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A comparison of filtration performance of triangular and circular cross-section fibre

Xiaolin Zhang & Xiangyu Jin[a]

College of Textiles, Donghua University, Shanghai, China

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Various filtering media, composed of different GSM of polyethylene terephthalate (PET) triangular and circular cross-section fibre nonwovens, have been selected to measure the filtration performance respectively. A middle-layer of polypropylene (PP) nonwoven material is added to form a three-layered sandwich composite PET/PP/PET filter. The fibre located in the upstream and downstream layers are triangular cross-section fibre, circular cross-section fibre and their mixture. The structure of materials including fibre fineness, thickness, pore size distribution and air permeability of webs has been studied in detail. The filtration efficiency and resistance of the filter materials are studied with NaCl aerosol particles in range of 0.3-3.0 μm at 32 L/min and 85 L/min flow rate. The results indicate that the filtration performance of triangular cross-section fibre is much superior than that of circular.

Keywords: Circular cross-section, Filtration performance, Polypropylene fibre, Polyester fibre, Triangular cross-section

1 Introduction

Air pollution is a worldwide challenge due to the ever-increasing industrial air emissions and the frequent sandstorm accidents, as well as automobile exhaust[1,2]. Particularly, particulate matter (PM) 2.5 (fine particles with a aerodynamic diameter < 2.5 μm) from air pollution was considered to be the major cause of adverse health effects ranging from the human respiratory tract to extrapulmonary organs[1, 3, 4]. Apparently, filtration has already been a kind of effective environmental management measure to separate various airborne particulate. To date, filtration materials include membranes[5,6], textile materials[7-9] and composite materials, etc. which are found beneficial to fight with PM 2.5. Nevertheless, textile materials are widely used because of highly

porous structure of woven and non-woven fabrics. Compared with woven fabrics filter medium, nonwoven materials have more interconnected pores and higher air permeability properties, making it a good candidate for filtration [7,8]

Pressure drop and filtration efficiency are the two mutual restrictive factors that affect filtration performance. For the problem, many groups have studied influences on filtering performance based on the characteristics of fibres including fineness[10,11], roughness[12], and cross-sectional shape. Payen *et al*.[13] focused on the influence of fibre fineness on filtration performance by mixing various fineness fibre. Wang *et al*.[14,15] pointed out that the incorporation of nano-particles, titania, silica enabled the fibrous membranes to increase filtration efficiency during electrostatic spinning. Heng *et al*.[16] studied the effect of structural characterisation on filtration performances utilizing PET-PA6 hollow segmented-pie bicomponents spunbond nonwovens and found that the filter consisting of fibres split into orange segment, hollow segmented-pie bicomponent, show superior filtration performance. Brownstein *et al*.[17] showed the filtering media possess high efficiency and low pressure drop using fibres with different length, gram per square

By going through the literature, it is found that (i) some studies focus on the theories of factors affecting filtration performance, (ii) compared to other filtering media, the strength and output of filters made of electrostatic spinning nanofibres are poor, and (iii) although the filtration efficiency of filters is high, the pressure drop is also high which is bad for respiration.

On view of above, this study focuses on the investigation of effect of fibre cross-section, triangular and circular cross-section on the filtration performance under the same conditions. To the best of

[a]Corresponding author.
E-mail: jinxy@dhu.edu.cn

our knowledge, this is probably the first attempt to discuss the fibre cross-section affecting filtration efficiency. A middle-layer of polypropylene (PP) nonwoven material was added to form a three-layered sandwich PET/PP/PET filter. The different gram per square meter (GSM) of upstream and downstream layers were made of circular cross-section fibre, triangular cross-section fibre and a mixture of them, that is C4-PET/PP/PET-C6, C4-PET/PP/PET-T6, T4-PET/PP/PET-T6, M4-PET/PP/PET-M6 (C4, C6– circular 40g/m^2, 60g/m^2; T4, T6– triangular 40g/m^2, 60g/m^2; M4– circular 20g/m^2 + triangular 20g/m^2; and M6– circular 30g/m^2 + triangular 30g/m^2).

2 Materials and Methods

2.1 Materials

Polypropylene (PP) of melt index 35 and polyethylene terephthalate (PET) of circular cross-section were provide by lab of Donghua University, Shanghai and PET with triangular cross-section was purchased from Huashun Co. Ltd, Zhejiang.

2.2 Sample Preparation

In order to obtain sandwich filtration materials, as shown in Fig. 1, PP melt-blown nonwoven materials (20 GSM) and PET of circular (40 GSM, 60 GSM) and triangular cross-section fibre (40 GSM, 60 GSM), combed into various GSM evenness webs, were needled in the nonwoven engineering center located at Donghua University. The upper layers act as a prefilter, in which the larger particles are intercepted and the smaller particles are trapped by the downstream-layer subsequently. The middle melt-blown layer provides the structural support and undertake some of filtering effect. Besides, the incorporation of PET outermost layers with the middle layer of PP reduce the damage from needle-punching.

As compared to PET webs of sandwich composite filtering medium, 20 GSM middle layer (PP) is much smaller, which aims to reduce the effect of PP on filtration performance. Upstream and downstream (layers 40 g/m^2 and 60 g/m^2) get sandwich composite filters without large pressure drop and show a change in filtration performance with cross-section, triangular and circular cross-sections.

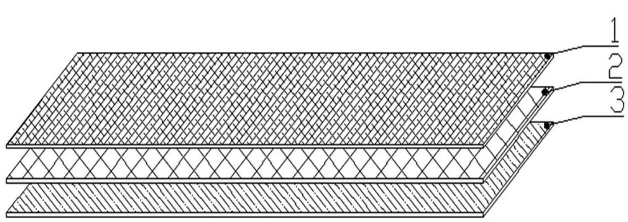

Fig.1 — Sketch of filter media [1, 2 and 3 are fabric layers]

2.3 Characterizations

The cross-section and diameter of PET circular and triangular fibres were measured by a scanning electron microscope (SEM, FEI Quanta-200, FEI CO.). The thickness of various filter materials was surveyed with YG141N digital fabric thickness gauge in accordance with GB/T3820-1997 standard. The air permeability of filter medium was determined with the numerical air permeability tester (YG461E) under a pressure drop of 100 Pa.

The pore diameter and distribution were examined by the pore size analyzer PMI CFP-1100AI; the highest frequency aperture as the effective pore size. The filtration resistance and efficiency of filter medium were measured by LZC-K_1 device in the 100 cm^2 test area at a flow rate of 85 L/min with the NaCl aerosol particles of various sizes ranging from 0.3 μm to 3.0 μm in accordance with GB/19083-2010 standards.

3 Results and Discussion

3.1 Fibre Diameter

The representative SEM images of PET circular and triangular cross-section fibre are shown in Figs 2 (a) and (b). As shown in Figs 2 (c) and (d), it is exhibited that both of fibre have a uniform distribution, though distribution of circular fibre deviates slightly from a normal distribution curve. The mean diameter of circular fibre is 14.6465 μm, which exhibits a standard deviation of 0.7996 μm. It is also shown that the maximum and minimum of circular fiber are 15.77 μm and 12.73 μm in diameter respectively. Triangular fibre with a mean fiber diameter being 14.787 μm shows a standard deviation of 1.04388 μm. Triangular fibre diameters with maximum and minimum of 16.19 μm and 12.46 μm are calculated from Fig.2 respectively. Based on the above data, it could be found that the diameter of both fibre is nearly equal, which is beneficial to further analysis in later research.

3.2 Thickness

It is well known that thickness has a significant impact on filtration performance. Thickness could be used to infer whether the incorporation of PET webs has greatly improved filtering efficiency or not as

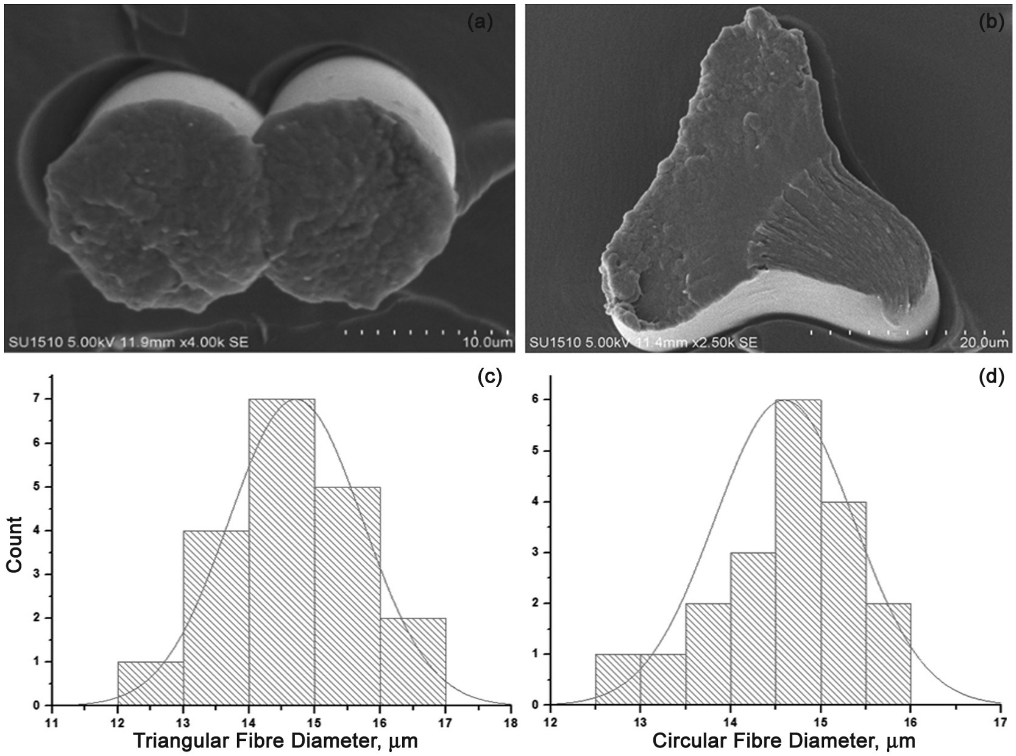

Fig.2 — SEM images of (a) PET circular fibre (×4000) & (b) PET triangular fibre (×2500); and fibre distribution graphs of (c) PET circular fibre & (d) triangular fibre

compared to polypropylene. It can also compare filtration efficiency of filter materials consisting of triangular fibre with circular ones.

As shown in Table 1, the thickness of PP with minimum is 1.198 mm and that of C4-PET/PP/PET-C6 with maximum is 1.7516 mm. The mean thicl ss of T4-PET/PP/PET-T6, C4-PET/PP/PET-T6 ıd M4-PET/PP/PET-M6 are 1.7512 mm, 1.751 mm and 1.7514 mm respectively, implying that the thickness of four kinds of composite filter materials is almost the same, which is beneficial for discussing the effect of fibre cross-section, triangular and circular cross-section on the filtration performance. In addition, it is also observed that the thickness of composite filter show just a bit improvement than that of PP melt-blown materials, which indicates that the incorporation of PET webs results in a great enhancement of filtration performance of composite filter media as compared to polypropylene. It can also be demonstrated that the filtering part of sandwich composite filtration materials may be divided into PP melt-blown nonwovens and PET webs, which is conducive for analyzing the effect of fibre cross-section, triangular and circular cross-section on the filtration performance.

Table 1 — Thickness of various filter materials

Thickness mm	C4-PET/PP/PET-C6	M4-PET/PP/PET-M6	C4-PET/PP/PET-T6	T4-PET/PP/PET-T6	PP
1	1.832	1.827	1.821	1.822	1.219
2	1.803	1.797	1.727	1.791	1.214
3	1.662	1.639	1.701	1.692	1.120
4	1.752	1.749	1.742	1.720	1.216
5	1.709	1.745	1.764	1.731	1.221
Average	1.7516	1.7514	1.751	1.7512	1.198

3.3 Air Permeability

Air permeability is usually used to evaluate the packing density of the webs, which significantly relates to filtration resistance. As shown (Table 2), the air permeability of the filter medium consisting of triangular fibre is higher than that of circular fibre using the same fineness and thickness, which is attributed to the larger specific surface of triangular fibre. Considering the average values of air permeability (Table 2), T4-PET/PP/-PET-T6 possesses the highest air permeability with maximum 431.36 L*s/m^2, and on the contrary C4-PET/PP/-PET-C6 shows the smallest as permeability with minimum 293.88 L*s/m^2, implying that the air permeability of filter increases with the increase in content of

Table 2 — Air permeability of various filter nonwoven materials

Air permeability, L*s/m^2	C4-PET/PP/-PET-C6	M4-PET/PP/PET-M6	C4-PET/PP/PET-T6	T4-PET/PP/-PET-T6
1	307.00	302.46	353.34	407.97
2	284.35	327.81	380.36	451.22
3	290.28	320.92	375.24	434.88
Average	293.88	317.06	369.65	431.36

triangular fibre within certain limits. It is found that the air permeability of triangular fibre is higher, due to the larger specific surface; as evident in the following model analysis. In addition, fibre with triangular cross-section having a smaller packing density is conducive to airflow permeation. It is expected that the higher air permeability is desirable in filtration as it is inversely proportional to resistance, which is discussed in the following analysis of filtration resistance.

3.4 Comparison of Specific Surface of Triangular and Circular Fibres

To further prove that the triangular fibre own larger specific surface than that of circular fibre, the specific surface (α) is calculated. In addition, different cross-section shapes numerially are represented by their shape factor (SF)[18]. SF is basically a geometrical parameter that relates a closed curve path to its equivalent circle perimeter to express the irregularity of cross-section[19]. Shape factor of any cross-section shape is determined as SF=1/α, where α is represented by S and V ($\alpha=S/V$); where S and V denote the values of superficial area and volume of fibre respectively. According to the α equation, the value of α increases with the increase of superficial area (S) under the same volume (V) conditions.

It is worth to point out that simple circular and triangular fibres could be considered as a cylinder and triangular prism respectively, which are used to calculate the specific surface of single fibre. Superficial area (S) is compared between triangular and circular fibre under the same volume (V), implying that the specific surface (α) wholly shifts towards higher value with the increase in superficial area(S).

In order to evaluate the specific surface (α), the parameters (V_c, V_t) are defined as follows:

$$V_c = \pi r^2 L;\ V_t = \frac{\sqrt{3}}{4} a^2 L$$

where V_c and V_t are the same volume of circular and triangular fibre respectively; L denotes both fibres length with the same value (the height of cylinder and triangular prism); r is radius of circular fibre cross-section; and a indicates the length of triangle sides for triangular fibre cross-section.

For convenient calculation, r and L are assigned the value of 1, that is r = 1; L = 1; according to V_c equation, the value of V_c is equal to π, suggesting $V_t=\pi$. Apparently, $a=\sqrt{\frac{4\pi}{\sqrt{3}}}$ by V_t equation. It has been widely accepted that the superficial area (S_c) of a cylinder is equivalent to $2\pi rL$ and that of triangular prism is $3aL$, that is $S_c=2\pi rL$, $S_t = 3aL$.

Substitute the values of r, a and L into the equations respectively. Then the results exhibit that S_t with value being about 8.08 is bigger than that of S_c with value being 6.28; that is,

$$S_c=2\pi rL=6.28; \text{ and } S_t=3aL=8.08$$

Based on above data analysis, it can be found that the specific surface of triangular fibre is indeed larger than that of circular fibre as calculated from this mathematical model. In addition, it agrees well with the test that the larger the specific surface (α), the better is the air permeability of material.

3.5 Pore Size and Distribution

The measurement of pore size distribution for PP melt-blown felt does not help in studying the effect of the fibre cross-section on the filtration performance. PP melt-blown felt exhibits a narrower pore size distribution after acupuncture which is beneficial for filtering in this study.

It is worth to point out that smaller pore size distribution is propitious to filter. For the sandwich structure composite filter used in this work, the pore size of the fluffy web located in the outermost layers of filter medium is ignored because of shaggy structure. Thus, the pore size distribution of filter medium is assessed by the middle layer PP.

As shown in Fig 3, the mean pore size is 38.0057 µm and 25.2336 µm for the PP nonwoven material before and after acupuncture respectively. The standard deviation of pore size is found to be 44.3273 and 37.0427 for PP before and after acupuncture respectively. The pore size distribution for PP before needling has a wider range with the minimum pore size being 10.3383 μm and larger pore size being 94.0206 μm. The PP nonwoven material with acupuncture shows a narrower pore size of 10.106 μm and 75.6572 μm for minimum and maximum pore size respectively. Apparently, it is demonstrated that PP nonwoven material possesses smaller pores and smaller pore size distribution range after needling, which are beneficial to high filtration performance.

3.6 Filtration Efficiency and Resistance

It is well known that filtration efficiency and resistance are the most important factors for filter medium. The filtration efficiency is defined as the ratio of the amount of dust trapped to original dust concentration, the pressure drop is used to evaluate the resistance of air flow through filter media.

As indicated in Fig. 4, M4-PET/PP/PET-M6 nonwoven filter medium has the best filtration efficiency for various sizes of NaCl aerosol particles, with the maximum 42.5% and 98.78% for 0.3 μm and 2.5 μm size particles respectively. Filtration resistance of the filter is lower than 55 Pa (Fig 5). The filtration efficiency of T4-PET/PP/PET-T6 sample is found to be 36.88% for 0.3 μm size particles and the filtering efficiency is 98.62% for 2.5 μm size particles. T4-PET/PP/PET-T6 filter possesses superior filtration efficiency for multifarious sizes of the NaCl aerosol particles and with smaller filtration resistance of 15.5 Pa and 39 Pa at 32 L/min and 85 L/min flow rate respectively, which could be deemed to be a better filter media. Although, the filtering efficiency of C4-PET/PP/PET-C6 does not appear to be much different from others, the pressure drop of 21 Pa and 58 Pa is the highest among them for diverse sizes of the NaCl aerosol particles at flow rate 32 L/min and 85 L/min respectively. Compared to other composite filters, C4-PET/PP/PET-T6 has the lowest filtering efficiency, but shows a lower filtration resistance. For the single filters of PP and PET, PET shows the minimum filtration efficiency and resistance for all sizes of particle at flow rate 32 L/min and 85 L/min that leads to no further analysis of quality factor. As demonstrated in Figs 4 (a) and (b), the single PP filter has a lower value of filtering efficiency. The pressure drop assigned to PP filter are 21 Pa and 53 Pa.

Based on above data analysis, it is shown that the incorporation of triangular fiber mostly result in a bit enhancement of filtering efficiency of filter media, which is mainly attributed to the change of airflow channel caused by tortuous structure of triangular fiber. The internal structure of triangular fibre is beneficial for holding up the airborne particulate but hinder airflow from moving ahead. Furthermore, as stated previously the filter medium composed of triangular fibres own higher specific surface, which results in more robust particle capture.

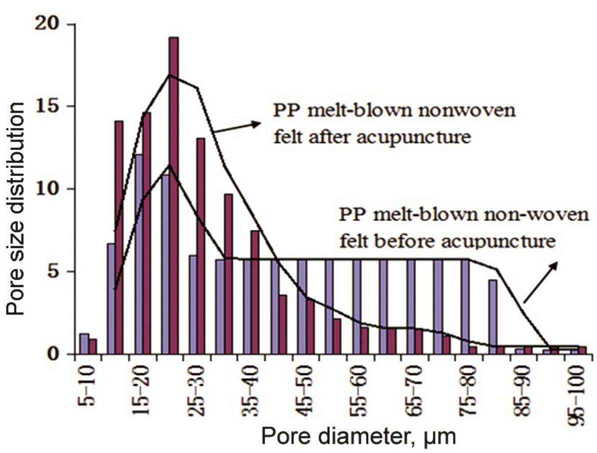

Fig.3 — Pore size distribution of PP melt blown nonwoven felt before and after acupuncture

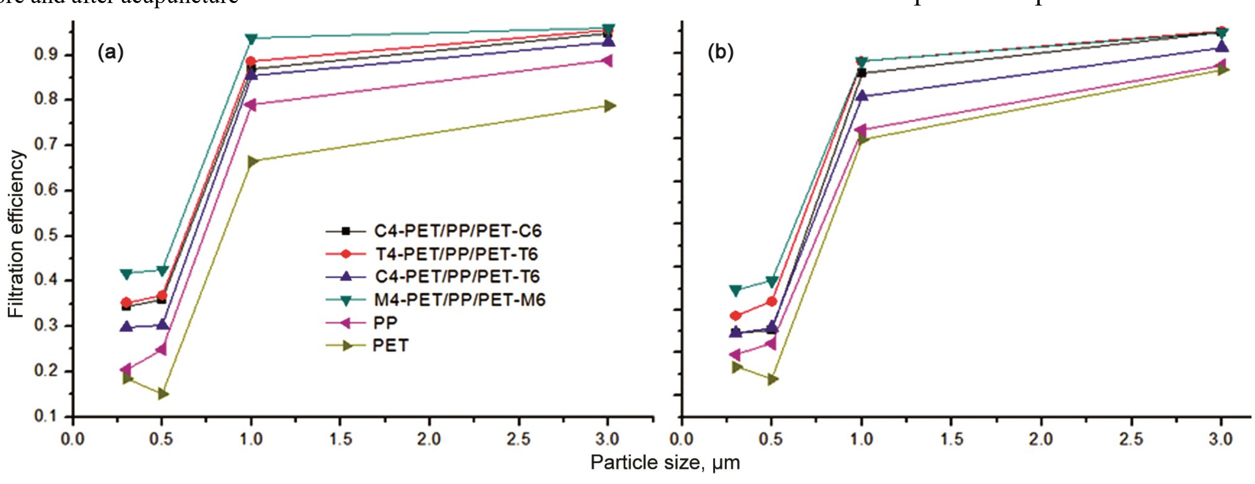

Fig.4 — Filtration efficiency for various filters at flow rate 32 L/min (a), and 85 L/min (b)

According to above analysis, it could be found that filtering efficiency of composite filter materials composed of triangular fibres shows just a little enhancement than that of circular fibre. But the filter medium consisting of triangular fibres shows lower pressure drop that accords with air permeability analysis. Thus, it is worth to point out that the filtration performance of filter medium cannot be characterized well merely in virtue of filtering efficiency or resistance instead of considering both them.

3.7 Quality Factor

To further characterize the filtering property of filter medium, the quality factor (Q) is calculated, as shown below:

$$Q = \frac{-\ln(1-y)}{p}$$

where y and p denote the average values of filtration efficiency and pressure drop of the filter respectively.

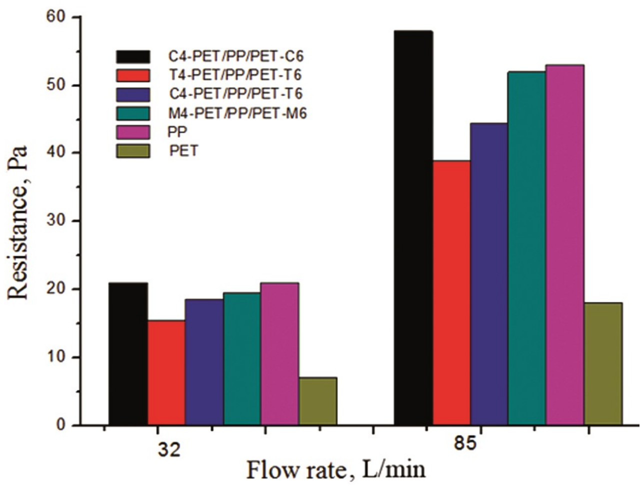

Fig.5 — Filtration resistance for various nonwoven filtering materials

The equation shows that the Q increases with the increase in filtration efficiency and decrease in pressure drop of filter. In addition, the quantity of Q is unit-less and determines the filtration performance of the filter media. It has been widely accepted that the larger the Q value, the better is the filtration efficiency of filter material.

The results of quality factor (Q) for filters are displayed in Figs 6(a) and (b). The Q factor shows that despite the sample C4-PET/PP/PET-C6 has a better filtration efficiency than C4-PET/PP/PET-T6, the filtering performance is still lower compared to C4-PET/PP/PET-T6. This is because, a good filter medium is not only evaluated by the filtering efficiency but also by the filtration resistance. As compared to M4-PET/PP/PET-M6 filter, the filtration efficiency of T4-PET/PP/PET-T6 sample is lower when the face velocity is 32 L/min and 85 L/min for various sizes of the NaCl aerosol particle, but it shows a considerable increase in Q factor (0.03), indicating the better filtration performance. For the filtering efficiency, as compared to the filter media consisting of circular fibre, the filter consisting of triangular fibre shows a slight improvement. But in terms of Q factor, filter medium composed of triangular fibre shows a great enhancement than that of circular fibre. The Q factor for PP filter medium exhibits the lowest value. The Q factors of M4-PET/PP/PET-M6, C4-PET/PP/PET-T6 and T4-PET/PP/PET-T6 filter are higher (0.001-0.05) than that of C4-PET/PP/PET-C6. Other conditions being equal, the filtration performance of filter medium composed of triangular fibre is better than that of circular fibre. As the Q equation expressed, it could be obviously observed that the higher Q factor requires better filtration efficiency and lower pressure drop. Finally, the filter

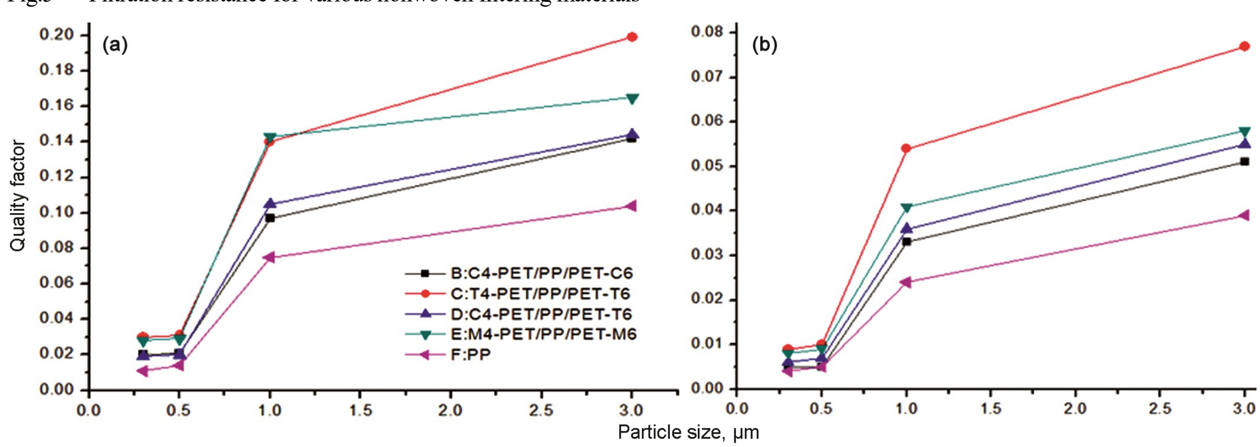

Fig.6 — Quality factor for various filters at flow rate 32 L/min (a), and 85 L/min (b)

medium consisting of triangular fibre has been studied for a better filtration material.

Filtration involves the combination of various mechanisms. Each filter medium combines diverse mechanisms to efficiently remove disparate particle sizes. Filtration mechanisms include: inertial impaction, interception and diffusion[20]. Inertial impaction works on particles of 1-10 μm suspended in the flow stream. Due to its inertia, heavy particles continued in the original direction and collides with the filter medium where it is trapped and held. Direct interception occurs when the particles, having a size range from 0.3 μm to 1 μm, follow the airflow around the filter but are intercepted by the filter media, because of the dimension of the particle being larger than the distance between the fibre and airflow path followed by particle. The particles are held to the filter medium by a molecular surface attraction known as Van der Waals' forces. Particles of less than 0.3 μm are not held in place by the viscous fluid and diffuse within the air stream. As the particles are traveling in the flow stream, they collide with the filter media and are arrested. Considering the characteristic of filter medium made of triangular fibre fabricated and tested in this research work, it can be concluded that the filter media composed of triangular fibres can be used as ULPA filter, if the efficiency has been improved.

Compared with other filters, the filtration efficiency of the sandwich composite filter materials is not particularly high. However, the study aims to illustrate the more robust filtration performance of triangular fibres than that of circular. Based on this study, discussed how to improve filtration efficiency without increasing resistance for various cross-section shapes fibre and what functions are going to endow with filters would be developed in my future work.

4 Conclusion

The filtration performance and the feasibility for air filter which were produced by triangular and circular fibre based on the needling reinforcement in high efficiency filtration were investigated. According to the results obtained in this work, it is concluded that the sandwich composite filtering materials composed of triangular fibres exhibit more robust filtration performance than that of circular, as evidenced from the larger quality factors.

The filtration efficiency of T4-PET/PP/PET-T6 filter with the pressure drop of 39 Pa, is 94.9717% for 2.5 μm particles at 85 L/min flow rate. Under the above test condition, filtering resistance is 58 Pa and 39 Pa for T4-PET/PP/PET-T6 and C4-PET/PP/PET-C6 respectively. The graphs display the quality factors of T4-PET/PP/PET-T6 filter with the maximum 0.077 and C4-PET/PP/PET-C6 filter with the minimum 0.051. Although the filtration efficiency of C4-PET/PP/PET-C6 is nearly equal to others, the pressure drop is higher than others and, on the contrary, Q factor of filter consisting of triangular fibres is larger. Apparently, for all the composite filters, the Q factors completely shift towards higher value with the increase in content of triangular fibre. Based on the above analysis, it could deduce that the filtration performance of filter medium composed of triangular fibre is superior than that of circular fibre.

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