Textile Product Design and Development
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Lecture – 23
Design Parameters Estimation of Nonwoven fabrics

We will discuss the design parameter estimation of nonwoven fabrics.

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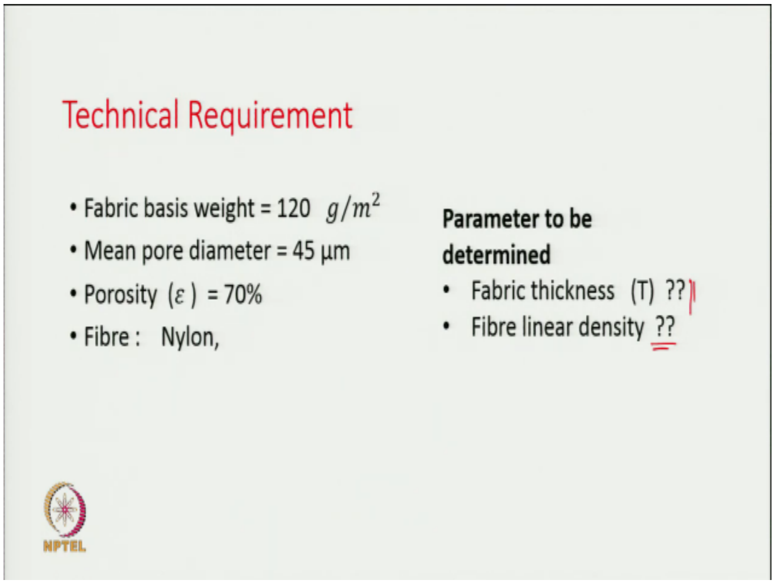

Let's assume the technical requirements specify that the fabric's basic weight should be 120 g/m^2, the mean pore diameter should be 45 µm, the porosity should be 70%, and the fibre material should be nylon. Given these parameters, we must determine the fabric thickness and the fibre linear density.

Some technical requirements or needs are given, and the manufacturer must manufacture them accordingly. The manufacturer needs to determine two important parameters: the fabric thickness so that the machine settings can be adjusted accordingly and the appropriate fibre linear density. This ensures that the mean pore diameter is approximately 45 µm, meeting the technical specifications.

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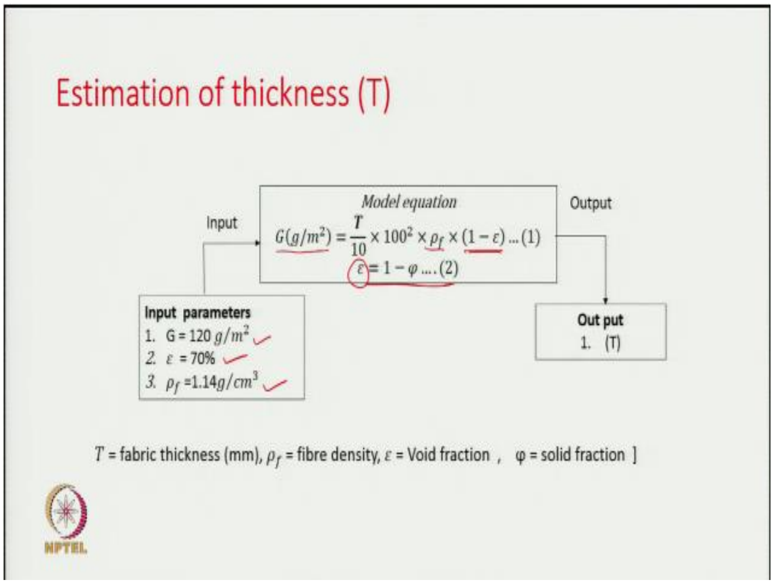

When estimating the fabric thickness, the basis weight is related to the fabric's thickness, fibre density, and porosity. This relationship can be expressed through an equation,

$$G\ (g/m^2) = \frac{T}{10} \times 100^2 \times \rho_f \times (1-\varepsilon)$$

Additionally, the relationship between porosity and fibre packing density is given by '$\varepsilon = 1 - \varphi$'. By utilizing these two equations, the required thickness of the fabric can be calculated.

The input parameters are the basis weight 'G', the porosity, and the fibre density. In this case, the fibre is nylon, so we use a density of 1.14 g/cm^3. If the fibre were polyester, the density would be 1.38 g/cm^3. The fibre density will vary depending on the specific material provided.

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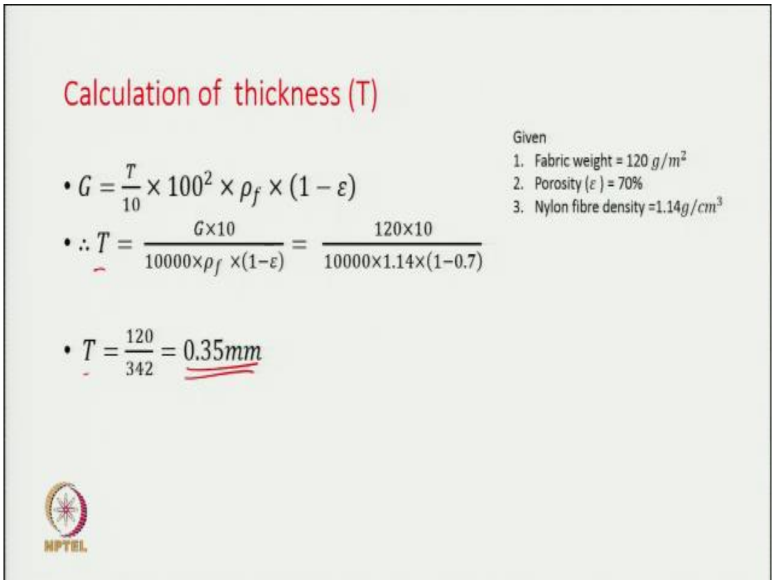

Using the previous equation, where the basis weight 'G' is provided, fabric thickness 'T' can be calculated. By applying the equation, the value of 'T' is found to be 0.35 mm. This means that, in this case, a very thin fabric must be produced with a thickness of only 0.35 mm.

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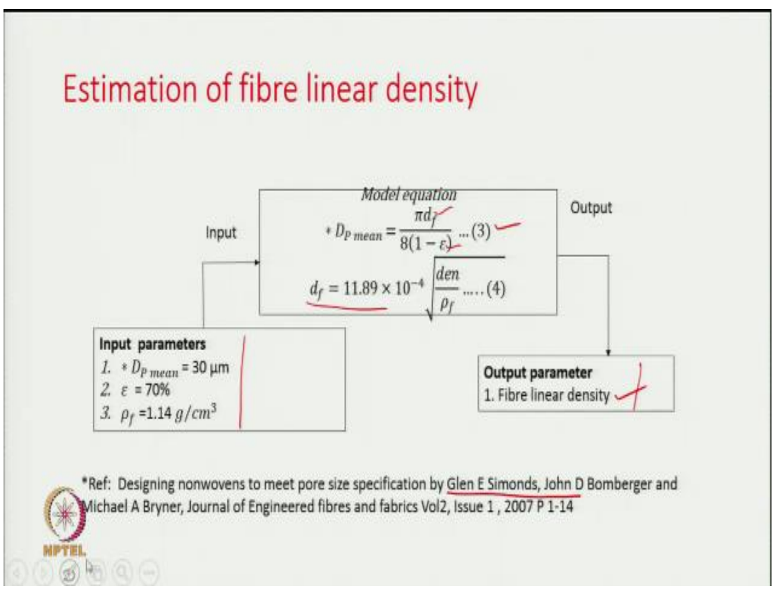

The next aspect is the estimation of fibre linear density. For this, two equations are used. Equation number 3 relates the average pore diameter to fibre diameter and porosity, which is

$$Dp_{\ mean} = \frac{\pi\, d_f}{8(1-\varepsilon)}$$

This equation was developed by researcher Glen E Simonds. Additionally, equation number 4 provides the relationship between fibre diameter and denier, which is represented by

$$d_f = 11.89 \times 10^{-4} \sqrt{\frac{den}{\rho_f}}$$

This is a straightforward equation where the relationship between fibre diameter and denier has been derived. By making use of these equations to find out the linear density of the fibre, the input parameters are the mean pore diameter '$Dp_{\ mean} = 30$', which are used for this calculation. By applying the model equations with these input parameters, the required fibre linear density can be calculated.

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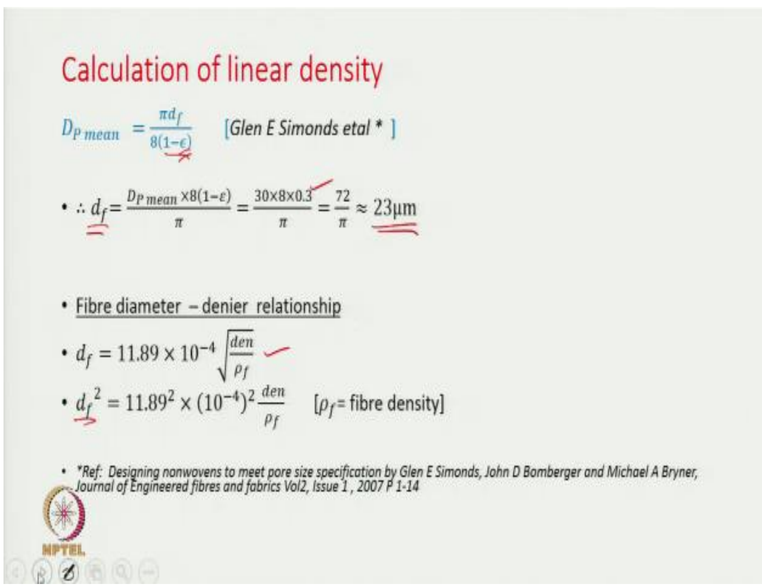

The diameter of the fibre can be determined by using the equation

$$d_f = \frac{Dp_{\ mean} 8(1-\varepsilon)}{\pi}$$

where '$Dp_{\ mean}$' is the mean pore diameter. The porosity 'ε' is assumed to be 0.7, and therefore, the packing fraction of fibres for solid volume fraction is '$1 - \varepsilon = 0.3$'. By substituting these values, the diameter of the fibre can be calculated, which gives 23 µm. By using the fibre diameter-denier relationship, as previously stated, the square of the fibre diameter can be determined.

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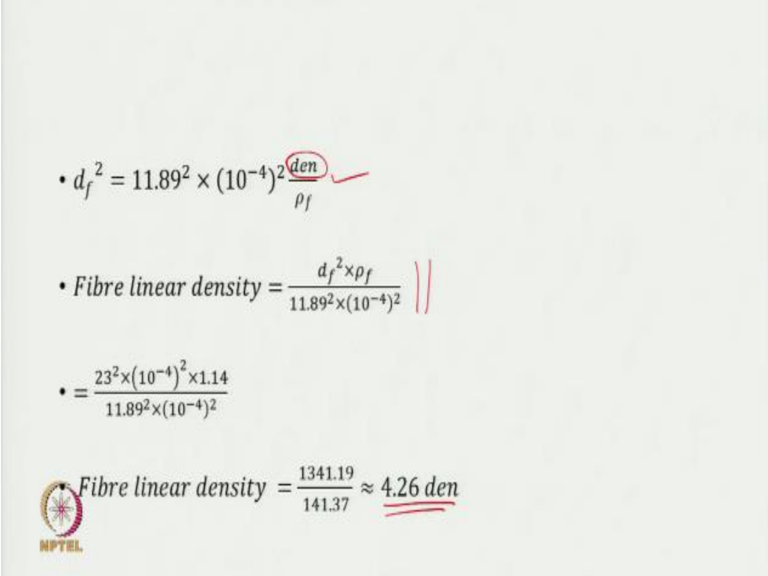

The equation of the square of the diameter of the fibre is given by

$$d_f^2 = 11.89^2 \times (10^{-4})^2 \frac{den}{\rho_f}$$

Therefore, the fibre linear density, or denier, can be rewritten in this format. The fibre linear density in terms of denier can be determined by substituting the appropriate values into the equations.

In this case, it is found that a fibre denier of 4.26 is required. This calculation relies on the relationships established by various authors in the field. Sometimes, these relationships may not be readily available in textbooks, and we might need to consult research papers to obtain them. By doing this, a fibre linear density of 4.26 denier can be estimated, which is the value we need to choose for the fibre.

By selecting this denier and using the previously calculated thickness value, which is 0.35mm, the design is made. This information is passed on to the production team. They need to arrange the machines and set the parameters of the machine to create a non-woven structure using fibres with a linear density of approximately 4.2 deniers. Additionally, they must ensure that the final fabric thickness is around 0.35 mm.

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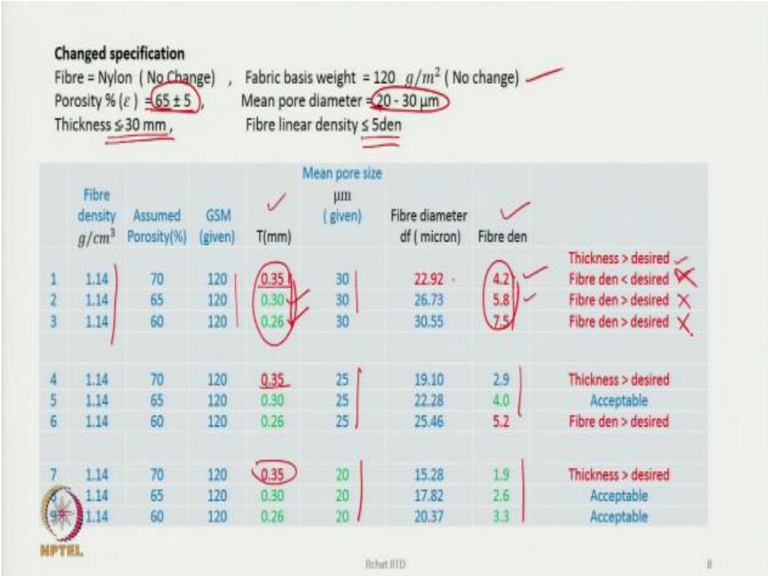

The results we obtain can sometimes lead us to modify the specification requirements. For example, while the basis weight remains unchanged, we might adjust the porosity to a range of 65±5 rather than a fixed value of 70. The pore diameter can also be specified within a certain range rather than a fixed value. Additionally, the thickness may need to be reduced to less than 0.30 mm, and the fibre linear density should be kept below 5 deniers. This means shifting from fixed values to a more flexible specification approach.

In these situations, we may have values that must fall within specific ranges or could be either less or more than a certain threshold. Such scenarios often arise when determining the appropriate fibre linear density and fabric thickness. To solve these problems effectively, we can utilize the equations mentioned earlier and implement them in Excel. An excel file and a table can be created, as mentioned in the slide. Fibre linear density remains constant for the fibre type used. Porosity value is considered within the range of 65±5%: 60%, 65%, and 70%. The values remain unchanged throughout the calculation. The thickness should be less than 0.30 mm as this is the requirement. The mean pore size should lie in the range of 20 to 30 µm.

Hence, the mean pore size is taken as 30, 25 and 20 µm, repeating them and calculating the fibre denier. The aim is to determine the fibre-denier values and, therefore, create three sets of known combinations. The two aspects are calculated: thickness and fibre denier. The answers are found and provided in the table. Out of these answers, answers which satisfy the requirements have to be evaluated. In the first row, the thickness exceeds the desired value, while the fibre denier is acceptable. Although the fibre denier meets the criteria, the thickness is greater than desired, so we must reject this solution. The rejection is because the fibre denier is acceptable, but the pore diameter exceeds 30 µm.

Therefore, this option is obviously not feasible, and similarly, the other choices are also unsuitable because the thickness exceeds the required value of 0.30 mm. The thickness must be 0.30 mm or less. Moving to the next option, the thickness is highlighted in green and meets the requirement. However, the fibre denier is 5.8, greater than the desired value of 5, so the fibre denier exceeds the limit. This option is also unacceptable, as are the others. In the third case, thickness is marked in green, indicating it meets the criteria, but the denier exceeds 5, so it still does not meet our requirements. In these cases, none of the options satisfy the necessary conditions, so we conclude they are not viable solutions.

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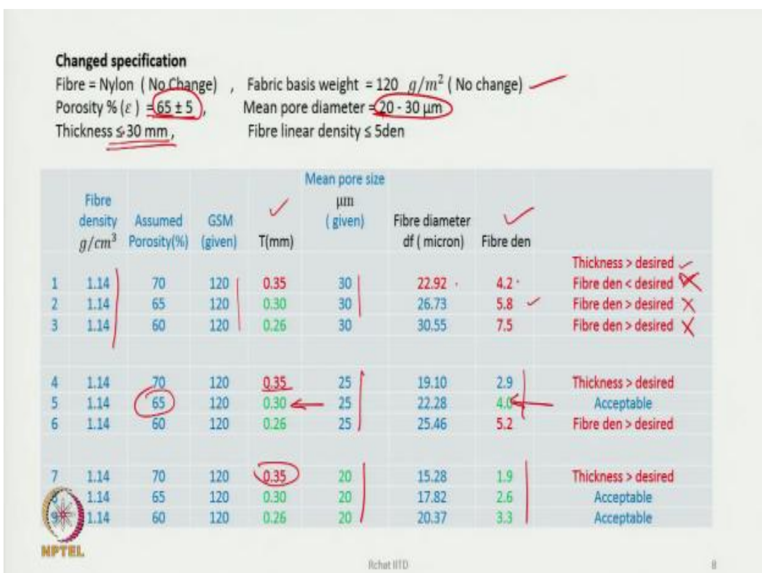

The green colour numbers in the table indicate that these combinations are meeting the requirements. Therefore, the acceptable combination is the one where we can use nylon fibre, but the porosity must be 65. In this case, if we choose a fibre with a denier of 4, it will meet the requirements. The fabric must have a thickness of 0.3 mm for it to be acceptable.

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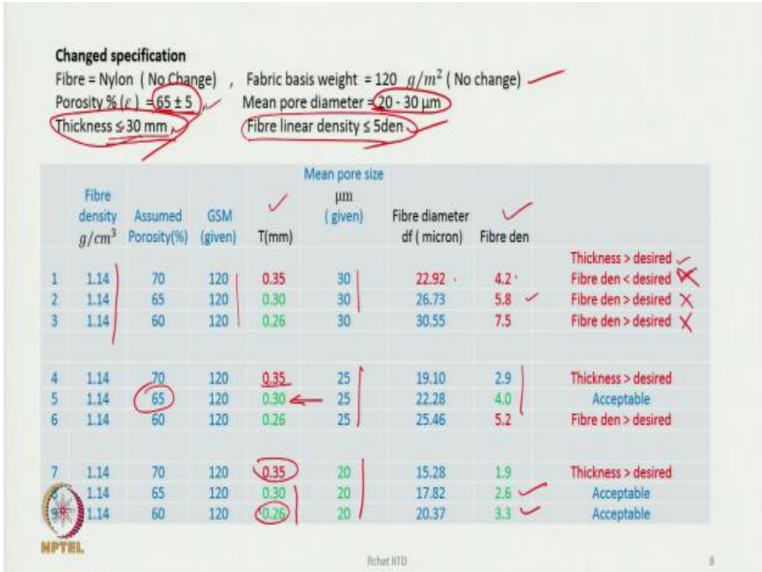

Similarly, in the last set, we must reject the first case because the thickness exceeds 0.3 mm. However, in the other two cases, both are acceptable since the fibre denier is less than 5 and the thickness is 0.3 mm or less. So, there are three valid options: either use 4 denier fibre and make a fabric with 0.3 mm thickness, use 2.6 denier fibre with a fabric of 0.3 mm thickness, or use 3.3 denier fibre with a fabric of 0.26 mm thickness.

All of these combinations will meet the requirements. This will provide the correct mean pore diameter and porosity. It will also ensure the appropriate fibre linear density and thickness values. These two factors can be considered constants, while the others are the requirements. By using an excel software, calculations can be made to obtain the answers.

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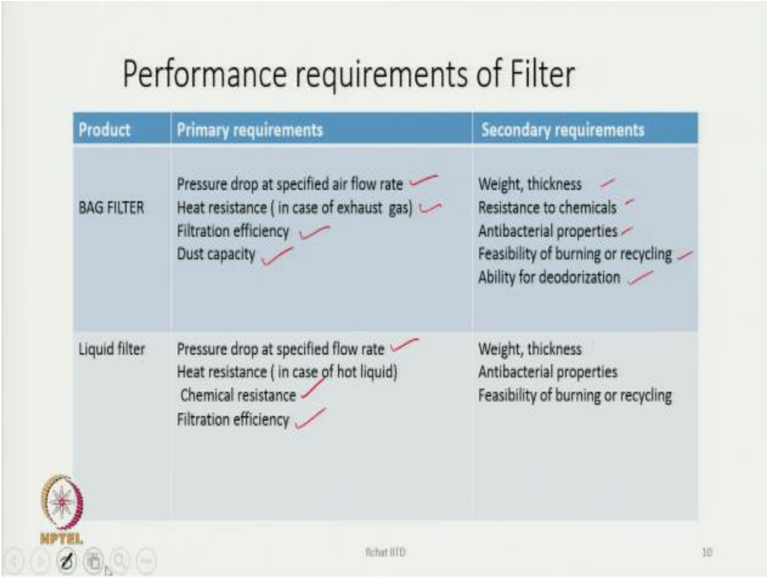

Next comes the nonwoven filter fabrics. The performance requirements for a filter includes several key factors. For a back filter, the most important criteria are pressure drop at a specified airflow rate, heat resistance, filtration efficiency, and dust capacity. Secondary requirements include weight, thickness, resistance, antibacterial properties, the ability to be burned or recycled, and deodorization capabilities. These are the secondary requirements.

For liquid filters, the pressure drop at a specified flow rate is always crucial. Heat resistance may be important depending on the application, and chemical resistance could also be significant. Filtration efficiency, along with weight and thickness, is always essential. These are the general requirements for filter fabrics.

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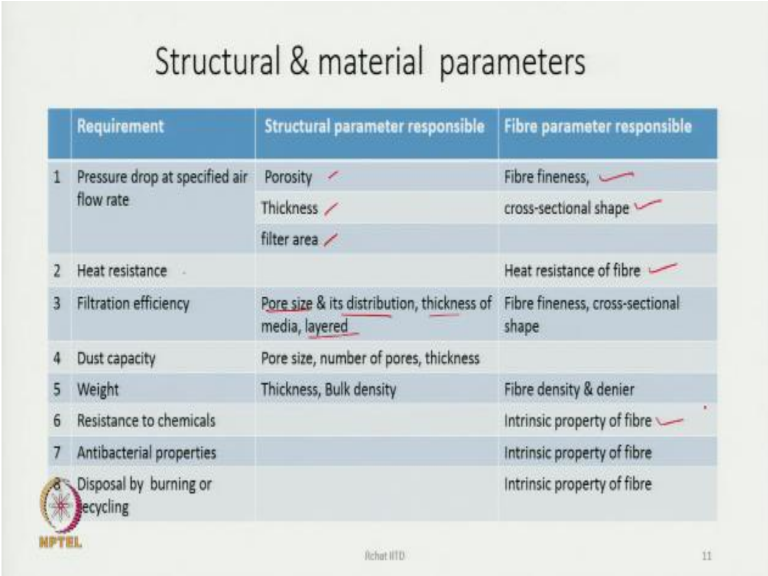

Structural & material parameters

	Requirement	Structural parameter responsible	Fibre parameter responsible
1	Pressure drop at specified air flow rate	Porosity	Fibre fineness,
		Thickness	cross-sectional shape
		filter area	
2	Heat resistance		Heat resistance of fibre
3	Filtration efficiency	Pore size & its distribution, thickness of media, layered	Fibre fineness, cross-sectional shape
4	Dust capacity	Pore size, number of pores, thickness	
5	Weight	Thickness, Bulk density	Fibre density & denier
6	Resistance to chemicals		Intrinsic property of fibre
7	Antibacterial properties		Intrinsic property of fibre
8	Disposal by burning or recycling		Intrinsic property of fibre

The important structural and material parameters are stated in the table. If the requirement is a pressure drop at a specified airflow rate, the key structural parameters are porosity, thickness, and filter area. For fibre parameters, fibre fineness and cross-sectional shape are important. In this context, the performance criteria, such as pressure drop, heat resistance, filtration efficiency, and others, are linked with the relevant structural and fibre parameters.

Pressure drop depends on factors such as porosity, thickness, overall filter area, fibre fineness, and cross-sectional shape. Heat resistance is primarily determined by the heat resistance of the fibre itself, while structural parameters have little impact. Filtration efficiency, however, depends on structural parameters like pore size and distribution, media thickness, and whether the structure is layered. Fiber parameters, such as fineness and cross-sectional shape, also affect filtration efficiency.

Similarly, the performance requirements alongside the corresponding structural and fibre parameters that influence them can be listed. The key structural parameters and fibre properties that impact performance can be identified for each requirement. For example, antibacterial properties depend on the intrinsic characteristics of the fibre, while the fibre’s inherent properties also determine chemical resistance. This type of table can help relate performance requirements with relevant parameters.

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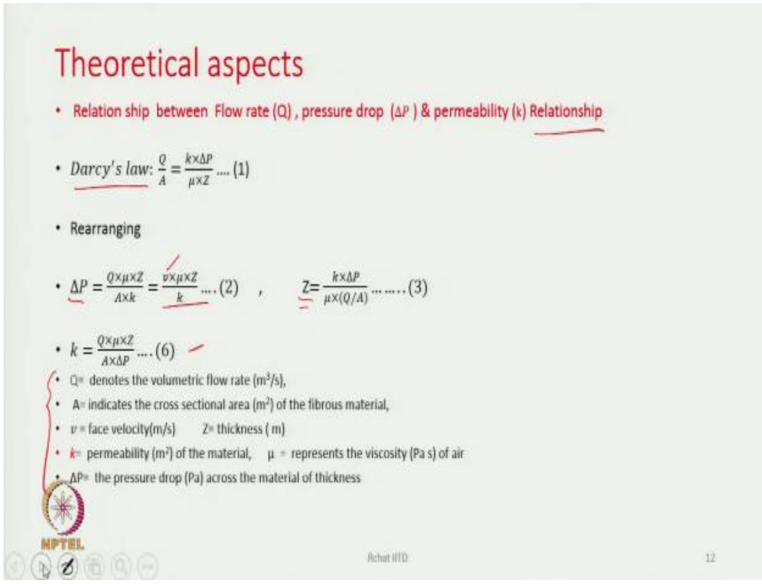

It is essential to know some theoretical aspects when designing filter fabrics, particularly the relationships between flow rate, pressure drop, and permeability. A fundamental equation in this context is Darcy's Law, which states that

$$\frac{Q}{A} = \frac{k \times \Delta P}{\mu \times Z}$$

Here, 'Q' is the volumetric flow rate, 'A' is the cross-sectional area, 'k' is the permeability of the material, 'ΔP' is the pressure drop, 'μ' is the viscosity of air and 'Z' is the thickness of the filter media. Taking this equation and rearranging it, 'ΔP' is expressed as

$$\Delta P = \frac{Q \times \mu \times Z}{A \times k}$$

In this equation, '$\frac{Q}{A}$' is replaced by 'v' which represents the phase velocity. Thickness can also be expressed in terms of other parameters, leading to the same equation presented in different forms. The goal is to place known values on the right-hand side of the equation and keep the unknowns on the left-hand side. This basic equation will be very useful for analyzing filters.

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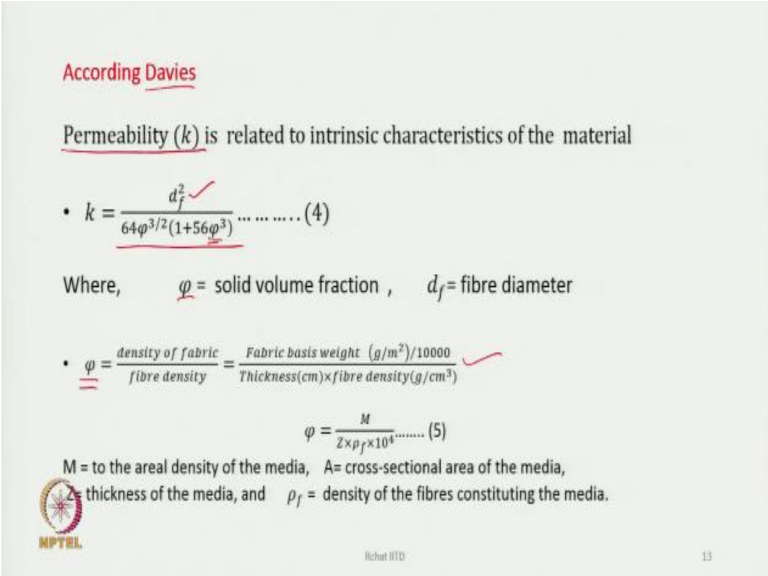

This is another interesting equation related to permeability. The permeability of fibrous media has been the focus of research by many scientists, resulting in numerous complex equations. One equation that is commonly used and found to be quite suitable for initial estimations. It allows us to quickly arrive at practical values, which can help in product development.

Hence, permeability is related to fibre diameter and solid volume fraction by the equation,

$$k = \frac{d_f^2}{64\varphi^{3/2}(1 + 56\varphi^3)}$$

This equation was developed by Davies and can be found online. The solid volume fraction represents the ratio of the fabric's density to the fibre density, which characterizes the proportion of fibre in a nonwoven structure.

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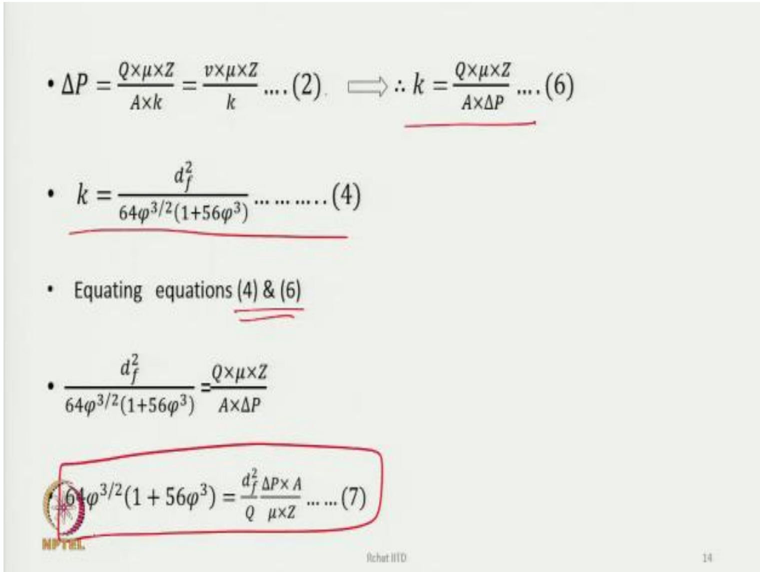

These equations can be utilized to derive values for 'k', the permeability. By equating equations (4) and (6), permeability can be expressed as a measurable quantity that can be obtained through experiments, which is represented by

$$\frac{d_f^2}{64\varphi^{3/2}(1+56\varphi^3)} = \frac{Q\times\mu\times z}{A\times\Delta P}$$

The left-hand side of the equation can also be measured, allowing us to quantify the diameter of the fibres. The solid fibre volume fraction can be found.

Therefore, the equation that has been arrived at is

$$64\varphi^{3/2}(1+56\varphi^3) = \frac{d_f^2}{Q}\frac{\Delta P\times A}{\mu\times z}$$

This equation is used to estimate the fibre parameters needed.

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Now, we will estimate the design parameters with an example.

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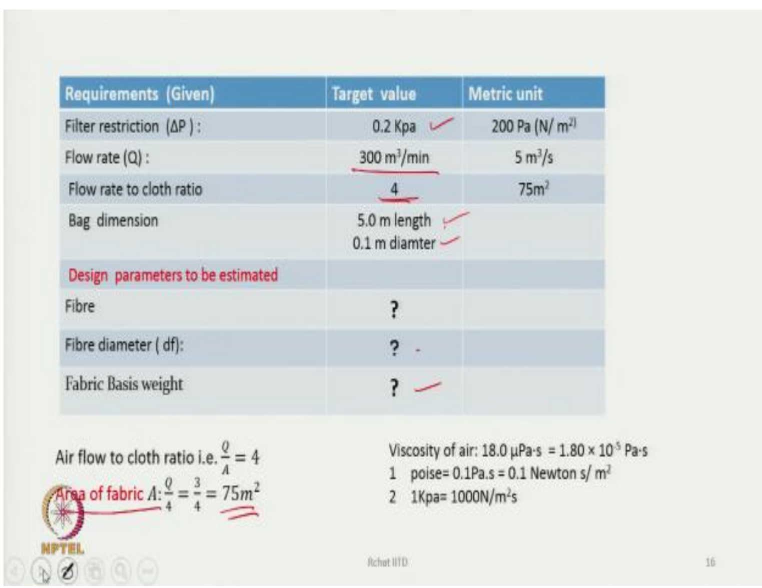

Consider the example of filter restrictions, where the pressure drop is 0.2 kPa, the flow rate is 300 m^3/min, and the airflow-to-cloth ratio is 4. The bag dimensions are 5 meters in length and 0.1 m in diameter. The appropriate fibre diameter and the fabric basis weight have to be estimated. To begin, we note that the airflow-to-cloth ratio is given as 4. This indicates that '$\frac{Q}{A} = 4$'. Hence, the area of the fabric can be expressed as ‘$A = \frac{Q}{4}$’. Substituting the value of ‘Q’ as 300 m^3/min, the area of the fabric is found to be 75 m^2. This is the first key piece of information we need.

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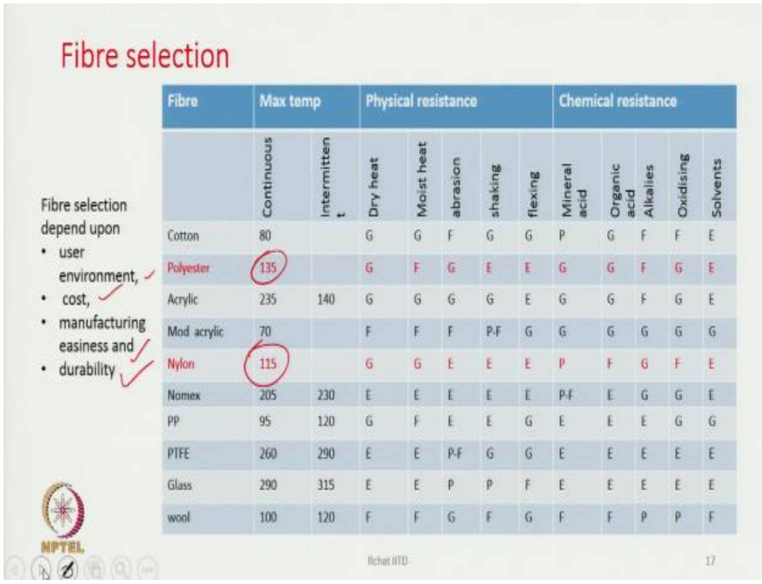

Fibre	Max temp		Physical resistance					Chemical resistance				
	Continuous	Intermittent	Dry heat	Moist heat	abrasion	shaking	flexing	Mineral acid	Organic acid	Alkalies	Oxidising	Solvents
Cotton	80		G	G	F	G	G	P	G	F	F	E
Polyester	135		G	F	G	E	E	G	G	F	G	E
Acrylic	235	140	G	G	G	G	E	G	G	F	G	E
Mod acrylic	70		F	F	F	P-F	G	G	G	G	G	G
Nylon	115		G	G	E	E	E	P	F	G	F	E
Nomex	205	230	E	E	E	E	E	P-F	E	G	G	E
PP	95	120	G	F	E	E	G	E	E	E	G	G
PTFE	260	290	E	E	P-F	G	G	E	E	E	E	E
Glass	290	315	E	E	P	P	F	E	E	E	E	E
wool	100	120	F	F	G	F	G	F	F	P	P	F

When selecting fibres, the table, which has qualitative values such as maximum temperature resistance, physical resistance, and chemical resistance, is considered. In this table, the ratings are defined as follows: ‘G’ for good, ‘M’ for fair, ‘P’ for poor, and ‘E’ for excellent. By evaluating these qualitative properties, we can determine that polyester and nylon are the most suitable options for filter fabrics.

The detailed things are not considered, but factors such as environment, cost, ease of manufacturing, and durability must be considered. Considering this, polyester or nylon is preferred. Given these considerations, it is important to note that while many fibres are available, some are more expensive, and others may only be suitable for specific applications. In high-temperature applications, polyester and nylon are not suitable. The specific user environment has not been stated in detail, so we can assume that these two fibres are appropriate for contexts that do not involve extreme heat. Therefore, we should consider the other parameters while excluding situations where polyester or nylon would be inadequate.

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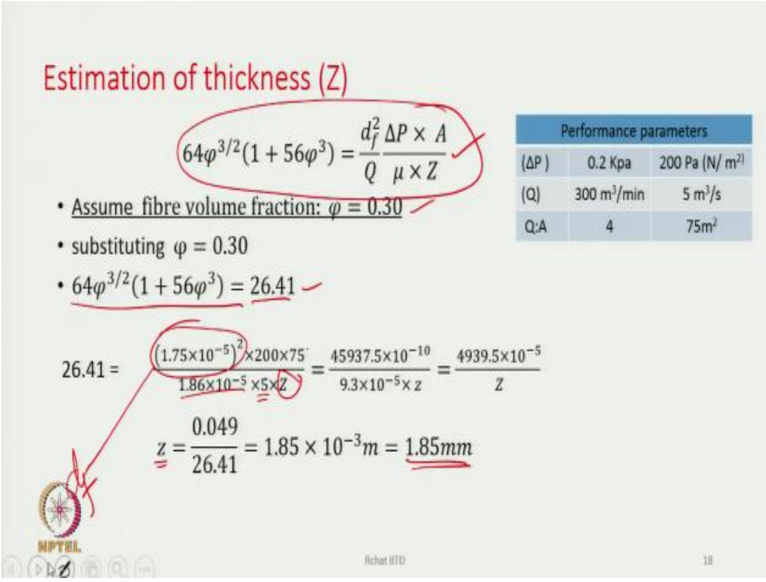

Making use of the equation

$$64\varphi^{3/2}(1+56\varphi^3) = \frac{d_f^2}{Q}\frac{A \times \Delta P}{\mu \times Z}$$

the fibre volume fraction chosen is 0.3. By substituting this value into the equation '$64\varphi^{3/2}(1+56\varphi^3)$', we obtain a figure of 26.41. Then, place this value into the equation, along with the other known values on the right-hand side. The only unknown variable is the 'Z', which represents the thickness of the fabric that has to be determined.

Some parameters have already been provided, such as the desired pressure drop (ΔP), which is 200 Pa. Additionally, we may have information regarding the fibre diameter or denier, which allows us to calculate the fibre diameter. Since the diameter square is part of the equation, we can utilize the given 'ΔP' value of 200 Pa in our calculations. '1.86 x 10^{-5} Pa s' is the viscosity value, and the flow rate (Q) is 5 m^3/s, while the thickness (Z) remains unknown. The diameter of the fibre (d_f) is given as 1.75 x 10^{-5} m.

The corresponding denier of the fibre can be calculated based on this diameter. After substituting the known values into the equation, it is found that the thickness of the fabric should be 1.85 mm.

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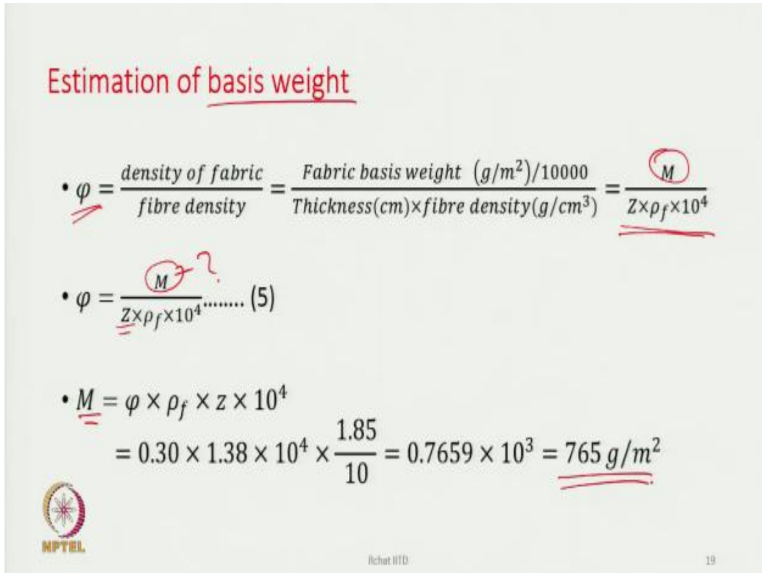

After estimating the thickness, the next step is calculating the basis weight (M). The solid volume fraction is related to the basis weight by the equation

$$M = \varphi \times p_f \times Z \times 10^4$$

By using the equation with the previously determined thickness (Z), the basis weight is calculated. It is found that the basis weight 'M' is found to be 765 g/m^2.

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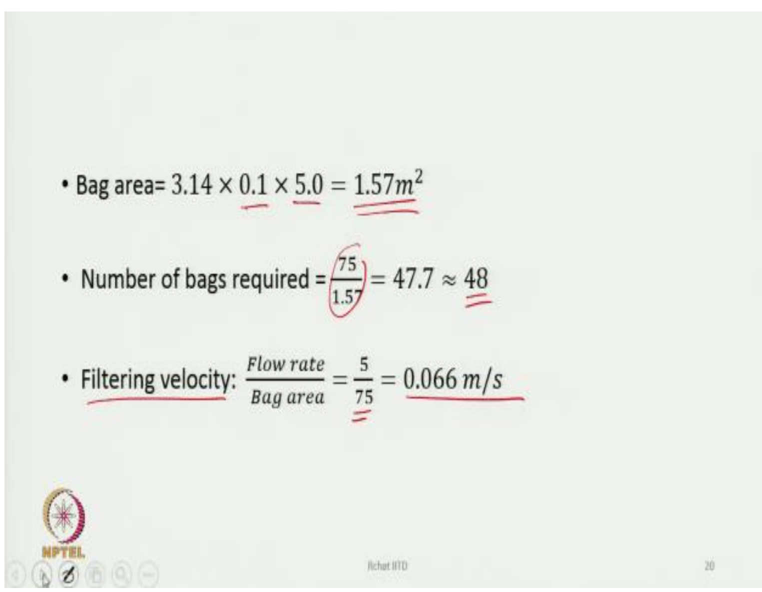

To determine the number of bags needed, the bag area can be calculated using the formula '$\pi \times D \times L$', where 'D' is the diameter and 'L' is the length. Dividing the total area required (75 m^2) by the area of an individual bag gives us approximately 48 bags. Next is the calculation of filtering velocity, which is the phase velocity of the air. It is found by

$$\frac{Flow\ rate}{Bag\ area}$$

resulting in a filtering velocity of 0.066 m/s.

The only assumption made here is related to fibre. Initially, we started with an assumed value for fibre diameter. Creating an Excel table allows us to explore different fibre values while keeping other parameters constant. This table shows the outcomes for various fibre diameters or deniers based on the commercially available linear densities. We input those values to determine the corresponding thickness and areal density of the fabrics. This process results in a solution space comprising multiple solutions for various fibre linear densities.

Once we have these solutions, we can select one or two optimal solutions based on the requirements. This methodology allows us to estimate certain important parameters related to filter fabric design. With this, the topic is concluded. Thank you.