Basic Research on Optimization of Heat-Retention Characteristics of Fiber Bulk Materials

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Abstract
The objective of this study is to investigate the possibility on the variable thermal resistance of fiber bulk materials as a heat insulating bedquilt for keeping a human being warm and comfortable independent upon the change in the environmental temperature. The system for maintaining the optimum thermal condition in the bed was realized by varying the porosity of the fiber bulk materials using the deformation of the thin wires of shape memory alloy by the temperature change.

The relations between the porosities and the apparent thermal resistances of the typical three kinds of fiber bulk materials were measured. As a result, it was clarified that the possible variable range of the apparent thermal resistance is about the double for the cotton fiber bulk materials with polyester fibers. Mixing of the fine metal wires, which is a substitute for shape memory alloy, had little effect on the thermal resistance in the range of the mixing fraction.

Furthermore, the considerations on the thermal characteristics of the fiber bulk materials were performed using the numerical analysis assuming heat conduction and radiation heat transfer. Finally, the experiment on the change in the volume of fiber bulk materials and in the thermal resistance was carried out actually by mixing the fine wires of shape memory alloy.

Keywords: fiber bulk materials, heat-retention characteristics, optimization, control of thermal resistance, shape memory alloy

1. Introduction
The bedding is a necessary and fundamental means for appropriately keeping the human sleeping environment. It is important for maintaining characteristics of the bedding optimum against the temperature change of the circumferential environment. Especially, considering the improvement in the consciousness of self health care with the recent life style change and the importance in the welfare field, the scientific research for a realization of the more comfortable sleep environment has been developed. The metabolic energy and the ambient temperature around the human in the sleep decrease in the night toward morning. However, since the property of heat retention of bedding is almost fixed, thermo-regulation in the sleep is apt to be disturbed by the change in ambient condition from the beginning of the sleep to a peep of day. It is not so difficult to cope with the reduction of the ambient temperature in the bed by using the means such as electric heating and it has been utilized in practice. However, the thermal condition for electric heating differs from that for the warming using the fiber bulk materials. That is, the condition giving the heat flux is quite different from that of natural change in body temperature corresponding to the change of the circumference environment. It is also difficult to realize the suitable condition for the sleeping because of the drying and giving of the surplus energy. The problem described above can be mentioned for the conventional bedding, and a realization of more comfortable sleeping environment is desired.

The objective of the study is to perform the basic research on variation of thermal resistance of fiber bulk materials for keeping heat retaining property optimum against the change of ambient condition, using the bedquilt as samples which is the most important means to keep thermal environment appropriate. The method in which the thermal resistance (the performance of heat insulation) is varied with the change in porosity of fiber bulk materials by its expansion and contraction is considered. Maintaining adequate temperature using the shape change of fiber bulk materials uniformly mixed with the thin wires of shape memory alloy against the temperature variation of environment is investigated. In this study, the passive method using the deformation of shape memory alloy by temperature change is chosen to deform fiber assembly. However, it is also possible to use other control methods such as an active deformation and the similar investigation will be also required for those cases.

The following items are examined.

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J.Text. Eng.
The range of heat retaining property (apparent thermal resistance) is clarified with varying the apparent volume of fiber bulk materials by measuring the relationship between the porosity of fiber assembly (bedquilt) and apparent thermal resistance.

The effect of mixing of thin wires of the shape memory alloy to change the fiber volume fraction on the thermal characteristic of the cotton fiber bulk materials is investigated experimentally.

The investigation of heat transfer mechanisms and characteristics are carried out using the numerical analysis of heat conduction and the effect of the radiation heat transfer in fiber bulk materials under the sleeping environment is also examined, corresponding to the items of (1) and (2).

The volume change of the cotton fiber bulk materials by mixing the thin wires of shape memory alloy was investigated.

Fujimoto and Niwa measured the effective thermal conductivity of fiber assembly of wool and polyester and investigated the effect of heat conduction and radiation heat transfer related to the above items of (1)～(3). As a result, although the heat conduction was controlling phenomenon in relatively large region of the fiber volume fraction, the effect of radiation remarkably appeared with decreasing fiber volume fraction, especially in the region smaller than 5% of fiber volume fraction. Since the boundary condition in such a measurement, in which the air-transfer was suppressed by putting the test material between two solid plates, was quite different from that of this study that was adapted to the practical usage.

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2. Experimental Apparatus and Method

The experimental apparatus for measuring the apparent thermal resistance of fiber bulk materials is shown in Fig.1. The apparent thermal conductivity $\lambda$ and the apparent thermal resistance $R$ were determined by the thickness $d$, the temperature difference $\Delta T$ between both surfaces and the heat flux $q$ of the fiber bulk materials under the assumption of one-dimensional heat conduction.

$$\lambda = \frac{qd}{\Delta T} \quad (1)$$

$$R = \frac{\Delta T}{q} \quad (2)$$

In order to realize the thermal conditions similar to the bedquilt in practical use, the cotton fiber bulk materials uniformly covered the upper surface of the heating plate of uniform temperature. Also, one-dimensional temperature distribution within the fiber bulk materials could be realized by adopting comparatively large dimension of the heating surface (about 6～16 times of the thickness of test materials). However, it could be considered that there was the case where the assumption of the one-dimensional conduction did not hold because of the possibility of the coexisting of the other heat transfer mechanism in the fiber bulk materials such as the radiation heat transfer. The examination will be described later. As shown in Fig.2, the heating plate had layered construction; that is, the heating plate, which was winded uniformly by the electric resistance wires with two electric insulation rubbers, was sandwiched between the square plates of copper and brass of 3 mm thick and 800 mm wide. Also, the square plate of styrene foam of 50mm thick and 1000mm wide attached at the underside of heating plate for thermal insulation. The heat flux passing through the fiber bulk materials was determined by subtracting the heat passing through the thermal insulating material of lower end from an output of the electric heater. Here, the heat flux was decided by using the effective thermal conductivity determined by the following method and the temperatures of both surfaces. First, the heating plate was installed perpendicularly and the both surfaces of the heating plates were covered by the two identical styrene form board. The thermal symmetry and the condition in which the heat flux was equally divided into both sides of the heater could be realized. Next, the steady heating was carried out and the effective thermal conductivity was determined from the temperature difference between both surfaces of styrene foam. The temperature measurement in the fiber bulk materials and of the copper plate by thermocouples was performed. The apparent thermal resistance was determined by those temperatures near the center of the plates. Taking the low thermal conductivity of fiber bulk materials into consideration, the thermocouple wires of enough length were placed on the isothermal plane of parallel to the heating plate, and the error in the temperature measurement by the conduction in the thermocouple wire was minimized.

Three kinds of test fiber bulk materials, i.e., the prime class cotton, the 2nd class cotton and the polyester mixing cotton regulated by JIS L 2001 were used in the experiment.
The apparent thermal resistance was measured under the various volume fractions of the fiber bulk materials. Moreover, the decrease of the thermal resistance should be considered for the case where thin metal wires having comparatively high thermal conductivity was utilized. The test materials and its arrangement in each measurement are shown in Fig.3 (a) (b) in order to clarify the effect of the mixing of the shape memory alloy wires. In the experiment, the stainless steel wire whose thermal conductivity was similar to the shape memory alloy wire was mixed in the fiber bulk material of polyester mixing cotton. The set of 400 pieces of cotton fiber bulk materials with uniformly arranged thin metal wires was prepared as shown in Fig.3(a). The test materials was uniformly installed in the central part where the cotton fiber bulk materials of the 200mm square was hollowed out as shown in Fig.3(b) and its apparent thermal resistance was measured. After the temperature distribution inside the test material had sufficiently reached a steady state when about several hours have passed from a commencement of heating, the experiment was carried out in a closed room. The fiber bulk materials of the fixed mass were used in the experiment. The adjustment of the fiber volume fraction was carried out for the variation of the thickness by applying the external force. No instrument for keeping its volume fraction was utilized. Also, the measurements were carried out for several times by changing the configuration of the cotton samples to prevent the scattering due to the effect of the heterogeneity of thin metal wires.

Taking the sleeping environment into consideration, the heating plate temperature and the ambient air temperature were almost equal to the human body temperature and the room temperature, respectively. Furthermore, the fiber volume fraction from 0.08 to 0.25, thickness from 50 mm to 140 mm, the volume fraction of metal wires from 0.0005 to 0.005 and the diameter of the stainless steel wires from 0.02mm to 0.1mm were selected as the experimental conditions. Here, the volume fraction of thin metal wires was decided based on the possibility to deform the cotton fiber bulk materials as described in Chap.4.3. The density and the thermal conductivity of the cotton used for calculation shown in Chap.3.1 were based on the literature.

3. Investigation of the Mechanism of Heat Transfer in Fiber Bulk Materials

3.1 Numerical calculation model of heat conduction for determining apparent thermal resistance

By the consideration on the structure of the actual fiber bulk materials, the numerical model shown in Fig.4 was made to examine the mechanisms and the characteristics of heat transfer of the fiber bulk materials with/without the mixing of thin metal wires. That is, as a structure of the fiber bulk materials, two-dimensional model in which air and fiber part are distributed discontinuously was made, and the numerical analysis considering heat conduction as a heat transfer mechanism was carried out using the control volume method. Since the thermal conductivity of the fiber is larger than air, the apparent thermal conductivity of fiber bulk materials might be affected by the configuration of the fiber bulk materials. Although the fibers got entangled each
other three-dimensionally in actual fiber assembly, the
calculation was performed according to the two-dimensional
model of two types. The fibers were at right angle and
parallel to the heat flow as shown in Fig. S(a) and (b),
respectively. The thermal resistance calculated might be
higher than actual one for the configuration shown in
Fig. S(a). On the other hand, it might be smaller for Fig.S(b).
The calculating area was corresponding to X-Z plane of
1mm square of the central part of the test material. The cross
section of fiber is assumed to be rectangular. The closed and
mesh squares shown in Fig.S denoted the fibers. The other
part were filled with air. Three types of fibers of cotton,
polyester and thin metal wire were set at the fiber parts, and
they were uniformly arranged according to their volume
fractions. The diameter of the cotton fiber measured by the
photomicrography was about 0.01mm. Therefore, the
regular lattice interval of 0.01 mm or 0.005 mm in the
calculation was adopted so as to correspond the lattice
interval with the dimensions of the cotton and polyester
fibers. The boundary conditions of adiabatic for both sides
and isothermal for the top and underside were adopted. The
physical properties for the calculation are shown in Table 1.

3.2 Correspondence of sound absorption mechanism
to layered structure on tufted carpet

In general, there are the cases in which the effect of
radiation heat transfer cannot be ignored even in the range of
near room temperature especially for the relatively high
insulation system. The effect of radiation on the heat transfer
characteristics of fiber bulk materials in the thermal
environment in the sleeping time should be examined. Here,
the effect was estimated by using the two flux model
considering absorption, radiation and scattering of the fiber
bulk materials of three-dimensionally and randomly
arranged between the parallel flat plates of black body
modeled by Li et al. 9).

\[
C_r = \frac{\sigma (T_1' - T_2')}{1 + 2 \beta f_q z} \frac{d}{T_1 - T_2}
\]

Where, \( \sigma \) : Boltzmann constant, \( R \) : Fiber radius, \( T_1 \) : Higher temperature, \( T_2 \) : Colder temperature, \( Q_{ext} \) : Average
attenuation efficiency factor, \( f_q \) : Fiber volume fraction, \( d \) : Fiber bed thickness, \( \omega \) : Scattering Albedo of the fiber, and
\( b_r \) : Reverse scattering fraction

4. Results and Discussion

4.1 Relationship between fiber volume fraction and
apparent thermal resistance

The one-dimensional temperature distribution in which
upper-and-lower surfaces of fiber bulk materials showed
good uniformity except for length of about 100 mm from the
edges of the heating plate was achieved as seen in Fig.6.
Therefore, in measuring apparent thermal resistance of fiber
bulk materials, the validity of the measurement of the fiber
bulk materials at the central part was confirmed.

The relation between the volume fraction of the fibers and
the apparent thermal resistances is shown in Figs.7-9 for the
cotton fiber bulk materials mixed with polyester wires,
cotton fiber bulk materials of 2nd and prime classes,
respectively. The fiber volume fraction and the thickness
were 11.2% and 110 mm, respectively, for each case. Since
the net mass of the fiber bulk materials was fixed as
mentioned above, the fiber volume fraction varied with
change of the thickness. The similar method was adopted in
the measurements shown later. From these figures, the
maximum thermal resistance appeared at about 11% of fiber
volume fraction for all fiber bulk materials, and it was
shown that the thermal resistance decreased with going away
from the maximum points. In case of the heat conduction
without the effects of air-flow inside and radiation as a heat
transfer mechanism, the thermal resistance should increase
with the decrease of the fiber volume fraction. Therefore, the
decrease of the thermal resistance with decreasing fiber
volume fraction might be due to the effect of the in- and
out-flow of the air in the fiber bulk materials remarkably
appeared in the relatively low region of fiber volume
fraction. The heat retaining properties at the most optimal
conditions for all materials in this experiment resembled
each other and the maximum thermal resistances were about
0.6 m²K/W independent upon the kind of test fibers. Also,
the decreasing rate of apparent thermal resistances against
the volume change increased in order of the cottons of
polyester mixing, second-class and prime class. That is, the
dependence of the apparent thermal resistance on the volume
fraction was remarkable for the polyester mixing cotton.
Therefore, the polyester mixing cotton was most suitable for
controlling the heat retaining property in comparison with
other kind of cottons. It is possible to expect the thermal
resistance change of about 1.5 times by the volume change
in the region from the relatively larger fraction of fibers to
the volume fraction where maximum thermal resistance
appeared.

Table 1 Physical properties for calculation

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity W/(mK)</th>
<th>Density kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0.026</td>
<td>1.76</td>
</tr>
<tr>
<td>Cotton fiber</td>
<td>0.059</td>
<td>81</td>
</tr>
<tr>
<td>Polyester fiber</td>
<td>0.209</td>
<td>71</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>16</td>
<td>7920</td>
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</tbody>
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Next, the measurement concerning the effect of the mixing of thin metal wires on apparent thermal resistance is shown. Here, considering the similarity of thermal effect of the shape memory alloy, thin stainless steel wires to which the thermal conductivity was comparatively close was used as mixing wires. The variation of the apparent thermal resistance against the volume fraction of fibers of the polyester mixing cotton with mixing of the stainless steel wires of volume fraction 0.002 and the diameter of 0.05mm is shown in Fig.7. It was confirmed that the similar tendency was shown to the case without mixing of the thin metal wires.

For clarifying the effect of the diameter of metal wires, the relation between the diameter of stainless steel wires and the apparent thermal resistance is shown in Fig.10 for the polyester mixing cotton of 0.112 fiber volume fraction. The ratio of volume fraction of mixed stainless steel wires to the cotton fibers was fixed as 0.002 (mass fraction of 0.156). Since the heat conduction was augmented by mixing stainless steel wires in comparison with the materials without the steel wires, the thermal resistance decreased slightly as shown in Fig.10. The thermal resistance varied almost linearly against the diameter of the stainless steel wire and decreased with decreasing wire diameter. The decreasing rate of the thermal resistance due to the mixing of stainless steel wires was less than about 0.22. However, the effect of the mixing of the thin wires on the heat retaining property could be comparatively small as long as the wire diameter was not extremely small and was almost negligible.

Figure 11 shows the variation of the thermal resistance with varying the mixing volume fraction of stainless steel wires of 0.05mm in diameter in the polyester mixing cotton (fiber volume fraction of 0.112). The apparent thermal resistance and its decreasing rate decreased with the increase in volume fraction of stainless steel wires.

4.2 Comparison between results of numerical analysis of heat conduction and experiment, and effect of radiation heat transfer

The variations of the apparent thermal resistance against the fiber volume fraction calculated by the heat conduction analysis are shown in Fig.12, 13 and 14. Symbols of ○ and ● in each figure denote the cases where the fibers were parallel and at right angle to the heat flow, respectively. The experimental results shown in Figs.7 and 9 are also shown for comparison.

As shown in Fig.12, thermal resistance for the case of orthogonal heat flux was high compared with the parallel case for the polyester mixing cotton because of the larger thermal conductivity of fibers than air. However, the difference between both cases was not so large and the similar trend of variations could be observed. As described above, the thermal resistance for actual fiber bulk materials, where the fibers are arranged irregularly and randomly against the heat flow, seemed to have the medium value between both models. Therefore, it could be possible to predict the heat conduction effect using this model. Although there was the quite large difference between the
results of the conduction calculation and the measurement in the range near the fiber volume fraction of 0.11 where the maximum thermal resistance appeared, this difference decreased with increasing fiber volume fraction. Figure 13 shows the result for the prime class cotton. The similar tendency to the result for the polyester mixing cotton was shown. However, the difference due to the arrangement of the fiber was smaller than that for the case of polyester mixing. Figure 14 shows the results of the calculation and the experiment with the mixing of thin metal wires in the polyester mixing cotton. As well as the case shown in Fig.7 where the effect of the mixing of the thin metal wires was not so large, the similar result was obtained for the polyester mixing cotton shown in Fig.12. However, it was the effect of the metal wires of relatively high thermal conductivity arranged heat flow direction continuously that the smaller thermal resistance was obtained for the case of same direction of the fiber to the heat flow, and it was originated from the difference with actual arrangement.

Next, the experiment and the analytical result calculated
by Eq.(3) on the effect of thermal radiation are shown in Fig.15. The values are expressed by using the apparent thermal conductivity for comparison with other results shown previously. In the experiment and the analysis, the temperature of the heating plate was from 36°C to 61°C, the temperature difference between the plate and the upper surface of the fiber bulk materials was fixed to 7.5K, the volume fraction and thickness of fibers were 0.112 and 110mm, respectively, considering the sleeping environment. The ambient temperature was fixed to 11 °C in the experiment. Since, in this experiment, it was difficult to test the effect of the radiation separately, the measurement for the system in which other heat transfer mode was coexisted was performed. The effect of the radiation was weak due to the analytical result as shown in Fig.15 and was about 0.03 in the total quantity of heat transferred. Although the thermal conductance due to the radiation increased with the decrease in fiber volume fraction, its contribution could be ignored within the range in this study. Moreover, it can be said that the effect of the temperature change was not large because there was less than 10% change in the total range of temperature variation in the experiment. Since the effect of the radiation was little from these results, the validity of the method for determining the apparent thermal resistance based on the temperature distribution of the fiber bulk materials could be confirmed in this study. Here, it was probable that the comparatively large temperature dependency appeared in the experiment was owing to the existence of the effect of the air transfer between the fiber bulk materials and the ambient.

On the basis of the analyses of heat conduction calculation shown in Figs.12-14 and the radiation heat transfer in Fig.15, in the region of the fiber volume fraction of actual bedquilt, there was no sufficient explanation to the mechanism of heat transfer only by considering the heat conduction and the radiation. It was shown that the effect of the natural convection, which originated from the air transfer between the internal and external fiber bulk materials due to the temperature difference, on the difference between the calculation and the measurement of thermal resistance must be considered.

4.3 Experiment on change of volume fraction due to deformation of shape memory alloy wires

Finally, the volume change of fiber assembly was confirmed experimentally using the wires of Nickel-Titanium shape memory alloy of 0.09mm in diameter mixed in the polyester mixing cotton. The photographs before/after the shape change due to heating are shown in Fig.16(a) and (b). The heat treatment was carried out to give the shape memory effect, after the wires of the shape memory alloy was fixed by the gypsum in the condition that the alloy wires intertwined each other to some extent. The temperature of transformation of expansion after the processing was set at about 38°C. The aspects of the fiber volume fraction and the thermal resistance before and after the shape change are shown in Table 2. Since the thermal resistance increased about 1.4 times with the decrease of the volume fraction from 0.21 to 0.11, it could be understood that the remarkable improvement in the heat retaining property could be confirmed. Also, the good agreement quantitatively with the result showing in Fig.7 could be seen.

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5. Conclusions

The peak of sound absorption coefficient in medium frequency range observed with tufted carpets in the installed

The following conclusions were obtained on the basis of the investigation on variable thermal resistance of the fiber bulk materials of the bedquilt for keeping heat retaining property optimum against the change of ambient conditions.

(1) It was clarified experimentally that the heat retaining property (the apparent thermal resistance) had peak value against the volume fraction of cotton fiber bulk materials and there was about the double on the variable control range of apparent thermal resistance by giving the volume change to the polyester mixing cotton.

(2) Due to the results of measurement under the condition of changes in the volume fraction and the diameter of the thin metal wires that simulated the shape memory alloy, the lowering of the heat retaining property by mixing of thin metal wires could be almost negligible.

(3) In the region of relatively large fiber volume fraction, the heat conduction was dominant, because the calculation considering heat conduction almost coincided with the experiment. However, the difference between the results of the heat conduction calculated and the measurement increased with increasing porosity. Within the ranges of the temperature and the fiber volume fraction of the experiment, the effect of the radiation was small. Therefore, it could be probable that the effect of the natural convection that originated from the temperature difference appeared in the region of practical use of the cotton fiber bulk materials in which fiber volume fraction was comparatively small.

(4) It was shown that the apparent thermal resistance could be varied widely (1.4 times) by changing the volume fraction of the fiber bulk materials applying the shape memory alloy actually.

Finally, the gratitude is expressed to the former undergraduate student of Yokohama National University, Mr. Hideaki Negishi and Shintaro Ohgi for their cooperation.

References


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