Effect of processing parameters on properties of layered composite needle-punched nonwoven air filters

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Layered composite needle-punched nonwoven fabrics have been prepared using 6 den and 15 den polyester staple fibres separately and in 50:50 proportion and their air filtration and other associated properties studied. Processing parameter such as punch density has also been altered to investigate its effect on filtration efficiency as well as on associated properties like dimensional stability, air permeability, compression-recovery, tensile strength, abrasion resistance and friction. Filtration efficiency values show an initial rise and then subsequent fall with incremental punch densities in case of layered fabric and those made with fine fibres. In case of coarse fibre, however, the values continue to increase with punch density. The pressure drop required to maintain a certain level of flux of air through the fabrics is also not too high as that of fine fibre fabrics. Dimensional stability of fabric layered with 50:50 proportion of 6 and 15 den fibres is also found to be higher as compared to that of the fabrics of other combinations. Compression / recovery performance of layered fabric is also found to be better. All these positive attributes of the blended 6 and 15 den (50:50) layered fabrics show that the composite needle-punched fabrics will perform better as air filters.

Keywords: Filtration efficiency, Layered composite, Needle-punched fabric, Nonwoven, Punch density

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1 Introduction
The air filters are routinely used to ensure the quality of indoor air, protect sensitive manufacturing processes and prevent harmful emission of particles, gases or microorganisms into the atmosphere. Everyday one breathes about 20 - 30 kg of air and consumes around 1 kg of solid and 3 kg of liquid food. As a consequence, it is expected that air should have the same quality standards as food and drink. The necessity of removing impurities or other gases from air has increased with respect to the degree of separation and necessity to separate finer particles. Correct designing has become a prerequisite for proper working of the air to filters so that they can help to keep environment clean and thus safeguard sensitive production processes and protect human beings. Microelectronic industries require ultra-clean manufacturing conditions and as a consequence has led developments in this area and has been a driving force behind many air filter innovations and improvements.

A filter medium is defined as the permeable material used for a filter that separates particles from a fluid passing through it. Textile filter fabrics are an essential part of countless industrial processes, contributing to product purity, savings in energy/production costs and a cleaner environment. A number of filter media are used for separating solid particles from gases (Table 1). But, in terms of efficiency, the other filter media rarely surpass the fabric filter, particularly when the particles are of the order of 1 micron or less in size. Fabric collectors are most efficient and versatile in separating out very fine particles, which settle down very slowly. Textile filter media can be divided broadly in two groups, namely woven and nonwoven. The nonwoven filters have advantages over woven counterpart in many

<table>
<thead>
<tr>
<th>Filtration principle</th>
<th>Filter efficiency, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10μm</td>
</tr>
<tr>
<td>High efficiency cyclone</td>
<td>85.0</td>
</tr>
<tr>
<td>Fabric filtration</td>
<td>99.9</td>
</tr>
<tr>
<td>Venturi scrubbing</td>
<td>99.8</td>
</tr>
<tr>
<td>Electrostatic precipitation</td>
<td>99.0</td>
</tr>
</tbody>
</table>

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aspects, like higher permeability of the media due to more readily available pores per unit area, higher filtration efficiency, no chance of yarn slippage as that of woven media and good cake discharge property. There have been drastic developments in filter media. The trends of nonwoven filter media in recent year involve lower cost, expansion of applications, improved temperature resistance, improved cake separation, lower pressure drop at a fixed efficiency and global usage.\textsuperscript{8,9}

The present study is intended to characterize different properties of graded fibrous filter media with respect to filtration efficiency and other properties associated to filtration such as dimensional stability, air permeability, tensile strength, compression/recovery and abrasion resistance.

2 Materials and Methods

The needle-punched nonwoven fabrics were prepared from 51 mm × 6 den and 51 mm × 15 den polyester staple fibre.

2.1 Preparation of Nonwoven Fabrics

The first step in the formation of nonwoven fabrics was the preparation of the web of required areal density with the help of carding machine and cross lapper. After web preparation, the bonding of fibres is done mechanically with the help of needle punching. The fibre web was fed onto an endless belt to pass into the machine between the stripper and the bed plate. The gap between the two plates determines the thickness of the web that can be fed. A laboratory model needle punching machine (Model—Automatex, MPR 1000, MAT 1252/C; working width—70 cm; maximum penetration depth—38mm; needle specification—5×18×36×3.5 CB) was used for nonwoven fabric preparation. Cross-laid webs of the width of about 68.6-76.2 cm comprising 6 and 15 den (separately) were cut at the edges to get a web of uniform width of about 63.5 cm. These webs were cut to required length and given an initial tacking with a nominal punch density in the machine. The tacked webs were then cut and layered in predefined combinations and punched with required punch densities from both the sides to get the final needle-punched fabrics. The details of fabrics are given in Table 2. The nominal fabric weight and the depth of needle penetration were kept constant for all the samples at 350 g/m\textsuperscript{2} and 12 mm respectively.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fibre fineness denier</th>
<th>Punch density punches/cm\textsuperscript{2}</th>
<th>Thickness mm</th>
<th>% Decrease in properties due to abrasion</th>
</tr>
</thead>
<tbody>
<tr>
<td>S11</td>
<td>15</td>
<td>120</td>
<td>7.0</td>
<td>0.19</td>
</tr>
<tr>
<td>S12</td>
<td>15</td>
<td>160</td>
<td>6.5</td>
<td>0</td>
</tr>
<tr>
<td>S13</td>
<td>15</td>
<td>200</td>
<td>7.0</td>
<td>0</td>
</tr>
<tr>
<td>S21</td>
<td>6 &amp; 15</td>
<td>120</td>
<td>5.5</td>
<td>0.24 (0)</td>
</tr>
<tr>
<td>S22</td>
<td>6 &amp; 15</td>
<td>160</td>
<td>4.5</td>
<td>0 (0)</td>
</tr>
<tr>
<td>S23</td>
<td>6 &amp; 15</td>
<td>200</td>
<td>5.0</td>
<td>0(0)</td>
</tr>
<tr>
<td>S31</td>
<td>6</td>
<td>120</td>
<td>3.0</td>
<td>0.21</td>
</tr>
<tr>
<td>S32</td>
<td>6</td>
<td>160</td>
<td>3.0</td>
<td>1.35</td>
</tr>
<tr>
<td>S33</td>
<td>6</td>
<td>200</td>
<td>5.5</td>
<td>0</td>
</tr>
</tbody>
</table>

Values in parentheses represent the abrasion in 6 den fibre side in fabric.

2.2 Fabric Testing

ASTM standard D6242 was followed to measure the mass per unit area of nonwoven fabrics. The specimens of the size 10.2 cm × 10.2 cm were cut randomly from different places and weighed in electronic balance with an accuracy of 0.01g and the average of 10 readings was taken. As nonwoven fabrics are highly compressible, a high pressure would give an inaccurate value of its thickness. The thicknesses of the fabrics were measured under 0.5 gf/cm\textsuperscript{2} pressure. Compression / recovery of a needle felt is important from the point of view of the potential compressive force acted on the filter by the air being filtered. Compression changes porosity also. Compression/recovery was studied in the Essediel thickness guage having pressure foot diameter of 25.4 mm. The pressure was increased from 20 gf/cm\textsuperscript{2} to 500 gf/cm\textsuperscript{2} and then brought back to 20 gf/cm\textsuperscript{2} in steps in time intervals of 30s and the readings (thickness) were taken after each increase/decrease of load. The air permeability was tested in the Textest FX3300 air permeability tester. The pressure drop was selected at 98 Pa as the fabrics were measured with 5cm\textsuperscript{2} adapter ring (the standard combination was followed). For testing under incremental pressure drop, the pressure drop was varied from 98 Pa to 196 Pa. The pre-selected test pressure was automatically maintained, and the air permeability of the test specimen was digitally displayed in pre-selected unit of measure. Abrasion of the samples was studied to have an idea about how the fabrics’ filtering property would be affected by erosion activity of air/gas. The study was made in the Nu-Martindale abrasion and pilling tester.
The testing conditions were: number of abrasion cycles per specimen—5000, rotational speed—47.5±2.5 rpm, face diameter of specimen—28.65 ±0.05 mm, specimen holder diameter—38mm and pressure used—9 kPa. Tensile test was done in Instron (Model 4202) using ASTM D 5035 test method. For measuring the dimensional stability of the needle-punched fabrics, the specimens (10cm × 10cm) were cut and put in the oven at 110°C for 1h with continuous hot air circulation. After taking out the samples, the dimensions were measured again to find any dimensional change. Percentage shrinkage was then calculated.

The filtration efficiency of fabrics was tested by particle counting in the up stream and the down stream sides of the filter fabric. The samples were tested for filtration efficiency by exposing 30.5cm × 30.5cm area of each sample to a flux of 8.495m³/min (300 ft³/min) (value so chosen to avoid distortion of the fabric due to air flow) of atmospheric air. The air at input was checked for particle size distribution before and after testing each sample. The particle counting of output air was done at four corners of the test area over an interval of 1 min. The locations were chosen in clockwise fashion and each of the samples was tested for 16 readings in four rounds. The pressure drop across the fabric was also noted time to time. The instrument (Measuretest) used for counting particle was a laser-based particle counter, which counted particle on the basis of light scattering principle. It had its own suction of 0.1 cfm. It was preset to measure particles of 0.1, 0.3, 1.0, 3.0 and 5.0μ size. Pressure drop was measured to keep flux of air across the fabric constant by a manometer having an oil of 0.81 g/cc density.

3 Results and Discussion

3.1 Thickness, Abrasion and Compression/Recovery

Table 2 shows the thickness values of fabrics at 0.5 gf/cm² pressure level. It has been observed that as the fibre fineness or proportion of fine fibre in the fabric increased the effective thickness of fabric decreases. With the increase in needling density the thickness reduces initially and then increases. The initial reduction in thickness is mainly due to the increase in compactness as the needling density increases, but above a certain limit the increase in thickness may be due to fibres breakage.

Table 2 also shows the per cent change in fabric weight and the air permeability after abrasion. It has been observed that all the fabrics have very high abrasion resistance. Here, the weights of fabrics have not changed significantly and the air permeability values do not increase due to abrasion. In almost all the cases the air permeability value has reduced showing compaction of fibres during abrasion under load and this phenomenon is more prominent in case of coarser fibre.

Figure 1 shows the recovery and compression behaviour of the fabrics. The fabrics with finer fibre give better recovery than the fabrics with coarser fibres. As the fibre fineness or the proportion of fine fibre increases the interlocking of the fibre increases and the fabric becomes more compact and stiff. So, it gives better recovery at corresponding punch densities. For each of the fibre combinations the recovery initially decreases and then increases again with the increase in punch densities. This may be due to the transition from a soft and resilient structure of less bonded fibres to an intermediate structure where lesser fibres are left free and finally, to a hard and stiff structure of highly bonded matrix reacting to external force in unison. Compressibility reduces with the increase in punch density as the structure becomes more rigid.

3.2 Air Permeability

Figure 2 shows that the air permeability of fabrics increases almost linearly with the pressure drop. All the samples were tested for air permeability at eight
different pressure drops. The pressure drop was varied at each of the five locations in each fabric sample. In case of fabrics with coarser fibres as the punch density increases the air permeability reduces consistently but as the fibre fineness or the proportion of fine fibre increases the air permeability initially reduces and then increases with the increase in punch density. This is due to the fact that with the increase in punch density the compactness of the fabrics increases due to more interlocking of the fibres, resulting in lowering of air permeability value for all fibres, but after a certain level of punch density the formation of pegs becomes more prominent and also fibre breakage starts in case of finer fibres, which results in higher permeability of air. Again as the flow rate through a certain area directly depends on the pressure differential (according to Darcy’s law), the curves are in straight line. Also, as the porosity of a needle-punched fabric depends on the fibres’ specific surface area, finer fibres give lower air permeability value at corresponding punch densities.

3.3 Tensile Strength

Figure 3 shows how the average peak load in machine direction (MD) and cross direction (CD) changes with the increase in punch densities and variation in fibre fineness. More load bearing capacity in machine direction indicates that the fibres in the cross-laid web are mainly oriented in machine direction. Moreover, the trend of peak loads with varying punch density varies between samples of
varying fibre proportion types. The sample made from solely 6 den fibres shows reduction in strength, which might be due to breakage of fibres at higher punch density. Fabrics made with 15 den fibres have an increment in strength initially and then decrement in load bearing capacity. This initial increase in strength may be due to the effect of decreased slippage with increment in punch density. The MD strength of samples made up of 50:50 proportion of 6 and 15 den fibres hardly shows any change in strength, which may be due to cancellation of change in load bearing capacity of component by that of another. CD strength of fabrics having 50:50 layering of 6 and 15 den fibres was in between that of other fabric types.

3.4 Dimensional Stability

The effect of punch density on the dimensional stability of the fabrics in terms of shrinkage % is shown in Fig. 4. The fabrics made of 6 den fibre show highest shrinkage followed by the fabric layered by 50:50 proportion of 6 and 15 den fibres. The fabric made with 15 den fibres hardly shows any change in strength, which may be due to cancellation of change in load bearing capacity of component by that of another. CD strength of fabrics having 50:50 layering of 6 and 15 den fibres was in between that of other fabric types.

3.5 Filtration Efficiency

The filtration characteristics of the fabrics are shown in Fig. 5. It is observed that other than samples made with 15 den fibres, the fabric of each type of fibre combination shows that the filtration efficiency first rises with increment in punch density and then decreases with further increase in punch density. This is due to the decrease in pore size with the increase in interlocking and compactness at initial increment in punch density and then increase in pores due to damage of fibres and formation of pegs with further increase in punch density. For 15 den fibre fabrics the compactness still goes on even with the increase in increment of punch density upto 200 punch/cm². The filtration efficiency values at very low particle size of dust (0.3 and 0.5 μ) sometime do show the proper trend, which may be due to sensitivity of the instrument and local disturbance of power supply to the particle counter.

4 Conclusions

4.1 The needle-punched fabrics have very good abrasion resistance. The air permeability value decreases due to continuous abrasion under certain load and the weight loss during the process is almost negligible.
4.2 Fabrics of all types of fibre fineness show an initial decrease in recovery followed by an ultimate increase in recovery value with the increase in punch density values. With the increase in finer fibre proportion the recovery of fabrics having corresponding punch density increases. Compressibility of the fabrics decreases with the increase in punch density.

4.3 With the increase in proportion of finer fibre content in the layered needle-punched fabrics the air permeability value drops down. The relationship between air permeability and pressure drop values is found to be linear. Other than the 15 den fibre fabric, with the increase in punch density from 120 punch/cm² to 200 punch/cm² the air permeability value at first decreases and then increases. However, in case of 15 den fibre fabric the air permeability value keeps on decreasing.

4.4 Machine direction breaking load is higher than that of cross direction. The 15 den fibre fabrics show increase in average load bearing capacity in machine direction with the increase in punch density, whereas 6 den fibre fabrics have a declining tendency in average peak load. In case of machine direction strength, the fabrics made up of 6 and 15 den show comparatively steady response in peak load with the change in punch density and the values lie in between that of other two fabric types.

4.5 The 6 den fibre fabrics are more crimped than 15 den fibre fabrics. Dimensional change is almost negligible and uniform in case of 15 den fibre fabrics and does not have any effect of punch density. Shrinkage was maximum for 6 den fabrics. In case of finer fibre fabrics, the shrinkage initially increases and then decreases as the punch density increases.

4.6 The filtration efficiency increases from coarser fibre fabric to finer fibre fabric. For 15 den fibre fabrics, the efficiency continues to increase from 120 punches/cm² to 200 punches/cm². But for other fibre combinations, the efficiency increases from 120 punches/cm² to 160 punches/cm² and then drops.

References
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