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Influence of the Needle Depth and Frequency on the Thermal Insulation Performance of Pre-Oxidised Fibre Felts

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Abstract
In this paper, the influence of the needle depth and frequency on the thermal insulation performance of pre-oxidised fibre felts was mainly investigated. The results showed that pre-oxidised fibre felts of a needle depth of 8 mm at a room temperature and working temperature of 100-200 °C had the best thermal insulation performance, while fibre for those of different needle depths with increasing temperature, the steady-state temperature difference increased linearly. With an increasing needle frequency, the thickness and gram weight of the pre-oxidised fibre felts showed a decreasing trend, while the coefficient of thermal conductivity exhibited an increasing one. For pre-oxidised fibre felts of different needle frequencies with increasing temperature, the steady-state temperature difference showed a linearly increasing trend.

Key words: *pre-oxidised fibre felt, needle depth, needle frequency, thermal insulation performance, thermal conductivity coefficient, back temperature.*

Introduction

PAN pre-oxidised fibres are a type of heat-resisting fibre emerging with the development of carbon fibres. It can be divided into two categories: one type is continuous filament bundles prepared specially as final products, and the other is as intermediate products applied in the heat preservation areas in the process of producing carbon fibres, because some pre-oxidised fibres are rejected due to technical parameters not meeting the requirements and the low rate of domestic carbon fibres with high performance in the process of preparing carbon fibres [1, 2]. Therefore, PAN pre-oxidised fibres as the final product and as an intermediate product not only have different controlled technological parameters but also various comprehensive technical indicators [3-5]. Final products of pre-oxidised fibres have different performance requirements according to the different purposes, while an intermediate product of pre-oxidised fibres belongs to non-combustible fibres due to its excellent thermal stability, high flame retardancy, the limited oxygen index being larger than 40%, and not melting and droping in the flame. Moreover, it has a low coefficient of thermal conductivity, low cost, resistance to the corrosion of acid and alkali as well as to a chemical environment, and good radiation resistant performance. It also has important application value in the field of heat insulation, as well as a textile processing performance not possessed of inorganic heat resistant fibres, all without posing any harm to the human body, as in the case of asbestos [6-9].

Due to the characteristics of the poor electrical conductivity, low crimp and brittleness fibre of PAN pre-oxidised fibres, which lead to high breakage during the process of spinning and weaving, low production efficiency and poor product quality [10-13], the fibres are difficult to turn into articles. Thus, at present most pre-oxidised fibre products are mostly produced through nonwoven technology, with needle nonwoven technology being common among them, where fibre pre-oxidised fibre needled felts are produced by pre-oxidised fibres undergoing the process of opening, combing into network, webbing and needling [14, 15]. In this paper, the influence of the needle depth and frequency on the thermal insulation performance of pre-oxidised fibre felts was mainly investigated.

Experimental

Main experimental materials

PAN pre-oxidised fibres were provided by Weiduo Technology (Tianjin) Co., LTD., the specifications of which are shown in ***Table 1.*** T-8112 type antistatic agent was provided by the Tianjin Technical University Textile Auxiliaries Co., LTD.

Experiment scheme

Pre-oxidised fibre needled felts are produced by PAN pre-oxidised fibres undergoing the process of opening, combing into network, cross webbing, pre-needling, and the main needling (multichannel).

Pre-oxidised fibres applied with the antistatic agent need to be combed into a network by a combing machine. Fabrics produced by a carding machine are of a single-layer network, the specific quantity and width of which cannot meet the requirements of folding into thick wires through the web machine, and then the subsequent processing is carried out. In this article, the method of webbing used was cross webbing, and the number of layers of the webbing was 30.

Fabrics after webbing are transferred to the pre-needle machine, where the pre-needling process mainly reinforces the fabrics, which are highly fluffy and with a small force between fibre nets. The fibre assemblies after experiencing the pre-needling process are transferred to the main needle-punching machine. The research emphasis in this paper was to explore the influence of the needle depth and frequency on the heat insulation performance of PAN pre-oxidised fi-

Table 1. *Specifications of pre-oxidised fibres [16].*

Average length, mm	Linear density, dtex	Average diameter, μm	Fracture strength, cN/dtex	Elongation at break, %	Crimp number, crimp number/cm
51.00 ± 0.02	1.66 ± 0.03	12.40 ± 0.02	1.53 ± 0.02	18.29 ± 0.02	4.40 ± 0.05

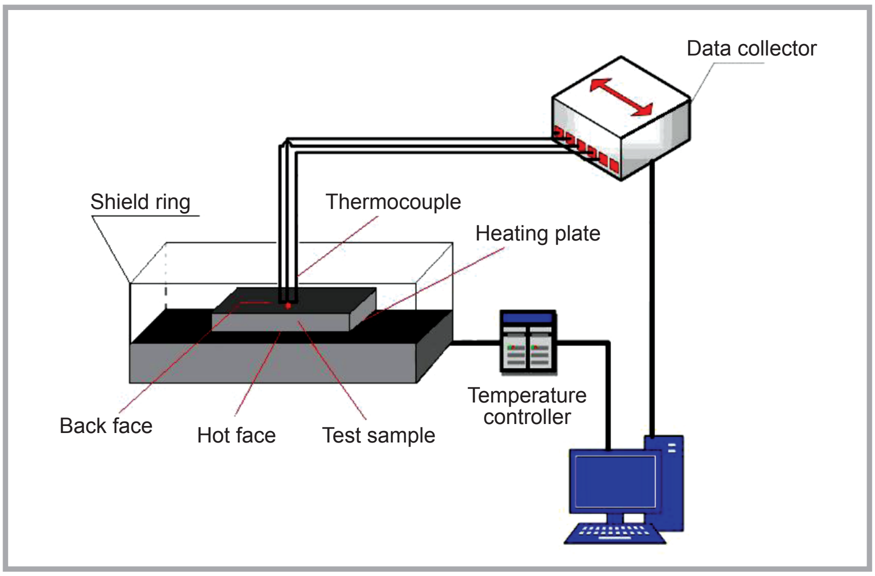

***Figure 1.** Schematic diagram of heat insulation test unit.*

bre felts, which is needed as in the process of practical experiments, the strength of pre-oxidised fibre is low, and a too large needle frequency will cause damage to and the fracture of fibres. Therefore, in this paper the design value of the needle frequency is lower than the conventional value of the needle frequency of fibres [16, 17]. The concrete implementation plan is as shown in ***Table 2***.

Testing and characterisation

The thickness test [16]

The thickness of samples was measured in accordance with GB/T24218.2-2009 (Textile Test Method of Nonwoven Clothes. Part 2: Determination of the Thickness).

The gram test [16]

The gram weight of samples was measured in accordance with GB/T24218.1-2009 (Textile Test Method of Nonwoven Clothes. Part 1: Determination of the Mass per Unit Area) .

The test of the coefficient of thermal conductivity [16]

A test of the coefficient of thermal conductivity of the sample was carried out using a TPS 2500S thermal constant analyser in a laboratory at a constant temperature and relative humidity of 20 ± 1 °C and 65 ± 5%, respectively.

The back temperature experiment [16]

A test device for the back temperature is shown in ***Figure 1***, where the size of the test sample is 50*50 mm, which makes the sample cover the heating plate. One piece of the samples of each group of experiments was respectively tested when the heating plate was at a temperature of 100 °C, 150 and 200 °C.

Results and discussion

Influence of the needle depth on the heat insulation performance of pre-oxidised fibre felts

Test results of structural parameters of pre-oxidized fibre felts

The needle depth refers to the length outside the fibre network after the needle punctures the fabric. The needle depth has a major influence on the physical structural indexes of nonwoven materials, as a change in the needle depth will firstly cause an alteration of their structural parameters, thus causing a change in the heat insulation performance of materials. Therefore, it was necessary to characterise the thickness and gram weight of the materials. The influence of the needle depth on the structural parameters of the nonwoven materials was mainly established by changing the distribution of fibres in the fabrics. Specifically, the difference in the depth of the needle puncturing the fabrics, which led to a variation in the needled agnail number experienced by the fabrics and in the degree of the redirection of fibres in the fabrics; thus causing a difference in the physical structure of the nonwoven materials. Test results of the thickness and gram weight of pre-oxidised fibre felts of various needle depths are shown in ***Table 3***, showing that with increasing needle depths, the displacement of surface fibres of the fabrics increased under the action of the pricker barb getting into the inner layer of the fabrics, which became closer gradually. In addition, surface fibres in the inner layer of the fabrics experienced repositioning, and the opportunity to return to the original state of fibres was reduced due to the spring-back stress, as a consequence of which the thickness and gram weight of the needled felts decreased. When the needle depth increased to a certain extent, the thickness and gram of the pre-oxidised fibre felts showed a stable trend; continuously

***Table 2.** Experimental scheme.*

Number	Needle number, channel	Needle depth, mm	Needle frequency, needle/min
1#	2	4	110
2#	2	6	110
3#	2	8	110
4#	2	10	110
5#	2	12	110
6#	2	8	80
7#	2	8	110
8#	2	8	140
9#	2	8	170
10#	2	8	200

***Table 3.** Influence of the needle depth on structural parameters of oxidised fibre felts.*

Samples	Thickness, mm	Gram weight, g/m^2
1#	5.26 ± 0.02	484.56 ± 0.03
2#	4.75 ± 0.02	423.85 ± 0.03
3#	4.84 ± 0.02	450.51 ± 0.03
4#	4.82 ± 0.02	448.74 ± 0.03
5#	4.96 ± 0.02	433.18 ± 0.03

increasing the needle depth will cause damage to fibres of the fabrics and fibre those puncturing the inner layer. Thus being shortened, the cohesive force between fibres decreased, and the increase in the rebound resilience of fibres caused the recovery trend of the thickness of fibre aggregation [18, 19].

Test results of the coefficient of thermal conductivity

Tests of the coefficient of thermal conductivity were carried out at room temperature, where the needle depths were 4 mm, 6 mm, 8 mm, 10 mm and 12 mm, respectively. The heat transfer performance at room temperature was also investigated. Test results are shown in ***Figure 2***. With increasing needle depths, the coefficient of thermal conductivity of the pre-oxidised fibre felts showed volatile changes at room temperature. The possible reason was that with the increasing needle depth, the thickness and gram weight of the pre-oxidised fibre felts were firstly led to decrease, and when the needle depth increased to a certain extent, the thickness and gram weight of the pre-oxidized fibre felts showed a stable trend. Then when increasing the needle depth, the thickness of pre-oxidised fibre felts had a tendency to rebound. Hence, the most possible reason of the volatile changes in the coefficient of thermal conductivity at room temperature of the pre-oxidized fibre felts for each needle depth was the volatile changes in physical structural indexes such as the thickness and gram weight. ***Figure 2*** shows that the coefficient of thermal conductivity of the pre-oxidised fibre felts was the minimum when the needle depth was 8 mm.

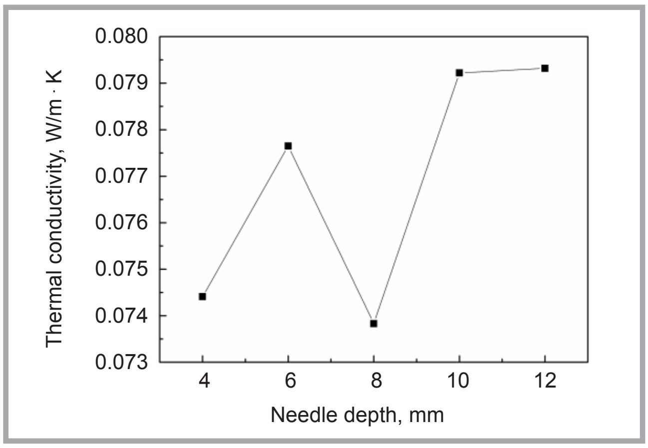

Figure 2. *Influence of needle depth on the coefficient of thermal conductivity.*

Experimental results of back temperature

To explore the heat transfer behaviour and heat insulation performance of pre-oxidised fibre felts of different needle depths (4 mm, 6 mm, 8 mm, 10 mm, 12 mm) under different temperatures, experiments of the back temperature were carried out when the heating plate temperature was 100 °C, 150 °C and 200 °C, respectively. ***Figures 3.a-3.e*** show the rising progress of the back temperature of samples 1#-5# recorded.

In order to further illustrate the influence of the needle depth on the heat transfer behaviour and heat insulation performance of pre-oxidised fibre felts, the rising progresses of the back temperature of the pre-oxidised fibre felts were obtained at the same temperature and different needle depths, respectively.

Figure 4 shows the rising curve of the back temperature of samples 1#-5# at a heating plate temperature of 100 °C. From the point of the transient state, before 90 s the back temperature of pre-oxidised fibre felts of various needle depths rapidly increased, and the curves overlapped with each other. In the transient state after this situation, the rising rate of the sample of a needle depth of 4 mm was significantly lower than the rest. At 180 s, the rising rate of the sample of a needle depth of 8 mm began to drop, and at the end of the transient state, the sample's curve intersected with the rising curve of the sample of a needle depth of 4 mm. Hence, from the transient state, for needle depths of 4 mm and 8 mm, pre-oxidized fibre felts showed a good heat insulation effect. From the point of the steady state, the steady-state average temperature of the sample of a needle depth of 8 mm was the minimum, which was 72.5 °C. The steady-state average back temperature of the sample of a needle depth of 12 mm was the maximum, which was 76.5 °C. The steady-state average back temperatures of the rest of the samples were close to each other. We can observe from ***Figure 5*** that with increasing needle depths, the steady-state temperature differences of the pre-oxidised fibre felts showed volatile changes. At a needle depth of 8 mm, the maximum steady-state temperature was 27.5 °C, at which the pre-oxidized fibre felts had the best heat insulation effect.

Characteristics of the thermal transmission of the transient and steady states of samples 1#-5# at a temperature of 100 °C were comprehensively analysed. At a needle depth of 8 mm, the pre-oxidized fibre felts had the best heat insulation effect [20, 21].

Figure 6 shows the rising curve of the back temperature of samples 1#-5# at a heating plate temperature of 150 °C. Before 90 s of the transient state, the back temperature of pre-oxidized fibre felts of various needle depths rapidly increased and the curves overlapped with each other. In the transient state after this situation, the pre-oxidized fibre felts of needle depths of 4 mm and 8 mm had a lower rising rate. Pre-oxidised fibre felts of a needle depth of 10 mm had the largest rising rate. The rising rate of pre-oxidized fibre felts of the other needle depths was among the above three rising rates. Hence, from the transient state at needle depths of 4 mm and 8 mm, the pre-oxidised fibre felts showed a better heat insulation effect. From the point of the steady state, the back temperature of the sample of a needle depth of 8 mm was the minimum, where the minimum steady-state average temperature was 101.1 °C. The back temperature of the sample of a needle depth of 10 mm was the maximum, where the maximum steady-state average temperature was 108.5 °C. The steady-state temperature of pre-oxidized fibre felts of other needle depths were between the above two steady-state temperatures, and the curves of the steady-state temperature overlapped and intertwined with each other. In the steady state phase. in order to more clearly show the influence of the needle depth on the effects of the heat insulation of needle melts, ***Figure 7*** was constructed, showing that with increasing needle depths, the steady-state temperature differences of the pre-oxidized fibre felts showed volatile changes. At a needle

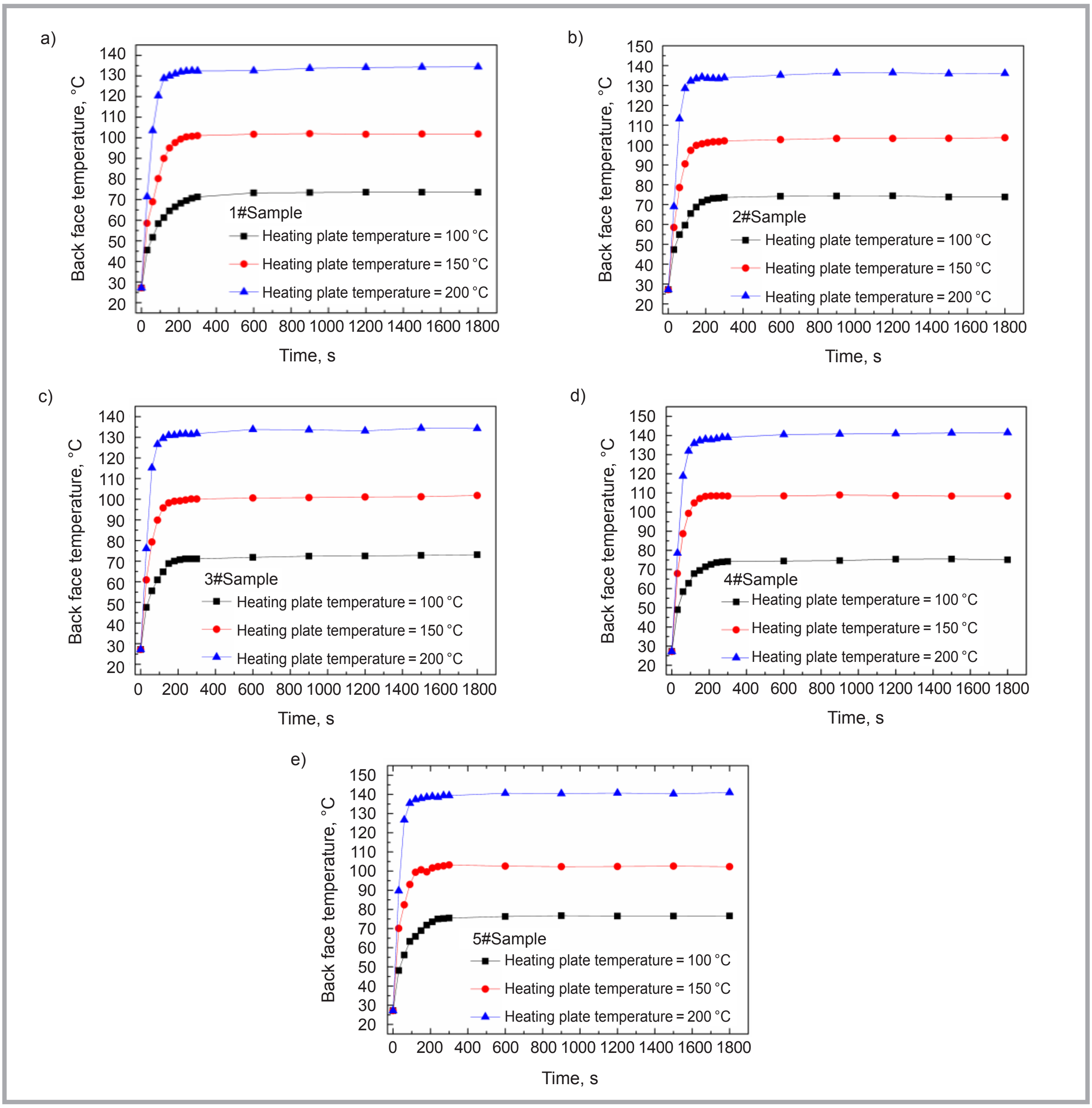

Figure 3. *Rising progress of the back temperature of samples 1#~5#.*

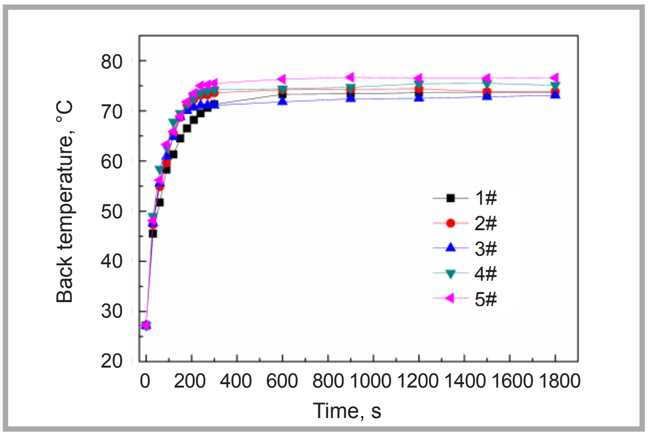

Figure 4. *Influence of the needle depth on the back temperature when the heating plate temperature was 100 °C.*

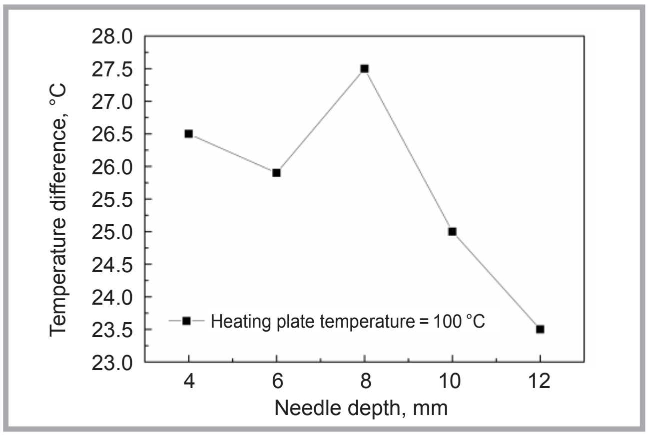

Figure 5. *Influence of the needle depth on the steady-state temperature difference.*

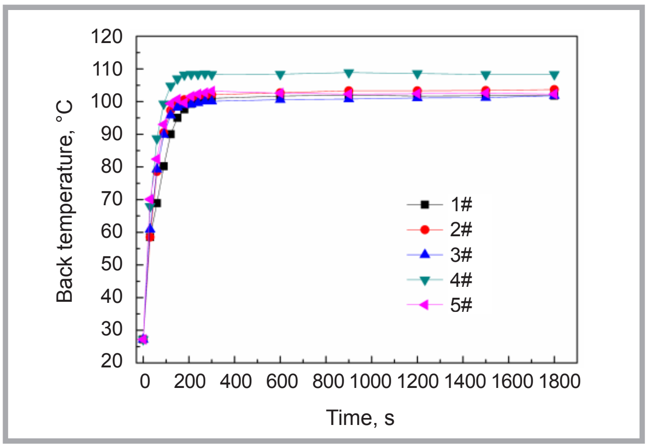

Figure 6. Influence of the needle depth on the back temperature when the heating plate temperature was 150 °C.

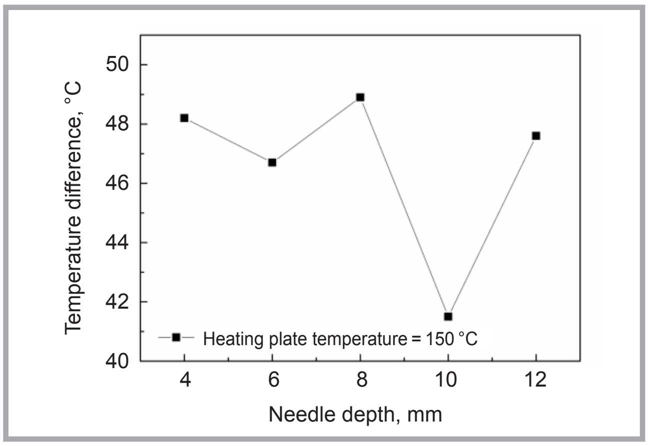

Figure 7. Influence of the needle depth on the steady-state temperature difference.

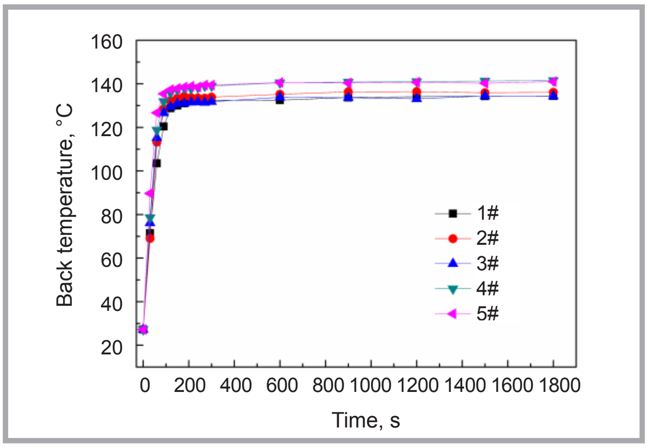

Figure 8. Influence of the needle depth on the back temperature when the heating plate temperature was 200 °C.

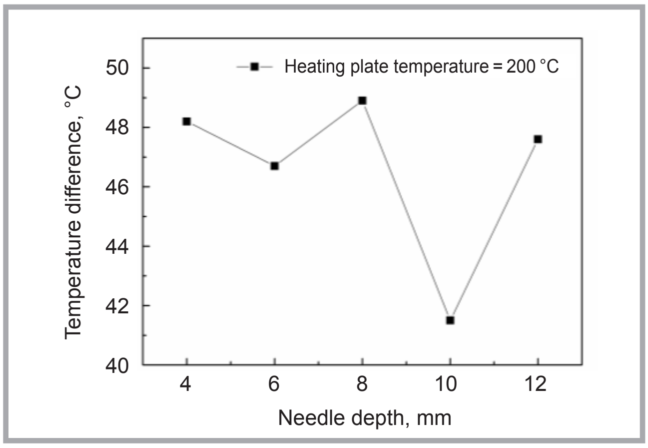

Figure 9. Influence of the needle depth on the steady-state temperature difference.

depth of 8 mm, the maximum steady-state temperature was 48.9 °C. Thus, we could analyse the heat transfer behaviour of the transient and steady states comprehensively. When the actual working temperature was 150 °C, at a needle depth of 8 mm, the pre-oxidised fibre felts had a better heat insulation effect.

Figure 8 shows the rising curve of the back temperature of samples 1#-5# when the heating plate temperature was 200 °C. Before 120 s of the transient state, the back temperature of pre-oxidized fibre felts of various needle depths rapidly increased, and the curves overlapped with each other. In the transient state after this situation, the rising rate of the back temperature of the pre-oxidized fibre felts of a needle depth of 8 mm was the lowest, while pre-oxidised fibre felts of a needle depth of 12 mm had the largest rising rate. The curves of the rising rate of pre-oxidized fibre felts of other needle depths intertwined and overlapped with each other. Hence, from the transient state, at a needle depth of 8 mm, the pre-oxidized fibre felts had a better heat insulation effect. From the point of the steady state, the back temperature of the sample of a needle depth of 8 mm was the minimum; the minimum steady-state average temperature was 133.8 °C. The back temperatures of pre-oxidised fibre felts of the other needle depths were close to each other, and all were higher than that of the pre-oxidised fibre felt with a needle depth of 8 mm. In the steady state phase, in order to more clearly show the influence of the needle depth on the heat insulation effects of needle melts, ***Figure 9*** was constructed, showing that with increasing needle depths, the steady-state temperature differences of the pre-oxidized fibre felts showed volatile changes, among which at a needle depth of 8 mm, the pre-oxidized fibre felts had a better heat insulation effect. Thus, we could analyse comprehensively the change in the back transient-state and steady-state temperatures of samples 1#-5# at a temperature of 200 °C. At a needle depth of 8 mm, the pre-oxidized fibre felts had the best heat insulation effect.

An increase in needle depth would cause a volatile change in the thickness and gram weight of pre-oxidised fibre felts, thus leading to a volatile change in the heat insulation performance of pre-oxidized fibre felts at room temperature and at a temperature of 100-200 °C, including when the needle depth was 8 mm. Within the range of the working temperature studied, pre-oxidised fibre felts had the best heat insulation performance.

In order to explore the influence of the working temperature on the heat insulation performance of pre-oxidized fibre felts, the relation between the working temperature and temperature difference of pre-oxidized fibre felts 1#-5# in a steady state was obtained. As shown in ***Figure 10***, with increasing temperature, the steady-state temperature differences of pre-oxidized fibre felts of various needle depths increased linearly, which showed that it still had a certain heat insulation performance at a higher temperature.

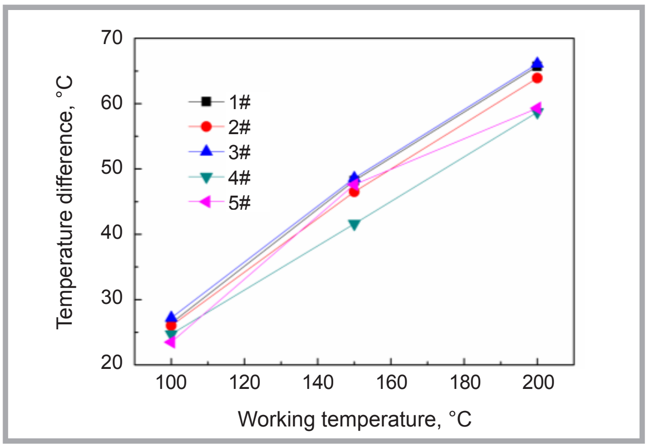

Figure 10. *Influence of the working temperature on the steady-state temperature difference.*

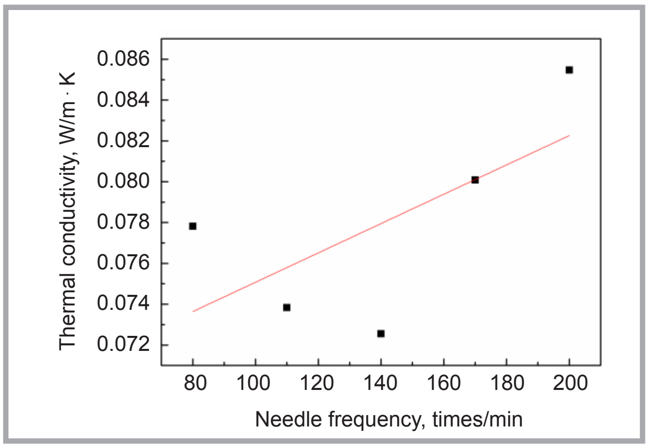

Figure 11. *Influence of the needle frequency on the coefficient of thermal conductivity.*

Influence of the needle frequency on the heat insulation performance of pre-oxidised fibre felts

Test results of the structural parameters of the pre-oxidized fibre felts

The needle frequency was one of the most important process parameters of the needle-punched nonwoven materials, ***Equation (1)*** showed that when the pinning density and output speed of the fabrics were constant, the needle frequency determined the needle density. Hence, in this section, the needle density was varied to change the needle frequency, thus causing a variation in the physical structure indicators of the needled felts.

$$D = \frac{N \times n}{10000 \times v} \qquad (1)$$

where,

D – needle density, needle number;

N – pinning density of needle plates, pinning number;

n – needle frequency of prickers;

v – output speed of fabrics.

As shown in ***Table 4***, the thickness and gram weight of the pre-oxidised fibre felts both showed decreasing trends. ***Equation (1)*** showed that when the pinning density and output speed of the fabrics remained at a certain value, an increase in the needle frequency caused a rise in the needle density. With increasing needle density, the needle barbs drove into the surface fibres of the fabrics vertically, getting into the inner layer, where fibres locked with each other. The thickness decreased with increasing needle density. The needle pressure led to the deformation of the fabrics, which experienced diffusion. Due to the resistance as well as the ratio of the input and output speeds experienced by the fabrics, drafting was caused, leading to a decrease in the gram weight.

Table 4. *Influence of the needle frequency on the structural parameters of pre-oxidized fibre felts.*

Samples	Thickness, mm	Gram weight, g/m^2
6#	4.89 ± 0.02	478.52 ± 0.03
7#	4.84 ± 0.02	450.51 ± 0.03
8#	4.31 ± 0.02	407.21 ± 0.03
9#	4.28 ± 0.02	441.29 ± 0.03
10#	4.04 ± 0.02	332.58 ± 0.03

Test results of the coefficient of thermal conductivity

In order to explore the influence of the needle frequency on the heat conduction performance of the pre-oxidized fibre felts, tests of the coefficient of thermal conductivity were carried out on samples of pre-oxidised fibre felts of different needle frequencies. The test result is shown in ***Figure 11***. Within the lower range of 80-140 times/min, the needle frequency had a little influence on the coefficient of thermal conductivity of the pre-oxidized fibre felts at room temperature, and the values of the coefficient of thermal conductivity were close to each other. Values of the coefficient of thermal conductivity were 0.07782 W/m·K, 0.07383 W/m·K and 0.07255 W/m·K, respectively, at room temperature. When the needle frequency was 80 times/min, 110 times/min and 140 times/min, the heat conduction performance of pre-oxidized fibre felts prepared in the range of the process condition was poor, while the thermal insulation performance was good.

Experiment of the back temperature

To explore the heat transfer behaviour and heat insulation performance of pre-oxidized fibre felts of different needle frequencies (80 times/min, 110 times/min, 140 times/min, 170 times/min, 200 times/min) at different working temperatures, the heating plate temperature were respectively set at 100 °C, 150 °C and 150 °C. The experiment result of the back temperature is shown in ***Figures 12.a-12.e***.

In order to further illustrate the influence of the needle frequency on the heat transfer behaviour and heat conduction performance of pre-oxidised fibre felts, the rising processes of the back temperature of pre-oxidized fibre felts of different frequencies were respectively obtained at the same temperature.

Figure 13 shows the rising curve of the back temperature of samples 6#-10# at a heating plate temperature of 100 °C. Before 60 s of the transient state, the back temperature of pre-oxidized fibre felts of various needle frequencies rapidly increased, and the rising curves overlapped each other. In the transient state after this situation, the rising rate of the back temperature of pre-oxidised fibre felts with a needle frequency of 80 times/min was significantly lower than that of other samples. From the point of the

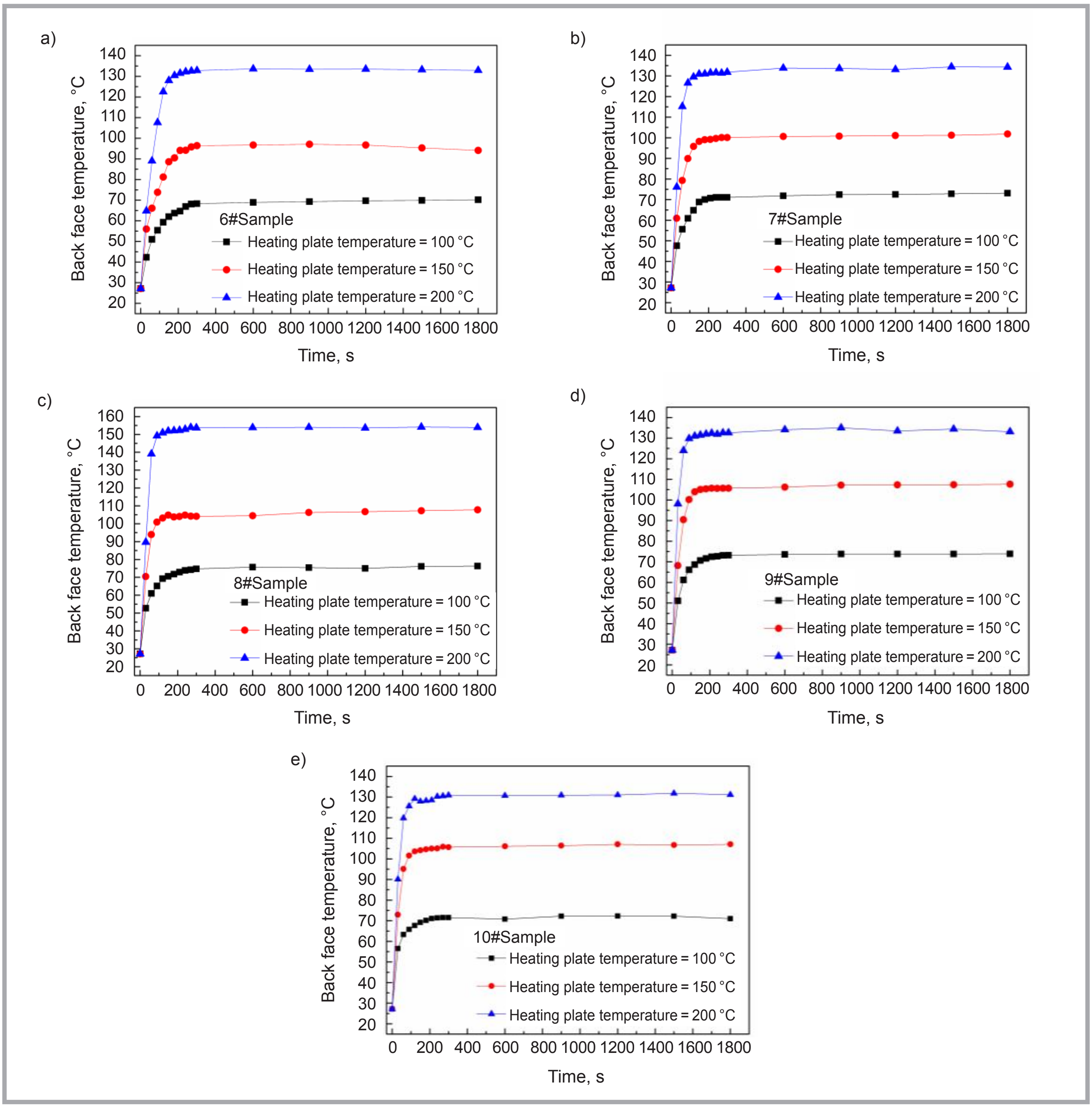

***Figure 12.** Rising progress of the back temperature of samples 6#~10#.*

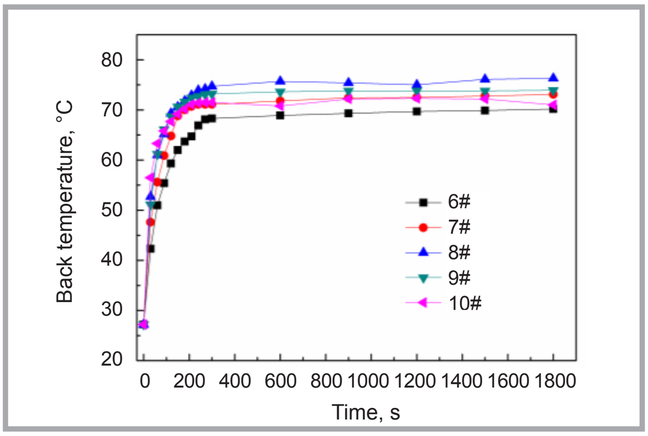

***Figure 13.** Influence of the needle frequency on the back temperature when the heating plate temperature was 100 °C.*

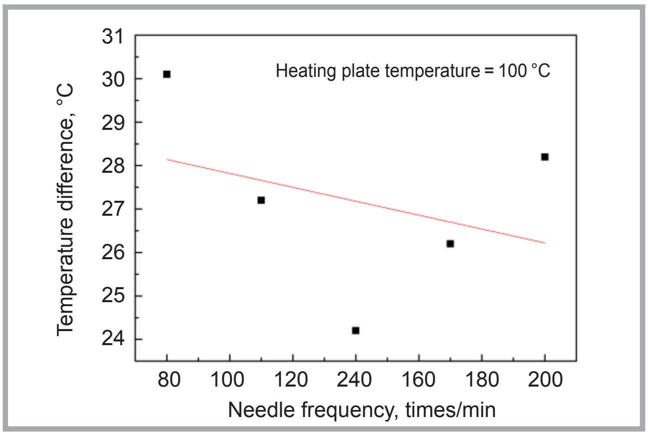

***Figure 14.** Influence of the needle frequency on the steady-state temperature difference.*

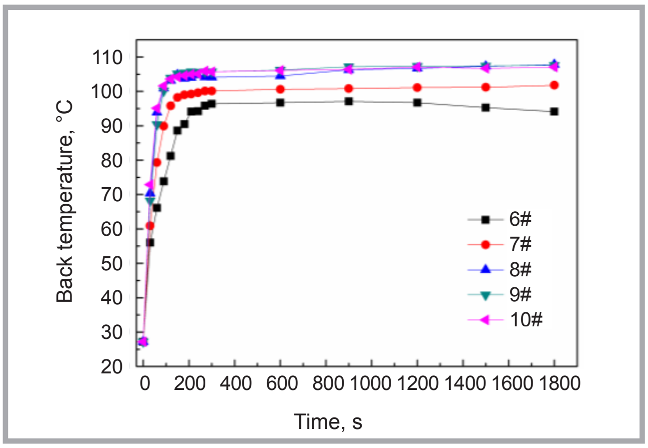

Figure 15. Influence of the needle frequency on the back temperature when the heating plate temperature was 150 °C.

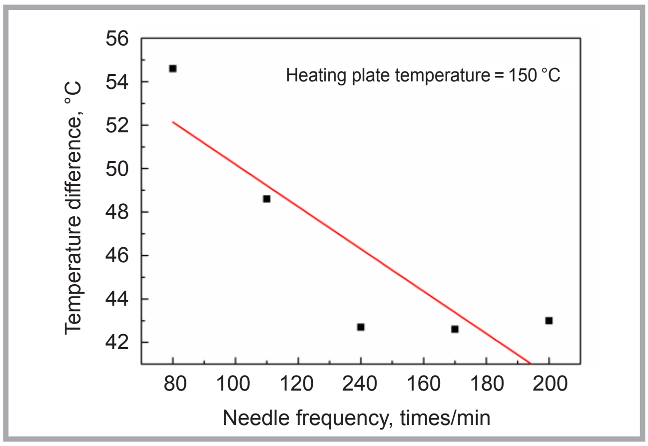

Figure 16. Influence of the needle frequency on the steady-state temperature difference.

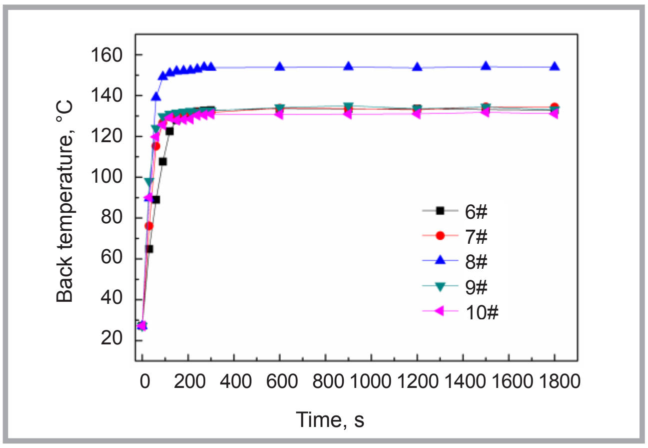

Figure 17. Influence of the needle frequency on the back temperature when the heating plate temperature was 200 °C.

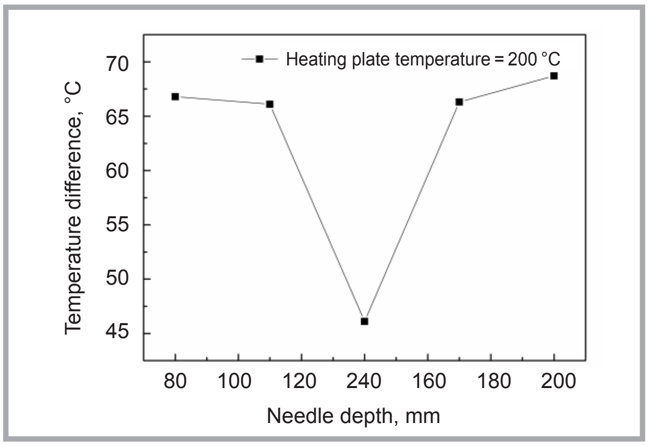

Figure 18. Influence of the needle frequency on the steady-state temperature difference.

steady state, the steady-state temperature of pre-oxidized fibre felts of a needle frequency of 80 times/min was the minimum, where the minimum steady-state average temperature was 69.6 °C. The steady-state temperature of pre-oxidised fibre felts of a needle frequency of 140 times/min was the maximum, where the maximum steady-state average temperature was 75.7 °C.

In order to further analyse the steady-state heat insulation effect of samples 6#-10# of pre-oxidised fibre felts at a working temperature of 100 °C, ***Figure 14*** was constructed as a fitting curve, which shows that with increasing needle frequencies, the steady-state temperature difference decreased linearly, which meant that the steady-state heat insulation effect showed a weakening tendency; the main reason may be that the increase in needle frequency caused an increase in needle density. Moreover, the thickness and gram weight of the needled felts were both reduced; the tightness of the needled felts increased, within a certain range of needle density; the volume density of the needled felts increased, and the root number of contained fibres per unit volume increased, leading to the heat transfer of the solid phase intensifying, thus causing the weakening of the heat insulation effect. The heat transfer behaviour of pre-oxidised fibre felts of different needle frequencies in the transient and steady states at a working temperature of 100 °C was comprehensively considered, where the needle frequency of 80 times/min, pre-oxidized fibre felts showed good heat insulation performance.

Figure 15 shows the rising curve of the back temperature of samples 6#-10# when setting the heating plate temperature at 150 °C. Before 30 s of the transient state, the back temperature of pre-oxidised fibre felts of various needle frequencies rapidly increased, and the rising curves overlapped each other. In the transient state after this situation, the rising rates of the back temperature of pre-oxidised fibre felts of a needle frequency of 80 times/min and 100 times/min were significantly lower than for pre-oxidized fibre felts of other needle frequencies. Moreover, the rising rate of of a needle frequency of 80 times/min was significantly lower than that of needled felt of a needle frequency of 110 times/min. Furthermore, the rising rates of pre-oxidised fibre felts of various needle frequencies were close to each other. From the point of the steady state, the steady-state temperature of pre-oxidized fibre felts of a needle frequency of 80 times/min was the minimum, where the minimum steady-state average temperature was 96 °C.

When the heating plate temperature was 150 °C, in order to better analyse the steady-state heat transfer behaviour and heat insulation effect of pre-oxidized fibre felts, the relation between the needle frequency and the steady-state temperature difference was obtained, the fitted

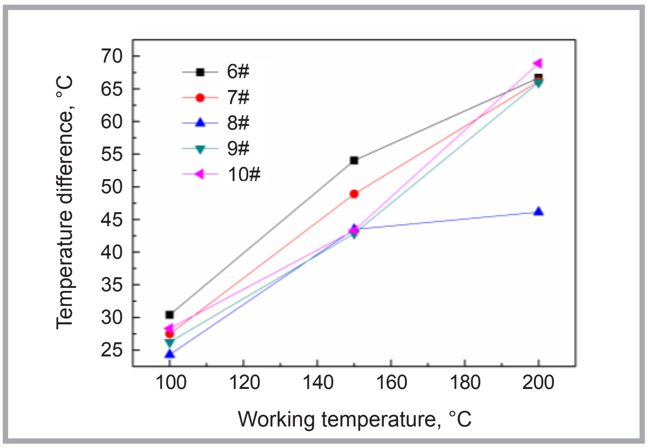

***Figure 19.** Influence of the working temperature on the steady-state temperature difference of pre-oxidised fibre felts.*

curve of which is shown in ***Figure 16***. We can observe that an increase in needle frequency caused a linear decrease in the steady-state temperature difference, namely a decrease in the heat insulation effect. The most likely reason for this was that the increase in needle frequency caused an increase in needle density. In addition, the thickness and gram weight of the needled felt were both reduced, and the volume density increased, which led to the heat transfer of the solid phase intensifying, thus causing the weakening of the heat insulation effect.

The heat transfer behaviour of pre-oxidized fibre felts of different needle frequencies in the transient and steady states at a working temperature of 150 °C was comprehensively considered, where at a needle frequency of 80 times/min, the pre-oxidized fibre felts showed good heat insulation performance.

Figure 17 exhibits the rising curve of the back temperature of samples 6#-10# when setting the heating plate temperature at 200 °C. Before 120 s of the transient state, the rising rates of the back temperature of pre-oxidized fibre felts of a needle frequency of 80 times/min and 200 times/min were both lower. Then in the transient state the rising rate of the back temperature of pre-oxidized fibre felts of a needle frequency of 140 times/min was the largest. The rising curves of pre-oxidised fibre felts of various needle frequencies overlapped each other.

From the point of the steady state, the steady-state temperature of pre-oxidized fibre felts of a needle frequency of 200 times/min was the minimum, where the minimum steady-state average temperature was 131.1 °C. The steady-state temperature of pre-oxidized fibre felts of a needle frequency of 140 times/min was the maximum, where the maximum steady-state average temperature was 153.9 °C.

When the heating plate temperature was 200 °C, in order to better analyse the steady-state heat transfer behaviour and heat insulation effect of the pre-oxidized fibre felts, the relation between the needle frequency and the steady-state temperature difference was obtained, shown in ***Figure 18***. We can observe that with an increase in the needle frequency, the steady-state temperature difference showed a tendency to decrease at first and then increase. The minimum steady-state temperature difference was obtained when the needle frequency was 140 times/min, where the minimum steady-state temperature difference was 46.1 °C. The maximum steady-state temperature difference was obtained when the needle frequency was 200 times/min, where the maximum steady-state temperature difference was 68.9 °C. The possible reason for this was that the needle frequency brought about an increase in the volume density of the needled felts, leading to a decrease in the steady-state temperature difference to a certain extent; the heat insulation effect weakened along with this situation. However, if we continued to increase the needle frequency, the volume density increased to a proper value, while a smaller porosity and pore diameter inhibited heat convection at a higher temperature. Although the conduction of the solid phase intensified, the inhibitory effect of the heat convection was greater than the heat conduction, causing an increase in the heat insulation effect.

When the working temperature was 200 °C, the transient-state and steady-state heat transfer behaviours of samples 6#-10# were comprehensively considered. At a the needle frequency of 200 times/min, the pre-oxidized fibre felts showed good heat insulation performance.

To explore the influence of the working temperature on the steady-state temperature difference of samples 6#-10, ***Figure 19*** was constructed. It exhibits that with increasing temperature, the temperature differences of samples of pre-oxidized fibre felts of various needle frequencies basically showed a linear increase.

When the working temperature was between 100 °C and 150 °C and the needle frequency 80 times/min, the pre-oxidized fibre felts showed better heat insulation performance, while when the temperature was increased to 200 °C, pre-oxidized fibre felts of a needle frequency of 200 times/min displayed the best heat insulation performance. This proved that at a higher temperature, a larger needle frequency brought about a larger volume density. Decreasing the porosity and pore diameter favoured the occurrence of heat convection [22].

Conclusions

(1) Within the range of needle depth studied, at 8 mm, pre-oxidised fibre felts had the best heat insulation effect at room temperature and a temperature of 100-200 °C. With increasing temperature, for pre-oxidized fibre felts of different needle depths, the steady-state temperature increased linearly.

(2) With increasing needle frequency, the thickness and gram weight of the pre-oxidized fibre felts showed a decreasing trend, while the coefficient of thermal conductivity showed an increasing trend. When the working temperature was 100 °C and 150 °C, pre-oxidized fibre felts of a lower needle frequency (80times /min) had a good heat insulation effect, and when the working temperature was 200 °C, pre-oxidized fibre felts of a higher needle frequency (2000 times /min) also had a good heat insulation effect. For pre-oxidised fibre felts of different needle frequencies, the steady-state temperature showed a linearly increasing trend.

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