Computational Modeling of High-efficiency Air Filter media and Its Structural Design

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Abstract

For removing solid particles fibrous nonwoven filter media are widely utilized. For estimation of filter characteristics, the pressure drop and particle collection efficiency are used. To predict filter efficiency and pressure drop of high efficiency air filters, efficiency of a single fiber has been extensively investigated. The filter characteristics depend generally on the structure of the filter, operating conditions and characteristics of the filtration particles. However, the relationship between filter structures and their properties was not established clearly. In this study, several multi-layered filter media such as, meltblown and spunbond nonwovens were designed and the modeling of pressure drop and filter efficiency were developed with experimental values. As well as to investigate the filter characteristics of designed filter media, morphological structures were observed and air permeability, pore size, particle collection efficiency and pressure drop were measured experimentally.

Keywords : Air filter media; meltblown nonwoven; spunbond nonwoven; pressure drop; particle collection efficiency

1. Introduction

According to increase of industries, environmental purification requirements have become more and more important at the many industrial fields. Until now, high-performance gas filter media was mainly manufactured with glass fiber. But noxious dust in the air(fine dust, oil mist and fume) required to the gas filter media with high filter efficiency and low pressure drop [1]. For evaluation of characteristics of filters, the pressure drop and the particle collection efficiency were used. These parameters depend on the filter structure, operating conditions and characteristics of the aerosols filters [2]. To predict filter efficiency and pressure drop of filters, efficiency of a single fiber has been extensively investigated [3,4]. In these days, fibrous nonwoven filter media were used for removing filtration particles. Fibrous filters are used in various industries for dust collection and environmental protection [5]. Specially, meltblown nonwovens are highlighted material as the filter media caused by its net structure composed with fine fibers and fiber assembly structure with wide surface area. The meltblown nonwoven consists of fine fibers with 3~10 . Because of random arrangement structure, high chemical stability, high productivity and low manufacturing cost, meltblown nonwovens applied to the various fields [6,7]. Highly filtering efficiency and low pressure drop on the filtering material are the perfection that everybody tries to achieve [8]. For the performance improvement of meltblown nonwoven as the filter media, electric charging methods were widely used [9,11]. The electret filter is used to clean gas streams of dilute particle concentrations at low pressure drop and high efficiency [12]. Compared to the non-charged fiber, aerosol collection efficiency of the electret fiber can be significantly high. Therefore, electret filters are often employed to enhance the collection efficiency of HEPA and ULPA filters. Because of the Polypropylene (PP) has the lower surface tension than the other polymers, pressure drop were rarely occurred when it used to separate of gas or liquid particles [13].

A number of authors have been studying the clogging of filters with solid aerosols for many years. However, the role of the filter structure and property relationship with performance of the media has not established. In this study, a new model is developed to predict the filtration behavior of filter media. The experimental and theoretical values of characteristics of single-layered filter media were compared. And multi-layered filter media with PP meltblown and Polyethylene terephthalate (PET) spunbond nonwoven were designed. The morphological structures of filter media were observed. The air permeability and pore characteristic with structure and the pressure drop and filter efficiency with structure and flow rate of filter media were measured.

2. Previous study of filter media modeling

There are five basic mechanisms by which an aerosol particle can deposit on a neutral fiber [1]. These are interception, inertial impaction, Brownian diffusion, gravitational settling and electret force. The filter efficiency is the result of a combination of these mechanisms. The influence of the neighboring fibers in calculating single fiber efficiency was first taken into account by Kuwabara (1959) and Happel (1959). Kavies (1963), Juda and Chrosciel (1970), Bergman, Taylor and Miller (1978), Kanaoka and Hiragi (1980), Payatakes and Okuyama (1982) were developed a filtration models for pressure drop and filter efficiency. In this study, based on these previous studies the new model is developed with the following four assumptions ; 1) The spunbond and meltblown nonwoven webs exist on the circular cylinder fibers, 2) The fibers lie in the plane of web horizontally

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and do not bend at crossover sections, 3) All fibers in the filter media experience the same flow field and all fibers are perpendicular to the main flow direction, 4) Effects of particle characteristics on the pressure drop and filtration velocity on the filter efficiency are not take into account. In the usual filter, pressure drop and filter efficiency are the functions of fluid viscosity, filtration velocity, filter packing density, fiber diameter, filter thickness, packing density of collected particles and filtration particle diameter. Figure 1 shows the processing parameters and their symbols used in this study affecting on the pressure drop and filter efficiency of filter media. Figure 2 shows the schematic diagram of filtration model.

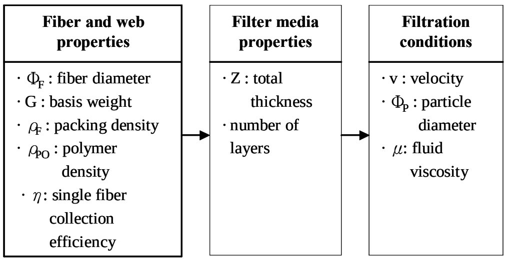


Figure 1. Processing parameters and their symbols affecting on the filtration characteristics of filter media.

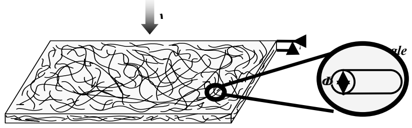


Figure 2. Schematic diagram of filtration model.

Thus, the new pressure drop and filter efficiency model in this study appeared equation (1) and (2), respectively.

$$\Delta P = a\mu v G \frac{\rho_F^{1/2}(1+b\rho_F^3)}{\rho_{PO}\cdot\phi_F^2} \quad \textbf{(Eq.1)}$$

$$E = 1-\exp\left[-\frac{cG\eta}{\rho_{PO}\cdot\phi_P(1-\rho_F)\pi}\right] \quad \textbf{(Eq.2)}$$

At the equation 1 and 2, used symbols appeared Figure 1 and a, b and c is constant number.

3. Structural design of filter media

Table 1. Characteristics of sample nonwovens.

Non -woven	Material	Bonding method	Symbol	Basis weight (gsm)	Fiber diameter ( )	Thick -ness (mm)
Melt-blown	PP	-	MB	14.47 ±2.02	2.29 ±0.81	0.184
			M1	25.14 ±2.35	6.21 ±2.12	0.254
			M2	38.24 ±3.45	7.48 ±2.59	0.289
Spun-bond	PET	Hot-air	S1	30.52 ±3.08	33.89 ±6.50	0.104
		Calen-dering	S2	92.37 ±3.37	30.40 ±2.97	0.304

Three kinds of meltblown and two kinds of spunbond nonwovens were used for media and substrate materials. Table 1 appears the basis characteristics of used nonwovens for computational modeling and structural design in this study. Table 2 shows the structural design conditions of filter media.

Table 2. Structural design conditions of filter media.

Number of layers	Composition	Sample ID
1 layer (S1 or S2 or M1 or M2)	S1	1
	S2	2
	M1	3
	M2	4
2 layer (S1 or S2 / M1 or M2)	S1M1	5
	S2M1	6
	S1M2	7
	S2M2	8
3 layer (S1 or S2 / M1 or M2 / S1 or S2)	S1M1S1	9
	S1M2S1	10
	S2M1S2	11
	S2M2S2	12
	S1M1S2	13
	S2M1S2	14
4 layer (S1 or S2 / M1 or M2 / M1 or M2 / S1 or S2)	S1M1M1S1	15
	S2M1M1S2	16
	S1M2M2S1	17
	S2M2M2S2	18
	S1M1M1S2	19
	S1M2M2S2	20
	S1M1M2S1	21
	S2M1M2S2	22
	S1M1M2S2	23
	S2M1M2S1	24

4. Experimental

4.1 Material and sample preparation

The used materials and the structural design composition appeared Table 1 and 2, respectively. The ultrasonic bonding method was used for 1~4 layered filter media bonding. To treat ultrasonic bonding the used pressure was 27.5psi and speed was 0.3m/min.

4.2 Morphological structure

The SEM(S-3200N, Hitachi) was used for the observation of morphological structures for designed filter media.

4.3 Air permeability and pore characteristics

The air permeability was measured by air permeability measuring unit(FX-3300, Textest) with KS K 0570(Frazier method). The sample size was 20 and used pressure was 125Pa. For measurement of the pore characteristics on the filter media, capillary flow analysis(CFP-1200-AEL, PMI) was used.

4.4 Pressure drop and filter efficiency

The filter efficiency measuring unit(model 8130, TSI) was used for pressure drop and filter efficiency of filter media. The sample size was 100 , the flow rates were 5~80L/min and NaCl was used as filtration aerosol.

5. Results and discussion

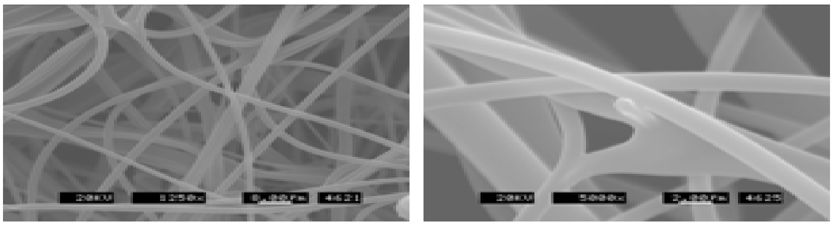
5.1 Morphological structure

5.1.1 Single layer

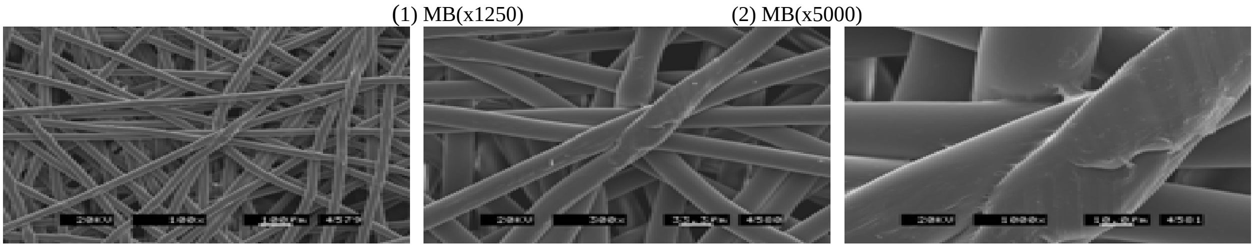
Figure 3 shows the morphological structures of sample nonwovens. As the Figure 3, surface of S2 sample has wider melting area than that of S1 sample. It depends on the different of bonding method. And the surface of fibers composed of S1 sample appeared the scratching forms by hot-air.

5.1.2 Multi-layer

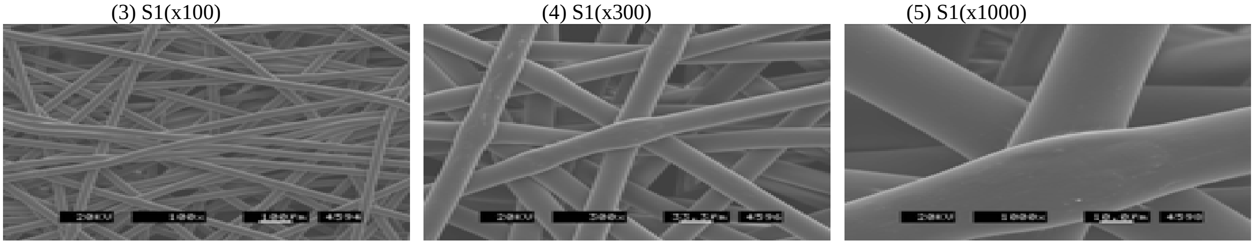
Figure 4 shows the cross-sectional structure of layered filter media. According to the SEM images, spunbond and meltblown nonwovens had the random fibrous structure.



(1) MB(x1250) (2) MB(x5000)

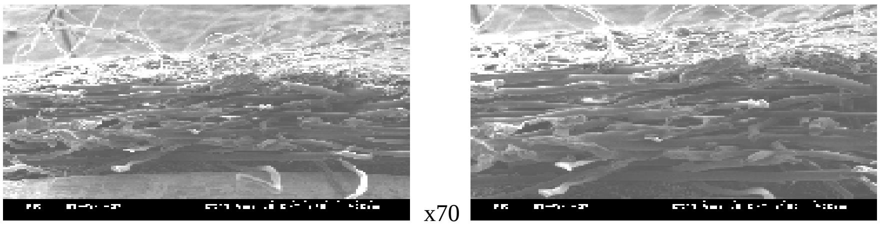


(3) S1(x100) (4) S1(x300) (5) S1(x1000)

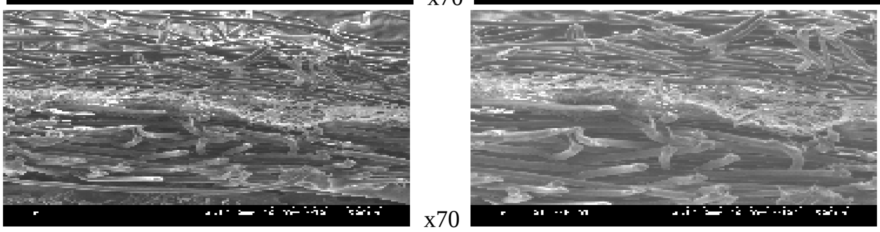


(6) S2(x100) (7) S2(x300) (8) S2(x1000)

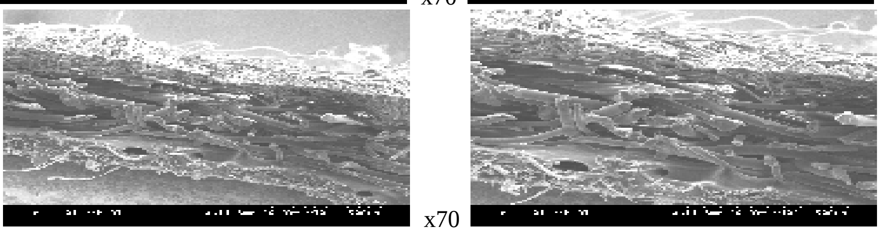
Figure 3. Morphological structure of single-layered filter media.



x70 x100 (1) 2 layer-SM



x70 x100 (2) 3 layer-SMS



x70 x100 (3) 3 layer-MSM

Figure 4. SEM images of designed filter media.

5.2 Air permeability and pore characteristics

5.2.1 Single layer

Figure 5 and 6 show the results of air permeability and pore size distribution of single-layered filter media. Among the three nonwovens, air permeability of S2 sample was the highest value. Minimum pore size of S1 was smaller than that of the S2. But, maximum pore size of S1 was lager than that of the S2 sample. These results appeared to non-uniformed distribution of fibers composed of S1.

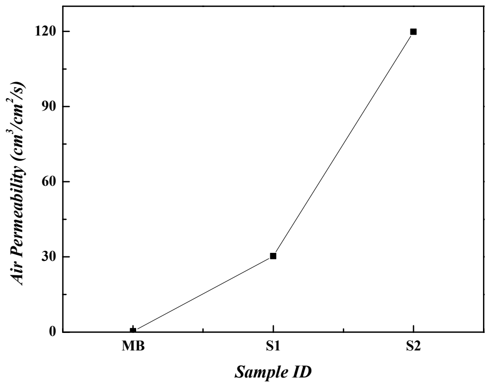


Figure 5. Air permeability of single-layered filter media.

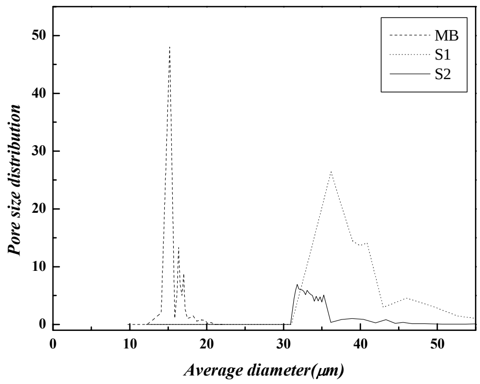


Figure 6. Pore size distribution of single-layered filter media.

5.2.2 Multi-layer

Figure 7 and 8 appear the measuring results of air permeability and pore size of designed filter media, respectively. Generally, the multi-layered filter media had the lower air permeability and the smaller pore size than those of single-layered filter media. When the sample 15 and 18 compared to each other, filter media used S2 had the higher air permeability and bigger pore size than those of S1 sample. Comparison of sample 21/22 and 23/24, the filter media used S1 spunbond nonwoven in top sheet had the lower air permeability than that of S2. According to these results, air permeability and pore size were significantly affected on nonwoven structure.

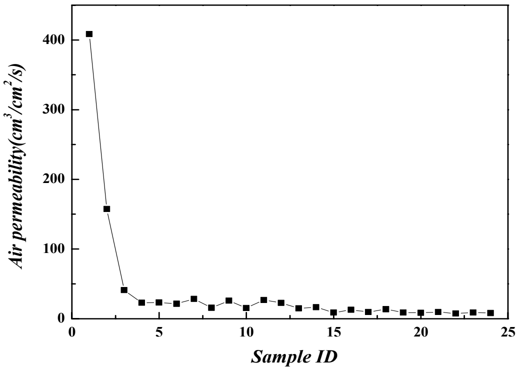


Figure 7. Air permeability of multi-layered filter media.

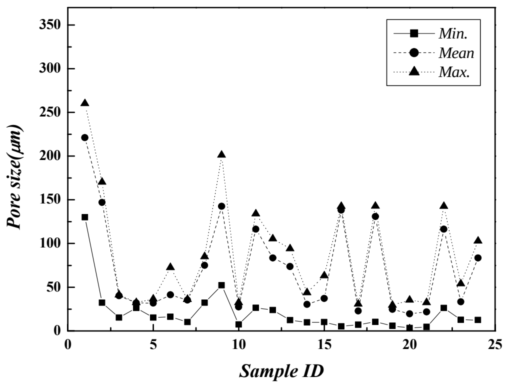


Figure 8. Pore characteristics of multi-layered filter media.

5.3 Pressure drop and filter efficiency

5.3.1 Single layer

Figure 9 appear the pressure drop and filter efficiency of single-layered filter media. As the filtration velocity increased, filter efficiency decreased and pressure drop increased.

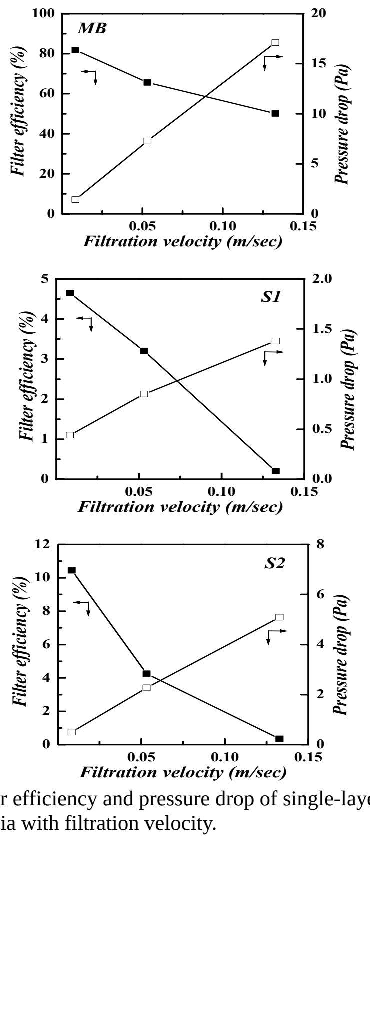


Figure 9. Filter efficiency and pressure drop of single-layered filter media with filtration velocity.

5.3.2 Multi-layer

Figure 10 and 11 shows the pressure drop and filter efficiency of designed filter media with different filtration velocity. When the filtration velocity increases, the pressure drop increases and filter efficiency decreases. The filter efficiency was not proportion to number of layers. It was affected on the characteristics of single layers. The filter media used spunbond nonwoven arranged to the top had the lower pressure drop and the higher filter efficiency than that of the filter media used meltblown nonwoven arranged to the top. According to the sample 21~24, when the filter media used to S1 as the top sheet, the lower pressure drop and the higher filter efficiency than that of the filter used to S2.

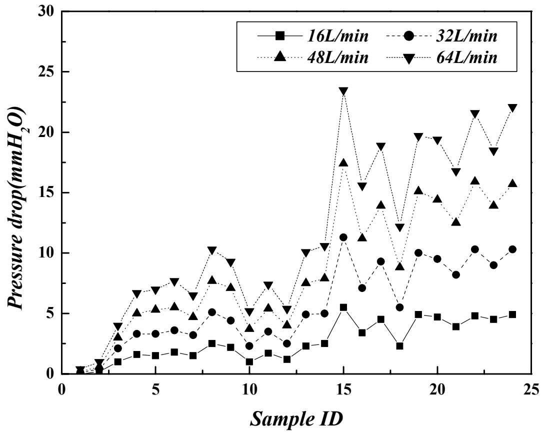


Figure 10. Pressure drop of designed multi-layered filter media for different filtration velocity.

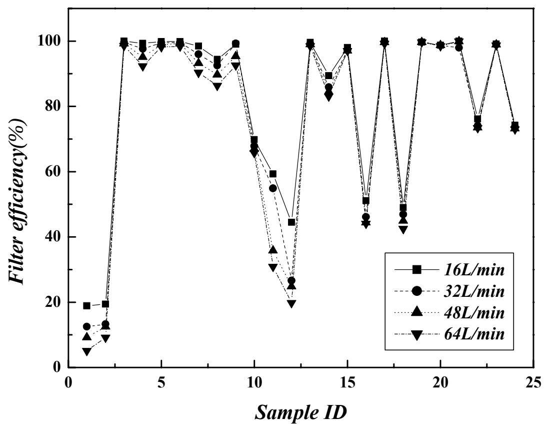


Figure 11. Filter efficiency of designed multi-layered filter media for different filtration velocity

5.4 Comparison of filter media characteristics of experimental and computational results

Table 3 shows the results of comparison of the pressure drop model with experimental results with filtration velocity. And Table 4 appears the comparison results of filter efficiency model and experimental values of single-layered filter media with different filtration velocity. According to these results, the new pressure drop on the filtration model was suitable for meltblown filter media. Generally, experimental values were larger than that of the theoretical value, because the particle characteristics were not considered with pressure drop model. At the fast filtration velocity, two values were similar to each other. From the results of comparison of filter efficiency modeling value and experimental value, filter efficiency increased with increasing particle size.

Table 3. Pressure drop values of theoretical experimental results for different filtration velocity.

Sample	Pressure drop(Pa) / v(L/min)	Theoretical value	Experimental value
MB	5	1.07	1.42
	32	6.84	7.29
	80	17.09	17.11
S1	5	0.03	0.44
	32	0.20	0.85
	80	0.50	1.38
S2	5	0.03	0.44
	32	0.20	0.85
	80	0.50	1.38

Table 4. Filter efficiency values of theoretical experimental results for different filtration velocity.

Sample	**MB**				**S1**				**S2**			
v(L/min) / Φp( )	**5**	**32**	**80**	**Theoretical value**	**5**	**32**	**80**	**Theoretical value**	**5**	**32**	**80**	**Theoretical value**
100	0.82	0.61	0.54	0.52	0.05	0.05	0.03	0.84	0.15	0.06	0.05	0.99
120	0.82	0.61	0.51	0.58	0.06	0.07	0.01	0.89	0.13	0.05	0.04	0.99
200	0.85	0.59	0.51	0.76	0.06	0.06	0.02	0.97	0.11	0.04	0.04	0.99
250	0.86	0.59	0.55	0.83	0.06	0.07	0.02	0.99	0.10	0.05	0.03	1.00
300	0.87	0.61	0.50	0.88	0.06	0.06	0.04	0.99	0.10	0.04	0.02	1.00
400	0.89	0.67	0.59	0.94	0.07	0.04	0.05	0.99	0.12	0.07	0.05	1.00
500	0.91	0.63	0.58	0.97	0.10	0.04	0.05	0.99	0.10	0.04	0.00	1.00
600	0.91	0.67	0.63	0.98	0.09	0.05	0.05	0.99	0.10	0.04	0.07	1.00

6. Conclusion

The new model of pressure drop and filter efficiency were proposed in this study and the modeling values were compared with experimental values. And 1~4 layered filter media were designed with meltblown and spunbond nonwovens. Among the single-layered nonwoven sample, spunbond nonwoven bonded by hot-air had the highest air permeability and widest pore size distribution. The pressure drop modeling value of meltblown nonwoven was similar to the experimental value. The experimental value was higher than that of the theoretical value.

From the results of comparison of filter efficiency modeling value and experimental value. As the particle size was increased, filter efficiency increased. According to the measuring results of air permeability and pore size of designed filter media, the multi-layered filter media had the lower air permeability and the smaller pore size than those of single-layered filter media. The air permeability and pore size were strongly affected on the used nonwoven structure.

At the comparison of single-layered filter media, as the filtration velocity was increased, filter efficiency decreased and pressure drop increased. In the case of the multi-layered filter media, as the filtration velocity is increase, the pressure drop increases and filter efficiency decreases. When the spunbond nonwoven, bonded by hot-air was used to substrate material, it had the higher air permeability and bigger pore size than those of the spunbond nonwoven bonded by calendaring. The filter efficiency was not proportion with the number of nonwoven layers. But it was significantly affected on the characteristics of the used nonwovens structure and lamination methods.

Acknowledgements

The research work is financially supported by Silver Star Co. (Project # 0401-DF1-0363)

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