Chapter 7

Quality Aspects of Nonwoven Needle-Punched Polyester Filter Fabrics for Cement Dust Control Using Box-Behnken Factorial Design Technique
CHAPTER 7

QUALITY ASPECTS OF NONWOVEN NEEDLE-PUNCHED POLYESTER FILTER FABRICS FOR CEMENT DUST CONTROL USING BOX-BEHNKEN FACTORIAL DESIGN TECHNIQUE

The present chapter deals with the assessment of the influence of web weight, needle density and needle penetration on the filtration properties of needle-punched nonwoven polyester filter fabrics using Box-Behnken design of experiments.

7.1 Introduction

The choice of material to be used in filter is often the most important factor that must be considered if optimum performance is desired. The filter medium should be selected primarily for its capability to retain the solids that must be separated from the fluid, with an acceptable length of life. The filtration conditions (whether involving hot acids, extreme heat, etc.) and type of filtration (whether gas or liquid) are also important considerations. Both woven and non-woven fabrics are used for filtration purposes but non-woven fabrics are preferred to woven fabrics for improved performance in case of air filtration. Among the non-woven, the needle-punched filter fabrics are the fastest growing of all types of filter media. Many researchers have carried out extensive work on filtration and mechanical properties of filter fabrics which are governed by many factors. Fibre length and fibre fineness plays an important role on filtration and mechanical characteristics of filter fabrics. In order to secure high strength to the needled fabric, it is necessary to use long fibres. Finer fibres will yield greater strength to the fabric provided that the fibre damage is avoided. The permeability and hence the filtration properties are greatly influenced by the fibre fineness. If fabric weight and density are kept constant, air-permeability varies linearly with the fibre diameter and hence fineness. When a very dilute aerosol of submicron particles are filtered, the capture efficiency varies linearly with d/s, where d is the effective particle diameter and s is the inter-fibre spacing. A decrease in fibre linear density at constant fabric weight results in an increase in both capture efficiency and pressure drop.

Fabric weight increases with the increase in web weight. There is, however, a reduction in weight during needling operation. This reduction may be due to a drafting action, giving an increase in length, as the web is dragged through the gap between the bed and stripper plates.
It is also partly caused by recovery of fibres pulled down by the needles into the holes in bed plate, when the needles are withdrawn they will tend to pull the fibres up again, and the recovery forces will lead to a spreading of the web. The percentage reduction decreases with the increase in web weight, probably because the heavy-weight webs develop a higher frictional resistance to spreading. The spreading of the web due to needling depends on the following factors:

- Needling density
- Needle Penetration
- No. of passes
- Distance between bed and stripper plate
- Draft
- Fineness of fibre
- Type of fibre

Fabric thickness and linear density of needled fabric increase linearly, though not proportionately, with fabric weight. This may be due to the fact that increase in web weight and hence in thickness increases both the effective distance of barb penetration and the effective number of barbs penetrating the web greater fibre entanglement. Also, higher web weight provides higher frictional resistance for movement of punched fibres thus increasing the forces compacting the fabrics. The fabric weight has a significant influence on the shape of the stress-strain curve. The initial modulus increases with the fabric weight due to the increase in density and entanglement which causes less freedom of fibre movement and greater frictional restraints. Fabric tenacity also increases. However, beyond a certain fabric weight the tenacity falls owing to fibre breakage during needling should depend on needle penetration and needling density. Air permeability is lower in case of heavier fabric. Air permeability is almost inversely proportional to the fabric weight. Abrasion resistance increases with increased fabric weight.

For a particular web weight, the fabric weight decreases with increasing needling density. Higher needling causes spreading of fibres during punching thus reducing fabric weight. Higher needling causes higher fibre breakages, thus assisting the spreading of fibres. The needling has a great influence on the stress-strain curve. Up to a certain needling, the modulus, tenacity and breaking extension increases and after that limit, all tend to decrease. The initial rise is due to higher entanglement and the fall is due to the breaking of fibres and tearing of the web. The thickness of the fabric decreases with the needling density but fabric
density first increases followed by a decrease after certain limit. This is due to fibre damage and loss of fibre during needling.

Fabric weight is increased very slightly by needling and the fabric thickness reduces causing increased fabric density. Increased fabric density with needling causes increased pressure differentials.

The barb penetration depends on both the thickness of the web and needle penetration through the bed plate. The spreading of the web increases as the needle penetration increases which in turn leads to steady fall in fabric weight/unit area.

Fabric density, modulus and tenacity on the other hand go through maximum values. The improvement in mechanical properties are due to greater entanglement of fibres, as greater number of barbs play their role at higher penetration. Breaking extension for the same reason falls.

At higher needling densities, the fabric weight decreased with increasing depths of needle penetration. Increase in needle penetration also leads to decreased thickness of the fabric. The above changes in fabric weight and thickness cause the fabric density to increase with increase in needle penetration. Filtration efficiency depends on needle dimension and needle density as these cause more opening for dust to flow through. Filter having higher permeability will have less resistance compared with filters having lower permeability and so will collect more dust.

7.2 Materials and Methods
7.2.1 Materials
7.2.1.1 Preparation of fabric samples

Fifteen non-woven needle-punched fabric samples were prepared from 100% Hollow Polyester fibre having linear density 3.3 dtex and staple length 51 mm. Box-Behnken design is used to prepare the sample. Three variables namely Web weight, Needling density and Needle penetration were selected at three levels (viz. -1, 0, +1). Actual levels of three variables are given in Table 7.1.

The fabrics were prepared from parallel laid web which was obtained by feeding opened fibres in the ‘DILO’ Laboratory model card. The card is a roller and clearer type card with a vibrating doffer comb. The width of the card is 700 mm. Following are the speeds of different cylinders:-

235
Swift = 119 rpm (192 m/min)  
Licker-in = 32 rpm (170 m/min)  
Stripper = 245 rpm  
Doffer = 4.55 – 30 rpm  
Worker = 2 – 20 rpm  
Inlet group = 0.74 – 7.4 rpm

The speed of the swift was fixed while the speed of the doffer was variable during operation of the machine. The speed of the inlet group was varying accordingly with the variation of the speed of the doffer. The web was condensed on the collecting drum.

The carded web was fed to ‘DILO’ Needle loom type –II/6. This loom is mainly meant for the needling webs of synthetic and other fibres and needling is done from top.

Technical data of DILO NEEDLE LOOM:

Maximum width : 600 mm
Transport of material : Continuous by draw-off roller, covered with profile rubber band, drive by draw-off gear, pressure roller pneumatically operated, pressure adjustable, pneumatic with air maintenance unit, without compressor, air consumption 5.0 NL at 6 per each up and down stroke of the pressure roller.
Drive for Transport of material : By draw-off gear, with electric remote adjustment, range of adjustment 1:6, drive by base gear driven by main shaft.
Needle beam : Torsion-free Construction
Stroke of needle beam : 60 mm
Guidance of needle beam : Floating rocket motion beam guiding system.
Number of strokes/stroke frequency: Infinitely variable during running up to maximum 1200 rpm, elimination of vibrations by a mass balance system and vibrating dampers.
Stitching plate : Perforated, needle arrangement random,
Penetration depth : Adjustable during running by means of a handwheel.
Stripper plate : Fixed, Adjustable in height during running by means of a handwheel.
Needle boards: Width of each board 200 mm, needle arrangement random, 4000 drills/set on 1 m working width, without needles.
DILO Needle looms are built in various types. Depending on the number of needles per 1 m working width and on the set advance per stroke there results a certain stitching density per passage in the material.

Stitching density (cm²) = Needles per cm working width x 10/Advance per stroke in mm

Production capacity (m/min) = Number of strokes/min x advance in mm/1000

Penetration depth = Depending on the type of machine the penetration depth can be set manually or by push buttons.

Distance between stripper plate and stitching plate: Adjustable by adjusting the stripper plate by means of handwheel according to the scale attached.

**Operation of DILO Needle loom:**

In the needle punching unit, there are two needle boards. The size of each board is 63 cm x 17 cm. One can use both the needle boards simultaneously in order to reduce the number of passes required to achieve the desired punching density. Each needle board consists of 53 x 23 = 1219 needles of 36 gauge. The boards are kept in position pneumatically. A pressure of 4-6 psi is maintained to get the best result.

The unit is operated from a panel board from which the other units namely card & cross-lapping units are operated. The needling density is controlled by controlling the delivery rate of the machine, a scale is provided with the machine which indicates the delivery and strokes/min to achieve a particular punching density in a single pass. The feed rate is kept 10-15% lower than the delivery.

In the present work, the needle density needed was 300, 400 and 500. For this purpose, the following setting was used:

- For 100 punches/sq.cm : Strokes = 300/min, feed = 1.0 m/min, production = 1.2 m/min
- In the card, the area of the web delivered was = 2.06 m x 0.70 m = 1.442 sq.m.

Normally, 15-20% extra material is fed, because the GSM of the fabric changes after punching. The change in area is directly dependent upon the number of passes needed to achieve the required punching density. Thus the extra material is to be fed keeping in mind, the number of passes.

In the present work, for higher punching density, an extra feed of 60-70% was given to achieve the desired gsm. The change in area of the needled fabric is also directly dependent on the needle penetration. Higher the needle penetration, higher will be the expansion &
hence higher amount of extra feed is given. In fact, the amount of extra feed is determined by the number of passes and the needle penetration.

**Table 7.1: Experimental plan for nonwoven fabric variables**

<table>
<thead>
<tr>
<th>Combination No.</th>
<th>Web weight gsm</th>
<th>Needle density punches/sq.cm</th>
<th>Needle penetration mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
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<td>0</td>
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<tr>
<td>5</td>
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<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>7</td>
<td>-1</td>
<td>0</td>
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</tr>
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<td>1</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
</tr>
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<td>10</td>
<td>0</td>
<td>1</td>
<td>-1</td>
</tr>
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<td>-1</td>
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</tr>
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<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
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</tr>
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<td>14</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 7.2: Actual values corresponding to coded level**

<table>
<thead>
<tr>
<th>Coded level</th>
<th>Actual Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Web weight gsm (x1)</td>
<td>Needling density (x2)</td>
</tr>
<tr>
<td>-1</td>
<td>300</td>
</tr>
<tr>
<td>0</td>
<td>400</td>
</tr>
<tr>
<td>1</td>
<td>500</td>
</tr>
</tbody>
</table>

7.2.2 Methods

**7.2.2.1 Evaluation of fabric thickness and GSM**

The thickness of the fabrics was measured by R & B Cloth thickness tester. The testing was carried out under the pressure of 20 gms/sq.cm. Ten observations were taken randomly for each fabric sample. GSM was measured using electronic balance.
7.2.2.2 Evaluation of fabric filtration properties

7.2.2.2.1 Experimental set-up
Experiments were conducted in a fabricated apparatus using 10 cm diameter “patch” filter samples mounted in the apparatus. The filtration test apparatus includes:
   1) A unit of controlled feeding of particulate matter
   2) A test chamber with provision for convenient placement of a patch filter
   3) A sampling filter to capture particles passing through the test filter
   4) A suction pump mounted at the exhaust end
   5) Devices for cleaning the test filter
   6) Means for continuous monitoring of the pressure difference across the test filter
   7) An orifice meter located between the pump and the test filter

7.2.2.2.2 Air permeability
Air Permeability is the rate of flow of fluid under a given pressure differential across the fabric. Air permeability is measured by the instrument developed in the laboratory. Experiments are conducted with dust free air to estimate the effect of variables on the air permeability at 10 mm-WG pressure differentials. Air permeability values are calculated in cc/sq. cm/sec from the calibration curve and the area of the fabric.

7.2.2.2.3 Filtration efficiency, pressure drop and dust collection capacity
Experiments are conducted with dusty air using cement dust having mean volume diameter of 105.02 µm, keeping face velocity constant as 30 cm/sec. The fabric filters were tested for their filtration efficiency tests. Pressure drop were also recorded in mm-WG using manometers.

The filtration efficiency is determined by the following formula:

\[
\text{Filtration efficiency} = \frac{\text{Mass of dust collected on the test filter}}{\text{Mass of dust collected on the (test filter + Sampling filter)}} \times 100\%
\]

Dust collection capacity was calculated by using the following formula:

\[
\text{Dust collection capacity (mg/sq.cm)} = \frac{\text{Weight of dust deposited on the filter}}{\text{Working area of the filter}}
\]
Dust feeding was done at the rate of 0.5 gms/min. The dust laden air was sucked through the fabric by the suction pump. The fabric was weighted after each 60 seconds. It was observed that as the dusty air was fed to the fabric, the reading of both manometers M1 and M2 are changing. The orifice meter reading was adjusted constantly.

### 7.2.2.2.4 Categorization of Cement dust:

For testing the filtration efficiency, pressure drop and dust collection capacity, standard cement dust was used. The particle size of the dust particles were measured in Malvern Particle Size Analyser, which is a laser based computerized instrument.

The cement dust was dried to get rid the excessive moisture present. The particles obtained after the size distribution measurement was kept in moist free place for using it for the fabric sample testing.

In Malvern system, a beam of laser radiation strikes an assembly of particles, some of it is transmitted, some of it is absorbed and some of it is scattered. The light source is a low power He-Ne laser of 633 nm wavelength which is expanded and filtered to such a diameter so as to make representative sampling realistic. This is passed through the cement particles to be measured. These cement particles then scatter light of angles dependent on their size distribution. The scattered light was collected in the forward plane by a Fourier transform lens and focused on to a multi-element detector.

The cement dust particles were subjected to liquid floatation in a cell PS-I of the apparatus. Tri Chloroethylene was used as a dispersant medium. An optimum obscuration of 0.2829 was maintained to obtain good results at the volume concentration of 0.0079%. The focal lense of the Fourier Transform Lens was 63 mm. The specific surface area of the cement dust particles obtained through this procedure was 0.1268 m²/gm. A undersize histogram was obtained after finishing the cement particle size distribution. The lowest particle size was obtained for cement dusts is 3.89 µm and the highest particle size obtained is 118 µm. 50% mass median cement particle size are below 44.15 µm, 10% cement particle size are below 21.54 µm, & 90% cement particle size are below 90.44 µm. The beam length for this testing was kept 53 mm. The particle size distribution of cement dust used is given in Table 3.2.
7.2.2.5 Porosity and pore size measurement:

Porosity of non-woven fabrics was calculated from the ratio of volume of void present in the fabric to the total volume of the fabric expressed as percentage.

\[
\text{Porosity (\%) } = \frac{\text{Volume of voids}}{\text{Volume of fabric}} \times 100 = \frac{\text{Volume of fabric} - \text{Volume of fibres}}{\text{Volume of fabric}} \times 100 = 1 - \frac{\text{Fabric density}}{\text{Fibre density}} \times 100
\]

For capillary flow porometry a wetting liquid is used to fill all the pores of the sample and a nonreacting gas is used to remove the liquid from pores and permit gas flow. The differential pressures on the sample and gas flow rates through wet and dry samples are measured. The differential pressure is substituted in below mentioned equation to obtain the pore throat diameter of through pores.

\[ D = 4 \gamma \cos \theta / p \]

These measurements are used to compute the largest, the mean and the range of through...
pore throat diameters. Pore distribution, gas permeability and surface area are also determinable.

PMI Capillary Flow Porometry instrument at NIT Jallandhar was used for the measurement of pore size.

**PMI Capillary Flow Porometry**

In this instrument gas flow rate through a sample is accurately measured as a function of differential pressure. Gas permeability is computed from the gas flow rate in any desired unit including Darcy, Gurley and Frazier. This instrument can also measure flow rates through a sample whose pores have been filled with a wetting liquid. Such data can be used to compute other important characteristics of textiles like the largest pore diameter, mean flow pore diameter and pore distribution. The liquid (Galwick) was used for the purpose of pore size assessment.

**Fig. 7.0b : PMI Capillary Flow Porometry tester**

**Test Conditions:**
- **Fluid** – Galwick
- **Surface Tension** – 15.9 Dynes/cm
- **Tortuosity factor** – 0.715
- **Type of test** – Wet Up/Calc. dry, Linear
- **Filter flow % = 100 x Wet flow/Dry Flow**
INCR FF% = Filter flow % (Current) - Filter flow % (Previous)
PORE DISTRIBUTION = INCR FF%/ DIAMETER (Previous) - DIAMETER (Current)

Test results for Sample having GSM-396)
Mean flow pore pressure = 0.130 psi
Mean flow pore diameter = 50.8158 microns
Bubble point pressure = 0.081 psi
Bubble point pore diameter = 81.686 microns
Smallest detected pore diameter at 100% CFF = 18.8072 microns
Largest detected pore diameter = 81.6849 microns
Standard deviation of avg. pore diameter = 37.4917 microns
Maximum pore size distribution = 1.6161
Diameter at maximum pore size distribution = 23.0757 microns
10% cumulative filter flow occurs at 75.5668 microns
25% cumulative filter flow occurs at 66.2852 microns
75% cumulative filter flow occurs at 35.3465 microns
90% cumulative filter flow occurs at 26.0469 microns

Test results for Sample having GSM-404)
Mean flow pore pressure = 0.103 psi
Mean flow pore diameter = 64.1751 microns
Bubble point pressure = 0.061 psi
Bubble point pore diameter = 107.3801 microns
Smallest detected pore diameter at 100% CFF = 20.0773 microns
Largest detected pore diameter = 107.3801 microns
Standard deviation of avg. pore diameter = 50.0113 microns
Maximum pore size distribution = 1.1550
Diameter at maximum pore size distribution = 25.9467 microns
10% cumulative filter flow occurs at 98.8086 microns
25% cumulative filter flow occurs at 85.1210 microns
75% cumulative filter flow occurs at 42.5291 microns
90% cumulative filter flow occurs at 29.5416 microns

Test results for Sample having GSM-196)
Mean flow pore pressure = 0.043 psi
Mean flow pore diameter = 154.2092 microns
Bubble point pressure = 0.029 psi
Bubble point pore diameter = 228.0048 microns
Smallest detected pore diameter at 99.55% CFF = 58.1212 microns
Largest detected pore diameter = 228.0048 microns
Standard deviation of avg. pore diameter = 111.1835 microns
Maximum pore size distribution = 0.6763
Diameter at maximum pore size distribution = 122.1042 microns
10% cumulative filter flow occurs at 213.3528 microns
25% cumulative filter flow occurs at 191.1739 microns
75% cumulative filter flow occurs at 115.1943 microns
90% cumulative filter flow occurs at 83.6592 microns

Test results for Sample having GSM-208)

Mean flow pore pressure = 0.044 psi
Mean flow pore diameter = 148.5470 microns
Bubble point pressure = 0.03 psi
Bubble point pore diameter = 221.8706 microns
Smallest detected pore diameter at 99.55% CFF = 58.1212 microns
Largest detected pore diameter = 221.8706 microns
Standard deviation of avg. pore diameter = 104.9318 microns
Maximum pore size distribution = 0.6806
Diameter at maximum pore size distribution = 116.9328 microns
10% cumulative filter flow occurs at 207.3195 microns
25% cumulative filter flow occurs at 185.2798 microns
75% cumulative filter flow occurs at 109.9326 microns
90% cumulative filter flow occurs at 79.7913 microns

Justification of not using properly Pore measurement equipment:

After measurement of 4 samples, the machine was out of order and it remained idle for many months due to unforeseen reasons and could not be measured for other samples within stipulated time, Therefore, the results were not included in the chapter but were included in the Appendix 6.

7.3 Results and discussion

The experimental results for the various filtration properties of non-woven filter fabrics were fed into a computer, and the response surface equations for each property were obtained. The response surface equations for the Air Permeability and Filtration Parameters i.e., filtration efficiency, pressure drop and collection capacity along with the multiple correlation coefficient are shown in Table 7.3.

In these regression equations only significant terms have been included by using forward step-wise regression procedure. The negative co-efficient of a variable in a response surface equation indicates that a particular property decreases with the increase in that variable while positive coefficient of the variable indicates that the property increases with increase in that variable. It is observed that good correlation exists between the variables for different filtration properties.
7.3.1 Air permeability

7.3.1.1 Effect of web weight and needle density

Fig. 7.2a shows the effect of web weight and needle density on the air permeability of the fabrics at constant level of needle penetration (12 mm).

It can be observed from the figures that at any level of needle density when the web weight is increased the permeability decreases. From the figure, further observations can be made that with the increase of needle density at various level of web weights, the permeability rises.

The decrease in air permeability with the increase in web weight can be attributed to the higher total surface area with the higher web weight. Fabric thickness and fabric density also increases with the increase in web weight. The decreasing trend of air permeability with the web weight may be due to the more resistance offered by thicker and denser fabric.

The increase in air permeability with the increase in needling density may be due to the fact that with the increase of needling density, fabric thickness as well as fabric density decreases. Moreover, at higher level of needling density, the formation peg holes to be greater which ultimately results in higher air permeability,

Fig. 7.1 - Variation in fabric thickness of non-woven polyester fabrics [(a) web weight vs needling density; (b) web weight vs needle penetration; (c) needling density vs needle penetration]
Fig. 7.2- Variation in air permeability of non-woven polyester fabrics [(a) web weight vs needling density; (b) web weight vs needle penetration; (c) needling density vs needle penetration] 

From the above study, it may be concluded that with the help of contour curves (Figure 7.2a) various definite permeability values can be obtained by different combinations of gsm & punches/sq.cm. One can choose optimum values of permeability either by selecting higher gsm and lower punches/ sq.cm or by selecting lower gsm with higher punches/sq.cm from various combinations. For example, from Figure 7.2a, one can choose 450 gsm with 450 punches/sq.cm or 300 gsm with 150 punches/sq.cm to get 40 cc/sq.cm/sec permeability values. However, similar values can be obtained from 400 gsm (approx.) with 250 punches/sq.cm. It is preferable to produce filter fabrics with 400 gsm with 250 punches/sq.cm to obtain 40 cc/sq.cm/sec permeability value, as because higher gsm (400) will produce durable fabric and by lowering punches/sq.cm (250), the productivity will be more as well as less chances of damages of nonwoven structure as compared to the fabric with 450 gsm and 450 punches/sq.cm or nonwoven filter fabrics of 300 gsm with 150 punches/sq.cm. Moreover, from the above curves, one can obtain permeability values at same gsm with varying punches/sq.cm or vice-versa.
7.3.1.2 Effect of web weight and needle penetration

The effect of web weight and needle penetration on the permeability values at constant level of needle density (300 punches/sq.cm) are shown in Fig. 7.2b.

It can be seen from the figure that the permeability value is decreased with the increase of web weight at all level of needle penetration. However, with the increase of needle penetration at all level of web weight, the permeability values are found to be increased, especially at higher level of penetration.

The reason for decreasing trend of permeability with the increase of web weight is that higher the web weight higher is the total fibre surface area restricting the air flow. Another probable reason is that with the increase of web weight, the thickness of the fabric increases (as evident from the Fig. 7.1a) and thicker is the fabric lower is the air flow. Further, increase in web weight resulted in dense fabric and denser is the fabric more is the air drag and hence less is the air flow.

The decrease in permeability with the initial increase in needle penetration may be due to the fact that with the increase in needle penetration more number of fibres will be caught by the barbs resulting in better interlocking of fibres which in turn will cause higher fabric compactness. The increased compactness of the fabrics offer more resistance to air flow and so the permeability of the fabric reduces.

Though, at lower web weight the permeability value does not change at lower penetration, however, with the increase of penetration, increasing trend has been observed. With the increase in needle penetration, change of fibre arrangement along the direction of air flow resulted reduced air drag. These may be predominating over the effect of the fabric density. At much higher level of needle penetration the number of fibres which break become high and so the size of the pore/pegs will be more which causes the air permeability values of the fabric to increase.

From the above study, it may be concluded that with the help of contour curves (Figure 7.2b) various definite permeability values can be obtained by different combinations of gsm & needle penetration values (mm). One can choose optimum values of permeability either by selecting higher gsm and lower penetration or by selecting lower gsm with higher penetration (mm) from various combinations. For example, from Figure 7.2b, one can choose 300 gsm with 8 mm penetration or 400 gsm with 15 mm penetration to get 50 cc/sq.cm/sec permeability values. It is preferable to produce filter fabrics with 400 gsm with 15 mm penetration to obtain 50 cc/sq.cm/sec permeability value, as because higher gsm (400) with
moderate penetration (15 mm) will produce durable fabric. Moreover, from the above curves, one can obtain permeability values at same gsm with varying penetration values or vice-versa.

7.3.1.3 Effect of needle density and needle penetration

Fig. 7.2c depicts the effect of needle density and needle penetration on the permeability values at constant web weight (400 gsm).

It may be seen from the figure that the permeability value increases with the increase in needling density. However, the permeability value is found to be decreased with the initial increase of needle penetration, but at higher levels of needle penetration, the permeability value rises.

The decreasing trend of permeability at the initial stages of needle penetration may be due to the consolidation of web structures resulted in dense fabric. However, after certain limit of needle penetration, any further increase of needle penetration, the permeability values are found to be increased mainly because of peg formation. The channels created in the fabric due to the passage of needle is attributed as one of the main reason for the rise in air permeability. Similar reason may be attributed for needle density also.

From the above study, it may be concluded that the contour curves will be helpful in getting a series of combinations of penetration & needle density values for a definite permeability. For example, in order to get 40 cc/sq.cm/sec permeability values, there are many combinations of ND & NP, i.e., 400 p/sq.cm with 10 mm penetration or 300 p/sq.cm with 14 mm penetration, 250 p/sq.cm with 8 mm penetration and so on. However, one can choose the values of penetration up to 10 mm & punches/sq.cm values up to 300-350 so that fiber breakages do not take place and denser fabric is formed.

7.3.2 Filtration efficiency

7.3.2.1 Effect of web weight and needle density

The effect of web weight and needling density on the filtration efficiency at constant needle penetration i.e., 12 mm are shown in the Fig. 7.3a.

From the figure, it is found that with the initial increase in web weight, higher efficiency at all level of needle densities is observed. However, after 400 gsm of web weight, it is
gradually reduced. This is due to the fact the less collection capacity of dust at higher web weight resulting in lower efficiency, as evident from the Fig. 7.5a. It is also observed from the Fig. 7.3a that at initial level of web weight, increase in needle density show no significant difference in filtration efficiency values. However, at higher web weight, a slight decrease in filtration efficiency is observed with the increase of penetration.

This can be explained as to the fact that with the initial increase in web weight, total fabric surface area increases. Another reason which may attribute to higher filtration efficiency are fabric thickness and fabric density. Increase in fabric surface area will be able to retain more amount of dust. Due to the increased fabric thickness, a dust particle will have to travel more distance through the fabric which will lead to a greater chance of dust particles being separated from air stream, as the chance of collision of dust particles with the fibres in the fabric increases with the increase in path distance. Again, increased fabric density rises air resistance which in turn enables retention of higher quantity of dust particles but at the same time increases the pressure drop as seen from the Fig. 7.4a. The increased filtration efficiency with the increase in web weight can also be supported by the increasing trend of dust collection capacity with the increase of web weight.

The fall in filtration efficiency with the further increase in needle density is due to the fact that increased needling density creates more pegs & hence more paths of dust to flow through, leading to a drop in filtration efficiency.
From the above study, it may be concluded that Figure 7.3a will be helpful in selecting various ranges of gsm & punches/sq.cm values to obtain definite filtration efficiency. From the Figure 7.3a one can choose 350-450 gsm with 200-250 punches/ sq.cm to obtain maximum obtainable filtration efficiency (99-100%) for 1 minute filtration time.

### 7.3.2.2 Effect of web weight and needle penetration

The results of filtration efficiency with the increase of web weight and needle penetration at constant needle density i.e., 300 punches/sq.cm are shown in the Fig. 7.3b. From the figure, filtration efficiency is found to be increased with the increase in web weight up to certain limit at all level of needle penetration. It is also observed from the figure that initially with the increase in needle penetration, there is no significant change in filtration efficiency and thereafter decreases at each level of web weight. The reasons for increasing filtration efficiency with the increase in web weight are already explained. After certain limit, any further increase of needle penetration may create peg holes through which dust particles may escape causing reduced filtration efficiency.

From the above study, the conclusions can be drawn that the Figure 7.3b may be useful in selecting various combinations of fabric weight and needle penetration values for obtaining maximum filtration efficiency. From the Figure 7.3b one can choose 350-450 gsm with 8-10 mm to obtain maximum obtainable filtration efficiency (99-100%) for 1 minute filtration time.
7.3.2.3  Effect of needle density and needle penetration
The effect of needle density and needle penetration on the filtration efficiency shown in the Fig. 7.3c at constant web weight (400 gsm).
From the Figure, it may be seen that with the increase in either needle density or needle penetration, the filtration efficiency falls.
As discussed earlier that peg hole formation and fibre breakages may occur and thus lowering the filtration efficiency. As in practice, the fibres in the pegs lie in parallel direction to the gas flow during filtration & thus do not form a good barrier to the passage of small dust particles. Increase in the depth of needle penetration will effectively increase the size of the pegs, which in turn would cause reduction in filtration efficiency.

It may be concluded from the above study that the both needle density & needle penetration values can be selected according to optimum requirements of filtration efficiency. From Figure 7.3c, for example, There are many possibilities, like 200 punches/sq.cm with 14 mm penetration, 300 punches/sq.cm with 8 mm penetration and so on. However, it is better to select in between 200-250 gsm with 12-14 mm penetration so as to produce less fibre damage and durable filter fabric as well as obtaining highest possible filtration efficiency.

7.3.3  Pressure drop
7.3.3.1  Effect of web weight and needle density
Fig. 7.4a shows the effect of web weight and needling density on the Pressure drop at constant needle penetration i.e., 12 mm.
It is observed from the figure that the increase in web weight shows higher pressure drop at all level of needle densities. From the figure, it is also observed that at each level of web weight, the pressure drop of the fabrics first increases with increase in needle density and then it falls.
The above phenomenon can be explained as to the fact that with the increase in web weight, total fabric surface area increases. Another reason which may be attributed to the higher fabric thickness and fabric density with the increase in web weight. Increase in fabric surface area will be able to restrict air flow and thus causing more air drag. Again, increased fabric density rises air resistance which in turn enables retention of higher quantity of dust particles but at the same time increased the pressure drop as seen from the Fig. 7.4a.
The rise in pressure drop with the initial increase of needle density can be attributed to the fact that the initial increased needle density leads to an increased entanglement of fibres within the fabric which increases the density & hence it offers more resistance to flow.

The fall in pressure drop is ascribed to the decrease in density due to higher needling action. Hence, the resistance to flow decreases with the further increase in needle density.

Figure 7.4a will be helpful in selecting the ranges of fabric weight and needle density values to obtain minimum values of pressure drop. From the Figure 7.4a lower pressure drop level (12-15 mm-WG) may be obtained by using 250 gsm with 200 punches/sq.cm and 450 punches/sq.cm. One should select 200 gsm with 200 punches/ sq.cm for higher productivity and less chances of breakages. However, from the filtration efficiency studies, 350-450 gsm is preferable with 250-300 punches/sq.cm,
7.3.3.2 Effect of web weight and needle penetration

Fig. 7.4b shows the effect of Web weight and Needle penetration on Pressure drop at constant needle density (300 punches/sq.cm).

The pressure drop results are found to be increased with the increase of web weight at all level of penetration. However, at higher level of penetration range, more pronounced effect is found. With the increase of penetration, no significant effect is found.

With the higher web weight, denser fabric is formed, causing lower air flow and thus higher air drag is resulted. At higher gsm, the fabric thickness increases and hence, with the increase of penetration, more barbs will actuate for fibre locking and therefore, better consolidation of web structure takes place, resulting in dense fabric. Dense is the fabric, lower is the air flow causing more pressure difference.

*From the above study, Figure 7.4b will be beneficial in optimizing pressure drop values for various combinations of gsm & needle penetration. Though, lower pressure drop values (15-20 mm WG) are obtained for 300-400 gsm with 8-10 mm penetration, however, as mentioned earlier, 350-400 gsm will be useful in obtaining higher filtration values. Therefore from the above figure, it may be concluded that with the 350-400 gsm with 8-10 mm penetration would give acceptable pressure drop limit (20-24 mm-WG).*

7.3.3.3 Effect of needle density and needle penetration

Fig. 7.4c gives the results of pressure drop variation of the filter fabrics with the changes of both Needle density and Needle penetration at constant web weight level (400 gsm).

Pressure drop results are showing downward trend with the increase in needle density upto certain limit and thereafter increases. From the figure it is also seen that as the needle penetration increases, the pressure drop increases up to certain level of needle density and then falls.

The initial decrease of pressure drop with the increase in needling density is due to the peg formation. The fall in pressure drop with further needle density & penetration can be attributed to the fact that with the higher needle density and penetration, the peg hole size increases and as the more barbs penetrating the webs, more number of fibres break resulting in larger pore size. In both the cases, the fibres allow more aerosol to pass through which results in fall in pressure drop.

With the further increase of needle density and denser the fabric more restriction of easy air flow, thus increasing the pressure difference. The initial rise is due to the fact that the
consolidation of the fibres increases with the needle penetration, which increases the fabric density, and hence, higher pressure drop results.

Figure 7.4c will be helpful in selecting ranges of needle density and needle penetration values in getting minimum pressure drop values for 400 gsm fabric. However, from the figure, optimum ranges of needle density and penetration are 350 punches/sq.cm and 10 mm penetration respectively. From the above studies, one can conclude that 300-400 punches/sq.cm with 8-10 mm penetration would give acceptable level of pressure drop for 400 gsm fabric.

Fig. 7. 5- Variation in collection capacity of non-woven polyester fabrics [(a) web weight vs needling density; (b) web weight vs needle penetration; (c) needling density vs needle penetration]
Table 7.3: Response surface equations for fabric characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Response surface equations</th>
<th>Squared multiple regression coefficient (R²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabric thickness, mm</td>
<td>3.654 + 1.06 x₁ -0.25 x₂ -0.17 x₃ +0.29 x₁²+ 0.08 x₂²+0.09 x₃²</td>
<td>0.994</td>
</tr>
<tr>
<td></td>
<td>+0.03 x₁ x₂ -0.09 x₂ x₃+0.03 x₁ x₃</td>
<td></td>
</tr>
<tr>
<td>Air permeability, cm³/cm²/sec</td>
<td>43.43 - 14.37 x₁ +5.47 x₂ +2.81 x₃ -0.006 x₁²- 2.77 x₂²+2.13 x₃²</td>
<td>0.979</td>
</tr>
<tr>
<td></td>
<td>+0.27 x₁ x₂-0.76 x₂ x₃-1.8 x₁ x₃</td>
<td></td>
</tr>
<tr>
<td>Filtration efficiency, %</td>
<td>99.36 - 1.17 x₁ -0.44 x₂ -0.61 x₃ -6.93 x₁²+ 0.22 x₂²+0.04 x₃²</td>
<td>0.967</td>
</tr>
<tr>
<td></td>
<td>+0.3 x₁ x₂+0.16 x₂ x₃-0.4 x₁ x₃</td>
<td></td>
</tr>
<tr>
<td>Pressure drop, mm-wg</td>
<td>22.33 + 7.63 x₁ -1.13 x₂ -0.25 x₃ -1.17 x₁²+ 1.83 x₂²+0.08 x₃²</td>
<td>0.971</td>
</tr>
<tr>
<td></td>
<td>+0.5 x₁ x₂-0.75 x₂ x₃+0.25 x₁ x₃</td>
<td></td>
</tr>
<tr>
<td>Collection capacity, mg/cm²</td>
<td>55.48 - 1.88 x₁ +0.29 x₂ +0.37 x₃ -6.85 x₁²- 0.59 x₂²+0.61 x₃²</td>
<td>0.988</td>
</tr>
<tr>
<td></td>
<td>+1.07 x₁ x₂-0.36 x₂ x₃-1.04 x₁ x₃</td>
<td></td>
</tr>
</tbody>
</table>

7.4 Conclusions

7.4.1 Air permeability

Increase in web weight decreases air permeability. Air permeability value increases with higher needling density and penetration. From the present study, it may be concluded that the contour curves will be helpful in getting a series of combinations of gsm, penetration & needle density values for a definite permeability. It is preferable to produce filter fabrics with 350-400 gsm with 250-300 punches/sq.cm to obtain optimized permeability value. From the studies, it can be concluded that one can choose 300 gsm with 8 mm penetration or 400 gsm with 15 mm penetration to get optimum permeability values. It is also preferable to produce nonwoven needle-punched filter fabrics with 300-350 punches/sq.cm with 8-10 mm penetration to obtain optimum values of Air permeability.

From statistical analysis, it is observed that there are good squared multiple regression correlation co-efficient values (0.979) between all the variables (i.e., web weight, needle density and needle penetration) and the response values (i.e., Air permeability values), which indicates that there are relationship between the variables and the response values.
There are negative impacts of the web weight as well as squared values of web weight on air permeability, which indicated that with the increase of web weight, permeability values were decreased, which is quite evident that with the increase in GSM, fabric thickness, fabric density increased resulted in lowering value of air permeability. Whereas there are positive impacts of needle density and needle penetration on the permeability values which indicated that with the increase of both the needle density & needle penetration values resulted in increase of air permeability, which may be due to the peg formation with the increased punches/sq.cm or needle penetration values. Similarly, when there is interaction of web weight and needle density, there are positive impacts of the above variables on the response values, i.e., air permeability values are increased, which may due to peg formation with the increased punches/sq.cm, however, when there is interaction of web weight and needle penetration, there are negative impacts of the above variables on the response values, i.e., air permeability values are decreased, which may due to increased fabric density due to consolidation of fibres with the increased penetration. The interaction with the needle density and needle penetration also resulted in negative impact on air permeability.

7.4.2 Filtration efficiency

Higher filtration efficiency is found with the increase of fabric weight at all level of needle density and needle penetration up to certain point and thereafter it decreases. No significant difference is found with the increase of needle density and needle penetration, however decreasing trend is observed after 400 gsm. Combination effect of needle density and needle penetration show initial increase of filtration efficiency thereafter reduction takes place.

From the contour curves of the present study, it may be concluded that a series of combinations of gsm, penetration & needle density values can be obtained for getting maximum possible filtration efficiency. One can choose nonwoven needle-punched filter fabrics with 350-400 gsm with 250-300 punches/sq.cm and 300-400 gsm with 8-10 mm penetration as well as with 250-350 punches/sq.cm with 8-10 mm penetration.

From the statistical results, it can be seen that there are good squared multiple regression correlation co-efficient values (0.967) between all the variables (i.e., web weight, needle density and needle penetration) and the response values (i.e., Filtration efficiency values). There are negative impacts of web weight as well as squared values of web weight on the
filtration efficiency, which indicate that with the increase of web weight, filtration efficiency value decreases. Similarly, there are negative impacts of Needle density and needle penetration with the filtration efficiency values which indicate that with the increase of both the needle density & needle penetration resulted in decrease in filtration efficiency, may be due to increased peg formation.

Similarly, when there is interaction of web weight and needle density, there are positive impacts of the above variables on the response values, i.e., filtration efficiency values are increased, however, when there is interaction of web weight and needle penetration, there are negative impacts of the above variables on the response values, i.e., filtration efficiency values are decreased.

The interaction with the needle density and needle penetration also resulted in positive impact on filtration efficiency.

7.4.3 Pressure drop
Pressure drop is found to be increased with the increase of fabric weight at all level of needle density and needle penetration. Pressure drop decreases with the increase in Needle density. However, Increase in needle density for a given needle penetration causes an initial decrease in pressure drop and thereafter reverse trend is observed after certain level. At lower needle density, increased pressure drop results with an increase in needle penetration, however after certain limit of needle density, pressure drop decreases with the further increase of penetration.

It may be concluded from the contour curves of the present study, that a series of combinations of gsm, needle density and penetration values can be obtained for getting minimum pressure drop. One can choose nonwoven needle-punched filter fabrics with 350-400 gsm with 250-300 punches/sq.cm and 300-400 gsm with 8-10 mm penetration as well as with 250-350 punches/sq.cm with 8-10 mm penetration to obtain minimum acceptable pressure drop limit.

Also, from statistical analysis, it is observed that there are good squared multiple regression correlation co-efficient values (0.971) between all the variables (i.e., web weight, needle density and needle penetration) and the response values (i.e., Pressure drop values). There is a positive impact of web weight on the pressure drop, which indicates that with the increase of web weight, pressure drop value increases, which may be due to increased fabric density. Similarly, there are negative impacts of needle density and needle penetration on the
pressure drop values which indicate that with the increase of both the needle density & needle penetration resulted in reduced pressure drop, may be due to peg formation.

Similarly, when there is interaction of web weight and needle density as well as web weight and needle penetration, there are positive impacts of the above variables on the response values, i.e., pressure drop values are increased, which may be due to increased fabric density.

The interaction with the needle density and needle penetration also resulted in negative impact on pressure drop, may be due to increased peg formation.

**7.4.4 Optimisation**

From the contour curves of the filtration properties, one can conclude that optimum level of needling parameters are between 300-350 punches/sq.cm with 13-14 mm penetration with 400-450 gsm web weight.