Manufacturing and Properties of the Fibrous/Aluminum Foil Thermal Insulation Composite

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Abstract

Heat energy is essential in the human's life, and it is an important resource in the economical and social development. In this study, the fire-retardant fibrous materials (FR-FTI) were prepared by the fire-retardant polyester fibers (FRPF) and the low melting point polyester fibers (low-T_m fibers). The linear-density of the FRPF, the layers of the loose nonwoven and the low-T_m fiber content were changed in the preparation of the FR-FTI. The thermal conductivity of the FR-FTI, tensile strength and the LOI was evaluated to study the processing parameters on the properties of the FR-FTI. Besides, the aluminum foils were placed between the loose nonwoven of the FR-FTI to prepare the FR-FTI/A. the thermal conductivity of the FR-FTI was estimated to study the influence of the addition of the aluminum foils on the thermal transfer ability of the composites. The results showed that the effect of the low-Tm fiber content was interacted with the effect of the layer number of the loose nonwoven on the thermal conductivity of the FR-FTI.

Keywords: aluminum foil, nonwoven, fire-retardant, Polyester fiber

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1. Introduction

Technological advances in the textile industry have resulted in an ongoing demand for cost-effective processing techniques and textiles. In the past 40 years, nonwoven techniques and products have been developing and growing at a phenomenal rate, corresponding to such a demand [1,2]. Among the applications of textiles, nonwovens are one of the fastest-growing segments of the textile industry and constitute roughly one-third of the fiber industry [3].

Fire-retardant polyester fibers (FRPF), which are hollow and with a 3 dimension-crimp (3d-crimp) shape are regularly used as the stuff in the bedquilt, pillow and loose coat to substitute the natural fibers. The products of the FRPF could retard the air to convect in the hollow core structure of the fibers, and retain the original structure by the elastic 3d-crimp structure of the fibers.

Aluminum sheets with a thickness below 200 μm are described as foils. There are many applications of foils such as: thermal insulations, fin stocks, honeycombs, electrical coils, capacitors, transformers, cable foils, semi-rigid containers, caps, closures, pouches, bags, wraps, peel-off lids, household foils, lithographic plates, decorative products, etc. [4].

Heat energy is an essential resource in industry. As a least cost energy strategy, conservation should be supported in the energy for the future. Thermal insulation has wide applications in engineering. The primary function of thermal insulation is to reduce heat transfer between a system and its environments [5]. Thermal insulation is a major contributor and obvious practical and logical first step towards achieving energy efficiency especially in industrial application. It retards the rate of heat flow by conduction, convection, and radiation, and retards heat flow into or out of the thermal transfer mechanism due to its high thermal resistance [6].

In this study, the FRPF were mixed with the low melting point polyester fibers (low-T_m fibers) to prepare the fire retardant fibrous thermal insulation composite (FR-FTI) by the nonwoven manufacturing process. The reinforcement condition of FR-FTI and the efficiency of thermal transfer were estimated by the tensile strength and the thermal conductivity, respectively. The LOI of the FR-FTI was measured to estimate the fire-retardant property of the FR-FTI. Besides, the aluminum foil was placed between the FR-FTI and formed by the thermal plate pressing to evaluate the thermal retarding property of the aluminum foil in the FR-FTI.

2. Experimental

The fire retardant polyester fibers (FRPF), which are hollow and with a 3d-crimp shape, staple length of 51 mm and the fineness of 7.78 dtex and 13.33 dtex were used to be the main raw. The low melting point polyester staple fibers (low-T_m fibers) were blended with the FR-hollow 3d-crimp PET fibers at different weight ratio 10 %, 20 %, 30 %, 40 % and 50 %. The blended fibers were opened, carded, lapped and pre-pressed by the thermal calender to prepare the loose nonwoven. Moreover, 1, 2, 3, 4 and 5 layers of loose nonwovens were thermal plate pressed to form the FR-FTI at 180 °C for 6 min, and the thickness of FT-FTI was fixed at 10 mm by the 10 mm thickness of the spacer of iron bar in the thermal plate pressing. The density of FR-FTI were 0.023, 0.046, 0.069, 0.092 and 0.115 g/cm^3 respectively when the loose nonwovens were 1, 2, 3, 4 and 5 layers. Besides, the aluminum foil was placed between each layer of the loose nonwoven and thermal plate pressed at 180 °C for 6 min to prepare the FT-FTI/Aluminum foil composite (FR-FTI/A). The illustration of the composition of the FR-FTI and FR-FTI/A are shown *in Fig. 2* and *Fig. 3* separately.

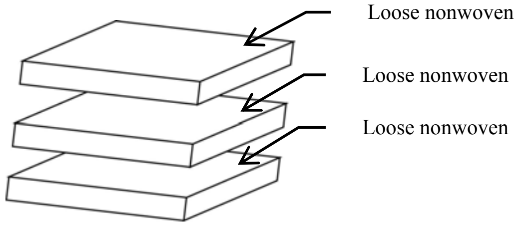

Fig. 2 Composition of FR-FTI

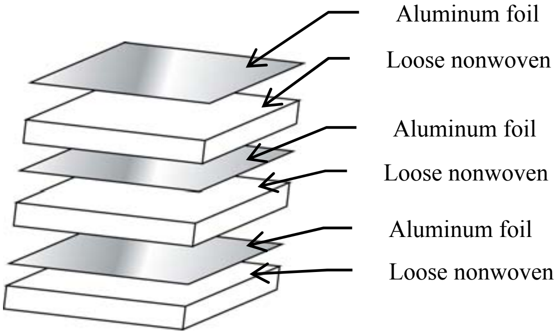

Fig. 3 Composition of FR-FTI/A

In this study, the tensile strength of the FR-FTI and FR-FTI/A was tested by the Instron 5566 material testing machine according to the ASTM D5035 standard. The samples with the dimensions of 25.4 mm × 180 mm were employed in the machine direction (MD) and the cross direction (CD) separately. The results of the tensile strength were obtained by averaging the values of at least six specimens. The extension rate of clamp was fixed at 300 mm/min; the gauge length of the clamps was set at 75 ± 1 mm.

The thermal conductivities of the specimens with dimensions of width 200 mm, length 200 mm and thickness 10 mm were evaluated by DYNATECH (UK) Guarded-Hot-Plate apparatus (TCFGM), according to ASTM C177. Two specimens were fixed between the plates at both sides. The hot plates were heated directly via electrical resistance and ramped to 60 °C. Water flow was infused into the cooling plates and was controlled by the flow rate of 2.3~5 ml/s for cooling. The specimens were maintained to be heated till the difference of the flowing out water temperature was less than 0.1 °C during 30 min. The data were gathered to evaluate the thermal conductivity of the specimens. The schematic of the Guarded-Hot-Plate Apparatus is shown in *Fig. 4*.

The limiting oxygen index test was performed by the specimens with dimensions of width 6.5 mm, length 150 mm and thickness 10 mm. The specimens were tested by Dynisco (USA) Limiting Oxygen Index analyzer, according to ASTM D2863. The flow velocity of gas in the chamber was set at 4 cm/s; the gas was flowed into the chamber for 30 seconds to purge the system before each test of specimen.

The scanning electron microscopy was used to observe the microscopic structure of the FR-FTI. The specimens were coated with gold layer for 30 seconds and were examined by HITACHI (Japan) S-3000 scanning electron microscopy.

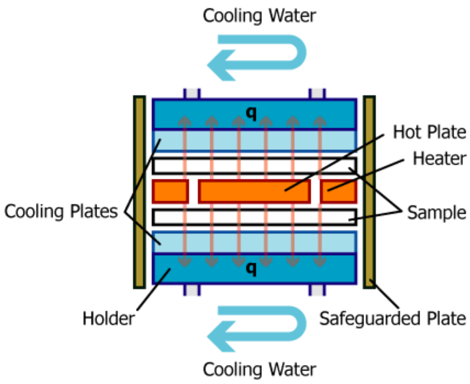

Fig 4 Schematic diagram of Guarded-Hot-Plate Apparatus

3. Results and discussion

3.1 Tensile Strength of the FR-FTI

The results listed in *Table 1*, are the tensile strength of FR-FTI with various content of low-T_m fiber and various layer number of the loose nonwoven when the linear-density of FRPF was 7.78 dtex, the tensile strength of the composites in CD was higher than that in the MD. The larger tensile strength occurred in the CD, because the CD was the primary orientation of arrangement of the fibers on the nonwoven web. The tensile strength of the FR-FTI was raised when the low-T_m fiber content increased. The maximum tensile strength was obtained when the 50 % weight ratio of low-T_m fiber was added, because the FRPF was bonded by the melted low-T_m fibers and the strength of the low-T_m fibers were larger than that the strength of the FRPF. Hence, the tensile strength of the composites increased when low-T_m fiber content increased till 50 %.

Table 1 Tensile strength of FR-FTI with various content of low-T_m fiber and various layer number of loose nonwoven when linear-density of FRPF was 7.78 dtex

Low-T_m fiber content (%)	Layer number of loose nonwoven (layer)					
	CD			MD		
	1	3	5	1	3	5
10	92.93	225.70	334.66	65.36	146.04	230.80
20	129.98	345.08	557.86	83.64	201.60	325.79
30	169.29	466.81	827.11	106.73	284.50	513.38
40	206.54	559.49	1061.00	121.71	322.35	646.17
50	215.31	671.15	1302.66	140.65	405.40	747.94

Unit of tensile strength: (N)

3.2 Thermal conductivity of the FR-FTI and FR-FTI/A

Table 2 lists the tensile strength of FR-FTI with various content of Low-T_m fiber and various layer number of the loose nonwoven when the linear-density of FR-FTI was 7.78 dtex. When the layer number of the loose nonwoven were 1, 2, 3 and 4 layers, the thermal conductivities were decreased by the addition of the low-T_m fibers, and the thermal conductivities increased when the low-T_m fiber increased from 0 % to exceed a specific value. Furthermore, the values were different at the various layer number of loose nonwoven. They are 50, 50, 30 and 20 % at 1, 2, 3 and 4 layers of the layer number of the loose nonwoven respectively. Besides, the thermal conductivity of the FR-FTI increased at 5 layers nonwoven, when low-T_m fiber content increased from 10 to 50 %. This resulted from that the density of the FR-FTI was changed by the various layer number of the loose nonwoven, and this influenced the efficiency of the low-T_m fibers on the thermal conductivity of the FR-FTI, because the low-T_m fibers could form the bonding points on the contact points between fibers to reduce the air convection, and the bonding points provided a interface of the thermal conduction to increase the thermal conductivity of the FR-FTI, too.

Table 2 Thermal conductivity of FR-FTI with various content of low-T_m fiber and various layer number of loose nonwoven at 7.78 dtex of FRPF

Low-T_m fiber content (%)	Layer number of loose nonwoven (layer)				
	1	2	3	4	5
10	0.151	0.144	0.132	0.125	0.119
20	0.147	0.139	0.136	0.116	0.123
30	0.146	0.134	0.115	0.127	0.130
40	0.127	0.122	0.117	0.131	0.141
50	0.126	0.116	0.122	0.137	0.143

Unit of thermal conductivity: ($Wm^{-1}k^{-1}$)

Fig. 5 shows the condition of the bonding point when the low-T_m fiber content was 10 % and 50 %. The quantity of the bonding points as 50 % of the low-T_m fiber content was more than that of the 10 %. In the similar way, the degree of the thermal insulation of the FR-FTI was influenced by the layer number of the loose nonwoven. When the density of the FR-FTI increased, the fibers became closer with each other in the FR-FTI. Therefore, the degree of the air convection was decreased by the contacted fibers to increase the thermal conductivity of the FR-FTI. However, when the density continuously increased, the fibers continuously became closing with each other and caused the conduction point increased and further increased the thermal conductivity of the FR-FTI. From this reason, the layer number of nonwoven had an interaction with the low-T_m fiber content on the effect of the thermal conductivity.

Fig. 6 shows the effect of the linear-density of FRPF and the layer number of the loose nonwoven on the thermal conductivity of the FR-FTI when the low-T_m fiber content was 30 %. When the linear-density of the FRPF was 7.78 dtex, the thermal conductivity of the FR-FTI was lower than that of the 13.33 dtex, because the finer linear-density of the FRPF caused the structure of the FR-FTI more compact than the higher ones. Besides, the lowest thermal conductivity was obtained at the 4 layer loose nonwoven when the density of the FRPF was the 13.33 dtex, and that was obtained at the 3 layer loose nonwoven when the density of the FRPF was 7.78 dtex. This revealed that the fibers were closer with each other in the FR-FTI at the 7.78 dtex linear-density of the FRPF more than that at 13.13 dtex. Therefore, the optimal layer number of the loose nonwoven at the 7.78 dtex FRPF was less than that the 13.13 dtex one.

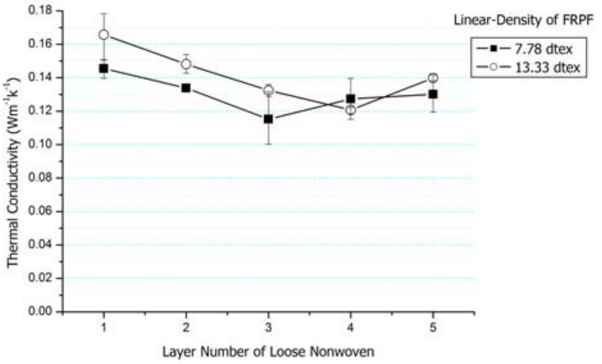

Fig. 6 Effect of linear-density of FRPF and layer number of loose nonwoven on thermal conductivity when low-T_m fiber content was 30 %.

Fig. 7 shows the effect of the aluminum foil and the layer number of the loose nonwoven on the thermal conductivity of the FRPF when the linear-density of the FRPF was 7 dtex. The thermal conductivity of the FR-FTI was higher than that of the FR-FTI/A at the 7.78 dtex except for the 2 layer nonwoven. This resulted from that the thermal conductivity of the aluminum foil was higher than that of the FR-FTI.

The lowest of the thermal conductivity of the FR-FTI/A was obtained at the 2 layers nonwoven. Comparatively, the lowest thermal conductivity of the FR-FTI was obtained at the 3 layers nonwoven when the linear-density of the FRPF was 7.78 dtex. This caused the increase of the layer of the aluminum foil to promote the conduction in the FR-FTI/A simultaneously. Therefore, the thermal conductivity of the FR-FTI/A was increased by the conduction of the aluminum foil when the layer number of FRPF was 3.

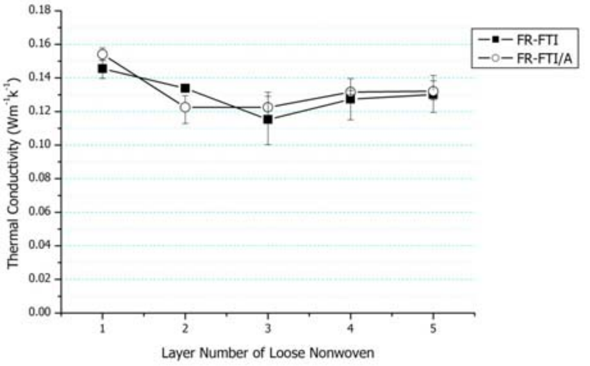

Fig. 7 Effect of aluminum foil and layer number of loose nonwoven on thermal conductivity when low-T_m fiber content was 30% and linear-density of FRPF was 7.78 dtex

Fig. 8 shows the effect of the aluminum foil and the layer number of the loose nonwoven on the thermal conductivity of the FR-FTI and FR-FTI/A when the linear-density of the FRPF was 13.33 dtex. The thermal conductivtiy of the FR-FTI/A was lower than that of the FR-FTI when the layer number of the loose nonwoven was less than 4 layers. The thermal reflection property of the aluminum foil makes the thermal conductivity to reduce about 0.09 $Wm^{-1}k^{-1}$. The efficiency of the aluminum foil on the reducing of the thermal transfer appeared on the 13.33 dtex FRPF but not on 7.78 dtex, because the 13.33 dtex FRPF was thicker than the 7.78 dtex one. Therefore, the contact area between the fibers and the aluminum foils was less. The conduction between the fibers and the aluminum foils hence less than the contribution of the reflection of the aluminum foils caused the increase of thermal conductivity of the FR-FTI/A when the layer number of the loose nonwoven less than 4 layers.

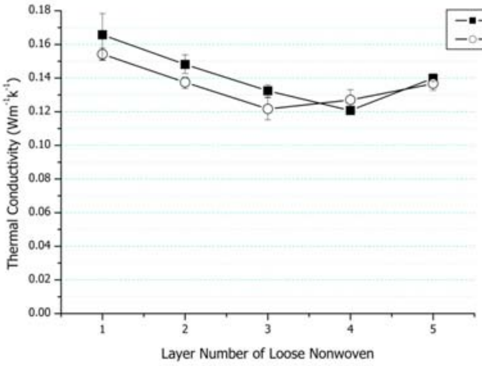

Fig. 8 Effect of aluminum foil and layer number of loose nonwoven on thermal conductivity when low-T_m fiber content was 30% and linear-density of FRPF was 13.33 dtex

3.3 LOI of the FR-FTI

Table 3 lists the LOI of the FR-FTI in various layer number of the loose nonwoven and various content of low-T_m fiber, this shows that the LOI decreased when the low-T_m fiber content increased. This is resulted from the low-T_m fibers were not processed by the fire retardant agent. Therefore, when the low-T_m fibers were increased in the FR-FTI, the weight ratio of the FRPF decreased and the LOI decreased. Besides, the LOI was increased by increasing the layered number of the layer nonwoven, because the density of the FR-FTI was increased and the content of the combustion supporting gas in the FR-FTI was decrease by increasing the layer number of the loose nonwoven.

Table 3 LOI of FR-FTI with various content of low-Tm fiber and various layer number of loose nonwoven when linear-density of FRPF was 7.78 dtex

Low-T_m fiber content (%)	Layer number of loose nonwoven (layer)				
	1	2	3	4	5
10	31	33	34	35	35
20	30	31	32	34	35
30	30	31	32	34	34
40	29	30	31	31	31
50	29	30	30	30	31

Unite of limiting Oxygen index: (%)

4. Conclusion

In this study, the tensile strength of the FR-FTI was increased by increasing the loose nonwoven and the low-T_m fiber content. The tensile strength increased till the 50 % of the low-T_m fiber content was added. The results of the thermal conductivity of the FR-FTI revealed that the optimal layer number of the loose nonwoven was influenced by the various content of the low-T_m fiber. The highest of the thermal conductivity of the FR-FTIT was 0.151 $Wm^{-1}k^{-1}$, and the optimal thermal conductivity was 0.115 $Wm^{-1}k^{-1}$. The thermal conductivity of the FR-FTI was increased about 0.036 $Wm^{-1}k^{-1}$ of the thermal conductivity by the optimal manufacturing process. Besides, the thermal conductivity decreased at the 7.78 dtex FRPF When the FR-FTI combined with the aluminum foils and the layer number of the loose nonwoven was less than 4, but the thermal conductivity of the FR-FTI/A still higher than the optimal thermal conductivity of the FR-FTI, because the effect of the thermal conduction of the aluminum foils on the increase of the thermal conductivity was better than the effect of the reflection of the aluminum foils on the decrease of thermal conductivity. Results of the LOI of the FR-FTI showed that the LOI was increased by decreasing the low-T_m fiber content and increasing the layer number of the loose nonwoven.

Acknowledgements

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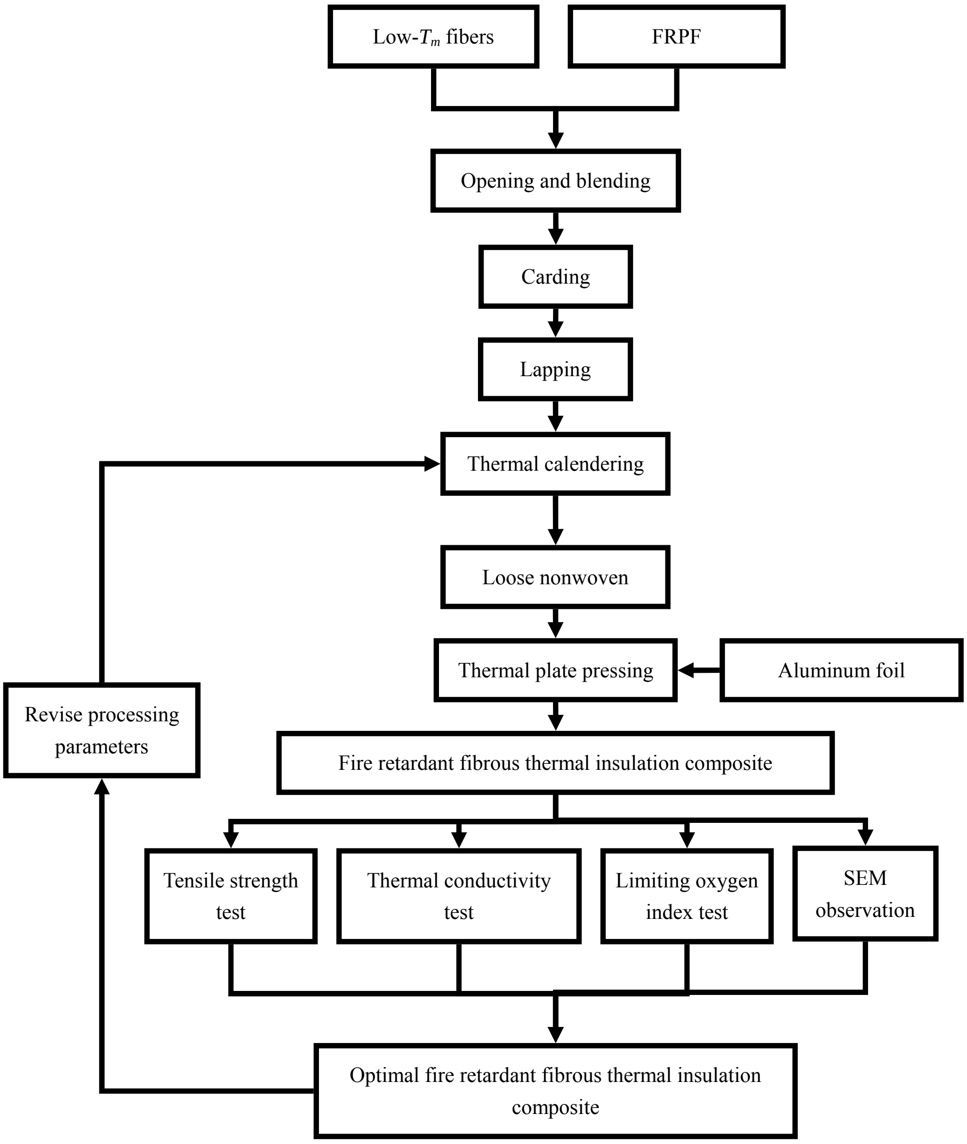
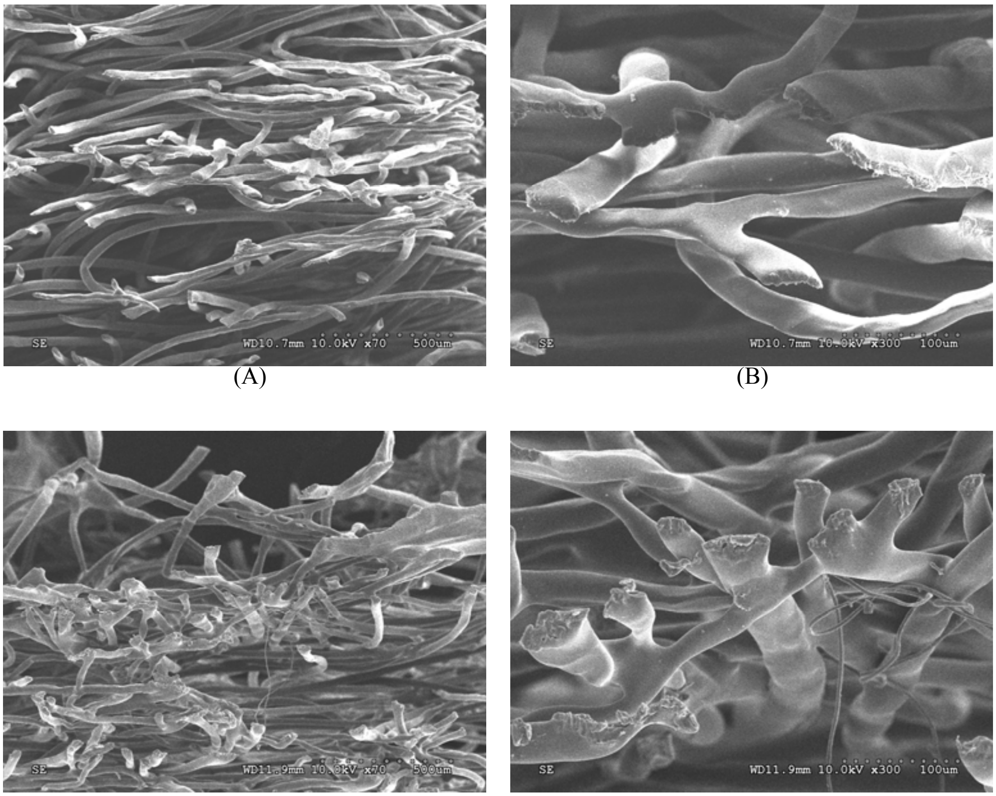


Fig. 1 the process of the experiment



(A) (B)

(C) (D)

Fig. 5 SEM micrographs of structure morphology of FR-FTIs: (A) and (B) were obtained from the FR-FTIs at the 7.78 dtex FRPF, the 3 layer number of loose nonwoven and 10 % of the low-T_m fiber content, original magnifications were 70× and 300× respectively. (C) and (D) were obtained from the FR-FTIs at the 7.78 dtex FR-hollow fibers, the 3 layer number of loose nonwoven and the 50 % of low-T_m fiber content, original magnifications were 70× and 300× respectively.