THE EFFECT OF FACE VELOCITY, PLEAT DENSITY AND PLEAT ORIENTATION ON THE MOST PENETRATING PARTICLE SIZE, PRESSURE DROP AND FRACTIONAL EFFICIENCY OF HEPA FILTERS

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ABSTRACT

The increasing need for clean air in critical industrial applications has highlighted the importance of the role of air filters in providing improved air quality. Actual performance of air filters installed in air handling units and in the intake of gas turbines tends to deviate from the performance predicted by laboratory results. Therefore, accurate filter performance prediction is important to estimate filter lifetime, and to reduce energy and maintenance operating costs. To ensure that the desired efficiency of a HEPA filter is attained, the effects of face velocity, pleat density and pleat orientation on the Most Penetrating Particle Size (MPPS) of pleated HEPA filters must be examined. This paper compares the effects of varying these parameters on the MPPS. The paper also presents the initial pressure drop response and fractional efficiency curves using DEHS testing according to DIN 1822 for vertical and horizontal pleat orientations. It analyzes the underlying reasons causing surface area losses for different flow rates, pleat density and orientation as well as the effects on filter permeability. The tests conducted in this study used full scale HEPA pleated V-shaped filters from Heating Ventilation and Air Conditioning (HVAC) and gas turbine applications.

KEYWORDS

Air filters; Fractional efficiency; Gas cleaning; Glass fibre; HEPA filter; Permeability; Pressure drop.

FILTRATION OF AIR

The assessment of air filter performance is complex and influenced by several parameters such as face velocity, filter medium properties, filter design and dust types and their loading conditions. The performance characteristics under study in this paper are initial pressure drop and fractional efficiency. To make an appropriate filter selection for various applications, the influential parameters affecting the filtration performance must be evaluated.

Several authors have studied the performance of clean filters[1-5] and others have considered loading filters with monodisperse aerosols[6]. Most of these utilise a flat fibrous filter medium and filtration performance is examined[7,8]. Other literature has also covered the effect of particle and fibre charge on filter performance[9,10]. The penetration of HEPA filters has been examined[11-13] and several studies investigate the performance of loaded HEPA filters with solid particles[14,15], liquids particles[16-18] and a mixture of both[19,20]. The literature scope, whether it is theoretical or experimental, is limited to the study of flat filters and small scale pleated panel HEPA filters, and the filter properties were not always fully reported. Although some studies were done on pleated filtration media, the literature available on pleated HEPA filters is rather limited and mainly based on numerical approaches used for performance analysis[23-31]. Unlike this study, the previous pleated filters studies have not considered a full scale HEPA filter constructed in a V-shape cartridge. The experimental work investigates the effect of face velocity, pleat density and pleat

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orientation on the initial pressure drop, fractional efficiency and associated MPPS of HEPA filters. Previous studies have considered the pleating density and highlighted the optimal pleat count[25-29].

FILTER PROPERTIES

The experimental work involved the testing of full scale glass fibre pleated cartridges of HEPA Class H10 according to DIN 1822[32]. Ten filters were manufactured by EMW Filtertechnik in Germany with pleating densities varying from 28 to 34 pleats per 100 mm. Table 1 lists all filters used for testing with their corresponding surface areas as well as their pleat orientation. The first eight manufactured filters were divided into two groups, designated A and B. Both groups underwent similar testing procedures and were challenged with DEHS to give data for the initial fractional efficiency. The remaining two filters, 28H and 28V, represent a pleating density of 28 per 100 mm with horizontal and vertical pleat orientation, respectively. Filter's 28H and 28V were manufactured to investigate the effect of pleat orientation on the initial pressure drop and fractional efficiency. Figure 1 shows the face dimensions of 592 x 592 mm with a depth of 400 mm. The filter cassette has a V-shape bank which contains eight pleated media panels.

The glass fibre media used in the filters is shown in Figure 2. Glass fibre filtration media was selected for all experiments as it exhibits better resistance to high temperatures and has smaller fibre size compared to synthetic media. Glass fibre media are highly porous with a low resistance to air flow. Filtration performance is affected by several variables such as filter medium thickness, permeability, packing density, fibre diameter as well as the design of the filter module itself. Operating conditions such as filtration velocity and temperature also affect the filter performance, in addition to the characteristics of the aerosol such as particle size distribution, particle shape and density. The filter properties of the media used in this study are listed in Table 2.

CLEAN GAS PERMEATION

The passage of clean gas throughout the filtration enabled the pressure drop and efficiency to be measured; the latter required challenging the filter with DEHS according to DIN 1822. There is no dust loading at this stage of the testing. The Reynolds number was used to verify the flow regime in the testing tunnel and through the filter medium. Reynolds numbers for the filter medium (using the fibre diameter) at flow rates of 500 and 5000 m^3/h were 0.00122 and 0.0122, respectively, and thus the flow inside the filter medium is laminar. Reynolds numbers in the rectangular feed duct to the filter (with a hydraulic diameter of 610 mm) at flow rates of 500 and 5000 m^3/h were 14,476 and 144,760, respectively and the flow inside the duct is turbulent.

The flow inside the filter medium can be interpreted using Darcy's Law to calculate the permeability, κ:

$$\kappa = \frac{\mu V h}{\Delta P} \tag{1}$$

where μ is the air viscosity, V the approach velocity of the air, h the filter medium thickness, and ΔP the pressure drop across the medium. The initial pressure drop was measured and is shown in Table 3 at different flow rates ranging from 500 to 5000 m^3/h at increments of 500 m^3/h, together with the corresponding permeability values.

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DEVIATION FROM DARCY'S LAW

The Darcy pressure drop model is examined and compared with the experimental work. The Darcy model gives a linear relationship between pressure drop response and flow rate, which also signifies that the permeability of the filtration medium does not change and that the pressure drop should vary linearly with the filtration velocity. However, the experimental results exhibit a non-linear response which means that the filter permeability is changing as the flow rate varies, even though the flow inside the medium is laminar. Figure 3 shows that as the face velocity or pleating density increase, so the permeability decreases. Increasing the filter surface area decreases the face velocity, and therefore, the pressure drop of the filter is expected to decrease. However, when the pleating density increases to extend the surface area, the pressure drop also increases and there must be a competing effect that leads to the deviation from Darcy's law.

At low pleat count, the face velocity is high and the pressure drop increases. On the other hand, over-pleating also causes an increase in pressure drop due to the increased viscous drag in the pleat spacing. It is evident from Figure 4 that while higher pleating densities provide additional surface area, the losses of surface area also increase as the face velocity increases, which in turn means the air stream cannot access all of the surface area provided. The pressure drop rise from higher pleating density is related to the flow inside the pleat where the viscous and inertial forces play a role in raising the pressure drop. Therefore, this effect will be competing with increase of surface area provided by the higher pleating density. Figure 4 also shows that losses are similar in the 30 and 32 pleating densities. Examining Table 3, Filters 32A and 32B have lower pressure drops than 30A and 30B, respectively. Filters with 32 pleats per 100 mm would be better from a pressure drop point of view and they have similar surface area losses compared to the 30 pleats per 100 mm filters. However, a comparison to determine the better pleat count is not complete until the filter efficiency curves are examined from both initial and dust loaded points of view. This is simply to check that the filter with 30 pleats per 100 mm has less surface area and has similar surface area losses when compared with 32 pleats per 100 mm filters. The area losses are not due entirely to one factor and there is no apparent optimal pleat density for a given rate. The data shows that the area of the filter media is fully utilized at 500 m^3/h and underutilized at higher flow rates.

For a pleat through which fluid flow obeys Darcy equation, the losses of media surface area are due to one or a combination of the following reasons:

- Pleat crowding, a geometric effect caused by an excessive number of pleats in the pleated panel. The filtration medium surface area losses occur because too many pleats are next to each other. Clearly, as the pleat density increases, so the surface area losses increase.

- Deflection of the entire pleated panel that causes permeability reduction or by viscous or shear forces at the corner of the pleat would have more influence on the filter surface area losses. In the absence of sufficient support on the back side of the pleated panels, the deflection is more pronounced.

- Pleat distortion at the corner of the pleat caused by delamination of the fibre layers from the filtration medium. Clearly, the higher the number of pleats, so the greater this effect has on permeability reduction of the filtration medium. The effect becomes more prominent as face velocity increases.

- Filtration medium compression occurs, and therefore the medium thickness will reduce resulting in higher pressure drop. Compression can also result from medium folding which leads to tension in the outer region of the pleated medium and compression at the inner region. Medium compression could also be due to the drag force exerted by flowing fluid on the surfaces of deposited particles or fibres forming the medium. The medium compression

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increases as the shear stress acting on the fibre surfaces increases, thereby causing the pressure drop to rise.

Figure 5 illustrates the loss in the tested filters' surface areas versus their pleating densities. It can be seen that as the pleating density increases so the surface area loss increases. This indicates that the entire surface area is not utilized, and higher pleat density leads to greater losses in the surface area of the pleated filter. Figure 5 also shows that higher pleating density has led to greater losses in the surface area of the filter. However, the focus of the design should be directed towards reducing surface area losses and not reducing the pleating density. Reducing surface area without verifying the efficiency requirement would compromise filter performance. It may also affect the mechanical/structural stability of the pleated panel. Surface area losses signify that the air flow does not get access to the total surface area, and as a result this part of the filtration medium does not participate in the filtration process and may have no substantial contribution to the enhancement of overall filter efficiency. This is an important aspect of the design of the filter because it would also reflect on the manufacturing cost.

The effective surface areas are listed in Table 4 for different flow rates and pleating densities. At low flow rates such as 500 and 1000 m^3/h, the full surface area of the filter medium participates in the filtration process, and there are no losses in the filter medium and no permeability reduction. However, when the flow rate and pleating density increase further, the area losses begin to occur. The effective surface area decreases with an increase of flow rate and pleating density. The surface area losses increase as pleating density increases suggesting that the filter is over-pleated and it may be possible to obtain equally good filtration using a lower number of pleats. For a fixed pleating density and a given flow rate, there exists a minimum pressure drop that meets the efficiency requirement of the standards.

EFFECT OF PLEAT ORIENTATION ON FILTER PERFORMANCE

Two filters having the same filter medium properties were manufactured in vertical and horizontal pleat orientations in order to study the effect on performance. Initial pressure drop and fractional efficiency were measured without dust loading. Table 5 tabulates the pressure drop starting at 500 m^3/h until 6000 m^3/h in addition to the MPPS and measured fractional efficiency. Fractional efficiency was conducted using DEHS for six flow rates starting at 500 m^3/h until 3000 m^3/h is reached. The filter cartridge with vertical pleats had a surface area of 24.4 m^2 whereas the horizontal pleat filter had an area of 23.5 m^2. The difference in surface area is nearly one square metre due to losses incurred after the addition of the casting material that connects the pleated fibrous material to the plastic housing. The horizontal pleat filter has more losses since the casting material covers more pleats compared to the vertical one.

Observations

1. From a pressure drop point of view, the vertical pleat filter has slightly lower pressure drop as shown in Figure 8. This is due to the vertical pleating which is thought to give more strength to the pleated media panel, and hence less deformation occurs at higher flow rates.

2. The MPPS shifts to a smaller particle size as the face velocity increases with both pleat orientations.

3. Fractional efficiency readings are very close for both pleat orientations at lower flow rates, but as the flow rate increases the horizontal pleating offers a pressure drop that becomes increasingly less compared to the vertical pleating.

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4. The slightly lower pressure drop of the vertical pleats is probably more than offset by the greater fractional efficiency of the horizontal pleats and the one square metre difference in total surface area, making the horizontal pleats a better practical option.

Figure 6 illustrates the pressure drop comparison between the flat sheet and horizontal and vertical pleats of the same medium. The flat sheet pressure drop response is linear while pressure drops for both pleating directions exhibit identical patterns. Their pleated pressure drop curves initially start with linear responses then as the face velocity increases they depart linearity and losses in surface area are more pronounced. The comparison of simulated and experimental pressure drop responses is also shown in Figure 6. This examination was conducted at the same face velocities to ensure that all the pressure drop readings can be compared. It can also be shown that permeability reduction due to flat medium compression is not that significant in comparison to other factors. The conclusion is that surface area losses and their consequential permeability reductions are mainly due to pleat crowding, pleated panel deformation and pleat deformation.

Surface area losses are compared in Figure 7. The vertical pleat orientation cartridge experienced higher losses when compared to the horizontal pleat orientation. Table 5 also shows the drop in fractional efficiency as the face velocity increases. It is evident that the vertical pleat orientation provides less efficiency readings and the HEPA H10 filter class is only attained for 500 and 1000 m^3/h flow rates for both pleat orientations. With reference to Figure 8, in terms of efficiency the vertical pleated filter seems to have lower efficiencies at lower and higher flow rates although it has the additional surface area. The horizontal pleated filter exhibits higher efficiency compared to the vertical pleated filter. The effect is more pronounced at higher flow rates such as 3000 m^3/h.

CONCLUSIONS

This study has presented an experimental investigation into the effects of face velocity, pleat density and orientation on the pressure drop response and initial fractional efficiency of full scale HEPA filters. The following conclusions can be drawn:

- The surface area losses increase as the pleating density and face velocity increase.

- Pleating density selection should be based on the corresponding effective filter surface area it provides and the total surface area. Furthermore, the pleating density selection should be made in conjunction with the requirement to achieve a desired efficiency.

- An increase in pleating density and face velocity decreases filter medium permeability.

- At low flow rates such as 500 and 1000 m^3/h the full surface area of the filter participates in the filtration process, and there are no losses in the filter medium area and no permeability reduction.

- The fractional efficiency decreases as the face velocity increases for particle sizes lower than the MPPS whilst the fractional efficiency increases as the face velocity increases for particle sizes greater than the MPPS.

- Pressure drop comparisons between vertical and horizontal pleated filters has shown that the vertical pleat filter has slightly lower pressure drop.

- The MPPS shifts to a smaller particle size as the face velocity increases with both tested pleat orientations.

- Fractional efficiency readings are very close for both pleat orientations at lower flow rates, but as the flow rate increases the horizontal pleating offers a pressure drop that becomes increasingly less compared to that of the vertical pleating.

- The slightly lower pressure drop of the vertical pleats is probably more than offset by the greater fractional efficiency of the horizontal pleats, making the horizontal pleats a better practical option.

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TABLES AND FIGURES

Filter	Pleat density (pleats/100 mm)	Surface area (m^2)	Pleat orientation
28A	28	23.9	horizontal
28B	28	24.6	horizontal
30A	30	26.6	horizontal
30B	30	26.6	horizontal
32A	32	27.3	horizontal
32B	32	27.3	horizontal
34A	34	28.8	horizontal
34B	34	28.9	horizontal
28H	28	23.5	horizontal
28V	28	24.4	vertical

Table 1: The filters tested and their surface areas.

HEPA (H10) filter medium	
Fibre diameter range (µm)	0.5-8.5
Average fibre diameter (µm)	2.1
Media thickness (µm)	500
Packing density	0.06
Porosity (%)	94
Fibre shape	circular

Table 2: Properties of the filter medium.

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Filter	28A, A_S = 23.9 m^2			30A, A_S = 26.6 m^2			32A, A_S = 27.3 m^2			34A, A_S = 28.8 m^2		
Q (m^3/h)	ΔP (Pa)	V_f (mm/s)	κx10^{-12} (m^2)	ΔP (Pa)	V_f (mm/s)	κx10^{-12} (m^2)	ΔP (Pa)	V_f (mm/s)	κx10^{-12} (m^2)	ΔP (Pa)	V_f (mm/s)	κx10^{-12} (m^2)
500	14	5.78	3.82	18	5.22	2.68	14	5.08	3.36	15	4.82	2.97
1000	30	11.57	3.57	30	10.44	3.22	27	10.17	3.48	29	9.64	3.07
1500	47	17.36	3.42	47	15.65	3.08	44	15.25	3.21	45	14.45	2.97
2000	66	23.12	3.24	65	20.86	2.97	63	20.34	2.99	63	19.27	2.83
2500	87	28.90	3.08	86	26.08	2.81	83	25.42	2.83	81	24.09	2.75
3000	111	34.68	2.89	108	31.30	2.68	105	30.50	2.69	105	28.91	2.55
3500	135	40.46	2.78	132	36.52	2.56	129	35.59	2.55	128	33.72	2.44
4000	162	46.24	2.64	159	41.74	2.43	155	40.67	2.43	153	38.54	2.33
4500	191	52.02	2.52	188	46.96	2.31	183	45.75	2.31	182	43.36	2.20
5000	222	57.80	2.41	218	52.20	2.21	213	50.84	2.21	213	48.18	2.09
Filter	28B, A_s = 24.6 m^2			30B, A_s = 26.6 m^2			32B, A_s = 27.3 m^2			34B, A_s = 28.9 m^2		
Q (m^3/h)	ΔP (Pa)	V_f (mm/s)	κx10^{-12} (m^2)	ΔP (Pa)	V_f (mm/s)	κx10^{-12} (m^2)	ΔP (Pa)	V_f (mm/s)	κx10^{-12} (m^2)	ΔP (Pa)	V_f (mm/s)	κx10^{-12} (m^2)
500	17	5.65	3.07	15	5.23	3.22	15	5.09	3.14	15	4.80	2.96
1000	30	11.29	3.48	30	10.46	3.22	29	10.19	3.25	29	9.61	3.06
1500	47	16.94	3.33	48	15.69	3.02	45	15.29	3.14	47	14.41	2.84
2000	66	22.59	3.17	66	20.92	2.93	63	20.38	2.99	63	19.21	2.82
2500	86	28.23	3.04	87	26.15	2.81	84	25.48	2.81	84	24.01	2.64
3000	108	33.88	2.90	111	31.38	2.61	107	30.57	2.64	107	28.82	2.49
3500	134	39.52	2.73	136.5	36.61	2.47	131	35.67	2.52	131	33.62	2.37
4000	161	45.17	2.60	165	41.83	2.35	158	40.76	2.39	159	38.42	2.24
4500	188	50.81	2.50	193.5	47.06	2.24	186	45.86	2.28	186	43.22	2.15
5000	218	56.46	2.40	226.6	52.30	2.13	216	50.95	2.18	218	48.03	2.04

Table 3: Initial pressure drop vs. face velocity and permeability for different pleating densities.

Pleat density Total A_s (m^2) Q (m^3/h)	28A 23.9 A_{Eff}	30A 26.6 A_{Eff}	32A 27.3 A_{Eff}	34A 28.8 A_{Eff}
500	23.9	26.6	27.3	28.8
1000	23.9	23.9	26.6	24.8
1500	22.9	22.9	24.5	23.9
2000	21.7	22.1	22.8	22.8
2500	20.6	20.9	21.6	22.2
3000	19.4	19.9	20.5	20.5
3500	18.6	19.0	19.5	19.6
4000	17.7	18.1	18.5	18.8
4500	16.9	17.2	17.7	17.8
5000	16.2	16.5	16.9	16.9

Table 4: Effective area vs. different flow rates for different pleating densities.

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Filter	Horizontal pleat, A_s = 23.5 m^2				Vertical pleat, A_s = 24.4 m^2			
Flow rate (m^3/h)	ΔP (Pa)	MPPS (μm)	Fractional efficiency	Filter class achieved	ΔP (Pa)	MPPS (μm)	Fractional efficiency	Filter class achieved
500	14	0.18	97.94	H11	12	0.17	97.89	H11
1000	30	0.18	95.33	H11	28	0.17	95.19	H11
1500	49	0.14	93.30	H10	46	0.17	92.25	H10
2000	69	0.16	91.22	H10	67	0.15	91.29	H10
2500	92	0.14	90.56	H10	89	0.12	89.95	H10
3000	117	0.14	89.38	H10	113	0.14	88.02	H10
3500	143				139			
4000	172				166			
4500	202				195			
5000	236				227			
5500	270				256			
6000	306				295			

Table 5: Pressure drop and MPPS measurements for horizontal and vertical pleats filters.

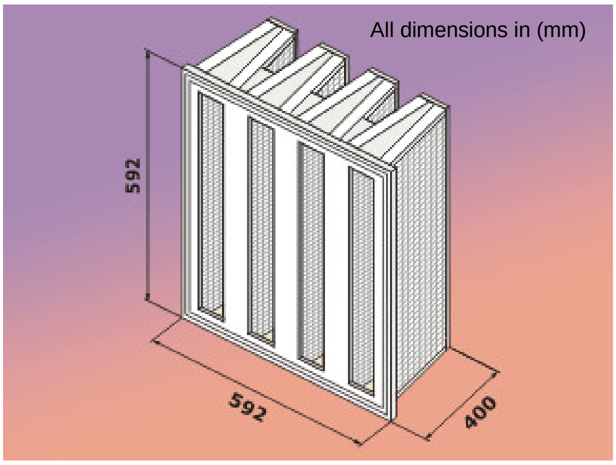

Figure 1: Pleated filter with the V shape design (EMW Filtertechnik).

Cite paper as: Al-Attar I.S., Wakeman R.J., Tarleton E.S. and Husain A., 2011. The effect of face velocity, pleat density and pleat orientation on the most penetrating particle size, pressure drop and fractional efficiency of HEPA filters, *Proc. Filtech Conference*, pp.318-329, Filtech Exhibitions, Wiesbaden, Germany.

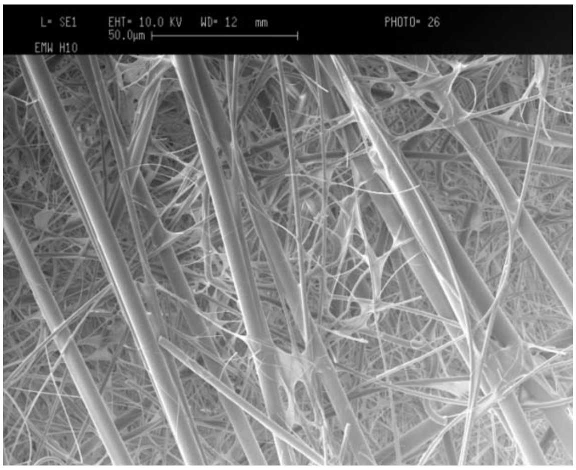

Figure 2: Image of the glass fibre HEPA filter medium (Class H10 according to DIN 1822).

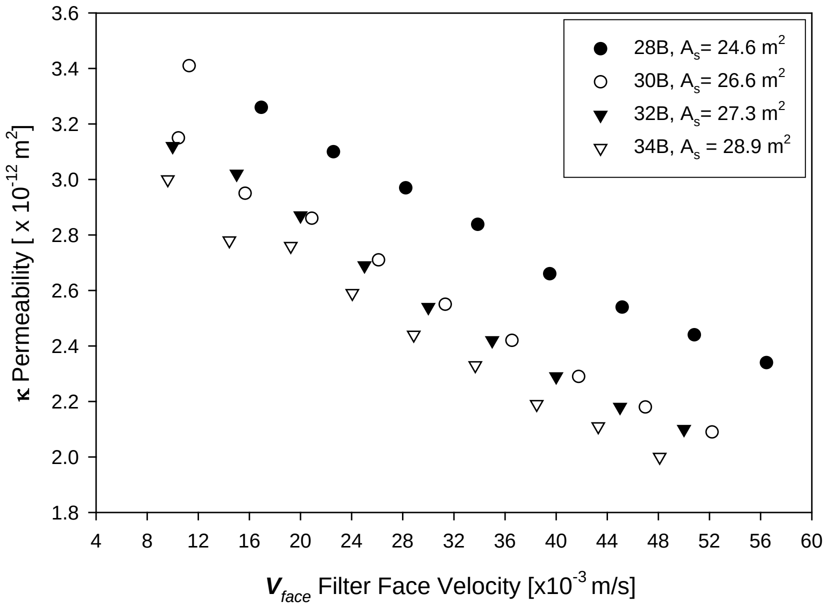

Figure 3: Permeability vs. face velocity for filters of Group B.

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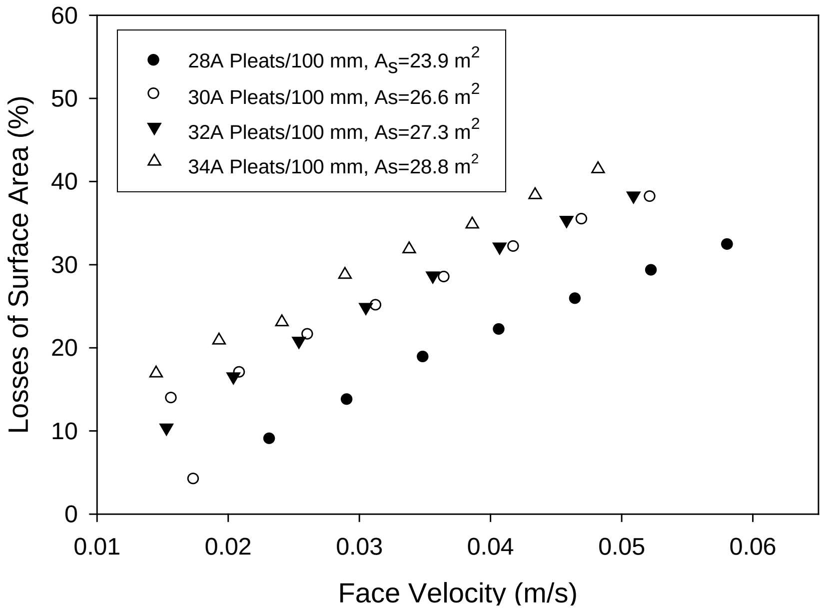

Figure 4: Loss of surface area for different pleating density filters at different face velocities.

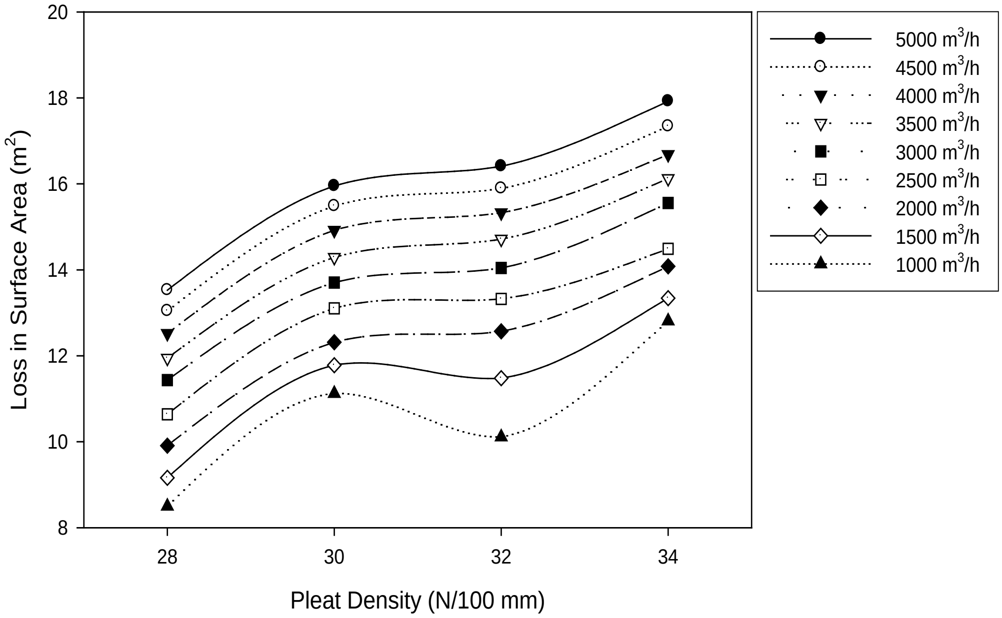

Figure 5: Loss of filter surface area for Group B vs. pleating density compared to the Darcy equation.

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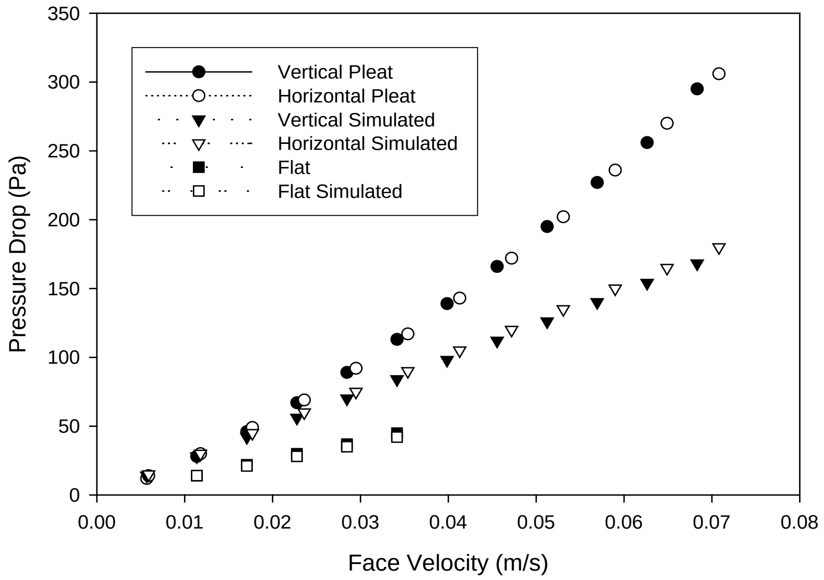

Figure 6: Comparison between simulated and experimental initial pressure drop for flat sheet, vertical and horizontal pleat filters at different face velocities.

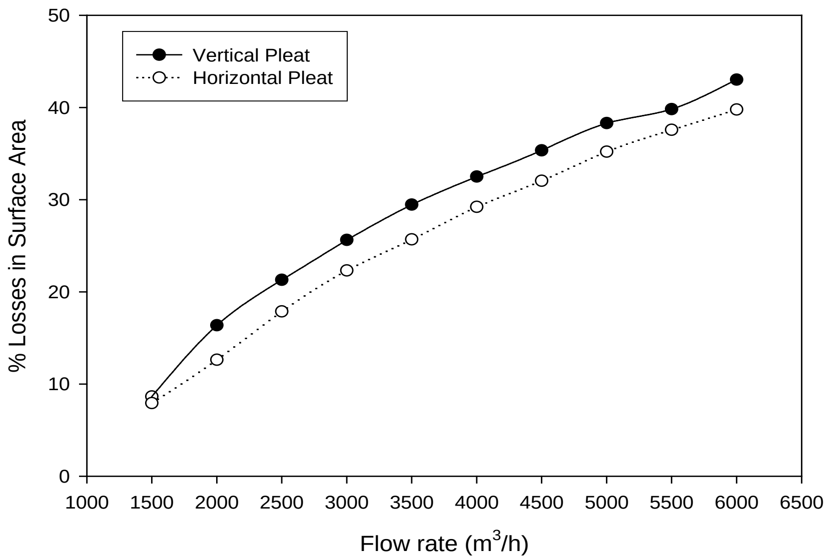

Figure 7: Surface area loss comparison between vertical and horizontal pleat filters at different flow rates.

Cite paper as: Al-Attar I.S., Wakeman R.J., Tarleton E.S. and Husain A., 2011. The effect of face velocity, pleat density and pleat orientation on the most penetrating particle size, pressure drop and fractional efficiency of HEPA filters, *Proc. Filtech Conference*, pp.318-329, Filtech Exhibitions, Wiesbaden, Germany.

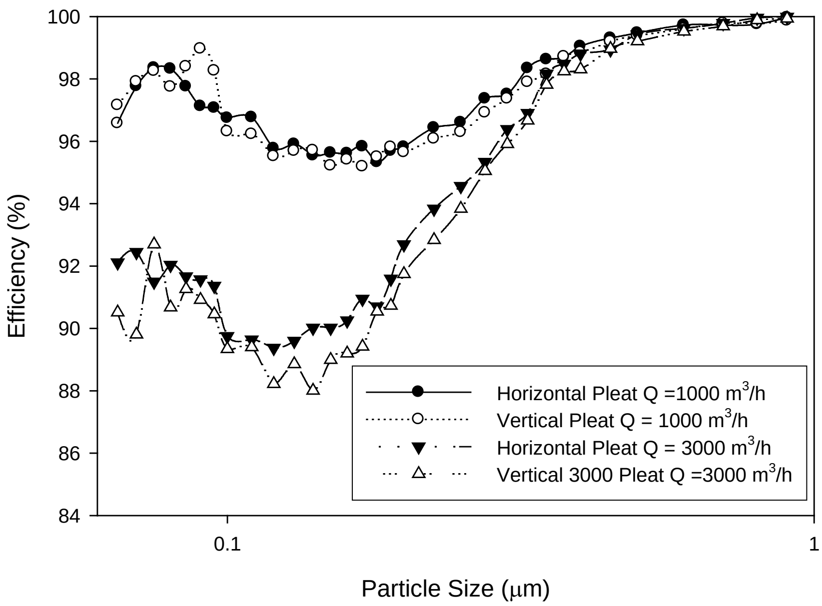

Figure 8: Initial efficiency for vertical and horizontal pleat orientation at different flow rates.

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