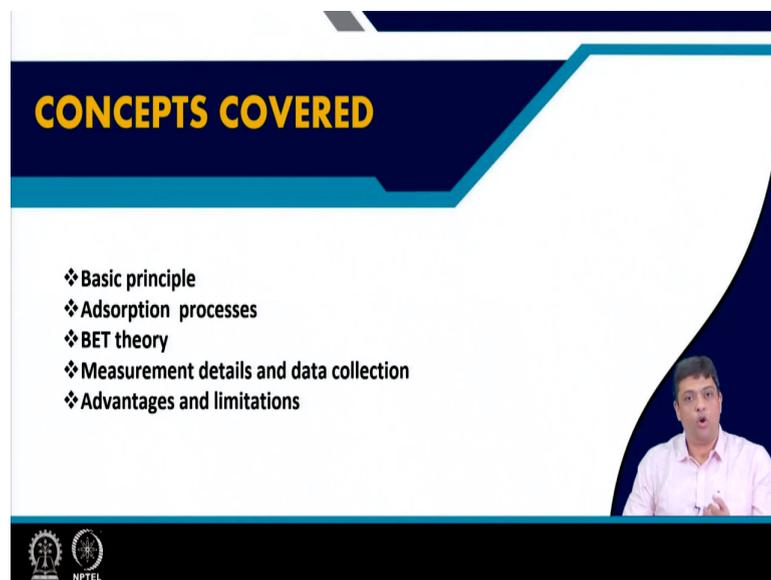


**Physics of Renewable Energy Systems**  
**Professor Amreesh Chandra**  
**Department of Physics**  
**Indian Institute of Technology Kharagpur**  
**Lecture 50**  
**BET Analysis**

Hello, I hope you are liking this course and we have reached to the final module of this course and we will continue with our discussion on few of the important characterization techniques that are used to characterize the materials that were discussed in this course and are also used in various energy systems that were presented to you.

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In today's lecture will give you the basic principle of working of a BET analyzer. What is the full form of BET, will tell you in a minute. What do we understand by the adsorption process and how this process is actually used to derive relationships which can be used to extract information about the pore, the pore volume and the other parameters such as surface area, etc. What is the BET theory?

As we have done in the earlier lectures we will also give you a video where we will show you how to collect the data, what is a typical BET analyzer looking like? How to obtain that data and then how to analyze the data? And finally, you will see the advantages and limitations of this characterization technique which is vastly use in today's world where we are talking about nanomaterials.



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**KEY POINTS**

- ❖ Surface area
- ❖ Porosity
- ❖ Various porous materials
- ❖ Isotherms

The slide features a dark blue header with the title 'KEY POINTS' in yellow. Below the header is a white area containing a bulleted list of four topics. In the bottom right corner, there is a small video inset showing a man in a white shirt speaking. At the bottom left, there are logos for NPTEL and other institutions.

The moment we talk about nanomaterials concepts of surface area, porosity, the nature of pores and the isotherms which are used to extract these informations become critical and I hope you would be able to clearly understand the forms of isotherms and how to extract the information pertaining to surface area porosity, pores or pore volume of various types of porous or nano structures.

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**Terms related to surface area analysis**

- **Pore:** Void between the two materials are called pore. The unit of the pore size is nm.
- **Pore size:** It is generally the distance between two opposite walls of the pore (diameter of cylindrical pores, width of slip-shaped pores). Average diameter of the pore called pore size. The unit of the pore size is nm.
- **Pore Volume:** It represents the volume of the each pore. The unit of the pore volume ( $\text{cm}^3 \text{g}^{-1}$ ).
- **Porosity:** Ratio of the pore volume ( $V_p$ ) and total volume ( $V_T$ ) of the nanoparticles.  
$$\text{Porosity} = \frac{V_p}{V_T} \times 100\%$$
- **Surface area:** The accessible area of the solid surface area unit mass of the materials. The unit of the pore size is  $\text{m}^2 \text{g}^{-1}$ .

The slide has a white background with a blue header. It contains five bullet points defining key terms. A central equation for Porosity is highlighted in a green box. In the bottom right corner, there is a small video inset showing a man in a white shirt speaking. At the bottom left, there are logos for NPTEL and other institutions.

We are talking about the analysis which will give us the surface area. In nano structures or nanomaterials what have we talked about? This surface to volume ratio is high with respect to

these materials, there are many terms which are critical and they define the usefulness of these nanomaterials. First term which becomes useful is the pore, how do we define the pore?

It is the void between the two materials. So, if I bring two materials together, then what is the gap or the void between two materials? So, that is what we are talking about and the unit of the pore size is nano meter. So, whenever you define or write the pore size, you should write them in terms of nanometer. The pore size it is generally the distance between two opposite walls of the pore.

The diameter of cylindrical pores, width of slip-shaped pores or any other type of pores which are there in porous structures or materials which are in the nanosize regime can be determined using this calculation, and the average diameter of the pore is called the pore size. Again the unit of the pore size is what, it is because it is the average diameter of the pore, pore was actually pore size was being written in nanometers.

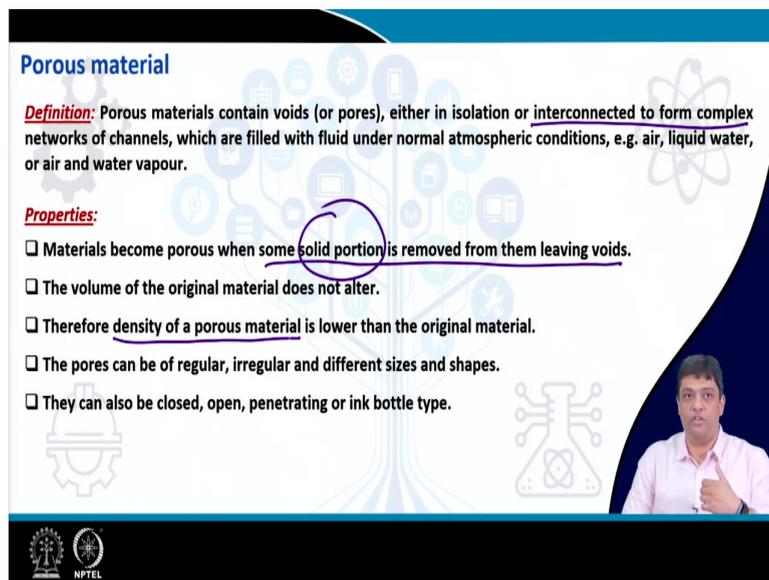
So, what you will call the overall values, they will be in terms of nanometers. Once you have the pore size in nanometers you then move to the pore volume, how big is the pore and is it a three dimensional structure and if you have a material to the 3D material, then you are talking about voids which would be three dimensional.

So, then you start talking about the term pore volume. It represents the volume of each pore and the unit of the pore volume is mostly in centimeter cube per gram. What is porosity? This is a common term which you will hear, it is a very porous material, it is a non-porous material, the porosity of a porous material is, so this is a common term which is used when you are talking about porous materials and porosity defines the ratio of the pore volume and total volume  $V_T$  of the nanoparticles.

So, porosity, the pore volume and the total volume. So, what happens if you have particles and now you have large number of particles arranged in the material and between two materials, what do you have? You have pore, the size is given in nanometers. So, you measure the pore volume and then you measure the total volume of the material and then you can get the porosity of the system.

And the most common term is the surface area of nanomaterials which are talked about and the surface area is the accessible area of the solid surface per unit mass of the materials. So, the accessible area of the solid surface area, but per unit mass of the material and therefore, its unit is meters squared per gram. So, these are the common term which defines the usefulness of the nanomaterials or are used to characterize the nanomaterials or sometimes to compare the nanomaterials. The question comes how to determine these parameters.

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**Porous material**

**Definition:** Porous materials contain voids (or pores), either in isolation or interconnected to form complex networks of channels, which are filled with fluid under normal atmospheric conditions, e.g. air, liquid water, or air and water vapour.

**Properties:**

- Materials become porous when some solid portion is removed from them leaving voids.
- The volume of the original material does not alter.
- Therefore density of a porous material is lower than the original material.
- The pores can be of regular, irregular and different sizes and shapes.
- They can also be closed, open, penetrating or ink bottle type.

The slide features a background with various scientific icons like a gear, a lightbulb, a microscope, and a flask. A small inset video of a presenter is visible in the bottom right corner. The NPTEL logo is at the bottom left.

To explain it further, let us take an example of a porous material. What is a porous material? A porous material is the one which contains voids either in isolation or interconnected structure which is a complex network of channels. So, the pores can be interconnected or you can have individual pore which is an isolated structure. Now, these are the voids which can be filled with fluid under normal atmospheric conditions.

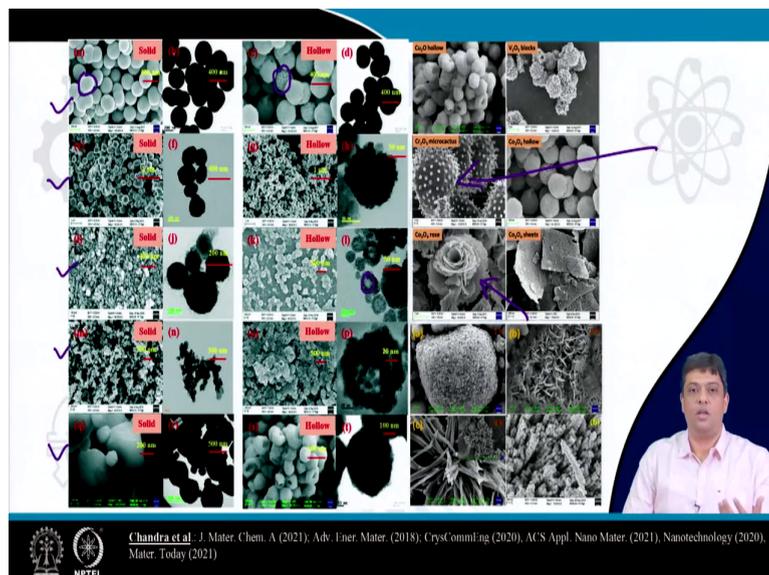
Fluids could be air; you could have water, water vapor or any other kind of fluid. How these porous materials are generally formed? These materials are the ones which are formed when some solid portion in them is removed and when these solid portions are removed, they leave behind voids. The overall the volume of the original material, the total volume which you are measuring, may not alter.

So, you may see that the overall volume seems to be same, but if you see the pore volume then you may see that has increased and if that has increased the porosity has actually increased. And how is a porous material formed? It is formed by the removal of the solid portion and if you remove some solid portion what will happen you would actually reduce the weight and therefore, the density of this porous material is lower than that of the original material. Is there a condition that the pores have to be regular shaped?

No, there is no such condition; the pores can be regular, irregular with different sizes and shapes. In addition to this, they can be closed open or any other type. So, the nature of the pores are quite complex and depending upon the nature of the pores what is happening, you are actually modifying the flow of the fluids which are getting trapped in this porous structure.

As a result, the performance of the material changes if you are talking about the formation of solid electrolyte interface, the terms which we have routinely used when we talked about batteries or super capacitors or fuel cells. So, that is the reason why as you change the water structure the SEI layer changes and the electrochemical performance gets modified.

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For example, let us take these materials, they are all materials made of various types of metal oxides and you can see these are the scanning electron micrographs of different types of metal oxides used in super capacitors or batteries.

Very simple question, are they all looking the same? You would say obviously not they have a very different structure; some of them have solid morphologies while some of them have the hollow morphologies, if you look into the transmission electron microscope of them while some of them have a structure which seems to be perforated.

Then you have materials which look like a cauliflower or you can have materials which are looking like cactus. So, there are materials with different shapes, sizes or what we termed as morphologies and obviously, their performance would be different and hence it is critical to determine the parameters such as pore size, pore volume, total volume, surface area and then the surface to volume ratio which will define the characteristics of these nanomaterials.

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**Classification of pores**

Classification by the International Union of Pure and Applied Chemistry

- Macroporous >50nm ✓
- Mesoporous 2-50nm
- Microporous <2nm
- Ultramicropores below 0.7nm
- Supramicropores 0.7~2nm

Pore size can be calculated by:

- ✓ Diameter of a cylindrical pore
- ✓ Distance between opposite walls in case of slit pores

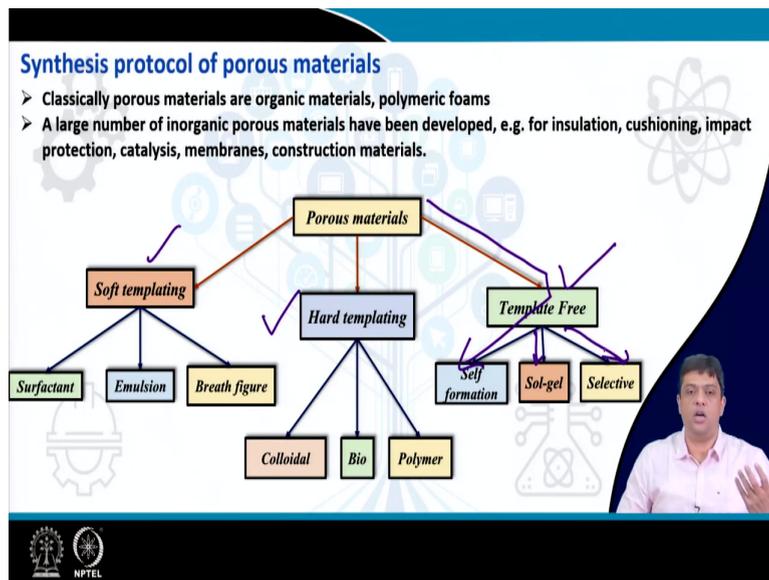
The slide features a background with a tree-like diagram of icons and a video inset of a man in a white shirt speaking. The NPTEL logo is visible in the bottom left corner.

And that is done using BET analysis. There are different types of bores with different shapes and sizes, this information must be clear by now. Now, you would say if there are different shapes, different sizes are all of them called just as pores or there are some classifications? And according to the International Union of Pure and Applied Chemistry, if you have pores which are more than 50 nanometers then you call them as macroporus.

If you have pores which are in the range of 2 to 50 nanometers, you call such pores as Mesoporus. And if you have pores which are in the range of 2 nanometers or lower then they are called as Microporus. A step further you can have Ultramicropores; those are below 0.7 nanometers and Supramicropores which are in the range of 0.7 to 2 nanometers.

So, if I asked you a very simple question, I give you a material and I say the material is a macroporous material, what am I indicating? I am suggesting to you that the material is such that the pores are having sizes which are 50 nanometers or more. So, this is the classification of pores. The pore size can be calculated by estimating the diameter of a cylindrical pore, and it is the distance between the opposite walls in case of a slit pores, this we saw earlier.

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As shown earlier, you can have different types of materials in different morphologies and you can obtain these materials using large number of synthesis protocols, they can include soft templating, hard templating, template free or the sub classifications of these headings. For example, template free synthesis of porous materials can include cell formation, Sol-gel or selective etching. So, you can use various types of synthesis protocols which you have heard or learned earlier and you can obtain these materials.

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### BET theory

- ❑ Gas adsorption or Nitrogen adsorption
- ❑ The name comes from Stephen Brunauer, Paul Hugh Emmett, and Edward Teller
- ❑ Directly measures surface area & pore size distribution
- ❑ BET theory deviates from ideal to actual analysis

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graph TD; A[BET theory] --> B[Gas adsorption or Nitrogen adsorption]; A --> C[The name comes from Stephen Brunauer, Paul Hugh Emmett, and Edward Teller]; A --> D[Directly measures surface area & pore size distribution]; A --> E[BET theory deviates from ideal to actual analysis];
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Once we have understood the origin of pores, what is a pore size, you have seen different types of materials, how do we obtain different types of materials, that is synthesis protocols, let us now try to understand what actually the BET theory is. The whole theory is based on gas adsorption desorption or it is also sometimes called as nitrogen adsorption desorption process.

The name BET comes from the name of the scientists which actually proposed this characterization to, they were Stephen Brunauer, Paul Emmett and Edward Teller. So, you have B, E and T, so it is also called as Brunauer, Emmet, and Teller technique. The importance that it can directly measure the surface area, the pore size, the pore size distribution and also the pore volume. Sometimes we would find that the BET theory deviates from ideal but moves towards actual analysis.

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**Basic Principle**

Ideal	Actual
No gas molecules	initial condition
Nitrogen gas molecules	Monolayer: Gas molecules come together
Saturated Nitrogen gas molecules	Multilayer: Gas molecules come together

The diagram includes a graph of  $Q_{ds}$  vs  $p/p_0$  and a small inset video of a presenter.

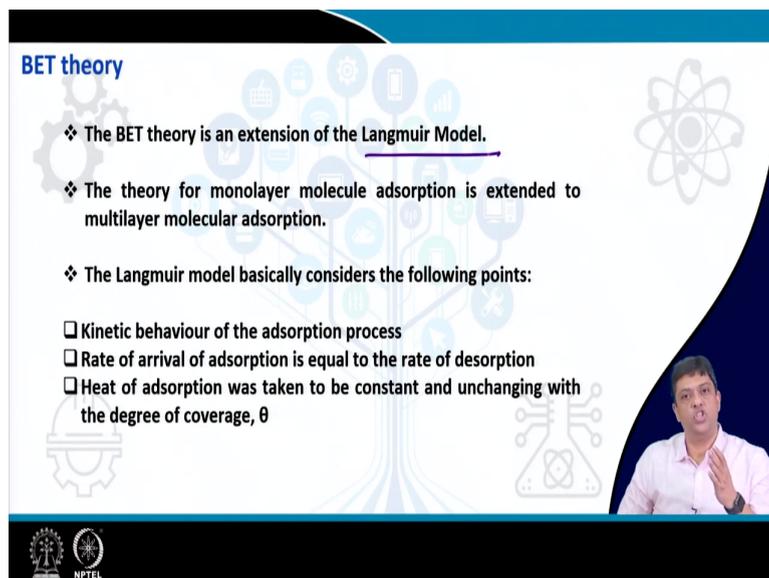
What is the basic principle? You have a porous material, when there is no gas molecule being impinged inside this material then you have condition on the top, you have the porous material with no gas molecule getting adsorbed. This is the initial condition and if you plot  $Q_{ds}$  by  $Q$  adsorbed as a function of  $p$  by  $p_0$  then you have no value.

Now you have nitrogen gas that gets adsorbed on the surface and then you can plot the quantity adsorbed, as a function of changing  $p$  by  $p$  value. Finally, you can obtain these

saturated nitrogen gas molecules when you have reached the condition of saturation and then you again plot the curve. For the second case you are talking about mono layer and for the third case, you are talking about the multi layer that is gas molecules coming together and forming multi layer adsorption.

So, this is what you are doing, you will understand this technique much more in a minute that you have a porous structure and then you are impinging gas and this gas molecules are getting adsorbed on the surface and the quantity of gas molecules actually get adsorbed will tell you the vacant spaces inside the material and if you can compare it with the standard then you will know what is the amount of gas molecules those have been adsorbed and you will get an idea about the pore volume in a material.

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**BET theory**

- ❖ The BET theory is an extension of the Langmuir Model.
- ❖ The theory for monolayer molecule adsorption is extended to multilayer molecular adsorption.
- ❖ The Langmuir model basically considers the following points:
  - Kinetic behaviour of the adsorption process
  - Rate of arrival of adsorption is equal to the rate of desorption
  - Heat of adsorption was taken to be constant and unchanging with the degree of coverage,  $\theta$

The slide features a blue header with the title 'BET theory'. The main content is a list of three bullet points. The first point is underlined. The second point is a continuation of the first. The third point is followed by a list of three sub-points, each with a checkbox. The slide also includes a small inset image of a presenter in the bottom right corner and the NPTEL logo in the bottom left corner.

This is a model which is an extension of the Langmuir Model. What happens in this model? You have moved from mono layer adsorption to multi layer adsorption and you consider the kinetic behavior of the adsorption process, you believe that the rate of arrival of adsorption is equal to the rate of desorption and heat of adsorption is taken to be constant which is not changing with the degree of coverage.

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**Assumption of BET theory**

The BET theory derivation is similar to the Langmuir theory but with following assumption:

- i. adsorptions occur only on well-defined sites of the sample surface (one per molecule);
- ii. the only molecular interaction considered is the following one: a molecule can act as a single adsorption site for a molecule of the upper layer;
- iii. the uppermost molecule layer is in equilibrium with the gas phase, i.e. similar molecule adsorption and desorption rates;
- iv. the desorption is a kinetically-limited process, i.e. a heat of adsorption must be provided;
- v. at the saturation pressure, the molecule layer number tends to infinity (i.e. equivalent to the sample being surrounded by a liquid phase).



Let us see what are the main assumptions, first, adsorptions occur only on well defined sites of the sample surface, so it will only occur on a well-defined surface. The only molecular interaction considered is the one where we believe a molecule can act as a single adsorption site for a molecule of the upper layer, so one molecule adsorbing one molecule of the upper layer. The uppermost molecule layer is in equilibrium with the gas phase that is similar to molecule adsorption and desorption rates.

What is the desorption process? It is a kinetically limited process that is heat of adsorption must be provided, so you need to heat. At the saturated pressure the molecule layer number tends to infinity. So, once you have reached the saturation pressure, the molecule layer number tends to infinity that is equivalent to the sample being surrounded by a liquid phase. So, this means that the sample is totally covered from all sides, by a liquid phase.

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**Adsorption process**

**BET theory extends the Langmuir theory from monolayer to multilayer adsorption**

Ideal physisorption behaviour

Single layer adsorption

Ideal solid surface

Real physisorption behaviour

3<sup>rd</sup> layer

2<sup>nd</sup> layer

1<sup>st</sup> layer

Actual solid surface

So, ideal physisorption behavior, you have one surface which is ideal surface and single layer adsorption. But what is the real condition, you do not have an ideal structure you get a non ideal structure which can have roughness on it. And then because of this roughness, the layers which will get adsorb would be different and you can have multi layer physisorption behavior. So, you move from the ideal condition to the real condition. That is the meaning which we had presented earlier.

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**BET theory**

➤ BET equation is given by:

$$\frac{1}{v \left[ \left( \frac{p_0}{p} \right) - 1 \right]} = \frac{(c-1) \left( \frac{p}{p_0} \right) + 1}{(v_m c) \left( \frac{p}{p_0} \right) + v_m c}$$

Where,

- $p$  and  $p_0$  are the equilibrium and the saturation pressure of adsorbates at the temperature of adsorption,
- $v$  is the adsorbed gas quantity,
- $v_m$  is the monolayer adsorbed gas quantity
- $c$  is the BET constant.

The BET equation is given by  $\frac{V}{p_0} \left( \frac{p}{p_0} - 1 \right) = \frac{c}{v_m} \left( \frac{p}{p_0} + 1 \right)$ , where  $p$  and  $p_0$  are the equilibrium and saturation pressures of the adsorbates at the temperature of adsorption,  $V$  is the adsorbed gas quantity,  $v_m$  is the monolayer adsorbed gas quantity and  $c$  is the BET constant.

So, now, you understand what is the adsorb gas and what is the monolayer adsorbed gas and how do we differentiate.

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**BET theory**

- The BET equation gives an adsorption isotherm which can be used to calculate the monolayer adsorbed gas quantity and the BET constant.
- The total surface area and the specific surface area can be calculated using the following equations:

$$S_{total} = \frac{v_m N s}{V}$$

and,

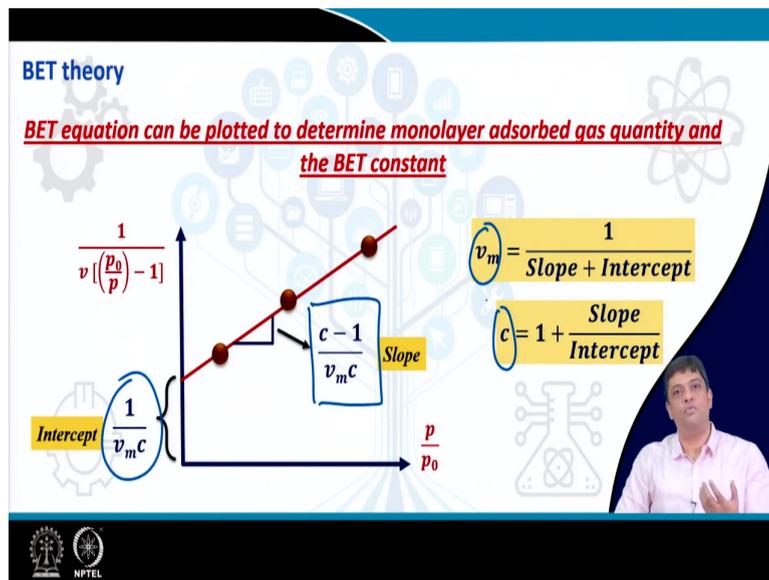
$$S_{specific} = \frac{S_{total}}{a}$$

where  $N$  is Avogadro's number,  $s$  is the adsorption cross section of the adsorbing species,  $V$  the molar volume of the adsorbate gas and  $a$  is the mass of the solid sample or adsorbent.

In the BET technique, what do we do? You use the BET equation and then you obtain an adsorption isotherm. This isotherm is then used to calculate the monolayer adsorb gas quantity and the BET constant. Now, we have two unknown parameters which are obtained. Once we have that, we can go a step further and determine the values of surface area and specific surface area. These are given by  $S_{total}$  and  $S_{specific}$ .

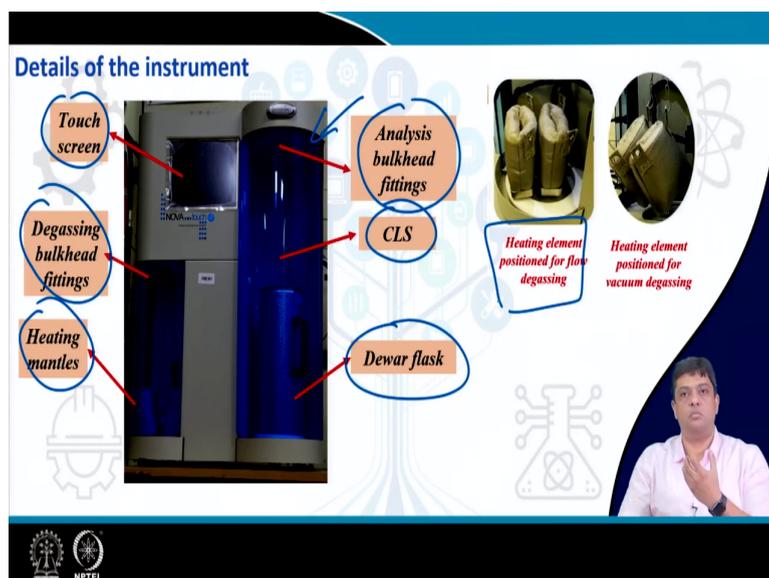
$S_{total}$  is equal to  $v_m N s / V$  where  $N$  is the Avogadro's number,  $s$  is the adsorption cross section of the adsorbing species, and  $V$  it is the molar volume of the adsorbate gas. And if you are talking about specific surface area, then you have  $S_{specific}$  which is  $S_{total} / a$ , where  $a$  is the mass of this solid sample or the adsorbent and generally you will find that people talk in terms of specific surface area.

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This is what you do when you are plotting the BET equation and from the slope you can get the value of c minus 1 by  $v_m c$  and the intercept gives you 1 by  $v_m c$ . And from there you will find that  $v_m$  is equal to 1 by slope plus intercept and c is equal to 1 plus slope by intercept. So, that is the way you actually obtain the values of  $v_m$  and c and then you can obtain the parameters of S total or S specific.

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This is a typical instrument for performing the analysis. You have the touchscreen; you have the degassing chamber which includes the degassing heads, the heating mantles. So, before

you actually perform the analysis, you have to degas the sample so as to ensure that all the pores are open and you have removed any kind of exhaust gases in these voids. So, then only you will get the real values for the material.

If you just measure the material without degassing you will get a value which has no meaning, why? Because you may already have adsorbed molecules and then you do not have any idea about the true nature of the pores or the pore volume. Then, this is your chamber where you load the sample which has been degassed and they include the analysis bulkhead fittings, the glass chambers and the nitrogen Dewar flask.

These are the heating element positions for flow degassing. So, this is what you have where they are, you have the sample and they are put inside and then they are switched on then they heat the tube and then you are removing the gas using a vacuum pump.

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**Measurement details**

- These steps ensure that the accuracy of the measurement.
- The initial sample preparation involves the following steps:
  - Weighing of approximately 20-30 mg of the sample and transferring it into a quartz cell.*
  - The sample must be thoroughly degassed.*

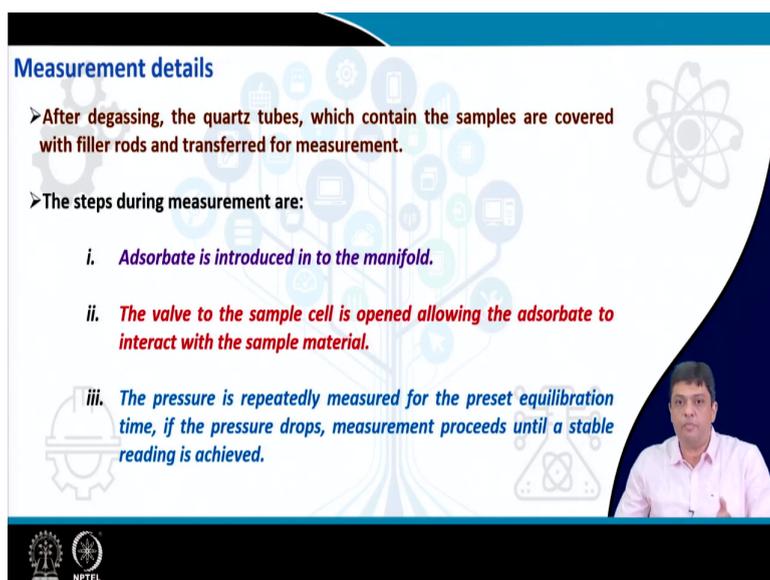
*Degassing is an important step before the measurement of surface area or pore size and volume. It ensures that the samples are cleaned of water or organic vapours.*

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These steps ensure that the accuracy of the measurement is maintained. So, degassing ensures that the accuracy of the measurement is maintained. While you are preparing the sample how much should you take? Generally, you take 20 to 30 milligrams of the sample and transfer them into the quartz cell, which is then connected to the degassing points and the samples are generally degassed 100 degrees if they can sustain these temperatures at 100 degrees for 12 hours or so.

So, this is a typical measurement which you will find and this is the meaning of what you read in the published literature or any other places. As mentioned degassing is an important step it ensures that the samples are cleaned of water or organic vapors that can be entrapped in the voids are on the surface of the materials.

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**Measurement details**

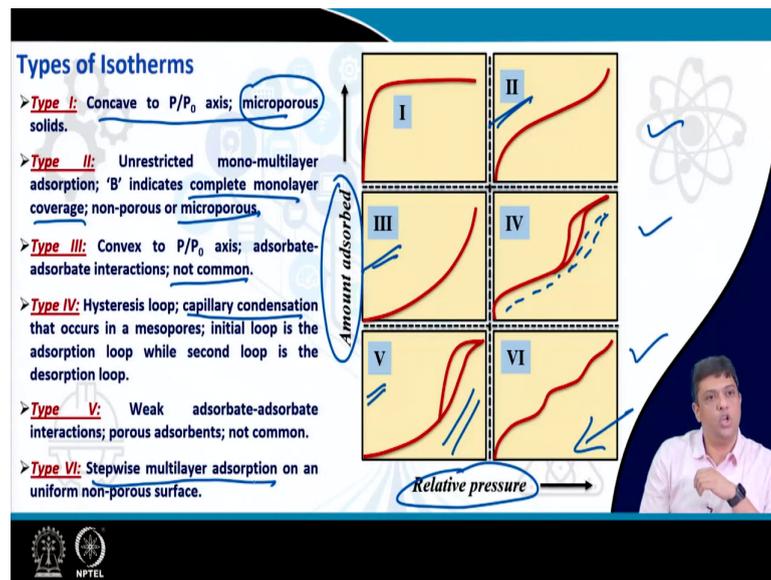
- After degassing, the quartz tubes, which contain the samples are covered with filler rods and transferred for measurement.
- The steps during measurement are:
  - i. Adsorbate is introduced in to the manifold.
  - ii. The valve to the sample cell is opened allowing the adsorbate to interact with the sample material.
  - iii. The pressure is repeatedly measured for the preset equilibration time, if the pressure drops, measurement proceeds until a stable reading is achieved.

The slide features a background with a stylized tree of icons and a video inset of a man in a pink shirt speaking. Logos for IIT Bombay and NPTEL are visible at the bottom left.

Once the samples are degassed, they are covered with filler rods and transferred to the chamber for measurement. The steps involved during measurements are the adsorbate is introduced into the manifold. The valve to the sample cell is open which allows the adsorbate to interact with the sample. So, the gas can then flow and interact with the sample.

Once you have allowed the adsorbate to interact with the sample material, you measure the pressure repeatedly, but if the pressure drops, then you introduce more gas and the measurement proceeds until a stable reading is achieved.

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So, once you have collected the data, you have information pertaining to amount adsorbed as a function of relative pressure. These are the different types of curves which you will encounter. So, for example, you can have type 5 like curve. So, you will have  $Q$  absorbed as a function of  $p$  by  $p_0$  and the nature which you will get will have a hysteresis nature, this also has a meaning. So, you see there is clear signal that the natures of the isotherms change.

For example, in type 1 you have concave nature to with respect to  $p$  by  $p_0$  axes. This is true for micro porous solids. If you have type 2 type curves, they indicate mono layer coverage which is complete and a non-porous or microporous type structure. Type 3 you can have adsorbate-adsorbate interaction which is slightly uncommon. Type 4, which you see many times is capillary condensation that occurs in mesopores.

Here the initial loop is adsorption loop, while the second loop is the desorption loop. This is what you mean by type 4. Type 5 indicates weak adsorbate-adsorbate interaction that is observing porous adsorbents and again not very common and if you have a curve which is looking like the one shown at the right most bottom this indicates step wise multi layer adsorption of a uniform non-porous surface.

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The slide features a white background with a blue header and footer. The title 'Safety instructions' is in blue. Three bullet points are listed in red and blue text. A video inset in the bottom right shows a man in a pink shirt. The background has a stylized tree graphic with various icons like a gear, Wi-Fi, and a smartphone. Logos for IIT Bombay and NPTEL are in the bottom left.

**Safety instructions**

- ❖ *Liquid nitrogen should be handled with care using proper gloves and glasses.*
- ❖ *Proper precautions should be taken while handling/changing the gas cylinders.*
- ❖ *Also, they should be thoroughly checked for leakage at regular interval.*

As indicated, the whole measurement is performed in liquid nitrogen condition then you must take precautions that no untoward incident takes place. Liquid nitrogen should be handled with care and with people who are trained to handle liquid nitrogen while they are taking all kinds of precautions.

You must also take precautions while you change the gas cylinders. When you have the gas cylinders, then before switching on any kind of experiments that are using gas cylinders or involve flow of gases, these kind of cylinders or outlets must be carefully and thoroughly checked for leakage at regular intervals, so that no untoward incident takes place or occurs.

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**Advantages and limitations**

**Advantages**

- ✓ *Low cost measurement method* ✓
- ✓ *Can measure porosity within a magnitude of 0.4 to 50 nm* ✓
- ✓ *Type, size and form of porosity can be defined from the type of isotherm*

**Limitations**

- ❑ *Can be used only for dried sample* ✓
- ❑ *Time consuming method* ✓
- ❑ *Not suitable for low surface area and micrometric particle size*

The advantages which are associated with this technique are, it is a low cost method, can measure porosity with high precision, and you can get a lot of information about the nanostructures. Limitation; mostly use for tried sample, quite time consuming method if you include from the time you have started preparing the sample, then you go for degassing, you collect the sample let the system cool down and followed by the analysis of the sample.

So, it is a time consuming method and it is not suitable for low surface area or micrometric particle size.

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Let us see how you proceed with this experiment. I hope you will be understanding everything which is being done here. So, you have the tube which is going to be fitted to the degassing port right at the bottom you can see the tube has a sample in this case we have taken carbon. You switch on the degassing let the system be heated at 100 degrees and let the system degas the sample for 12 hours or more depending upon the material.

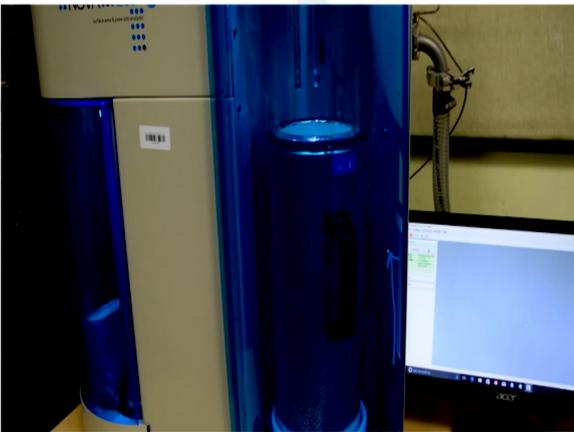
Generally it is 12 hours, but for different types of materials you may have to actually optimize even the degassing time and the temperature at which the degassing process has to be initiated or performed. So, all these steps are also critical to obtain reliable data.

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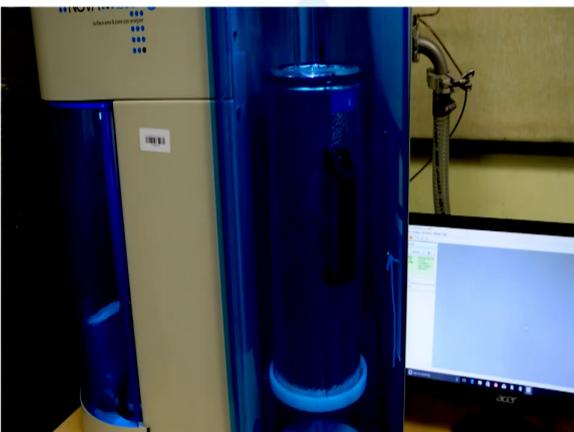




The image shows a laser Doppler velocimetry (LDV) setup. Two vertical cylindrical tubes are illuminated with a blue laser light. A computer monitor in the background displays a software interface. A speaker is visible in the bottom right corner.



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Then, once you have the gas the sample you have to fill the liquid nitrogen Dewar, transfer this Dewar to the measurement chamber. You will find that you can see that the Dewar is slowly rising so that it will move up and then it will cover the sample and the whole measurement will take place at the liquid nitrogen temperature.

You can clearly see that slowly the Dewar is rising and this is not a manual process what you are doing it is electronically controlled. When you switch on the instrument and you lead the program to start then the instrument will automatically perform these processes. You should ensure that the glass tube or the quartz tube is straight otherwise, if it hits the Dewar wall then it will lead to the breaking up the sample too and you will lose the sample.

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OriginLab TouchLab™  
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Graph: Vapor Pressure (kPa) vs. Molar Fraction (PPA)

Molar Fraction (PPA)	Vapor Pressure (kPa)
0.0	0
0.1	10
0.2	20
0.3	30
0.4	40

NPTEL

OriginLab TouchLab™  
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Graph: Vapor Pressure (kPa) vs. Molar Fraction (PPA)

Molar Fraction (PPA)	Vapor Pressure (kPa)
0.0	0
0.1	40
0.2	80
0.3	120
0.4	160
0.5	200
0.6	240
0.7	280

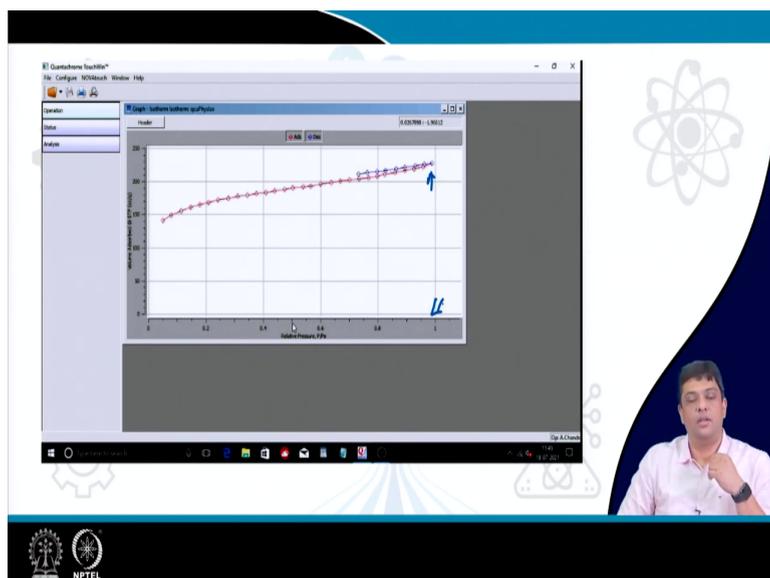
NPTEL

OriginLab TouchLab™  
File: Config1 - NCMiscLabk - Window - Help

Graph: Vapor Pressure (kPa) vs. Molar Fraction (PPA)

Molar Fraction (PPA)	Vapor Pressure (kPa)
0.0	0
0.1	40
0.2	80
0.3	120
0.4	160
0.5	200
0.6	240
0.7	280
0.8	320
0.9	360
1.0	400

NPTEL



Once this has been done, what is the next step? The next step is logical, you will collect the data and you will plot the value  $Q_{ds}$  as a function of  $p/p_0$  and the curve which you are getting is for carbon. Let us see what type of isotherm you obtain and then you can correlate with the isotherms which we have shown in the earlier slide and obtain the features which can be associated with this material.

Let us see what type of isotherm we get. You have reached to 0.95 of the value, so you have reached the 0.95 value of the ideal pressure which is there in the reference tube. So, you send in the gas upto 0.95 the value of the pressure that is there in the reference tube. Can you now find out what type of material is this, what types of loop or isotherm have you obtain by comparing with the earlier slide?

I will let you do this exercise and I have already given you the hint that we are measuring the carbon porous structures.

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## CONCLUSION

*Among various methods used for surface area and porosity determination, BET is an efficient and low cost method. It also has the ability of precisely measure porosity in the typical range 0.4 to 50 nm.*



And I hope that with this you would have realized that the BET method is amongst the most useful method to determine the surface area and information regarding pore size, pore volume or pore size distribution. It is also an efficient and low cost method and it can lead to precise measurements about nano materials and the parameters associated with them.

I thank you for attending today's lecture and in the next lecture we will move to another characterization technique which is extremely useful for electromechanical devices which have been discussed in this course. Thank you very much and have a nice day.