - 50) = 1237.5$ kcal

(ii) Let, t_F = temperature of feed after Heat exchanger

Hence, $FC_F(t_F - 30) = 1237.5$

or, $t_F = 30 + \frac{1237.5}{100 \times 0.98} = 42.62^{\circ}C$

Heat content of feed = 100 x 0.98 x 42.62 = 4176.76 kcal

Heat balance around evaporator gives,

$4176.76 + S(h + 525) = 48{,}217.5 + 2362.5 + Sh$

$S = 88.38$ kg

% decrease in steam consumption $= \frac{90.74 - 88.38}{90.74} \times 100 = 2.6$

And then again you have to calculate that what should be the you know, heat transfer to the feed stream there. That is basically the heat lost by the product stream. So here in this case from the material balance is same as that in the part A, you have to you know calculate that you know different stream amount based on that and since we have done it in part A, so we have to use all those you know, amount of streams of you know, FC, C p, all those things are here itself in this part of this problem.

So in this case heat transferred to the feed stream basically considering as Q and that will be is equal to heat lost by the product stream there. So this Q will be is equal to P into C p into dT. According to that you know sensible heat based on that specific heat capacity at constant pressure and the temperature difference. So it will be becoming as you know 25 into 0.9 into 105 minus 50. That is basically 1237.5 kilocalorie.

Now, let us consider that what should be the temperature of that feed after heat exchanger there. So in this case if we consider that temperature is t F. So we can say simply that this heat balance as F into C F, C F is the you know that specific heat capacity of that feed stream and F is the amount of feed which is supplied to that evaporator.

And the feed temperature is it is t F then from that, you know steam temperature, we can subtract it then we can get that you know, enthalpy change of that feed stream as here 1237.5. So in this case, what should be the you know temperature of feed stream.

So after solving this equation of this heat balance there for this feed stream then we can say that the t F will be is equal to will be equals to 42.62 degree Celsius.

Now heat content of feed that will be is equal to 100 into 0.98 into then 42.62 degrees Celsius This is your temperature difference from the reference temperature of 0 degree Celsius. Then finally, you can say that heat content of the feed will be is equal to coming as 4176.76 kilocalorie.

Similarly, if you do the heat balance around the evaporator, then you can say that this amount of feed that is entering and according to that what will be the energy which is there and what will be the energy supplied by that steam and that will be is equal to what is that it is that is coming out from that product stream there and also from that you know vapor components there from the evaporator.

So after substitution of this value then we can solve this you know S will be is equal to 88.38 kg. Now in this case, you will see that decrease in steam consumption you will see that it will be coming as 90.74 - 88.38 there because in this case this steam is 88.38. So earlier that steam was 90.74. So basically the reduction in steam consumption will be is equal to 2.6%.

So here in this way we can calculate that reduction that is what percentage decrease of steam consumption results if that we propose to run the concentrated solution through a counter current heat exchanger to preheat the feet, if the concentrated solution is thus cooled from 105 to 50 degree Celsius. So in this way we can calculate also the feasibility of that using what will be the amount of steam for that evaporator.

So before you know that just changing this you know temperature condition and also preheating condition you will see that maximum amount of heat is required for that evaporator. So to you know, economize that you know process what we have to do, you have to you know, on that you know preheat the solution by a certain you know heat exchange equipment, so that you will you know that utilizing less amount of steam for that evaporation process.

Now, let us do another example, for you know solving the energy of balance for that processes based on that energy balance equation. Let us do the example for drying process.

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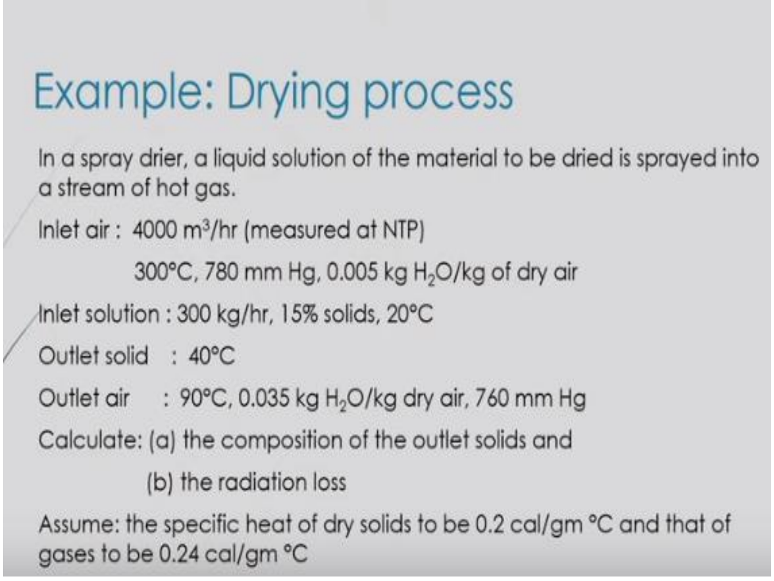

Example: Drying process

In a spray drier, a liquid solution of the material to be dried is sprayed into a stream of hot gas.

Inlet air : 4000 m^3/hr (measured at NTP)

300°C, 780 mm Hg, 0.005 kg H_2O/kg of dry air

Inlet solution : 300 kg/hr, 15% solids, 20°C

Outlet solid : 40°C

Outlet air : 90°C, 0.035 kg H_2O/kg dry air, 760 mm Hg

Calculate: (a) the composition of the outlet solids and

(b) the radiation loss

Assume: the specific heat of dry solids to be 0.2 cal/gm °C and that of gases to be 0.24 cal/gm °C

Now, problem is that in a spray drier, a liquid solution of the material to be dried is sprayed into a you know steam of hot gas. Now inlet air is given as 4000 meter cube per hour that is measured at normal temperature and pressure and temperature is 300 degrees Celsius and 780 millimeter mercury of pressure. And there per kg of drier contains 0.005 kg of moisture there.

Whereas inlet solution there 300 kg per hour to be supplied where 15% solids will be there at 20 degrees Celsius. So you have to dry these you know solution of this 15% solids that is called slurry. Now at the outlet solid, the temperature is 40 degree Celsius, whereas outlet air, you will see that condition is 90 degrees Celsius where moisture content will be 0.035 per kg of dry air at a pressure of 760 millimeter mercury.

Now in this case, you have to calculate the composition of the outlet solids and the radiation loss there. Assume that specific heat of dry solids to be you know 0.2 calorie per gram degrees Celsius and that of gasses to be 0.24 calorie per gram degree Celsius.

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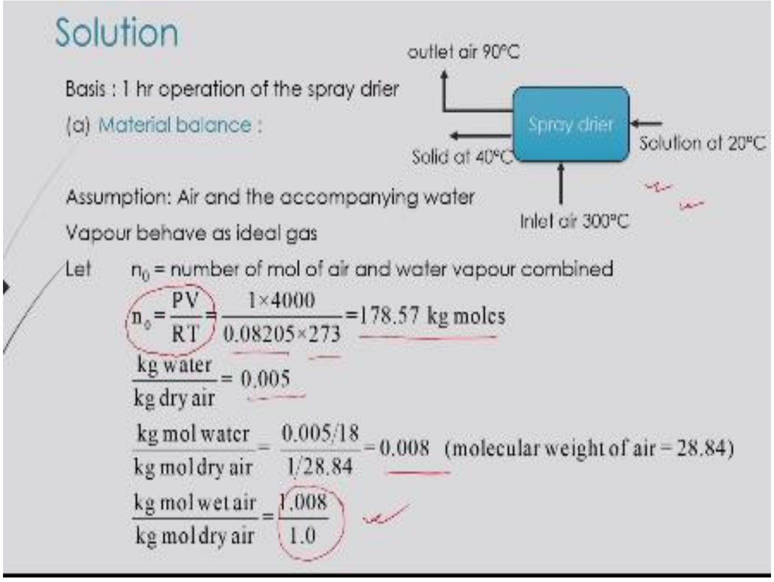

Solution

Basis : 1 hr operation of the spray drier

(a) Material balance :

Assumption: Air and the accompanying water Vapour behave as ideal gas

Let n_0 = number of mol of air and water vapour combined

$$n_0 = \frac{PV}{RT} = \frac{1 \times 4000}{0.08205 \times 273} = 178.57 \text{ kg moles}$$

$$\frac{\text{kg water}}{\text{kg dry air}} = 0.005$$

$$\frac{\text{kg mol water}}{\text{kg mol dry air}} = \frac{0.005/18}{1/28.84} = 0.008 \quad (\text{molecular weight of air} = 28.84)$$

$$\frac{\text{kg mol wet air}}{\text{kg mol dry air}} = \frac{1.008}{1.0}$$

Let us do the solution or solve this problem here. In this case consider that one hour operation of that spray drier. Here it is schematically represented in this slide. Here this spray drier where inlet solution at 20 degrees Celsius, where inlet air containing you know that certain moisture at 300 degrees Celsius to be supplied to that you know spray drier at 300 degrees Celsius.

And after drying you will see that outlet air will be coming at 90 degree Celsius with a certain moisture content and then solid whatever it is coming out as a dry product you can say that it will be at 40 degrees Celsius. Now, based on this you know you know schematic diagram and the streams, you will see that you have to do some material balance to find out what will be the you know moles of that is air in the or solution is coming to that you know spray drier all those things.

Now, assume that air and the accompanying water vapor behave as ideal gas there. So in this case let n 0 number of mol of air and water vapor combined is coming to that spray drier. So in this case since it behaves as ideal gas, so you can write this ideal gas equation here, n 0 will be equals to PV by RT. So if you substitute that pressure and volume there.

And that you know R value that is universal gas constant and then temperature of this normal temperature. So we can say that 178.7 that is 57 kg moles of you know that air and water vapor mixture is coming to that spray drier. Now, you know that, that inlet condition that water moisture per kg of drier is you know 0.005 kg. Whereas, if you convert it to mol then you have to you know divide this kg or mass by its molecular weight.

And finally, you can say that 0.008 you know that moles of that air and water vapor combined is coming to that sprayer. And kg mol of wet air by kg mol of dry air you can get it by this here simply just adding up that 0.008 to that one mole of dry air. So this is the ratio of that kg mol of wet air by kg mol of dry air.

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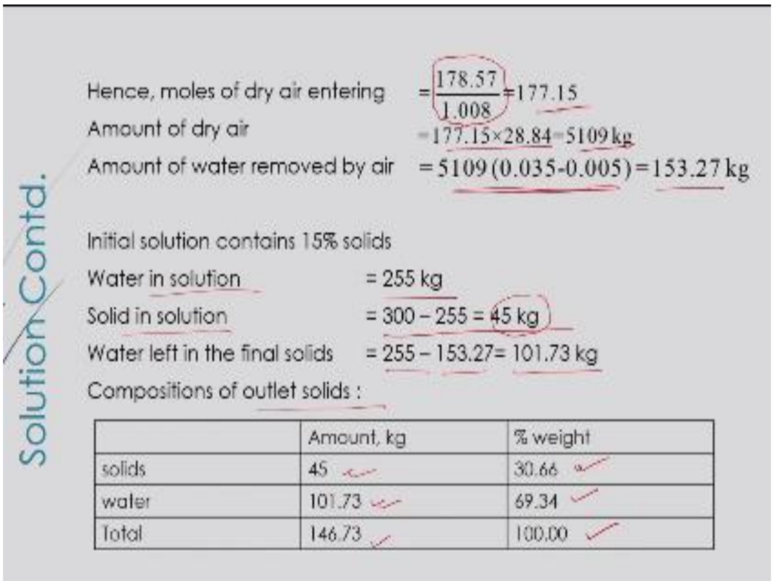

Solution Contd.

Hence, moles of dry air entering $= \frac{178.57}{1.008} = 177.15$

Amount of dry air $= 177.15 \times 28.84 = 5109$ kg

Amount of water removed by air $= 5109\,(0.035 - 0.005) = 153.27$ kg

Initial solution contains 15% solids

Water in solution = 255 kg

Solid in solution = 300 – 255 = 45 kg

Water left in the final solids = 255 – 153.27= 101.73 kg

Compositions of outlet solids :

	Amount, kg	% weight
solids	45 ✓	30.66 ✓
water	101.73 ✓	69.34 ✓
Total	146.73 ✓	100.00 ✓

After that, what you have to do that you have to find out the what will be the amount of dry air that is entering that amount of dry air entering to that spray drier that will be is equal to simply that you know 178.57 by 1.008. That will be 177.15 and amount of dry air then in terms of you know mass it will be coming that since it is moles then you have to multiply it by molecular weight then it is coming as 5109 you kg.

Now amount of water that is removed by air after drying then it will be as simply here that 5109 kg of dry air is coming. Then what is that moisture at inlet and outlet according to that, you can calculate what should be the you know moisture in that you know removed by that you know drying process.

Now initial solution that contains you know that 15% solids now water in solution that is 255 kg, solids in solution that is then 300 - 255 kg then it will be 45 kg that is in solid solution. Now water left in the final solids this is basically 255 minus this

153.27, that is your amount of water which is removed. So water left in the final solids it will be is equal to 101.73 kg.

Now accordingly you can calculate what will be the composition of that outlet solids. Now, solids is 45 kg, weight is 30.66%, water is 101.73 kg, then weight percent will be 69.34. Total is 146 point you know 73 kg and then you know weight percent will be 100% there. So accordingly you can calculate what should be that you know mol fractions also there.

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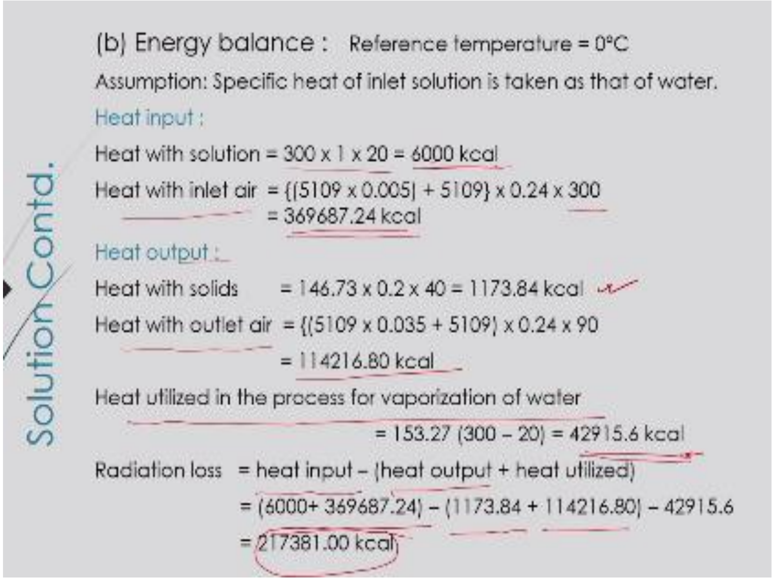


Solution Contd.

(b) Energy balance : Reference temperature = 0°C

Assumption: Specific heat of inlet solution is taken as that of water.

Heat input :

Heat with solution = 300 x 1 x 20 = 6000 kcal

Heat with inlet air = {(5109 x 0.005) + 5109} x 0.24 x 300
= 369687.24 kcal

Heat output :

Heat with solids = 146.73 x 0.2 x 40 = 1173.84 kcal

Heat with outlet air = {(5109 x 0.035 + 5109) x 0.24 x 90
= 114216.80 kcal

Heat utilized in the process for vaporization of water
= 153.27 (300 – 20) = 42915.6 kcal

Radiation loss = heat input – (heat output + heat utilized)
= (6000+ 369687.24) – (1173.84 + 114216.80) – 42915.6
= 217381.00 kcal

Now, if we do the energy balance, so what this you know spray drier with reference temperature of 0 degree Celsius, then we can have this you know heat with solution here 300 into 1 into 20 at the temperature here it will be is equal to 6000 kilo calorie. Heat with inlet air it will be you know that there as per that moisture content and it is you know specific heat capacity and then at that temperature difference, then it will come ultimate 369687.24 kilocalorie.

Similarly, heat output that will be calculated as per thus. Heat with solids this is this amount and that is simply CP dT into what is that amount of that solids there. Heat with outlet air, it will be coming as this amount. Heat utilized in the process for vaporization of water simply this one. So this amount of heat is basically utilized there. So what will be the loss of that heat energy there.

Now, you know that heat input is there, what would be the total heat input there we have calculated. This is 6000 plus you know that heat with inlet air and also heat with solution. This total amount will be as heat input whereas we will see that heat utilized in the process for the vaporization of water is 42915.6 kilocalorie. Now, if you subtract it you will get that what is that heat output there.

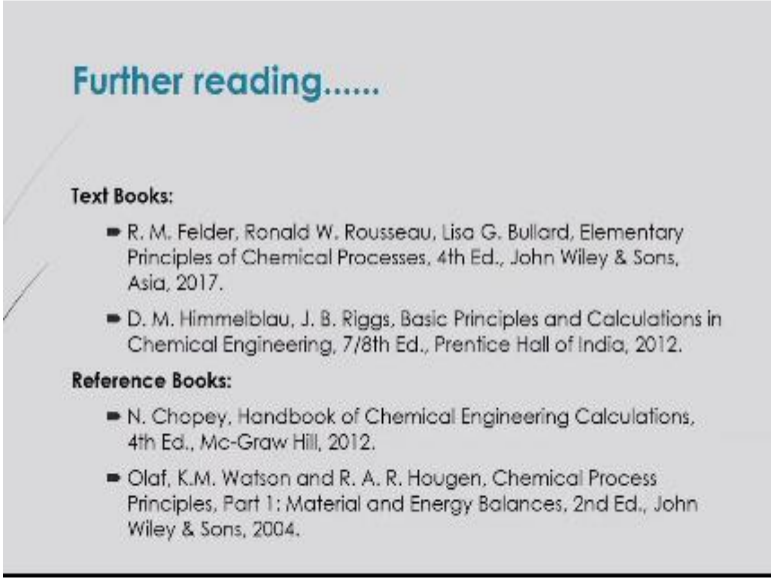
This heat output is basically that 1173.84 and plus 114216.80. Now, if you subtract these all you know that heat output, heat utilized from that heat input, you will see that this amount of heat will be you know lost by that you know radiation.

So this is you know that the basic you know calculation for this spray drier or energy balance and what will be the amount of heat or amount of you know enthalpy to be supplied to that sprayer with that solid solution and how that solid solution can be dried after just removing of heat energy by evaporation process or just by changing of you know enthalpy and also the moisture content of that drier in the inlet and at the outlet condition.

So these examples will help you to solve other different types of problems based on this you know concept and also we have discussed that the problem of energy balance for the distillation, we have described the you know entropy balance calculation and how to do this for you know refrigeration process, how to do this for evaporation process and also this drying process.

I would suggest you to you know further you know practice on this type of problems from this text books it is given here in the slides.

(Refer Slide Time: 1:00:36)



Further reading......

Text Books:

- R. M. Felder, Ronald W. Rousseau, Lisa G. Bullard, Elementary Principles of Chemical Processes, 4th Ed., John Wiley & Sons, Asia, 2017.
- D. M. Himmelblau, J. B. Riggs, Basic Principles and Calculations in Chemical Engineering, 7/8th Ed., Prentice Hall of India, 2012.

Reference Books:

- N. Chopey, Handbook of Chemical Engineering Calculations, 4th Ed., Mc-Graw Hill, 2012.
- Olaf, K.M. Watson and R. A. R. Hougen, Chemical Process Principles, Part 1: Material and Energy Balances, 2nd Ed., John Wiley & Sons, 2004.

I think it will be you know more useful if you do the or if you do the practice on this example given in the textbook there. So I also here suggest to consider the problem whatever discussed in the slides today’s lecture, to practice again and again so that it will be you know that useful for you to further understand the solving of other you know, other different types of problems based on this energy balance equation.

In the next class we will try to discuss more about that energy balance with more example there with different inlet and outlet streams and also we will discuss something more about that energy balance with some you know, reaction processes there. So thank you for your kind attention.