Principles and Practices of Process Equipment and Plant Design

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Module - 02
Lecture - 17
Design of absorbers

Hello, good day to all of you. Today, we are going to talk about the Design of absorbers. We will introduce you to this topic of adsorption, go with the fundamentals, look at the components of a practical adsorption system with examples.

Then, we will talk about the design inputs required when you are supposed to design an absorber. Then, perhaps, we will talk about the fundamental equations which govern this particular design and beyond that, it comes the actual design and we will talk about that when the time comes.

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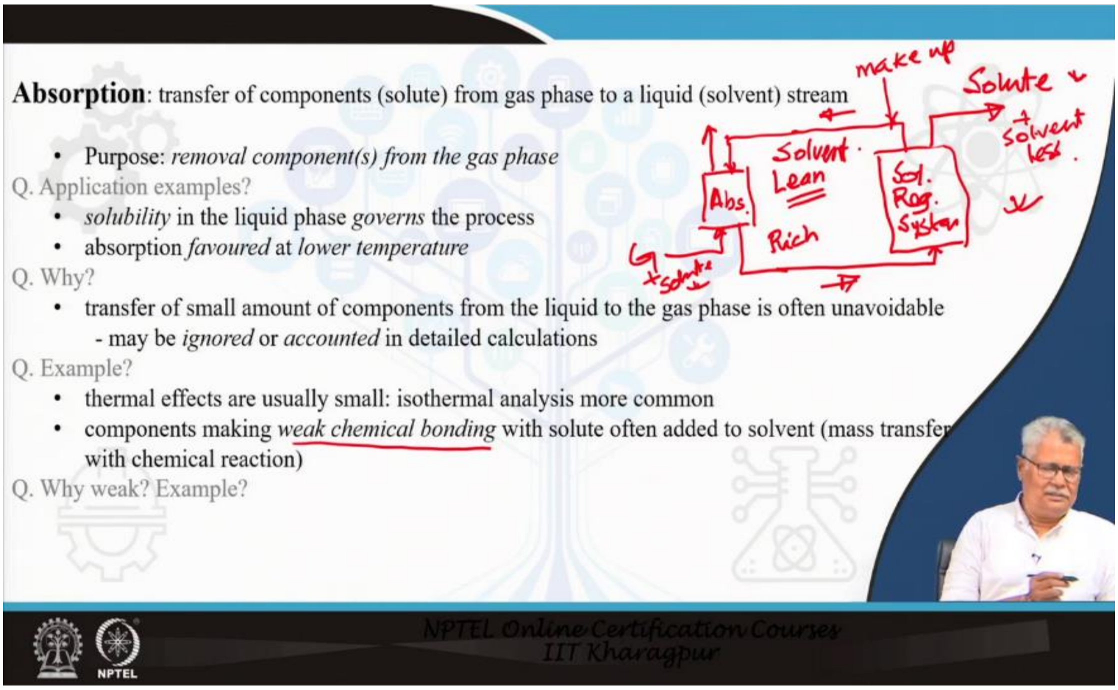

Absorption: transfer of components (solute) from gas phase to a liquid (solvent) stream

- Purpose: *removal component(s) from the gas phase*

Q. Application examples?

- *solubility* in the liquid phase *governs* the process
- absorption *favoured* at *lower temperature*

Q. Why?

- transfer of small amount of components from the liquid to the gas phase is often unavoidable
  - may be *ignored* or *accounted* in detailed calculations

Q. Example?

- thermal effects are usually small: isothermal analysis more common
- components making *weak chemical bonding* with solute often added to solvent (mass transfer with chemical reaction)

Q. Why weak? Example?

Let us look at the process of absorption itself. Absorption means a process in which we have some components which are present at a gas phase and they will get transferred to a liquid phase which is brought in contact with a gas phase. The liquid phase is called typically solvent and the transferred component is called the solute because it is more soluble as compared to the other components which are present in the gas phase to the liquid. So, it is a case of a solvent and a solute and the solute gets transferred from the gas to the liquid phase. It is rather obvious that the purpose of this exercise is the removal of the components which are more soluble and quite soluble in the liquid phase. So, quite naturally, the solvent and the solute form a pair that governs the process.

In fact, the solubility of the solute in the liquid governs a process of absorption. Let us look at a few examples. If I look at certain applications for example, if I have a stream of air that contains a component which I need to remove. Say, it contains a good amount of carbon dioxide. A good amount of carbon dioxide which I would like to remove, what can I do?

I can bring in a solvent that is alkaline in contact with this particular gas phase which contains the carbon dioxide and if the alkanol amine typically alkanol amine component in the liquid phase is used, it will be absorbing the carbon dioxide from the gas phase to the liquid phase. This is a typical example. Now, the entire process is governed by the solubility of the component in the liquid phase.

Normally, such phase transfer rather than transfer from one phase to the other is associated with the liberation of heat. So, quite naturally from the basic thermodynamics, we can guess that if that be the case, adsorption is favoured at a lower temperature. So, naturally, in the case of gas solubility, the solubility decreases if the temperature goes up and since here, you have the solubility as a major controlling parameter for absorption. The lower the temperature, the better will be the carrying capacity of your solvent or rather the liquid phase.

Now, it is not so, that if I truly say that all my absorption processes will have only one-way component transfer; that means, from the gas to the liquid. Often in real situations and real systems, you will find a part of the solvent would vaporize or if the solvent contains more than one component, one component will be vaporizing compared to the other and there will be a small amount of transfer for the liquid to the gas phase also.

This is inevitable in all the practical processes. However, since solubility, we have chosen the solute and the solvent in such a fashion so that there is very high solubility of the component in the liquid phase, the other transfer that is from the liquid to the gas phase is usually small and it is ignored in most cases or if you are going to do a detailed calculation, we may account for it also.

I can give you an example. The example could be like this. Suppose, I have ammonia mixed with air which is scrubbed or rather the ammonia is being removed by scrubbing with water. Ammonia has got very high solubility in the water phase. So, what happens? We expect all the ammonia or rather most of it from the gas phase will go to the liquid because it is highly soluble in water.

But at the same time, since the feed gas will not be saturated with water, some amount of water will also go to the gas phase and go out. So, this is an example, where there is a two-way transfer. We may ignore it and make a simplified calculation or account for it in detail. If you want a very rigorous design. In most cases, it is not required; particularly, for known systems.

We have also understood that the heat of solution will be involved in this and the thermal effects are usually small; that means, the solubility is represented by isotherms and isothermal analysis is more common. Now, let us talk about again absorption of ammonia from the gas phase to the liquid phase. Well, there is a limit to the physical solubility of ammonia.

In fact, it is not exactly physical, but there is a limit of solubility of ammonia and water. But if I want to have my solvent which is water to have even higher capacity what we could do is we could add a small quantity of mineral acid, which could be HCl which would react with the ammonia which gets dissolved and dissociates as the ammonium ion and definitely, removes the ammonium ion from the system and in fact, what happens is it increases the capacity of the solvent to absorb more and more amount of ammonia.

This is quite often the process and you often have cases, where we add chemicals to improve the capacity there effective solubility of the solvent which forms a weak chemical bonding. Here, I have got a question. Why weak chemical bonding? If you look at the absorption as a process, you will find that if you just look at the tower itself, the absorption equipment which I am showing here as a block.

So, this is my absorber. Here, I have my feed gas and here is my exit gas. I am feeding it with the solvent and where does it come from? Possibility from a solvent regeneration system. So, I am writing here another block, drawing it here solvent regeneration system and what is supplying the solvent to my absorber.

The solvent picks up the solute, this is my gas, picks up the solute because it can and that means, the solvent which is sent to the absorber is the lean solvent because it is lean in the solute. It is rich in solute. So, it is a rich solvent that is sent back for regeneration.

You will notice one thing, there is a flow of solvent from the regeneration system to the absorber system and from the absorber systems, the rich solvent goes back to the solvent regeneration system. In this quite naturally, you have something which is out and what it is? It is basically the solute.

So, what happens is this contains the gas plus the solute and the solute leaves from this stream. In most practical systems, you will find that the absorbent and the solvent regeneration system, work in pairs. In fact, most continuous systems will be consisting of almost an integrated system that works with the absorber and the regeneration system together and they both are continuous systems.

That means, here we have not only absorption but there is also a phase that means, there is another operation in the solvent regeneration, where we are removing the solute from the solvent itself. This could be by simple boiling which naturally reduces the solubility of the component in the liquid phase and it boils off. So, the solid component goes off from the top. It could also be a stripper, where it is stripped with an inert gas. It could be a re-boiled stripper, it could be a small distillation column itself.

So, you always find that the solvent regeneration system will be required to remove the solvent and rather, it will be required to separate the solid and the solvent here that means, for the rich solvent, regenerate the solute, regenerate the solvent, send it back again.

So, what happens is we do not want a permanent chemical bonding because if we have a permanent chemical bonding between the solute and the component, in that case, it will be very difficult to remove the solute from the solvent and regenerate my solvent. That is why the bond required in this particular case is weak.

There is another aspect to this also. For example, if you have a weak chemical bonding, what you normally find is your regeneration energy requirement will be quite less. So, the solvents are chosen such that it has got a high capacity for absorption of the solute and it should at the same time should be easier to regenerate and recycle as well.

The pump ability of the solvent and the rate of circulation of the solvent will depend on the capacity up to which it can be saturated and the system together is usually optimized while designing.

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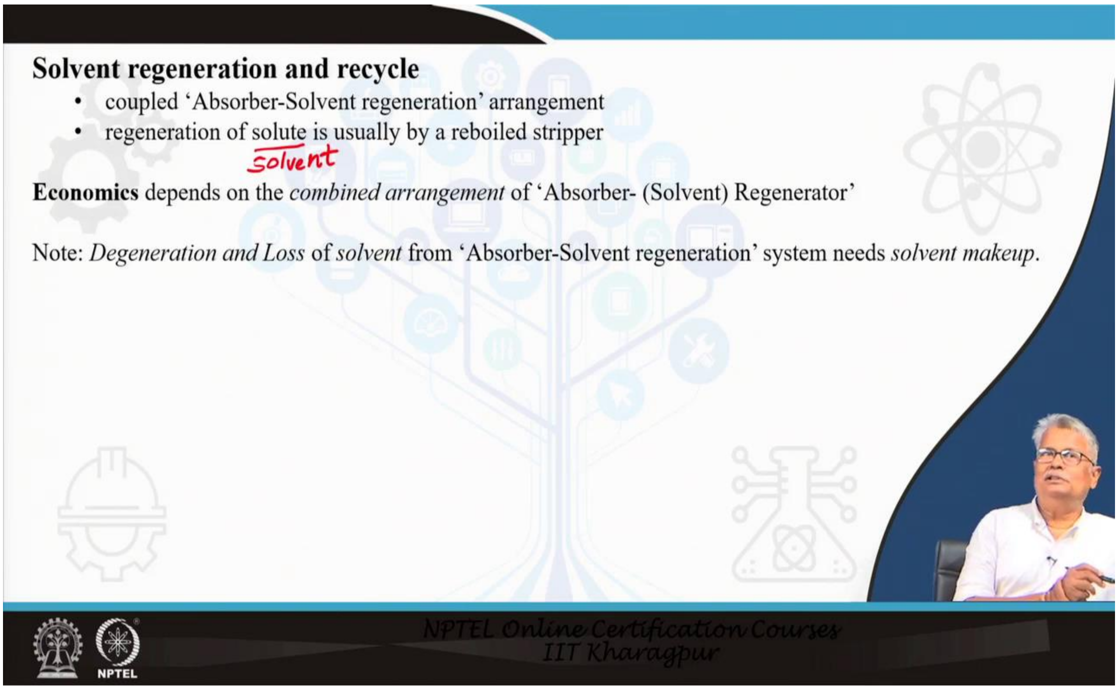

Solvent regeneration and recycle

- coupled 'Absorber-Solvent regeneration' arrangement
- regeneration of solute is usually by a reboiled stripper

Solvent

Economics depends on the *combined arrangement* of 'Absorber- (Solvent) Regenerator'

Note: *Degeneration and Loss* of *solvent* from 'Absorber-Solvent regeneration' system needs *solvent makeup*.

You have the solvent regeneration and recycle arrangement. It is an integral part of the absorption system. Absorption, where the absorber-solvent regeneration arrangement acts as a coupled system. The regeneration of the solute is usually done by a revolt stripper. It is the regeneration of the solute as well as the regeneration of the solvent itself, both are true.

Because the solute gets separated, you could also say that you are regenerating the solvent in this particular step. You will notice one thing that the economics depends on the combined arrangement and operation of the absorber regenerator.

Now, there is one thing which is also quite important. If I look at this particular previous diagram, what we find is that we are generating something like a gaseous stream here which contains the solute primary plus what? Some amount of solvent will be lost in this particular stream also.

So, you definitely need to have a makeup stream. It has to be added to make up for the solvent loss, not only that you have a physical loss of the solvent along with a gas stream during regeneration. You also have degradation of the solvent as the process goes on and naturally with time, you expect that you will require makeup either in the continuous form or in batches.

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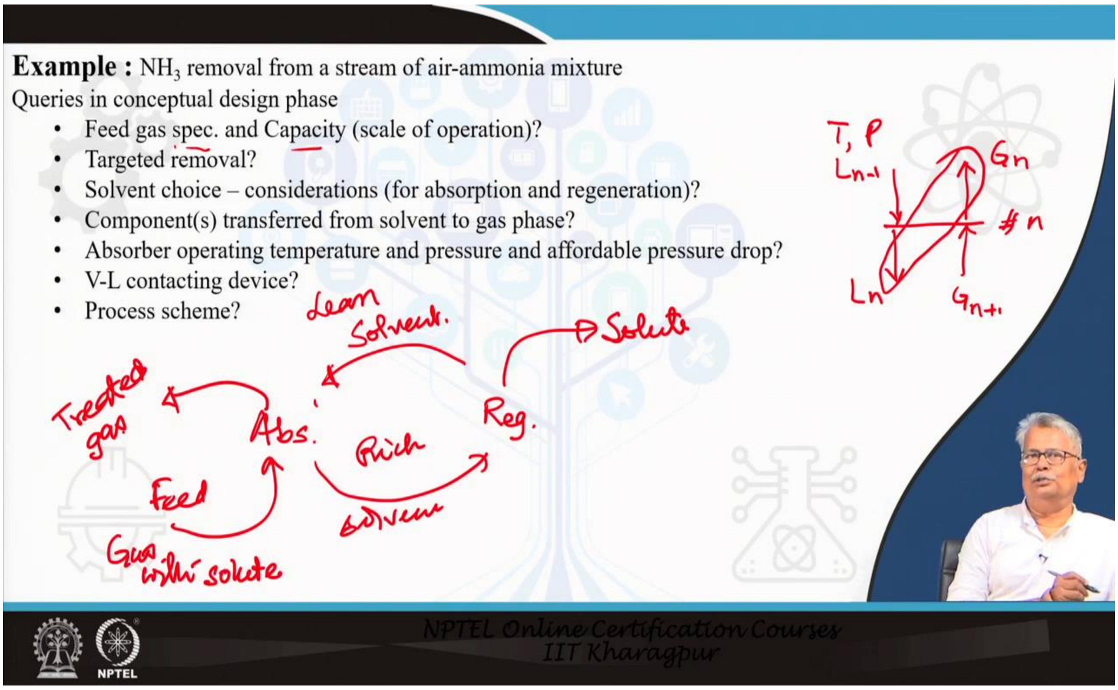

Example : NH$_3$ removal from a stream of air-ammonia mixture

Queries in conceptual design phase

- Feed gas spec. and Capacity (scale of operation)?
- Targeted removal?
- Solvent choice – considerations (for absorption and regeneration)?
- Component(s) transferred from solvent to gas phase?
- Absorber operating temperature and pressure and affordable pressure drop?
- V-L contacting device?
- Process scheme?

Here, we have an example and perhaps more details regarding the design, we try to frame while discussing this example itself. It is almost the same example here, which is ammonia removal from a stream of air ammonia mixture; that means, my air-stream is contaminated with ammonia. Possibly it has been picked up during a process and when I went out my air to the open atmosphere, I need to remove this ammonia.

There are certain queries in the conceptual design phase. We all know that during our introduction, we have said specifically that any process design starts with the conceptual feeds. There are certain queries or questions which are asked during this period. The first thing, what exactly is a feed gas; what is its composition that is what is meant by the specification. The specification would in addition ask for the temperature as well as the pressure of the stream itself.

The capacity means m^3/h of flow or normal m^3/h of flow based on which will decide what type of physical equipment we may employ and at least initially thing which will be more suitable; whether a packed tower or a tray tower or any other type. Quite naturally, it is a separation process and here, we are willing to separate the ammonia from the feed gas.

So, we need to know not only the initial concentration of ammonia but what should be the final concentration of ammonia which is acceptable. Possibly, we could also say that well I have roughly about 18% ammonia in my feed and we would like to remove roughly 95% of this. So, we need to know the target as well. If I find that my target is very stringent.

For example, my exiting gas should have a concentration of ammonia at the level of ppb or ppm. We definitely will be thinking of some specialized processes possibly a process in which there will be several means of removal to keep the final concentration very very low. So, the targeted removal parameter is also very important to design at the conceptual stage.

Next perhaps, comes the question of the solvent. We need to choose the solvent first. Now, the question is the simplest thing that we can use here is water because we all know ammonia is highly soluble in water.

Now, the question is not only that solvent choice is important while absorption, it should be easy to regenerate also and we will all understand during regeneration boiling of the rich solvent which is rich in ammonia can be done, but you will be losing a substantial amount of water from there also.

So, what you could do is you may think of certain additives which will form weak chemical bonds with this ammonia and increase its capacity so that your recirculation rate of the solvent is less and you lose less. It is also obvious that we have said earlier that while contacting, it is inevitable that some amount of the solvent some component will be going to your gas phase.

For example, if I have cold water which is being used as solvent at a temperature of around 25-30 °C and my feed gas is at a temperature of around 40 °C, what is expected to happen is some amount of water would vaporize from the solvent phase or the liquid phase and go out along with the gas which is treated.

We need to have an idea that how much of this loss is going to take place. If my solvent is cheap, we may not bother; but if the solvent is expensive, we definitely would like to have some operating conditions or some arrangement, where the solvent losses are kept to a minimum.

There is one very important thing. The observer is equipment, where I have two phases; I have the liquid, I have the gas which is coming in as well. Now, the gas streams come has to be passed through, after all, if it is any piece of equipment; the gas will definitely encounter a pressure drop as it passes through it. So, the gas will be available at a particular pressure and that pressure has to be slightly higher than the operating pressure of my absorber.

So, if I am thinking that I will be using a system in which my absorption will take place at atmospheric pressure my gas has either to be supplied at a pressure above atmospheric pressure or there has to be a blower or some such thing or a compressor or some such equipment so that the pressure drop in my equipment can be mitigated. So, both are important the supply pressure and the affordable pressure drop.

I just mentioned employing a blower or a compressor or whatever some such pressure boosting equipment and it is also a part of this conceptual design phase outcome as well. So, once, we get this temperature and pressure information, it is going to be used in the conceptual design what we may finally, develop into a final design.

Next comes the equipment itself. The vapour-liquid contacting device. Normally, we know that in the case of interface transfer basics, we have talked about stage-wise contacting. This we have covered during our distillation classes.

In say stage twice contacting device, its if it is an ideal stage of contacting, if it is an ideal stage of contacting, say this number is an nth stage and we have a gas approaching it and the gas going out; this is (n + 1) and it is G_n which is a leaving gas and I have a liquid which falls from the upper tray or upper stage which is L_{n-1} and this stream which is going out is L_n.

What is oriented is in an ideal trade, these two compositions will be in equilibrium. Now, in the case of distillation, you have found out how to find the number of ideal stages required in the vapour-liquid contacting in the case of distillation. Here, the calculation and the approach is very similar.

So, it is possible for you right now to understand that the number of ideal stages required for contact. Now, how to implement it in practice? Say if I have ideal trays hypothetically again I could provide the contacting device as a trade hour and to correct for the inefficiency of the trays, I will be providing certain additional contacting stages or contacting trays.

In the same way, I could also have the contacting being done in case of this type of vapour-liquid contacting in a packed bed which is more common in fact. One reason, these two are quite common, I mean the number of absorption processes are carried out and packed by day, you do not require too many towers; a too very number of ideal stages for the separation.

It is more because you would prefer to choose a solvent that has got high solubility for the component that you got to remove. Once you have decided about the vapour-liquid contacting device, we definitely will be talking about the process scheme. The process scheme naturally will be having the absorber and it will also have the regeneration system.

So, you will make a scheme in which the solvent will go from here, this is my lean solvent and this is my rich solvent, which will be going from the absorber to regenerator. The absorber will be fed with my feed gas from where my treated gas would come out and from my regeneration, I will be having my solute which was present in my feed gas. Quite naturally, I have not shown here, the loss of solvent and the makeup also which I already have illustrated earlier.

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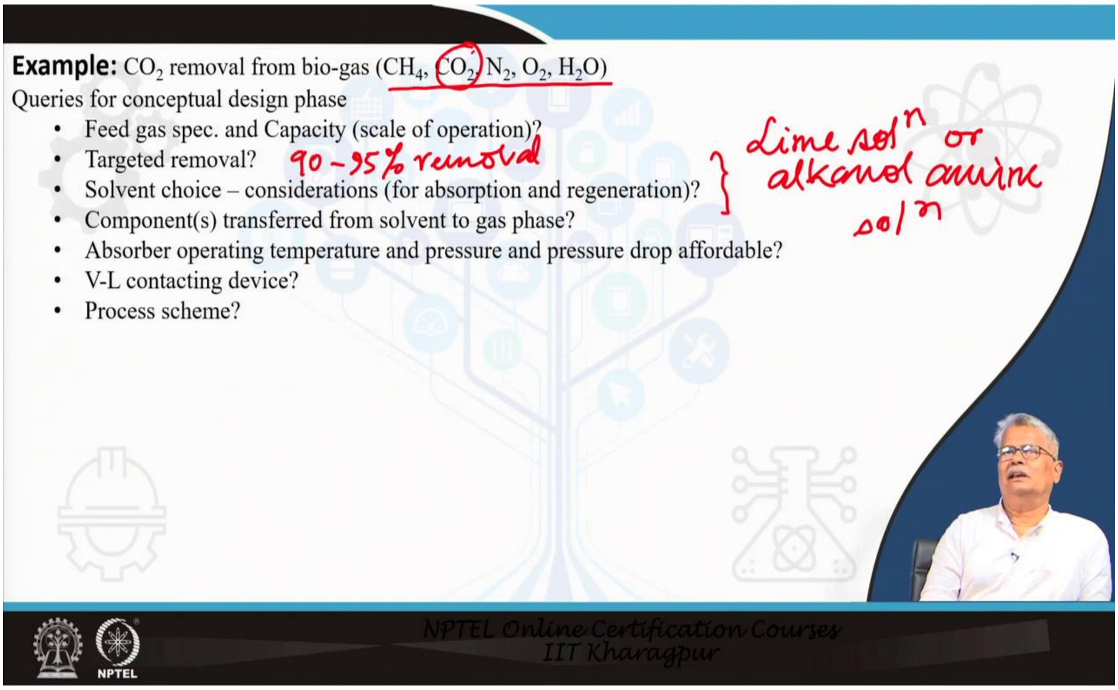

Example: CO_2 removal from bio-gas (CH_4, CO_2, N_2, O_2, H_2O)

Queries for conceptual design phase

- Feed gas spec. and Capacity (scale of operation)?
- Targeted removal? 90 – 95% removal
- Solvent choice – considerations (for absorption and regeneration)? } Lime sol^n or alkanol amine sol^n
- Component(s) transferred from solvent to gas phase?
- Absorber operating temperature and pressure and pressure drop affordable?
- V-L contacting device?
- Process scheme?

We have here another example with us. It is the CO_2 removal from the biogas. In fact, if you have biogas production, normally the gas that you will be producing will be a mixture of a good amount of methane fair amount of CO_2, a small amount of nitrogen-oxygen and it will be moist. If we try to handle this and we think of removing the CO_2 part of it primarily, we have to face the same questions and we go for the conceptual design by following the steps.

The feed gas specification has to be known. It is not a difficult thing to know the biogas specification and the quantity of the biogas which is expected. But remember in the case of biogas, you will have a fairly large variety of capacity; that means, possibly on some days you have higher production, on some days you have lower production.

So, and it is also expected that it is not going to be as high as a CO_2 removal system which may which you may encounter in some natural gas plant. We definitely will be having based on our scale of operation, a certain idea that what should be these operations. We need to know the targeted removal. If this purpose, if the purpose of this CO_2 removal system is primarily to increase the calorific value, possibly if I remove around 90-95% that should be good enough.

The choice of solvent here is something like this. It cannot be something very expensive. So, we may think perhaps whatever is more common which is available with us, we will be using that a domestic I mean a very common thing which is done and which can be done is a line solution. What is a line solution? Line solution is basically calcium hydroxide solution which will react with the carbon dioxide for calcium carbonate.

Yes, there are problems; in the sense, it will form since it is sparingly soluble, it will form a precipitate and it will form a solid sludge as well for whose removal you have to have an arrangement there. If you really want a more sophisticated system, possibly you should use some alkanol amine. Typically, 10% diethanolamine is a very good option for removing carbon dioxide.

Now, we have to think about the component that may get transferred from the gas whether we are using a line solution or we are using an alkanol amine solution, there will be some transfer of water which will be going from the liquid to the gas phase. The absorber operating temperature and pressure has to be just above atmospheric, we may require a blower.

If the pressure drop in my absorber is going to be large; but possibly, we are going to use a very simple arrangement, where the pressure drop is expectedly small maybe a few inches of water. It is the cheap equipment that we are looking for. So, in this case, possibly what we will be thinking about is just a packed tower.

The process scheme, if it is only for a small scale, we are not going to think about the regeneration because it is going to give us a solid carbon, a solid calcium carbonate precipitate. We will think of some sort of disposal thing and calcium hydroxide solution or line solution is not very expensive. Yes, we got to supply it regularly.

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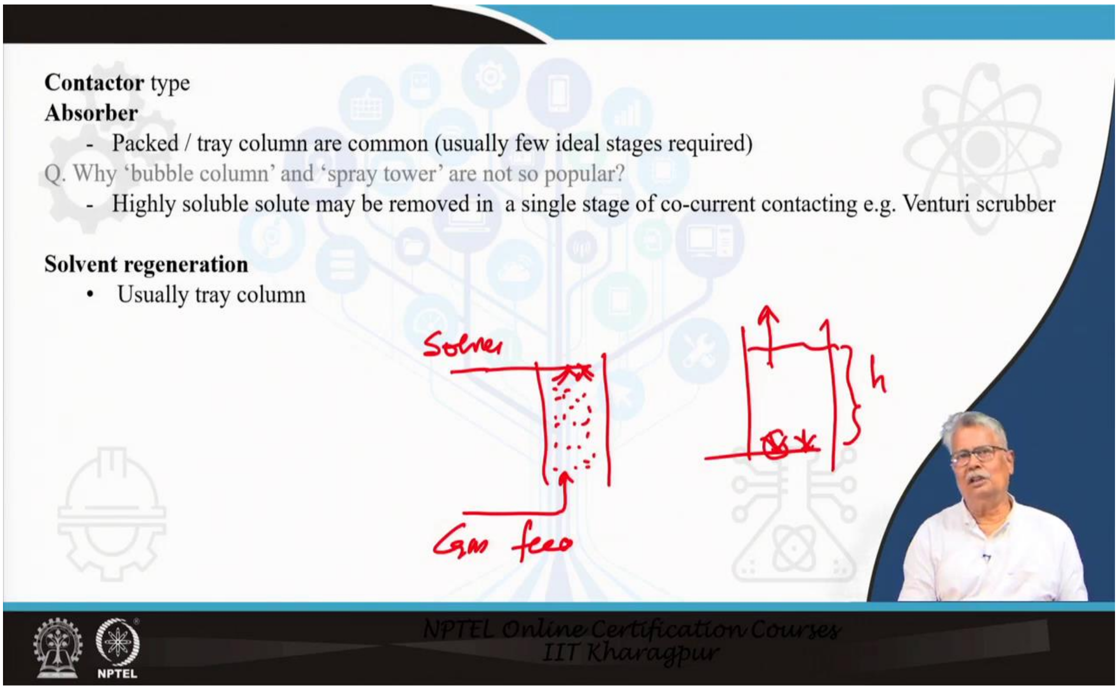

Contactor type

Absorber

- Packed / tray column are common (usually few ideal stages required)

Q. Why 'bubble column' and 'spray tower' are not so popular?

- Highly soluble solute may be removed in a single stage of co-current contacting e.g. Venturi scrubber

Solvent regeneration

- Usually tray column

Now, we focus on the contactor type. We usually have packed or tray columns. These primarily require a few ideal stages only. We will look at the details of these trays and the columns packed slightly later on possibly in the next class. I have a question here why not have a column which is filled with liquid, have a sparger at the bottom and let the bubble go out; that means, it is a bubble columned, why bubble columns are not popular?

You will simply understand one thing in a bubble column if the gas has to come out, it has to overcome this particular head. The liquid head of a reasonable height. So, you definitely will be having a reasonably high-pressure drop, if you are going to use a bubble column.

Then, the other option that you have is a spray tower in which you have the spray of your solvent from the top and you have the gas going up, the gas feed and you have the droplets of liquid contacting the gas in counterflow. This is also definitely possible, but usually, it will have less efficiency. A spray tower may not be a very good comfortable thing for your absorber in most cases.

We will look at the details of how to choose the mass transfer equipment based on the resistance of the mass transfer side; that means, whether the gas side resistance controls or the liquid phase resistance controls later on when we go for further details about choosing among different equipment and hardware. Solvent regeneration is somehow normally done with tray columns.

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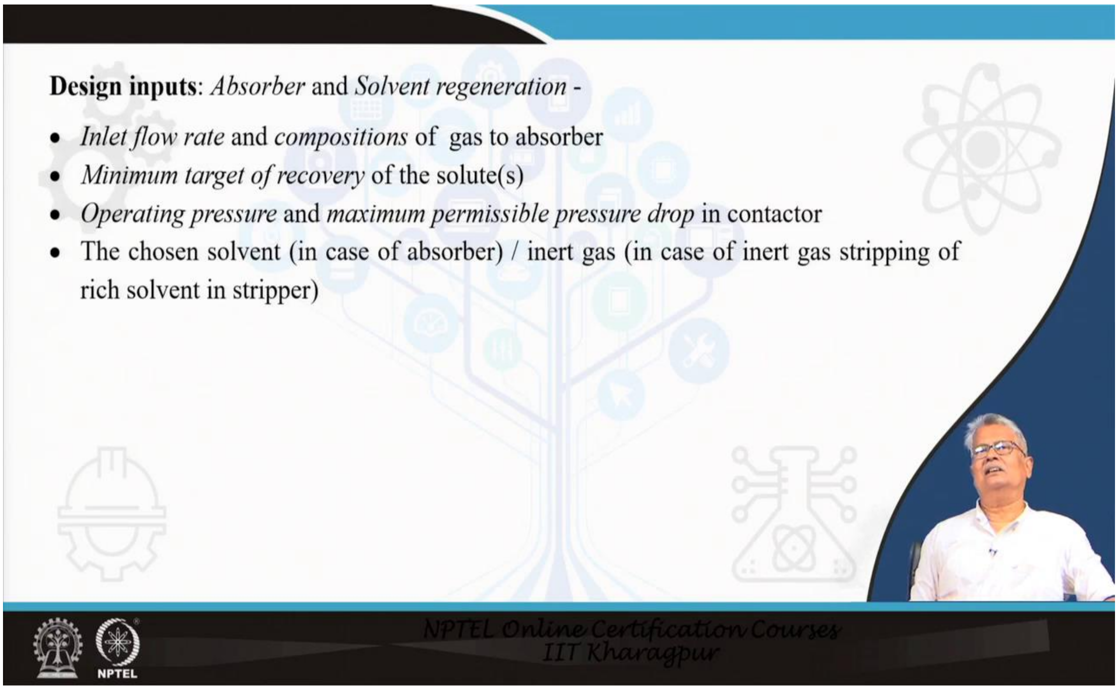

Design inputs: *Absorber* and *Solvent regeneration* -

- *Inlet flow rate* and *compositions* of gas to absorber
- *Minimum target of recovery* of the solute(s)
- *Operating pressure* and *maximum permissible pressure drop* in contactor
- The chosen solvent (in case of absorber) / inert gas (in case of inert gas stripping of rich solvent in stripper)

If you look at the design inputs, the flow rates, the minimum target of recovery, the pressure and the chosen solvent are the design inputs.

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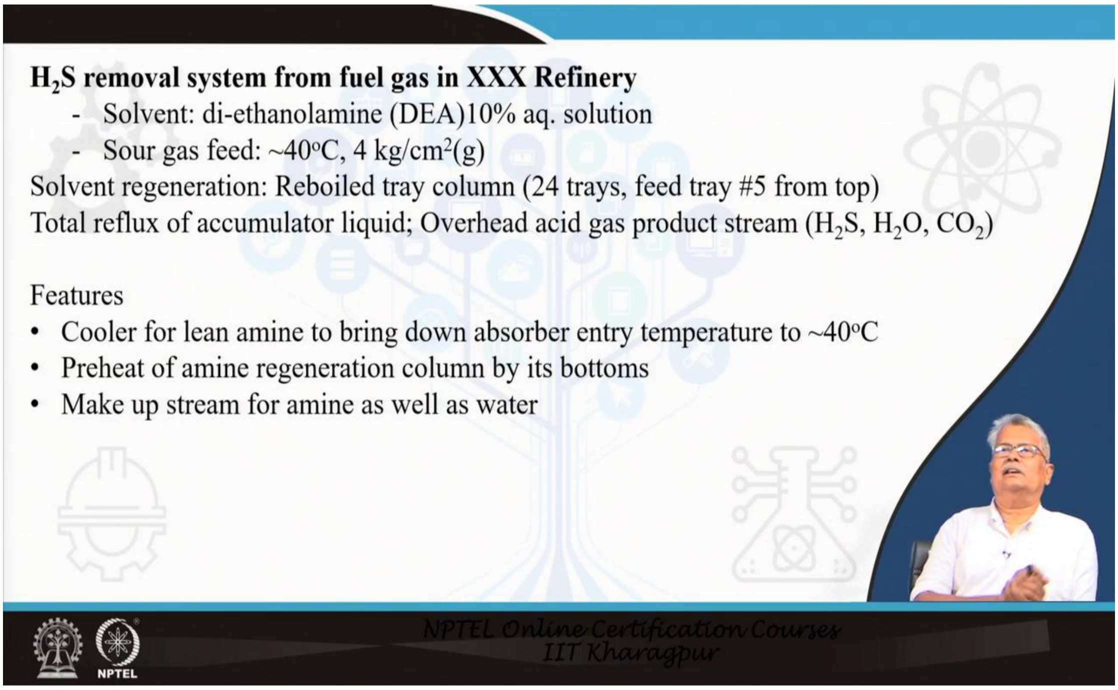

H_2S removal system from fuel gas in XXX Refinery

- Solvent: di-ethanolamine (DEA)10% aq. solution
- Sour gas feed: ~40°C, 4 kg/cm^2(g)

Solvent regeneration: Reboiled tray column (24 trays, feed tray #5 from top)

Total reflux of accumulator liquid; Overhead acid gas product stream (H_2S, H_2O, CO_2)

Features

- Cooler for lean amine to bring down absorber entry temperature to ~40°C
- Preheat of amine regeneration column by its bottoms
- Make up stream for amine as well as water

We have here another example in which we have a removal system from H_2S removal system from a fuel gas in a typical refinery. This example is from real life. This refinery uses 10% aqueous solution of diethanolamine. The sour gas feed is at a temperature of around 40 °C and a pressure of around 4 kg/cm^2 gauge. The absorber in this particular case is a packed tower.

The regeneration of the DEA solution is done in a distillation column which is a tray tower typically with a large number of trays 24 trays; the feed tray is on the 5, on the number 5 from the top. The top product which goes out from your system is gas over a which is called an acid gas which is primarily a mixture of H_2S, H_2O and CO_2 and you can watch here that you are going to lose certain some amount of H_2O from your system and this has to be made up.

There is another thing which is also there, you will notice that since we are talking about since we have talked earlier about a stripper, this is basically a stripper; but the feed tray is not on the top tray. The feed trays from number 5 from the top. The reason is basically to bring it below is that we do not want much of amine loss from the top, we want as only water, H_2S and carbon dioxide in the top, one of 2 trays.

That is the reason, we have the feed tray number 5 from the top and not number 1. You will also see if you are really following this that there will be a cooler using cooling water for the leach, amine to be brought down to the absorber entry temperature of around 40°C. Typically, it is around 45°C.

There will be preheating of the amine regeneration column by its bottom that reduces the preheat requirement or rather heat input to your column. You have to have loss-maker for the amine as well as water.

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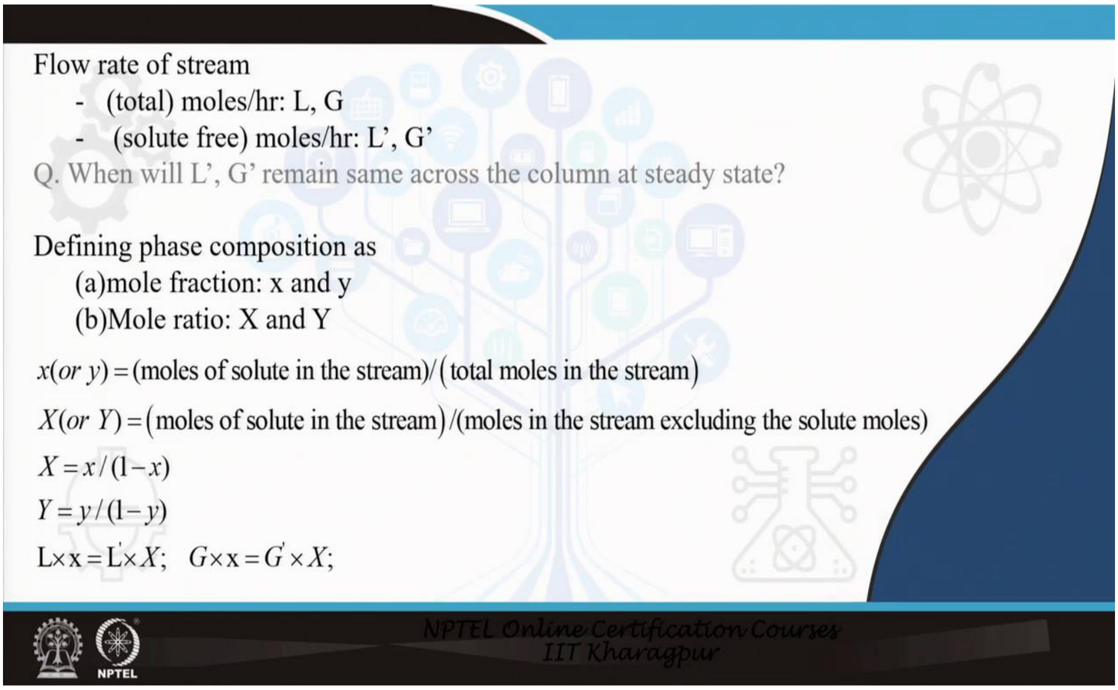

Flow rate of stream

- (total) moles/hr: L, G
- (solute free) moles/hr: L', G'

Q. When will L', G' remain same across the column at steady state?

Defining phase composition as

(a)mole fraction: x and y

(b)Mole ratio: X and Y

$$x(or\ y) = (\text{moles of solute in the stream})/(\text{total moles in the stream})$$

$$X(or\ Y) = (\text{moles of solute in the stream})/(\text{moles in the stream excluding the solute moles})$$

$$X = x/(1-x)$$

$$Y = y/(1-y)$$

$$\mathrm{L}\times\mathrm{x} = \mathrm{L}'\times X; \quad G\times\mathrm{x} = G'\times X;$$

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I think I will stop here and from the next class, we will start with the calculations which are related to the process design.

Thank you.