Chapter 4

Effective Thermal Conductivity of Cupra and Polyester Fiber Assemblies in Low Fiber Volume Fraction

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Additional information is available at the end of the chapter

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Abstract

In this study, the effective thermal conductivity of staple fiber assembly for wadding use is measured using KES-F7 II Thermo Labo II apparatus. Sample used are cupra, polyester (with round and heteromorphic section), and polytrimethylene terephthalate (PTT) fibers. Heat flux to calculate thermal conductivity is measured including heat leakage from sidewall and is calibrated in the analysis. Results are analyzed by nonlinear regression method. Results are obtained as follows. Thermal conductivity curve is convex downward in low fiber volume fraction (<3%). Thermal conductivity, λ, is expressed as following equation, $\lambda = A\phi + B/\phi + C$, where ϕ is fiber volume fraction, A and B are coefficients, and C is constant determined by nonlinear regression analysis. Based on this equation, the effective thermal conductivity is divided into three parts: $A\phi$, heat conduction in fiber; B/ϕ, radiative heat transfer; and C, heat conduction within air. By calibration, C component is divided into thermal conductivity of air, λ_{air} and heat leakage from sidewall of the sample frame. λ_{air} plays the most important role in thermal insulation property of fiber assembly, and component of heat conduction in fiber, $A\phi$, follows in higher fiber volume fraction. Component of radiative heat transfer, B/ϕ, is negligible small.

Keywords: effective thermal conductivity, fiber assembly, cupra fiber, polyester fiber, nonlinear regression

1. Introduction

In this chapter, a method to evaluate thermal insulation properties of staple fiber assembly for wadding use is proposed. Fiber assembly in low fiber volume fraction is a system which consists of a lot of air and a small amount of fiber, and its heat transfer mechanism is supposed to include convective and radiative heat transfer in addition to conductive heat transfer.

Therefore, it is not suitable to use thermal conductivity to evaluate thermophysical properties of fiber assembly. Instead, a concept of effective thermal conductivity is suitable to evaluate thermophysical properties of fiber assembly which can include different types of heat transfer mechanisms such as conduction, convection, and radiation. In this chapter, the effective thermal conductivity is used to evaluate thermal insulation properties of fiber assembly in low Fiber volume fraction, Φ for wadding use. In addition, a model to explain heat transfer mechanism within fiber assembly is proposed.

Effective thermal conductivity is measured based on guarded hot plate (GHP) method using KES-F7II Thermo Labo II apparatus (Kato Tech Ltd.). Fiber sample is put uniformly into sample frame made of polystyrene foam. In the measurement, sample system made of fiber assembly and sample frame is placed between heat source plate and heat sink, and heat flow to keep heat source temperature constant is measured.

Samples used are polyethylene terephthalate and cupra staple fiber assembly. Effective thermal conductivity is measured under various sample thickness and fiber volume fraction. The results are analyzed based on nonlinear regression method, and heat transfer mechanism within fiber assembly is discussed based on the result of analysis. Finally, designing of fiber assembly-based thermal insulation materials is investigated.

2. Background

Studies on heat conduction of fiber assembly have been conducted by Nogai et al. [1, 2], Fujimoto et al. [3], and Ohmura et al. [4] in Japan. Nogai et al. carried out theoretical and experimental study of heat transfer mechanism of polyester fiber assembly [1, 2]. Fujimoto et al. investigated the effective thermal conductivity of clothing materials for protection against cold [3]. Ohmura et al. studied the effective thermal conductivity of fibrous thermal insulation materials for building [4].

In all papers, it is confirmed that effective thermal conductivity- fiber volume fraction curve in low fiber volume fraction (<10%) shows the shape of convex downward. The fact that effective thermal conductivity curve has a minimum value gives a reason that fiber assembly have been widely used for thermal insulation materials. The minimum value in effective thermal conductivity curve was explained by increasing radiative heat transfer through pore space with increasing porosity based on their experimental and theoretical results and heat transfer model. Nogai et al. [1, 2] derived these facts based on uniaxial-oriented fiber assembly model considering conduction in fiber and radiative heat transfer. Fujimoto et al. [3] derived these facts based on serial-parallel model of heat transfer which is composed of fiber and pore part including radiative heat transfer.

In this study, effective thermal conductivity of fiber assembly in low fiber volume fraction is analyzed using empirical equation by nonlinear regression method [4–7]. The reason that fiber assembly has been used for thermal insulation materials is further investigated through the separation of heat transfer component of effective thermal conductivity.

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3. Method

3.1. Materials

Four kinds of fiber materials used in this experiment such as cupra fiber (CU), polyester fiber with round section (RPE), polyester fiber with heteromorphic (W-shape) section (WPE), and polytrimethylene terephthalate fiber (PTT) of which fineness and fiber length are almost the same. The web after opening and carding process is conditioned under the environment of 20°C and 65% RH for 24 h. Fiber assembly is served as sample after conditioning. The details of fiber samples are shown in **Table 1**.

Main parameter for the measurement of effective thermal conductivity is fiber volume fraction in this experiment. Thermophysical properties for different fiber materials which have different specific gravity are compared under the same fiber volume fraction. Fiber volume fraction is defined as the ratio of fiber volume to apparent volume of fiber assembly. Fiber volume fraction Φ is calculated using following equation.

$$\Phi = \frac{W}{\rho_f \, d \, h^2} \tag{1}$$

where W is sample weight (g), ρf is specific gravity of fiber (n.d.), h is side length of heat plate (cm), and d is thickness of sample (cm). Staple fiber sample (W g) is filled uniformly into the space surrounded by wall of polystyrene foam of which inner size is 5 cm square and constant height (2, 3, and 5 cm). **Figure 1** shows sample frame filled with fiber assembly. **Figure 2** shows a plan of sample frame.

In this experiment, the effect of fiber volume fraction and sample thickness on effective thermal conductivity of fiber assembly is investigated. Fiber volume fraction is changed by five

Sample code	Detail of sample	Fineness (dtex)	Fiber length (mm)	Fiber diameter (μm)	Specific gravity (n.d.)	Percentage of crimp (%)
CU	Cupra-ammonium (Cupra) staple fiber	1.4	38	11.84	1.50	8.79
RPE	Polyester staple fiber with round section	1.3	38	12.76	1.38	26.70
WPE	Polyester staple fiber with w-shaped heteromorphic section	1.4	38	24.22*1 / 6.27*2	1.38	14.80
PTT	Polytrimethyleneterephtalate staple fiber	1.7	51	15.02	1.34	15.43

*1: a longer axis, *2: a minor axis

Table 1. Details of fiber samples for wadding use.

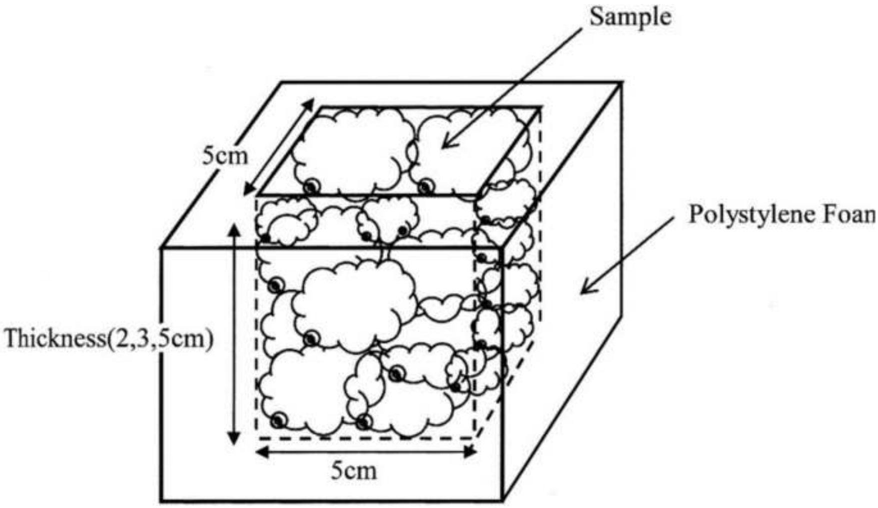

Figure 1. Schematic diagram of filling fiber sample into frame made of polystyrene foam.

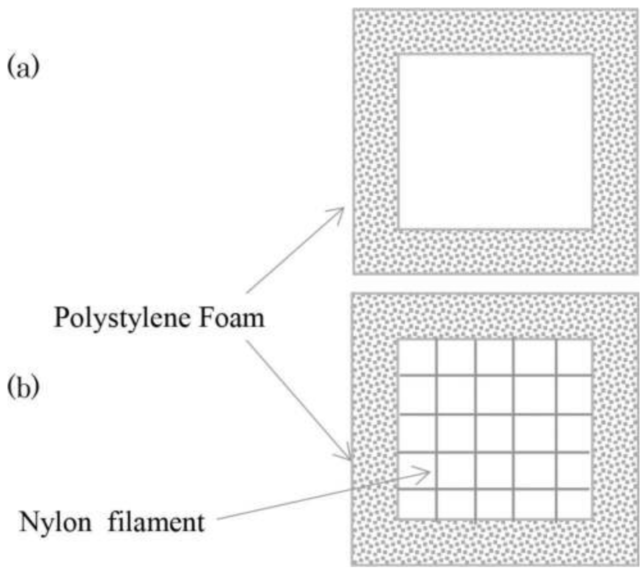

Figure 2. Frame made of polystyrene foam (a) top view and (b) bottom view.

stages such as 0.001, 0.005, 0.010, 0.025, and 0.030. Sample thickness is changed by three stages such as 2, 3, and 5 cm. One kind of fiber is, therefore, measured under 15 conditions. Sample weight for each fiber under different condition is shown in **Table 2**.

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3.2. Measurement method

Effective thermal conductivity is measured using KES-F7II Thermo Labo II apparatus (Kato Tech Ltd.) [8]. Heat flux which flows through fabric sample from heat source plate (BT-Box) to heat sink is measured based on guarded hot plate (GHP) method. Schematic diagram of measurement part (section) is shown in **Figure 3**. Fiber sample is put uniformly into frame made of polystyrene foam of which inner size is 5 cm square and constant thickness. Fiber assembly with sample frame is placed between heat source plate and heat sink and measurement of heat flow is carried out. The experiment is conducted in a controlled environment room of which temperature is 20°C and humidity is 65% RH.

Heat source temperature (BT-Box) is set at 30°C and temperature of heat sink is set at 20°C, and thus, temperature difference is 10°C. Heat source plate is placed on upper side of sample and heat sink is placed on lower side, and thus the direction of heat flow agrees with the direction of acceleration of gravity. Upper side of heat sink is made of metal plate and temperature of heat sink is controlled at 20°C by cooling device driven by Peltier element.

Sample	Volume fraction	Thickness of a sample		
		2cm	3cm	5cm
Cupra	0.001	0.075	0.113	0.188
	0.005	0.375	0.563	0.938
	0.010	0.750	1.125	1.875
	0.025	1.875	2.813	4.688
	0.030	2.250	3.375	5.625
Polyester	0.001	0.069	0.104	0.173
	0.005	0.345	0.518	0.863
	0.010	0.690	1.035	1.725
	0.025	1.725	2.588	4.313
	0.030	2.070	3.105	5.175
PTT	0.001	0.067	0.101	0.168
	0.005	0.335	0.503	0.838
	0.010	0.670	1.005	1.675
	0.025	1.675	2.513	4.188
	0.030	2.010	3.015	5.025

Table 2. Sample weight for each measurement condition (unit: G).

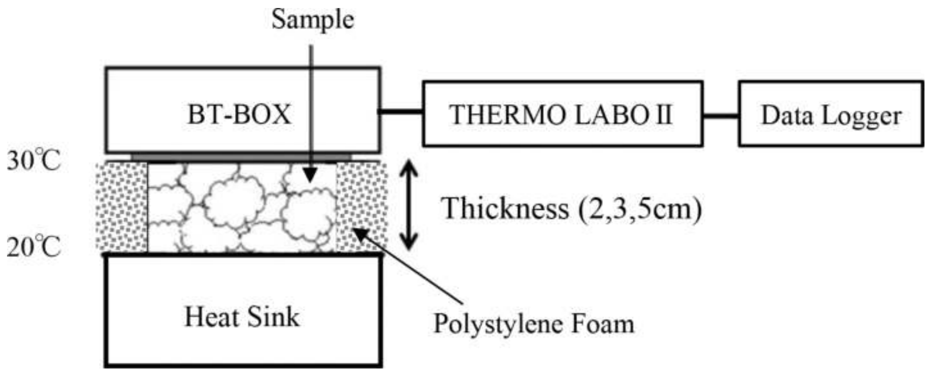

Figure 3. Measurement of thermal conductivity.

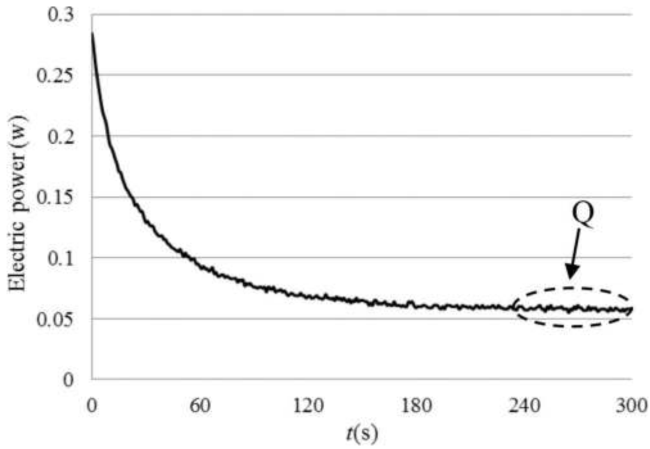

Figure 4. Method to obtain heat flux in steady state.

In the measurement, fiber assembly with sample frame is placed between heat source plate and heat sink, and electric power (W) is measured to keep heat source temperature steady state. Output signal of electric power is recorded with data logger which is connected to output terminal. Output signal is recorded at intervals of 1 s with time elapsed. An example of measurement is shown in **Figure 4**. Electric power is recorded against time from the contact between heat source and sample to the steady sate. Electric power, Q (W), is obtained from mean value between 4 and 5 min. Effective thermal conductivity, λ (W/mK), is calculated from the following equation:

$$\lambda = \frac{Qd}{A\Delta T} \tag{2}$$

where Q is electric power to keep steady state (W), d is sample thickness (m), A is area of heat source plate, and ΔT is temperature difference between heat source plate and heat sink (K).

In this experiment, a small amount of heat flow through insulation material is measured. Therefore, care must be taken so that measurement part (BT-Box and heat sink) is not affected by unexpected influence of heat caused by convective and radiative heat transfer. As for radiative heat transfer, board made of polystyrene foam is set up in the front, right, and left side of measurement part to block radiative heat transfer from operator. As for convective heat transfer, it is desirable that a device which may cause convection should be removed from the place where experiment is conducted.

4. Results

Effective thermal conductivity of staple fiber assembly is measured under three different thickness and five different fiber volume fractions. Results obtained from the measurement are investigated in connection with fiber volume fraction, sample thickness, fiber materials, and so on. In this experiment, three times of measurement were carried out for each condition, and mean value and standard deviation were obtained.

In the first place, the relation between effective thermal conductivity and fiber volume fraction is investigated in relation to fiber material. **Figures 5–7** show the results between effective thermal conductivity and fiber volume fraction. **Figures 5–7** show the results of 2, 3, and 5 cm thickness, respectively. In each graph, the ordinate denotes effective thermal conductivity (W/mK) and the abscissa denotes fiber volume fraction (n.d.). The fact that the level of the magnitude of thermal conductivity increases with increasing thickness is observed and this will be discussed later. Here, we concentrate on the relation between effective thermal conductivity and fiber

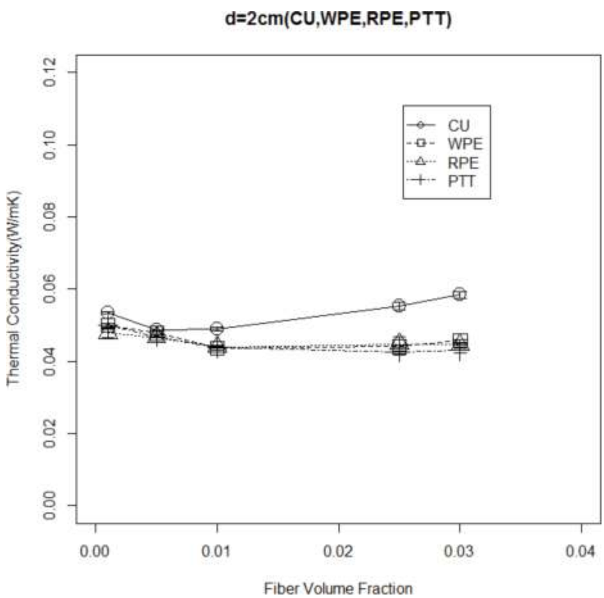

Figure 5. Thermal conductivity plotted against fiber volume fraction when thickness of sample is 2 cm.

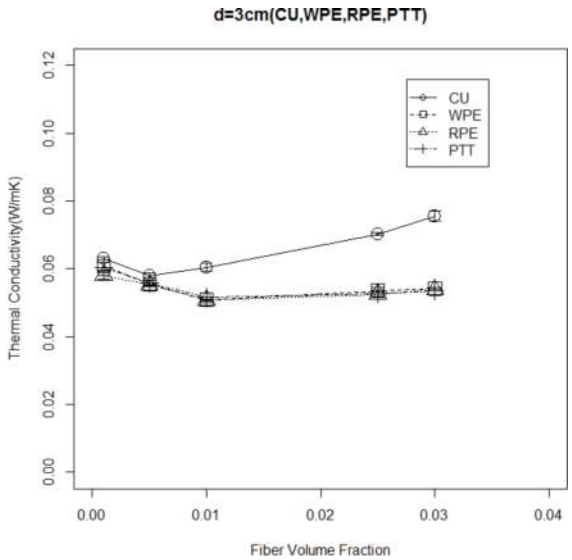

Figure 6. Thermal conductivity plotted against fiber volume fraction when thickness of sample is 3 cm.

volume fraction for the result of 5-cm thickness. Magnitude of effective thermal conductivity is compared under constant thickness. CU is the largest and polyester fiber group (RPE, WPE, PTT) follows. There is no significant difference among RPE, WPE, and PTT within the range of this method.

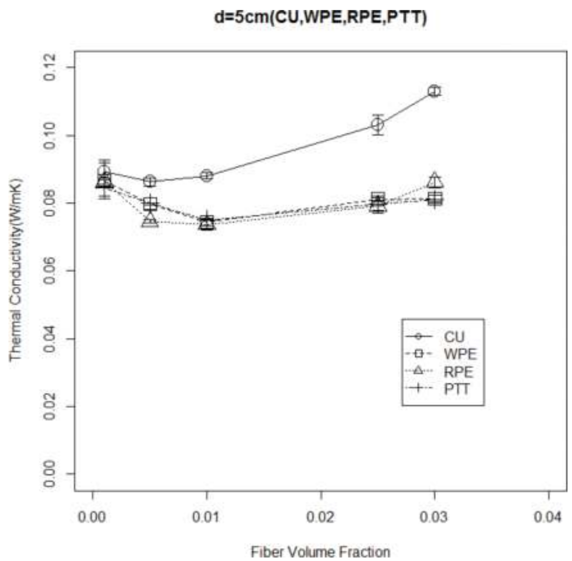

Figure 7. Thermal conductivity plotted against fiber volume fraction when thickness of sample is 5 cm.

Next, the effect of fiber material on the relation between effective thermal conductivity and fiber volume fraction is investigated. For each material, the shape of thermal conductivity curve is convex downward. The feature of the curve for each fiber material is as follows.

For CU, the minimum value of thermal conductivity lies around $\phi = 0.005$ and thermal conductivity increases with increasing ϕ. For RPE, WPE, and PTT, the minimum value of thermal conductivity lies around $\phi = 0.01$ and thermal conductivity increases a little to $\phi = 0.03$. For CU, thermal conductivity increases a little when ϕ decreases from 0.005 to 0.001. For RPE, WPE, and PTT, thermal conductivity increases a little when ϕ decreases from 0.01 to 0.001. With decreasing thickness from 3 to 2 cm, the level of thermal conductivity decreases and the shape of curve becomes flattened.

Figure 8 shows the relationship between effective thermal conductivity and sample thickness for $\phi = 0.01$. The ordinate denotes effective thermal conductivity and the abscissa denotes sample thickness. Clearly, thermal conductivity increases linearly against thickness for all samples.

Effective thermal conductivity obtained in this section is tentative value including leakage of heat from sidewall. In the following section, the separation of effective thermal conductivity into elemental process of heat transfer will be discussed. The thickness dependence of effective thermal conductivity shown in **Figure 8** will be investigated after the discussion about the separation heat transfer component.

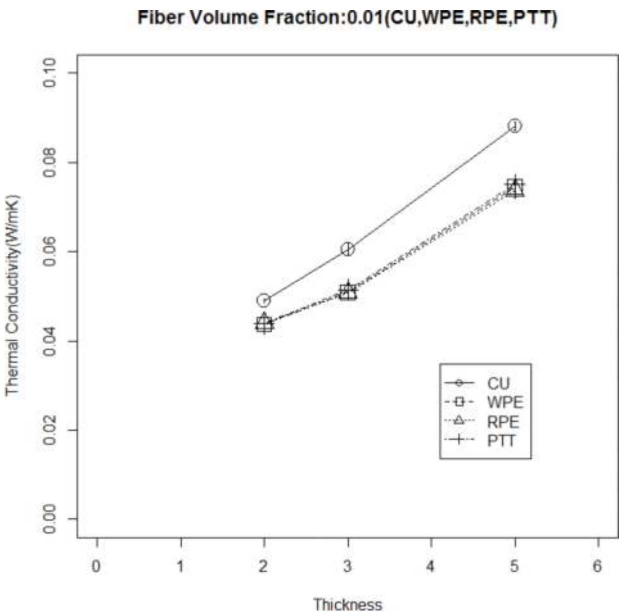

Figure 8. Thermal conductivity plotted against thickness when volume fraction of sample is 0.01.

5. Analysis

5.1. Analysis by nonlinear regression model

Because porosity of fiber assembly in this study is very large (97–99%), it is conjectured that the mechanism of heat transfer within fiber assembly is very much influenced by the effect originated from pore structure. The mechanism of heat transfer in fiber assembly consists of conduction in fiber, radiation in pore between fibers, and gas conduction (air), when forced convection does not occur. Here, it is supposed that heat flows through parallel model which is made of three components of heat transfer mentioned above. Measured value of effective thermal conductivity, λ (W/mK), is expressed by the following equation as a function of bulk density ρ(kg/m^3) [4–7]:

$$\lambda = A\rho + B/\rho + C. \tag{3}$$

where A (Wm^2/Kkg) and B (Wkg/m^{4}K) are constant coefficients and C (W/mK) is constant. The first term at the right side denotes conductive heat transfer in fiber, the second term

Parameter	Sample code	Thickness of a sample		
		2cm	3cm	5cm
A	CU	4.51×10^{-1}	7.51×10^{-1}	1.04
	RPE	-2.45×10^{-2}	3.76×10^{-1}	5.54×10^{-1}
	WPE	-1.68×10^{-2}	7.68×10^{-2}	2.51×10^{-1}
	PTT	-1.04×10^{-1}	5.25×10^{-3}	1.83×10^{-1}
B	CU	9.03×10^{-6}	1.04×10^{-5}	1.05×10^{-5}
	RPE	2.73×10^{-6}	6.42×10^{-6}	1.89×10^{-5}
	WPE	5.20×10^{-6}	9.62×10^{-6}	1.30×10^{-5}
	PTT	4.68×10^{-6}	8.10×10^{-6}	9.75×10^{-6}
C	CU	4.41×10^{-2}	5.20×10^{-2}	7.78×10^{-2}
	RPE	4.52×10^{-2}	5.18×10^{-2}	6.70×10^{-2}
	WPE	4.51×10^{-2}	5.13×10^{-2}	7.36×10^{-2}
	PTT	4.54×10^{-2}	5.25×10^{-2}	7.48×10^{-2}
Air		2.62×10^{-2}	2.62×10^{-2}	2.62×10^{-2}

Table 3. List of coefficients A, B, and constant C.

denotes radiative heat transfer, and the third term denotes conductive heat transfer through gas (air) in pore. (The details of parameters A, B, and C are shown in the Appendix.)

In this study, bulk density, ρ in Eq. (3) is replaced by fiber volume fraction, ϕ as follows,

$$\lambda = A\phi + B/\phi + C. \quad (4)$$

This is because ϕ plays an equivalent role of ϱ which expresses quantity of fiber. Results of the effective thermal conductivity of fiber assembly are analyzed by nonlinear regression method based on Eq. (4). Nonlinear regression analysis is carried out using **R** (ver. 3.1.1).

Estimated values of parameters A, B, and C obtained by nonlinear regression analysis are shown in **Table 3**, where A is coefficient of conduction in fiber, B is coefficient of radiative heat transfer, and C is conductive heat transfer in gas (constant). Calculated values of effective thermal conductivity using estimated values of A, B, and C are shown in **Figures 9–12**. **Figures 9–12** show the results of thickness of 2, 3, and 5 cm for CU, RPE, WPE, and PTT fiber, respectively. In each graph, the ordinate denotes effective thermal conductivity, λ(W/mK),

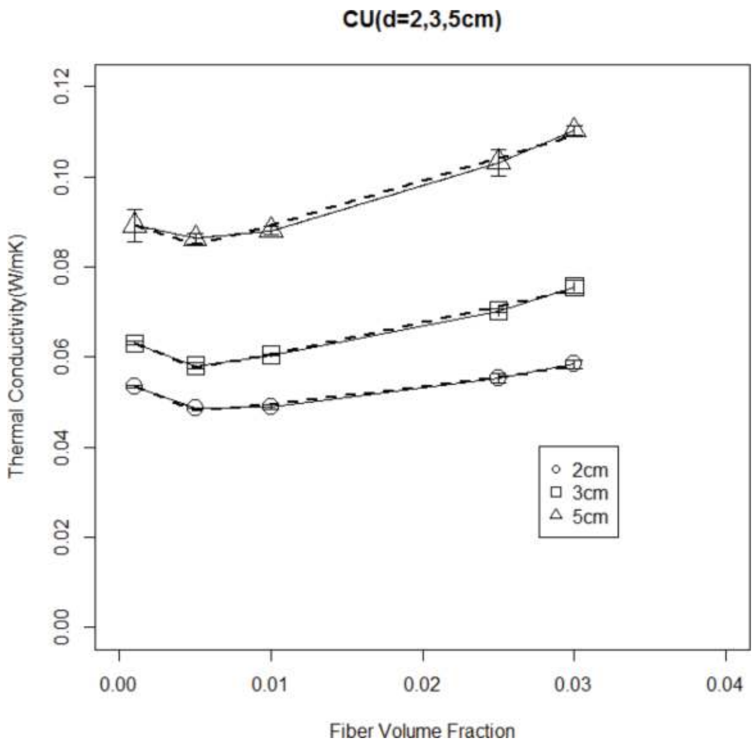

Figure 9. Comparison between calculated and measured values for CU. Symbols ○, □, Δ, and straight line: Measured values; broken line: Calculated values obtained by nonlinear regression analysis.

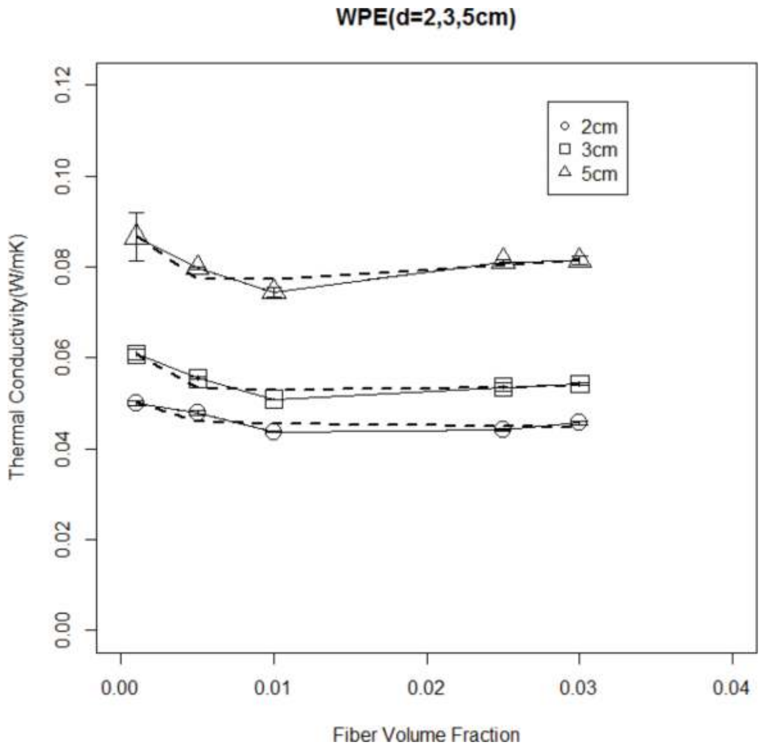

Figure 10. Comparison between calculated and measured values for WPE. Symbols ○, □, △, and straight line: Measured values; broken line: Calculated values obtained by nonlinear regression analysis.

and the abscissa denotes fiber volume fraction (n.d.). Symbols (○, △, □) and solid line show measured values, and broken line shows regression curve using estimated values of A, B, and C. As shown in figures, agreement between measured and calculated curves of effective thermal conductivity is very good.

5.2. Analysis of heat transfer components

Calculated curves of separation of components using estimated values of A, B, and C are shown in **Figures 13–16**. **Figures 13–16** show the results of 3-cm thickness for CU, RPE, WPE, and PTT fiber, respectively. The ordinate denotes effective thermal conductivity, λ(W/mK), and the abscissa denotes fiber volume fraction, ϕ(n.d.). Dashed line shows component of conduction in fiber, $A\phi$, dash-dotted line shows component of radiative heat transfer, B/ϕ, two-dot chain line shows component of gas conduction, C, and solid line shows the measured value of effective thermal conductivity. Based on these graphs, the ratio of each component to effective thermal conductivity and the effect of pore in fiber assembly can be discussed for each fiber materials. It is clear that the ratio among $A\phi$, B/ϕ, and C is different for different fiber materials.

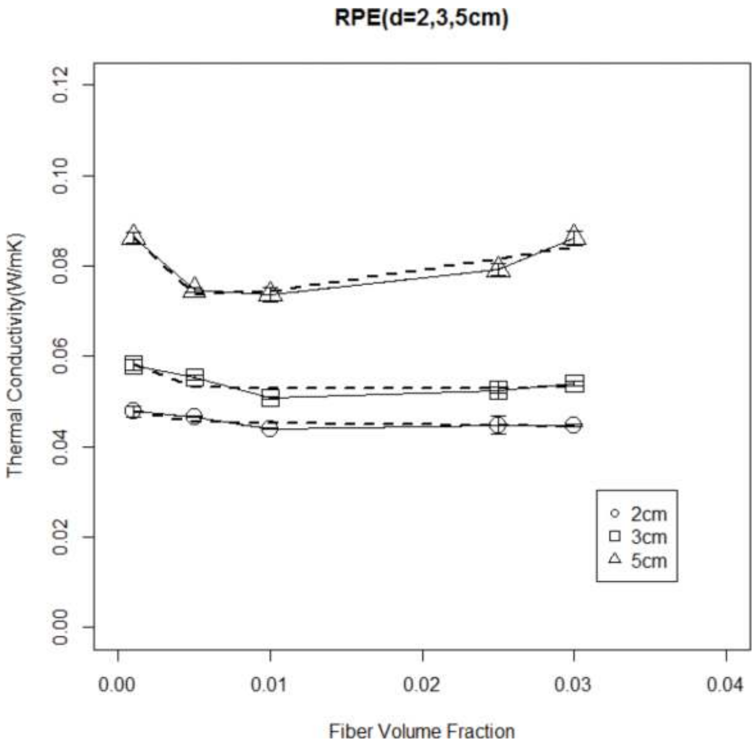

Figure 11. Comparison between calculated and measured values for RPE. Symbols ○, □, △, and straight line: Measured values; broken line: Calculated values obtained by nonlinear regression analysis.

First, component of conduction in fiber, Aϕ is investigated. Physical meaning of A is increasing rate of conduction in fiber against ϕ. As shown in **Table 3**, coefficient A varies with fiber materials. CU has large A value compared to polyester fibers (RPE, WPE, PTT), and increasing rate of conduction in fiber is also large. As a result, the ratio of Aϕ to effective thermal conductivity of CU is 30 percent at ϕ = 0.03. In contrast, the ratio of Aϕ of WPE is less than 20% at ϕ = 0.03. Large ratio of conduction in fiber and large increasing ratio to ϕ is the feature of CU fiber compared to polyester fibers.

Second, component of radiative heat transfer, B/ϕ, is investigated. Generally, the ratio of B/ϕ to effective thermal conductivity is negligibly small for all samples. Contribution of B/ϕ is slightly recognized below ϕ = 0.005. It is observed that component of radiative heat transfer increases with decreasing fiber volume fraction, ϕ, from 0.005 to 0.001. In this study, the ratio of radiative heat transfer is very small compared to the previous results obtained by Nogai and Fujimoto [1–3]. This may arise from the difference in the degree of fiber orientation in fiber assembly. While Nogai and Fujimoto [1–3] cover fiber assembly with high degree of fiber orientation, we concentrate on fiber assembly with random orientation. Because frequency of collision between radiant heat and fiber is very large for randomly oriented fiber assembly, decay of radiation energy by absorption may become large.

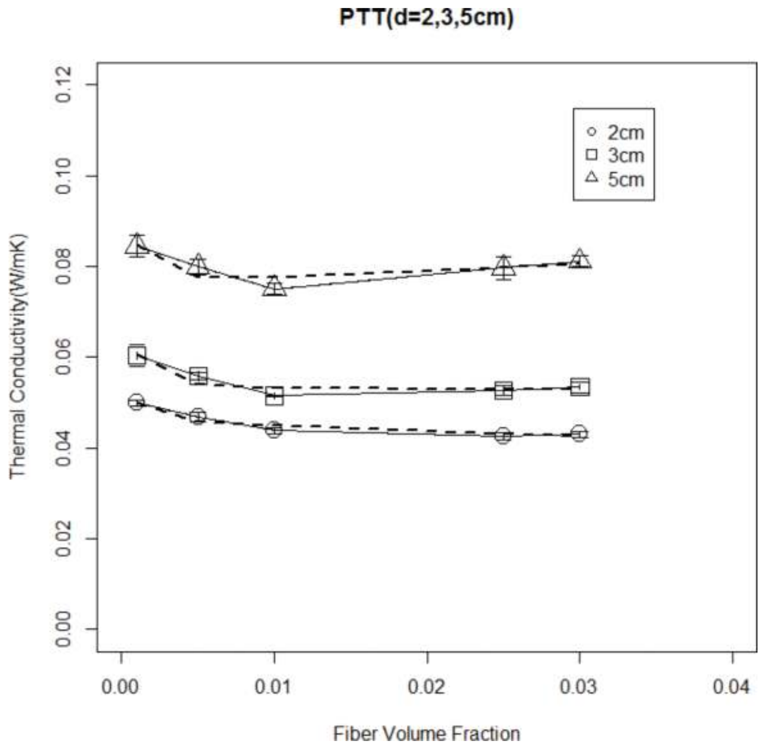

Figure 12. Comparison between calculated and measured values for PTT. Symbols ○, □, △, and straight line: Measured values; broken line: Calculated values obtained by using nonlinear regression analysis method.

5.3. Analysis of gas conduction

In this section, component of gas conduction, C, is investigated. Looking over **Figures 13–16**, it seems that component of gas conduction, C, occupies the dominant part in effective thermal conductivity in many cases. Therefore, physical meaning of gas conduction C is discussed, hereafter. Estimated values of C for samples of 2-, 3-, and 5-cm thickness are shown in the lower part of **Table 3**. It seems that C values for each thickness have almost constant value despite different samples. On the other hand, the value of thermal conductivity of air, λ_{air}, in this measurement condition (25°C, 1 atm) is 2.62×10^{-4} (W/mK) in Ref. [9]. Taking into consideration that parameter C has same value for same thickness and C must include thermal conductivity of air, λ_{air}, let us suppose that following relation holds:

$$C = \lambda_{air} + C' \tag{5}$$

where C′ is constant independent of fiber volume fraction, ϕ. Mean values of each thickness, C_{mean}, thermal conductivity of air, λ_{air} and C′ are shown in **Table 4** for the discussion in this section. It seems that C′ increases with increasing thickness. Relation between C′ and thickness

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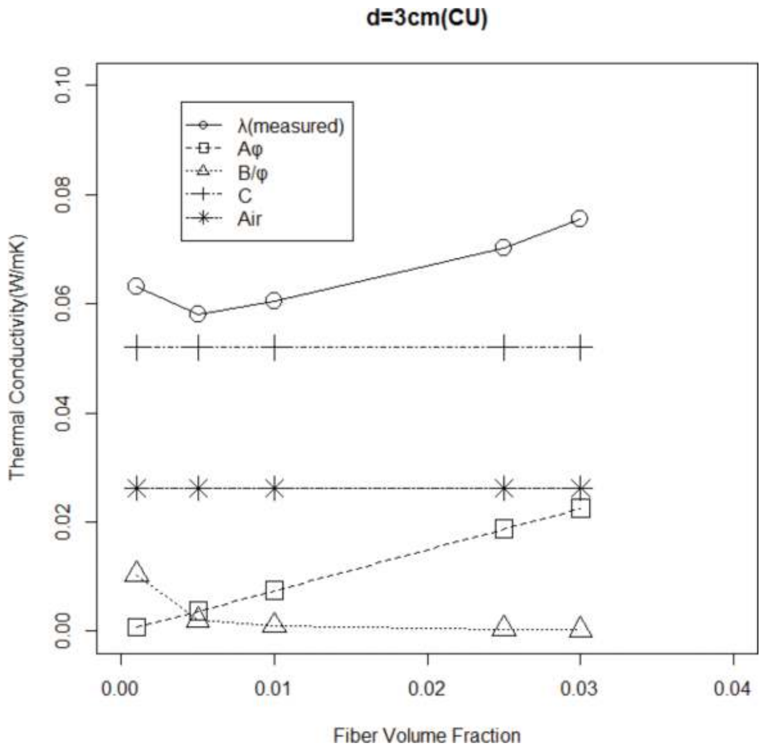

Figure 13. Separation of heat transfer component by nonlinear regression analysis for CU.

is analyzed by linear regression method. The results are shown in **Figure 17**. C′ and thickness, d, have good correlation, and the regression equation is given as follows,

$$C' = 0.9325\,d - 0.0425\ (R^2 = 0.996). \tag{6}$$

Because intercept is almost 0, C′ can be expressed approximately as linear function of d:

$$C' = k\,d\ (k\!:\!\text{constant}) \tag{7}$$

On the other hand, a function which expresses leakage of heat from sidewall of the frame is derived from another point of view. As inner side length of sample frame is 5 cm, total area of sidewall, A is expressed as following equation:

$$A = 4 \times 5 \times d\ (\text{cm}^2). \tag{8}$$

Here, temperature gradient along thickness direction is ignored for the simplification. Thus, leakage of heat per unit area along horizontal direction is assumed to be constant. Total leakage of heat from sidewall, Q′, is proportional to total area of sidewall which is expressed as follows:

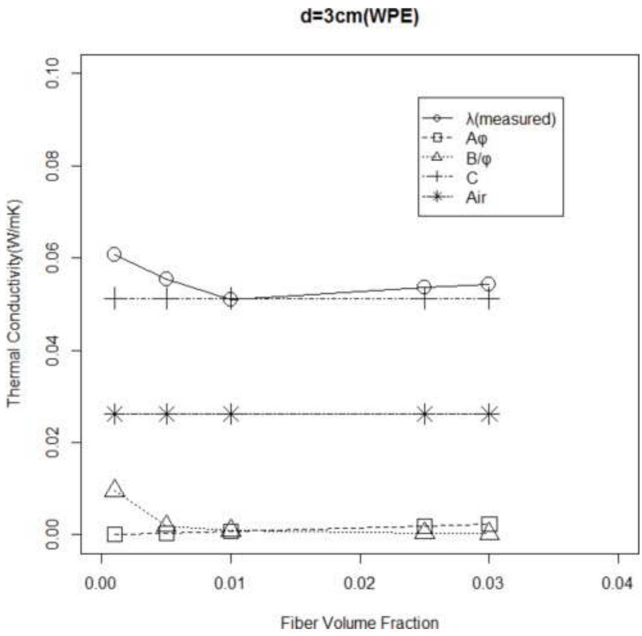

Figure 14. Separation of heat transfer component by nonlinear regression analysis for WPE.

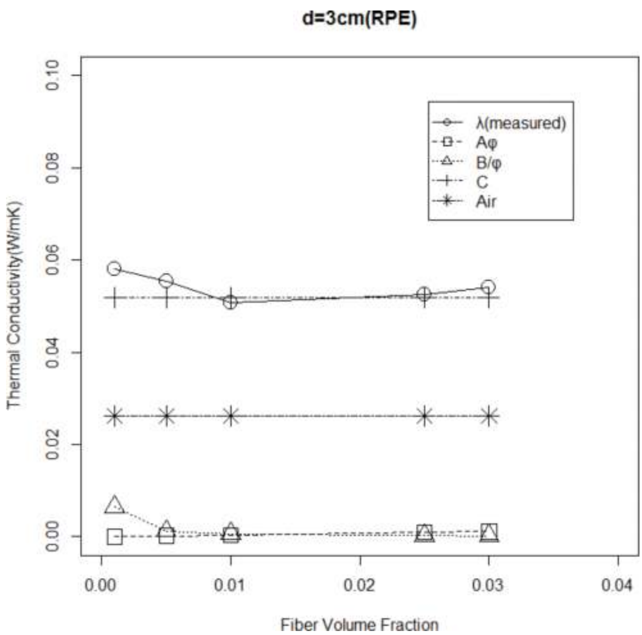

Figure 15. Separation of heat transfer component by nonlinear regression analysis for RPE.

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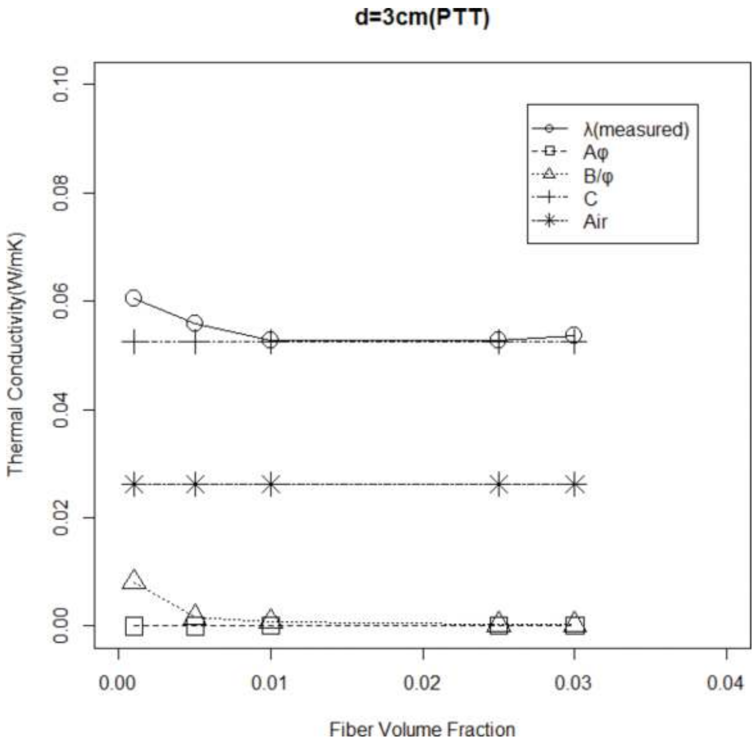

Figure 16. Separation of heat transfer component by nonlinear regression analysis for PTT.

$$Q' \propto A \propto d \qquad (9)$$

This equation predicts that total leakage of heat from sidewall is proportional to thickness, d, and equals 0 at d = 0. This property coincides with the expression, C′ = k d in Eq. (7). Summarizing the discussion above, C′ can be regarded as total leakage of heat from sidewall.

Based on the discussion above, total leakage of heat, C′, can be eliminated from C value. Here, C values in **Figures 13–16** can be replaced by λ_{air} (=C-C′). The results are shown in **Figures 18–21**, where the abscissa denotes true effective thermal conductivity. It is concluded that large part

Thickness (cm)	C_{mean}	λ_{air}	C′
2	4.495×10^{-2}	2.62×10^{-2}	1.875×10^{-2}
3	5.19×10^{-2}	2.62×10^{-2}	2.57×10^{-2}
5	7.33×10^{-2}	2.62×10^{-2}	4.71×10^{-2}
Unit: W/mK			

Table 4. Figures for calibration of leakage of heat.

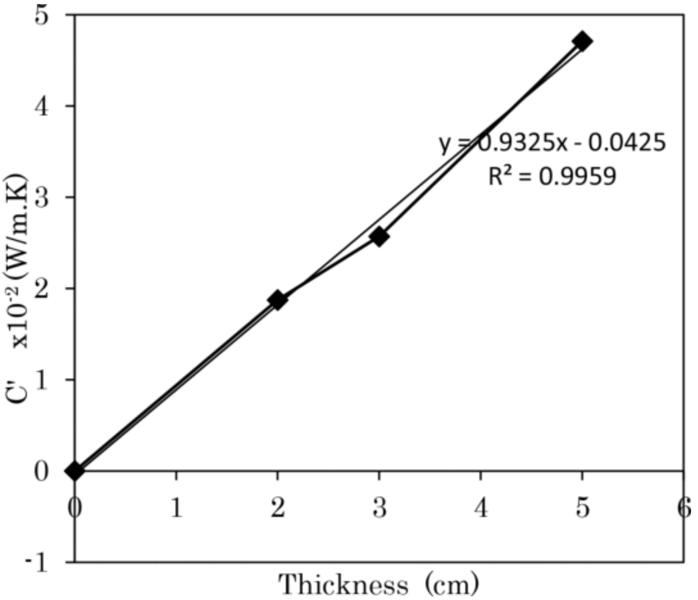

Figure 17. Function for the calibration of leakage of heat.

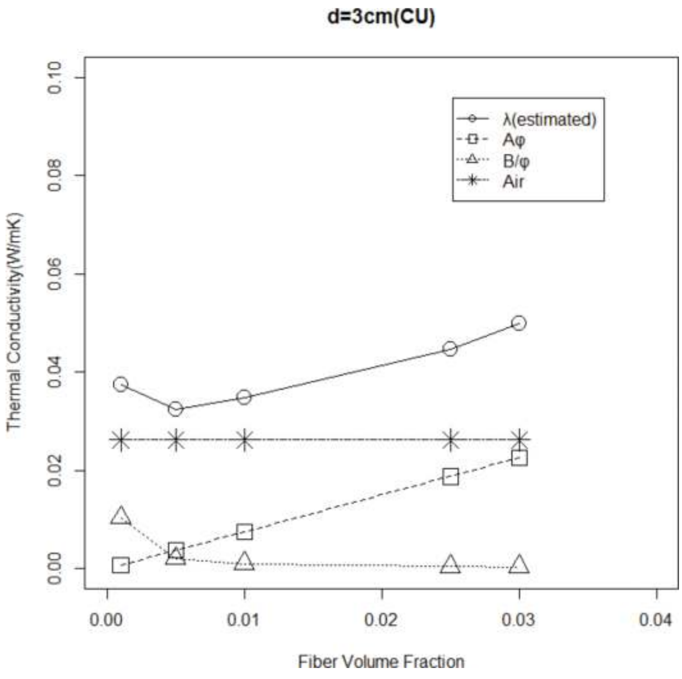

Figure 18. Estimated values of effective thermal conductivity and its component (sample: CU, d = 3 cm).

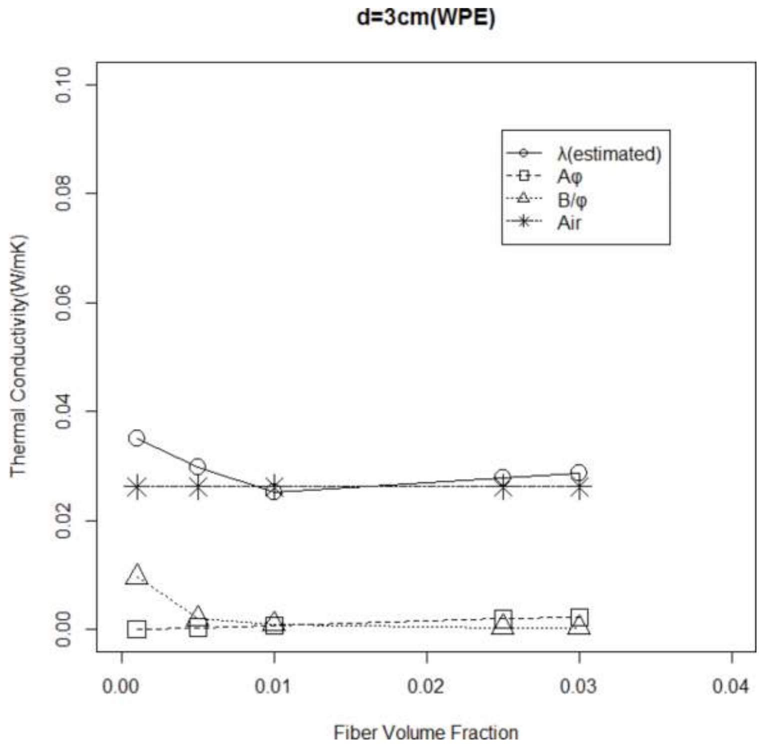

Figure 19. Estimated values of effective thermal conductivity and its component (sample: WPE, d = 3 cm).

of effective thermal conductivity of fiber assembly consists of thermal conductivity of air (still air), λ_{air}. It should be noted that the air is trapped by small amount of fiber ($\phi < 0.03$). (Explanation of this effect is given in the Appendix.)

Contribution of fiber material to the effective thermal conductivity is expressed by A, coefficient of conduction in fiber. Physical meaning of A is increasing rate of conduction in fiber and it consists of two parts, that is, heat conduction through fiber and heat conduction at contact point between fibers. It is conjectured that magnitude of A depends on contact effect between fibers compared to conduction through fiber. In this measurement, $A\phi$ component of cupra fiber (CU) is relatively large and that of polyester fibers (RPE, WPE, PTT) is relatively small. Polyester fibers have advantage in thermal insulation material because $A\phi$ component is small over the wide range of fiber volume fraction.

Based on nonlinear regression model, measured value of effective thermal conductivity can be separated into three components, such as conduction in fiber, radiative heat transfer, and gas conduction. Schematic diagram of the model is shown in **Figure 22**. Gas conduction plays the most important role in thermal insulation properties, which originates from immovable air trapped by fibrous network. Component of conduction in fiber has secondary contribution to thermal insulation properties, especially in the range of higher fiber volume fraction. Although radiative heat transfer slightly appears in low range of fiber volume fraction,

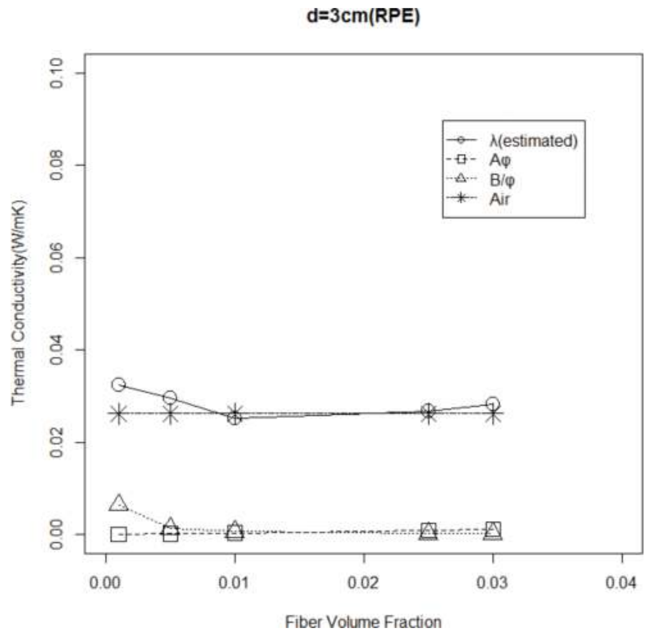

Figure 20. Estimated values of effective thermal conductivity and its component (sample: RPE, d = 3 cm).

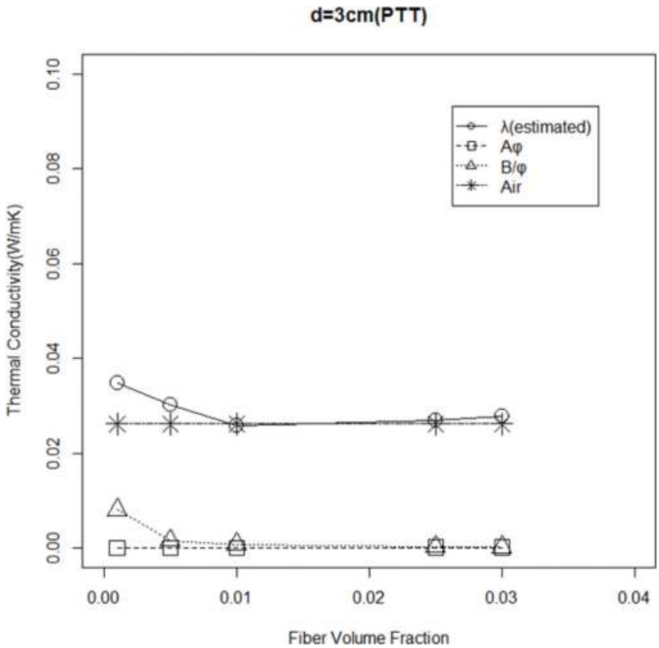

Figure 21. Estimated values of effective thermal conductivity and its component (sample: PTT, d = 3 cm).

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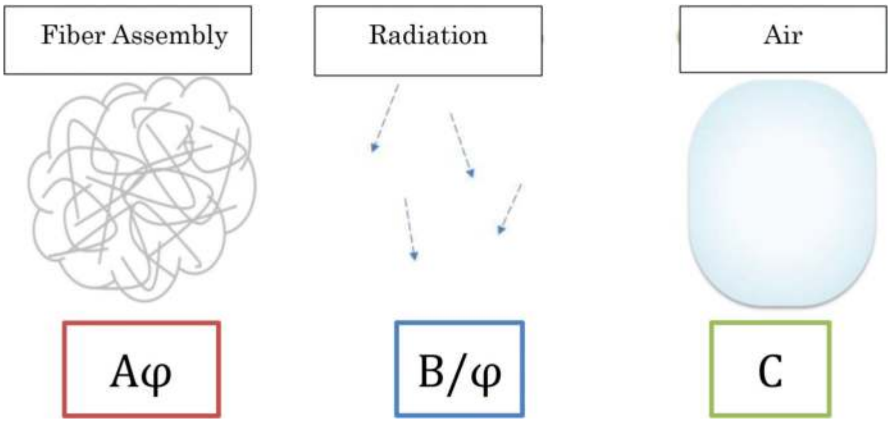

Figure 22. Mechanism of heat transfer in fiber assembly.

contribution of radiative heat transfer is negligible small to effective thermal conductivity of fiber assembly with random orientation. It is conjectured that relative ratio of each heat transfer component depends on fiber material and the effect of pore structure. These findings will be basic information for designing fiber assembly-based thermal insulation material.

6. Conclusion

In this study, the effective thermal conductivity of staple fiber assembly for wadding use is measured. Samples used are four kinds of fiber materials such as cupra fiber (CU), polyester fiber with round section (RPE), polyester fiber with heteromorphic section (WPE), and polytrimethylene terephthalate fiber (PTT).

Effective thermal conductivity is measured under five different fiber volume fractions, and effective thermal conductivity curve is obtained. Effective thermal conductivity curve is analyzed using empirical equation considering separation of heat transfer component. The results are analyzed by nonlinear regression method. Measurement is carried out including leakage of heat from sidewall of the sample frame. Calibration of leakage of heat is accomplished after the separation of heat transfer component by nonlinear regression analysis. Care must be taken so that the measurement system is not disturbed by radiative and convective heat transfer from outer environment. The results obtained are as follows.

1. The shape of effective thermal conductivity-fiber volume fraction curve is convex downward. For CU fiber, the minimum value of effective thermal conductivity lies around $\phi = 0.005$. For polyester fibers (RPE, WPE, PTT), the minimum value lies around $\phi = 0.01$.

2. Effective thermal conductivity can be separated into three components such as conduction in fiber, $A\phi$, radiative heat transfer, B/ϕ, and gas conduction, C.

3. Elimination of leakage of heat is accomplished after the separation of C component into thermal conductivity of air, λ_{air}, and leakage of heat from sidewall, C′.

4. Thermal conductivity of air, λ_{air}, has large contribution to total effective thermal conductivity, and conduction in fiber, $A\phi$ follows in the range of higher fiber volume fraction. Contribution of radiative heat transfer is negligible small through this measurement.

5. Effective thermal conductivity of CU is the largest, and those of polyester fibers (RPE, WPE, PTT) follows.

6. With decreasing thickness, the shape of effective thermal conductivity curve becomes flattened, and the difference between fiber materials becomes small.

Precise determination of C value is required for the precise measurement of effective thermal conductivity. These findings will be basic information for designing fiber assembly-based thermal insulation materials.

A. Appendix: Nonlinear regression model for effective thermal conductivity of fiber assembly

As porosity of fiber assembly in this study is very large (>97%), it is expected that heat transfer within fiber assembly is affected by the effect concerning pore as well as conduction in fiber. Mechanism of heat transfer consists of conduction in fiber, radiative heat transfer in pore, and gas conduction in air. If it is supposed that three components of heat transfer are arranged parallel to heat flux (parallel model), the effective thermal conductivity of fiber assembly, λ(W/mK), is expressed as a function of bulk density ρ(kg/m^3) as follows [4].

$$\lambda = \lambda_c + \lambda_r + \lambda_g. \tag{A1a}$$

$$= A\rho + B/\rho + C. \tag{A1b}$$

where λ_c is equivalent thermal conductivity of fiber, λ_r is equivalent thermal conductivity of radiative heat transfer, λ_g is equivalent thermal conductivity of gas conduction, A (Wm^2/Kkg) and B (Wkg/m^{4}K) are coefficients, and C (W/mK) is constant.

The first term in Eq. (A1b) denotes conduction in fiber, the second term denotes radiative heat transfer, and the third term denotes conductive heat transfer through gas. Here, the physical meaning of parameters A, B, and C are summarized based on literature [4] and other literatures concerning subjects in this study.

A.1. Conduction in fiber

Conduction in fiber consists of two components that is, conduction through fiber and conduction at contact point between fibers. The factors concerning conduction in fibers, therefore, are numbers of fiber and numbers of contact point per unit volume. These factors are expected to be increase with increasing bulk density. If the relation between these factors and bulk density is assumed to be proportional for the simplification, equivalent thermal conductivity for conduction in fiber, λ_c, is expressed using coefficient A as follows:

$$\lambda_c = A\rho. \tag{A2}$$

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A.2. Radiative heat transfer in pore.

Equivalent thermal conductivity of radiative heat transfer in pore within fiber assembly is expressed as follows:

$$\lambda_r = 4C_0 d\sigma\varepsilon T^3. \tag{A3}$$

where C_0 is constant coefficient (n.d.), d is distance between parallel plate (m), σ is Stefan-Boltzmann constant (W/m^2K^4), ε is emissivity (n.d.), and T is absolute temperature (K).

Let M be the mass of fiber assembly filled into cell and S be area of section, d = M/Sρ. Substituting M/Sρ for d in Eq. (A3), λ_r is expressed as,

$$\lambda_r = 4\,C_0 \frac{M}{S\rho} \sigma\varepsilon\, T^3 = \frac{B}{\rho} \tag{A4}$$

$$B = 4\,C_0 \frac{M}{S} \sigma\varepsilon\, T^3 \tag{A5}$$

Nogai et al. [1, 2] classifies contribution of total radiative heat transfer in fiber assembly into following four elements: between heat source and fibers, (2) between heat source and heat sink, (3) between fibers, and (4) between fibers and heat sink.

Equation (A3) expresses radiative heat transfer between heat source and heat sink (2).

A.3. Conductive heat transfer through gas

The third term, C (W/mK), is discussed in this section. It is confirmed that size of pore in this experiment is much larger than L, mean free path of air under atmospheric pressure. Therefore, it must be investigated that natural convection occurs or not by change of porosity.

To judge generation of natural convection in fiber assembly, it is not suitable to use Rayleigh number. Instead, modified Rayleigh number [10] to which shape factor of fiber assembly is added is used.

$$Ra = \frac{g\beta\Delta\theta\, d^3}{\nu\kappa} \frac{k}{d^2} \tag{A6}$$

where g is acceleration of gravity (=9.8 m/s^2), β is coefficient of body inflation (1/K), Δθ is temperature difference between heat source and heat sink (K), d is thickness of sample (m), ν is dynamic viscosity of air (m^2/s), κ is thermal diffusivity of air (m^2/s). k (m^2) is Darcy's transmission coefficient which depends on fiber diameter, t (m) and porosity, ϕ(n.d.).

$$k = \frac{t^2 \varphi^3}{122\,(1-\varphi)^2} \tag{A7}$$

If Ra is larger than critical modified Rayleigh number, Ra_{cr} (=39.5), natural convection occurs in fiber assembly.

An example of calculation of Ra for sample RPE is shown. Parameters concerning sample RPE (ϕ = 0.03, T = 25°C) are as follows:

$t = 1.276 \times 10^{-5}$ (m), $\phi = 0.97$, $g = 9.8$ (m^2/s), $\beta = 1/373$ (1/K), $\Delta\theta = 10$ (K), $\nu = 1.579 \times 10^{-5}$ (m^2/s), $\kappa = 2.215 \times 10^{-5}$ (m^2/s).

Ra is calculated as follows:

Ra = 0.0202 for d = 0.02

Ra = 0.0304 for d = 0.03

Ra = 0.0513 for d = 0.05

As Ra < Ra_{cr} (=39.5) for all cases, natural convection does not occur in fiber assembly in this case. Therefore, C is constant and λ_g = C. C is called as component of gas conduction.

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