Course: Adsorption Science and Technology: Fundamentals and Applications

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Week 01

Lecture 1 | Background of Adsorption

Hello everyone, welcome to this class on adsorption science and technology. So this is a course on adsorption principles and its technological use in process application. Adsorption is a very old process and it is one of the fine end processing step in separation or downstream industries. But this has been quite recently put to use in many advanced separation application and thus become very relevant in today's world and in the upcoming years. Now adsorption is a surface based process. And, it is one of the key features of adsorption is its high selectivity and separation efficiency.

Of course, this is one of the main, you know, motivation behind the use of this technology in various process applications. Starting from petrochemicals relating to, you know, these refining operations then your fine chemicals, agricultural products, water treatment, air separation there are many applications and you have already seen the content of this course which includes various you know application process. This is something which we will try to cover in this course starting from the basics to the advanced level. Now in today's class or the first lecture would actually be more on the background of this technology or this process and how it is you know fundamentally different from other physical based separation processes is something that we will mostly focus on today.

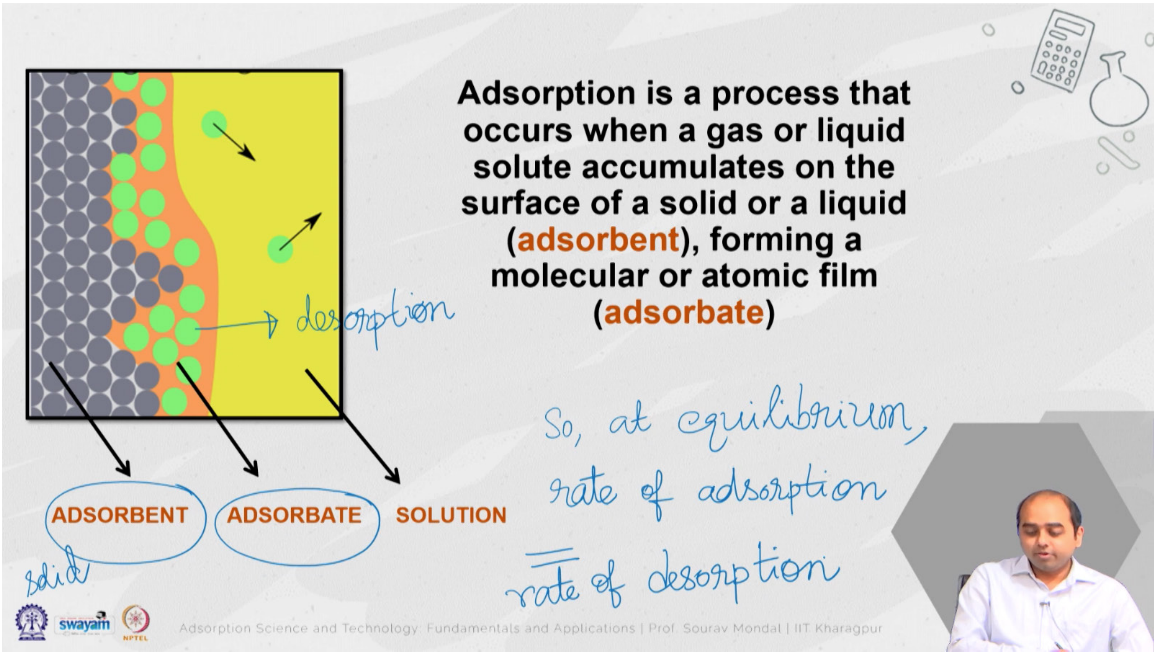
So, adsorption as I was saying is a surface phenomena. So, it involves all the processes whether it is a macroscopic or a microscopic process happens only at the surface or the interfaces. Typically, an adsorption process involves three different or distinct phases or you know domain. So, one is the solution phase that you can see here. One is the adsorbate phase, so the adsorbate phase essentially is the or are the molecules which are separated or which are you know bound to the adsorbent.

So, this adsorbent is essentially the solid phase. to which the adsorbate molecules are captured. Now adsorbents are mostly solid in nature. There are also examples of liquid adsorbents, but typically adsorbents are solid in nature. So, we will mostly restrict or refer to adsorbent as solid phase.

Adsorbate could be a liquid, could be a gas, could be you know a fluid or could be a multi component mixture. Now, these adsorbate molecules or the species which are getting adsorbed is present in the solution phase or with is mixed along with the carrier fluid which is referred to as the solution phase. So, the process of you know attachment of these adsorbate molecules or the species onto the adsorbent is referred to as adsorption. Now this is an equilibrium governed process which means that the free energy change of this process is very important and significant. So, the system tries to move towards a low energy state by this process of adsorption.

We will talk about more about the thermodynamics of this process in the upcoming lectures. So, here we want to talk about or today we want to focus about that how exactly this adsorption happens. So, let me try to explain this from a molecular perspective. So, typically the adsorbate molecules are the species is, when it approaches towards this solid phase there is a formation, I mean the first there has to be some sort of diffusion forming a small film which could be a molecular scale thickness film over the adsorbent molecules. Once the adsorbate a comes in contact or in close vicinity to these adsorbent molecules or the adsorbent solid / phases.

There is strong intermolecular attraction or intermolecular interaction between these two phases mostly of van der Waals type. It could be also chemical in nature which essentially talks about chemisorption and physisorption. But these intermolecular interaction reduces the overall free energy of the system. And the system moves towards a more orderly state or orderly arrangement, reducing the overall energy of the configuration or of this attachment process and thus the adsorption process reaches or attains an equilibrium and this is a stable process. Now, as adsorption continues there comes a situation when the concentration of the adsorbate species is higher in the adsorbent compared to the bulk or the solution phase.

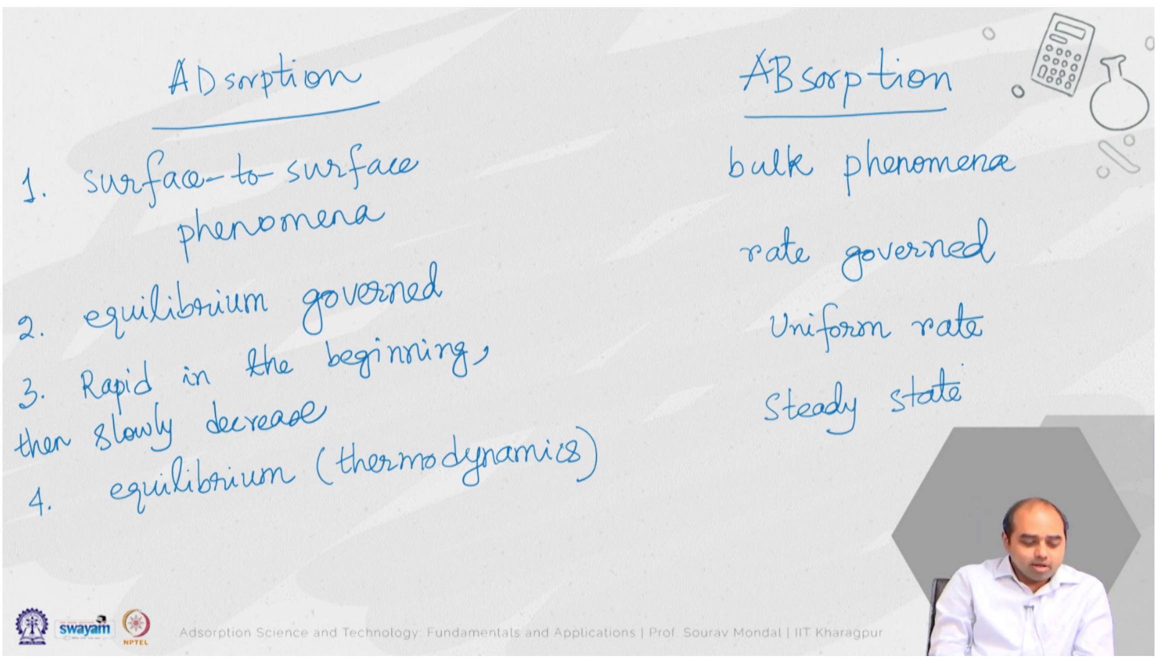


So, in that situation there is back diffusion of the molecules from the adsorbent or from the solid phase back to the solution phase known as desorption. So, at equilibrium, the rate of adsorption or you can consider it to be at the forward process of attachment is equal to the rate of desorption, and this ensures that the system is at equilibrium. So, until it attains an equilibrium that rate of adsorption is of course, more than the rate of desorption and when it reaches the equilibrium process the rate of forward you know process which is essentially attachment is equal to the rate of desorption. Desorption is nothing, but detachment of these molecules if the concentration is more in the solid phase compared to the bulk phase or the solution phase. these two becomes equal.

Now, one of the common misconception, which arrives in the study of this adsorption is that how or in what way it is different from absorption. So, let us try to understand that because absorption AB is also is a very important mass transfer based separation process. So, it is very important to highlight the key features of these two. So, AD adsorption is essentially a surface phenomena. The surface essentially means the location or the interface between the molecules of the solution phase to the solid phase.

It could be also you know inside adsorbent particles generally which are porous in nature, it could be also at the you know surface of the pores. So, whatever it is, it is the surface to surface phenomena. AB absorption is a bulk phenomena. As you know absorption AB based processes happens throughout the bulk of the system and the rate of this process is same at the surface as well as in the bulk matrix. So, this is one of the key difference between these two.

Another important difference is this that absorption AB is a rate governed process whereas AD adsorption is a equilibrium governed process. Of course, there is kinetics involved in adsorption too, but primarily it is the equilibrium you know state that determines the level of separation efficiency or the rate of mass transfer. Whereas, in the case of this absorption AB it is the rate kinetics or the rate of the process of the mass transfer rate is very important. So, naturally that is what you see in absorption it is quite fast, but then most rate governed process are not so selective. So, the selectivity in absorption AB is relatively much lower compared to equilibrium governed process.



And that is true not only for adsorption and absorption AB, it is true for any if you compare grossly between other equilibrium governed process and rate governed process the selectivity is much higher in the case of equilibrium governed process compared to a rate governed process. Third important difference or distinction between these two is that this absorption AB is the since the rate governed process it is uniform throughout the time of the operation. So, this AB absorption occurs at the uniform rate generally whereas, this AD adsorption is rapid in the beginning and then it slowly decreases. Next important thing is this is a I mean as you understand this adsorption is a equilibrium process. So, the equilibrium phenomena here is very dominant or let us say the thermodynamics of the system is relevant here.

Whereas AB is a steady state process I mean there is a dynamic nature to it, but essentially you get something of a steady state nature. So, there is no equilibrium or there is no forward and backward process involved in absorption. So, these are generally the major differences or the fundamental differences between this adsorption and AB adsorption which both of them are very popular mass transfer based separation process. Now, let us try to understand in detail about how this mechanism which I was referring in the beginning of this adsorption happens.

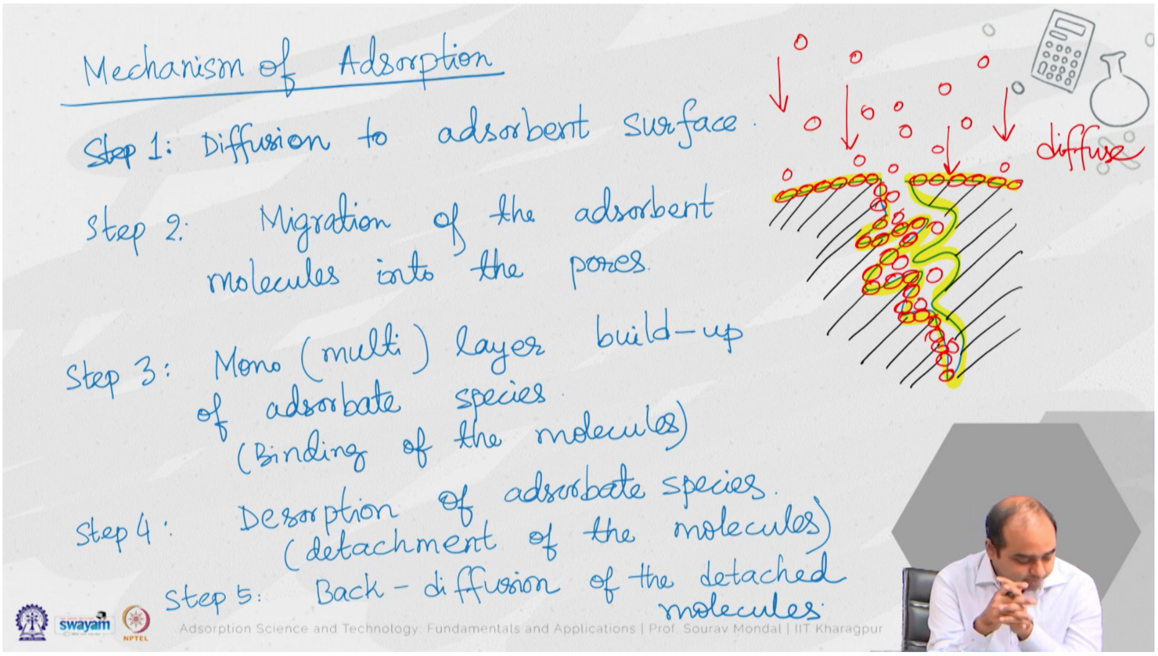
So, the first step. So this is a generally a multi step process. So the first step is diffusion of the molecules, to the adsorbent surface. So, unless diffusion happens there is possibly no adsorption which is possible. So, what do we mean here is that, let us consider this particular surface. So, I am trying to draw the surface of a particular a porous catalyst, something like this.

So, let us assume this to be your solid phase. So, which is hatched is the solid phase and we draw the adsorbate species you know coming from the bulk phase. So, at the first step the adsorbate molecules has to diffuse close to the surface of the adsorbent. So, let me once again you know highlight the surface of the adsorption where it is happening. This is the top surface and this is the interstitial, you know, pore surface area above which or on which this adsorption is happening. So, this is what is happening in this case.

First the molecules has to diffuse in close to the surface, then the next step is after this you know diffusion the next step is essentially this step 2 or you can say a sub step of this first one is this migration of the adsorbent molecule into the pores. So, again by diffusion these molecules would migrate or move inside these pores that is step 2. Because adsorption also happens on the surface of these pores so the and that is what you know makes any adsorbent particles to be porous in nature which essentially is to increase the active surface area of these solid adsorbent particles. So, that essentially the surface activity as well as the exposed surface area is much higher per you know volume of the particles . Step 3 is monolayer or whatever multilayer build-up of adsorbate species.

So, in the third step essentially you will start to see formation of the attachment or formation of this film happening on the surface of the exposed area in which this binding happens. So this is mostly happens here so I would expand this to something like binding of the molecules. Please note that fundamentally this process of binding is different from a chemical reaction because you are not producing any new product. Many a times it is confused, that the you know this process of binding or the process of adsorption is similar to a chemical reaction because here also you have a forward binding forward process known as adsorption and a reverse process known as desorption which is equivalent to a reversible chemical reaction. But fundamentally it is very different from a chemical reaction in the sense that no new product is produced at any stage in this process.

Step 4 is desorption of adsorbate species. So, during the desorption process the detachment of the molecules happens from the bound site of the adsorbent. So, both the adsorption or the binding and the detachment are spontaneous process. And the final step is again back diffusion of the detached molecules into the bulk phase. So, these are the 5 essential key steps of any adsorption process.



Unless the last step is completed the desorption is not complete and again the process I mean there is a concentration gradient which you know affects both step 1 and step 2. The thermodynamics are involved only in step 3 and step 4. Rest step 1, 2 and 5 all are transport processes are essentially either diffusion, convection, migration you can call it are related to a transport based process. Step 3 and 4 is a thermodynamic process. As you know the main driving force behind any separation process is the change in the chemical potential.

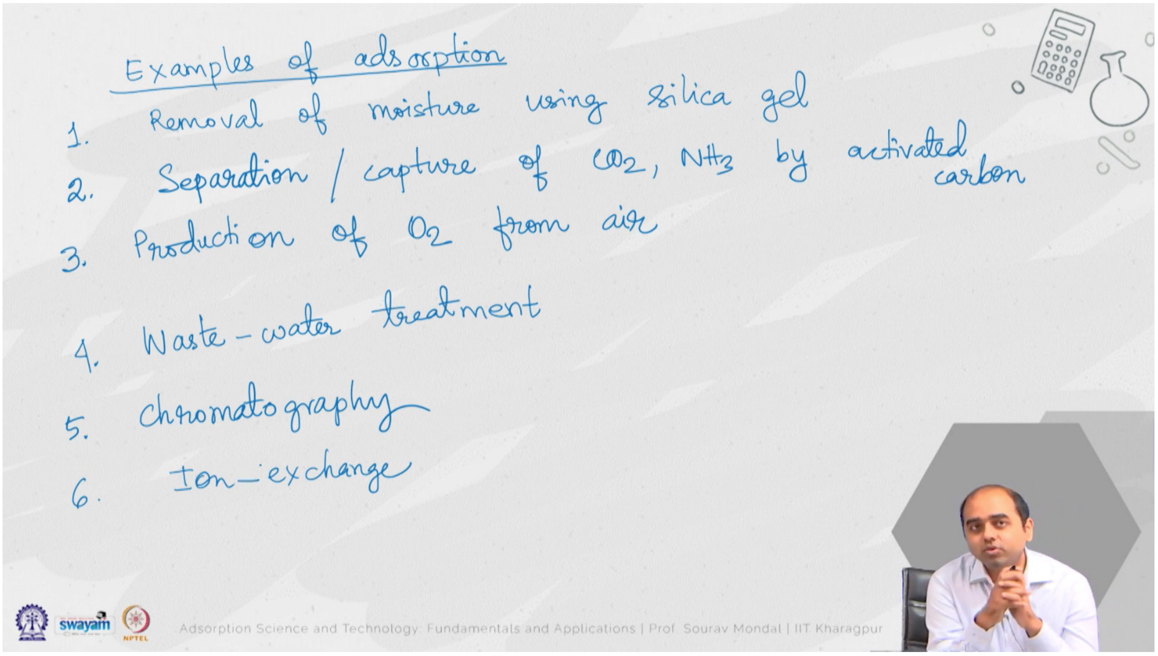
So, in this case as adsorption happens the chemical potential or the free energy change of the process actually reduce. So, that the delta G is negative in this case as it is a spontaneous process of this adsorption. Giving you some quick examples of where adsorption is very relevant or adsorption happens in real life scenarios. And this is one what in fact sets the background of this course altogether. A common example that you see is removal of moisture using silica gel.

So, you will see in many packaging products particularly which are sensitive to moisture, you will have the small sachet of a silica gel granules that is present. And these are essentially kept to you know remove the moisture which is developed or present in that packaging product it as it might affect the this quality and the life of that product. So, this removal of moisture using silica gel is by adsorption. A very popular example of adsorption is this separation or capture of CO_2 ammonia by activated carbon. Another popular example is production of oxygen or O_2 from air.

In this case you try to separate, you know, this nitrogen or you try to selectively adsorb the nitrogen using a particular adsorbent and the stream becomes enriched in O_2. So, this is the major application of oxygenator or the medical grade oxygenator that you have you know seen during the pandemic time. And we will of course, talk about in detail in the in some of the upcoming lectures. Separation of capture of carbon dioxide is also very popular these days because of you know CO_2 capture and decarbonization efforts made globally to reduce the carbon footprint. So, that is also I mean of course, there are other techniques.

There is also a technique for AB absorption using amine based solution, but essentially adsorption is also used at the fine step to reduce trace amounts of or low levels of CO_2 from the you know from the stream or the flue gas stream. Another popular example of adsorption that you see widely is in wastewater treatment. So, all of you I am sure have seen any water purifier that is used to produce drinking quality potable water. It use at one point of time some bit of activated charcoal or activated carbon to remove microorganisms to you know deodorize the water as well as remove color contaminants and essentially increase the quality of the water that is you know consumed. So, water treatment I mean this is of course for drinking water I am giving the example, but for normally for effluent treatments you know activated carbons are widely used for you know water treatments and you have also different kinds of you know slags that are you know developed for novel adsorbents.

Then you have different kinds of bio based adsorbents, biomass based adsorption which are highly selective. So, there is a wide application of adsorption in water treatment. Another common example of adsorbent adsorption which is used is in your chromatographic process. So many of you have heard about you know chromatography or high performance liquid chromatography, gas chromatography and there are whole lot of different gel permeation chromatography, ion chromatography which is available as analytical facilities as well as widely used in pharmaceuticals for you know production of high purity compounds. So, chromatography is a essential tool or an essential process which use absorption to selectively separate, you know, molecules from a continuous phase.



And the final example is on ion exchange. So, of course, here there is charge charge interaction, but since it is also equilibrium governed process it comes generally it can be considered within the purview of you know adsorption based process and these are something that we will be discussing throughout this course. So, I hope all of you have you know liked the first class and we will talk about more about different types and properties of the adsorbents in the next class. Thank you and see you in the next lecture.