A Study of Heat Transfer in Thermal Insulation Materials and Its Precise Measurement

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論文内容要約

Chapter 1:　General introduction and background

In chapter 1, the general introduction and background of this study was described. The conventional and current thermal insulation materials were introduced. The investigations of theoretical and experimental study and the developments of thermal insulation materials were introduced. Consequently, the motivation and objectives of this dissertation was mentioned: the theoretical study of heat transfer in thermal insulation materials, the precise and accurate thermal conductivity measurement of thermal insulation materials, the radiative heat transfer analysis of vacuum insulation panels, and the development of vacuum insulation panel potentially capable of building materials.

Chapter 2:　Fundamentals of heat transfer in insulation materials

In chapter 2, the fundamental of heat transfer in thermal insulation materials was explained. The heat transfer mechanisms and insulation performance of effective thermal conductivity, which can be separated into three contributions: solid thermal conductivity, gaseous thermal conductivity, and radiative thermal conductivity, were described.

Chapter 3:　Analysis of effective thermal conductivity based on diffuse approximation

In chapter 3, three contributions to heat transfer in thermal insulation materials were discussed. The effective thermal conductivities of thermal insulation materials were theoretically separated into three contributions: solid thermal conductivity, gaseous thermal conductivity, and radiative thermal conductivity based on diffuse approximation. The theoretical separation was performed for various conventional insulation materials using literature data of their effective thermal conductivities. Figure 1 shows the Comparison among radiative, solid, and gaseous thermal conductivity of perlite separated from the literature data of effective thermal conductivity.

The reduction of radiative heat transfer is essential issue for the improvement of insulation performance of porous insulation materials. Comparing the Rosseland mean extinction coefficients obtained from temperature dependence of effective thermal conductivity based on diffuse approximation, the radiative heat transfer of porous insulation materials are quantitatively discussed. However, the anisotropic-scattering and non-gray radiation analysis, which can take account into the wavelength dependence, is necessary for the detailed investigation in wide range of temperature.

Chapter 4:　Development of precise and accurate guarded hot plate apparatus using Peltier module

In chapter 4, a development of an accurate and precise measurement method for effective thermal conductivity of thermal insulation materials was performed. A guarded hot plate apparatus using a Peltier module was fabricated. A 2-D axisymmetric heat conduction analysis and calibration experiments for thermistor thermometers and Peltier module were conducted to develop the apparatus. Then, its accuracy and precision were discussed. The thermal conductivities of a high-density glass wool was measured as a reference insulation material. The expanded uncertainties were estimated to discuss the precision. The

2-D axisymmetric heat conduction analysis based on the measurement condition for vacuum insulation panel specimen was conducted. The temperature distribution and heat loss were calculated to discuss the accuracy.

The Peltier module was sensitive enough to measure the temperature difference and eliminate the heat loss between the main plate and guard plate. Figure 2 shows a time variation of temperature difference in the Peltier module when the entire system was steady state. The use of the Peltier module achieved a temperature difference control with uncertainty of 20 μK. The precision of the measurements by the apparatus was estimated. The expanded uncertainty of the thermal conductivity measurements was less than 5%. In particular, the expanded uncertainty for the thermal resistance measurement was 0.4%. The accuracy of the measurement by the apparatus was estimated from the heat loss. The bias error caused by the heat loss from the main plate to the guard plate was calculated as 0.13% for the vacuum insulation panel measurement condition. However, the accuracy also depends on the number and diameters of lead wires and the thickness of envelop of vacuum insulation panel.

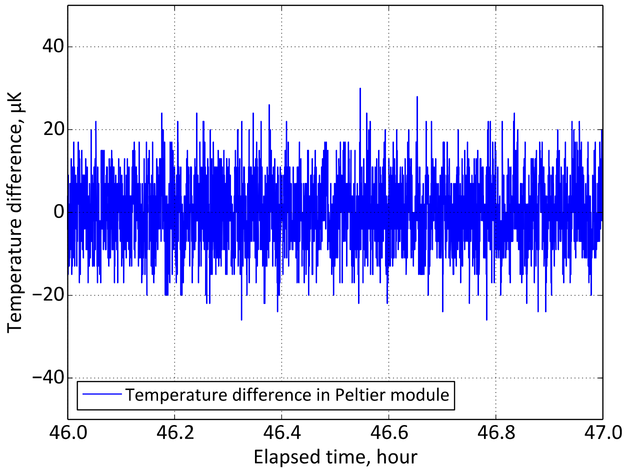

Fig. 2 Time variation of temperature difference in the Peltier module when the entire system was steady state.

Chapter 5: Measurement of effective thermal conductivity of vacuum insulation panels

In chapter 5, effective thermal conductivity measurements of commercial vacuum insulation panels were conducted using the developed guarded hot plate apparatus. The temperature dependence of effective thermal conductivity was measured. The solid thermal conductivity, radiative thermal conductivity, and gaseous thermal conductivity of the vacuum insulation panels were separately estimated based on diffuse approximation from the results.

The separate estimation indicated the effective thermal conductivities at 300 K of 3.34 mW/(m·K), 2.46 mW/(m·K), and 7.03 mW/(m·K), and the ratios of radiative thermal conductivities to effective thermal conductivities of 22%, 33%, and 25% at 300 K for the commercial vacuum insulation panel specimens A, B, and C, respectively. Figure 3 shows the measured effective thermal conductivities of one of the vacuum insulation panel specimens B and C against cube of average temperature with approximate line. This information contributes to improve the insulation performance of a vacuum insulation panel, and a reduction of radiative thermal conductivity achieves a development of vacuum insulation panel with a stable effective thermal conductivity against temperature condition. A radiation analysis based on not diffuse approximation but wavelength dependence has a grateful contribution to design a high-insulation performance vacuum insulation panel.

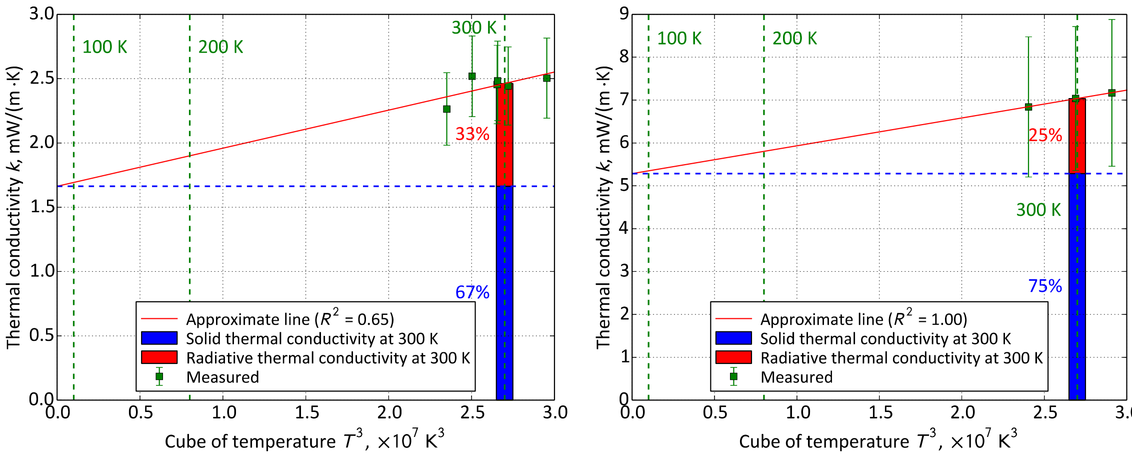

Fig. 3 Measured effective thermal conductivities of two vacuum insulation panel specimens B and C against cube of average temperature with approximate line.

Chapter 6: Development of vacuum insulation panel using expanded perlite

In chapter 6, a development of a vacuum insulation panel potentially capable for building material using expanded perlite was focused on. The design guide of VIP core material using expanded perlite was proposed based on a radiative heat transfer analysis using the radiation element method using ray emission model (REM^2). The comparison between diffuse approximation and the radiation element method by ray emission model and the dependences of particle diameter and temperature condition were examined.

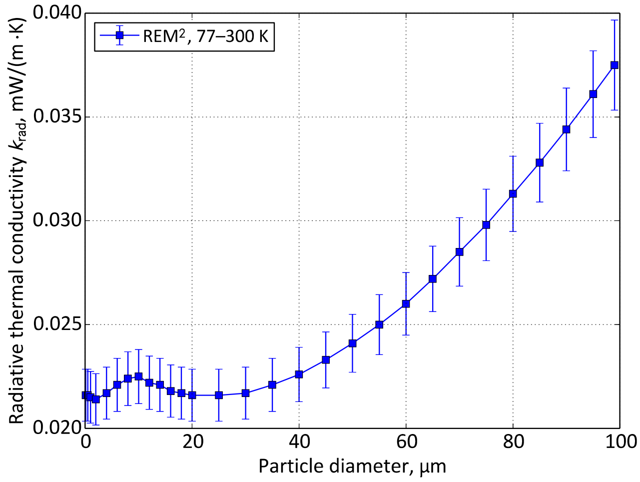

Fig. 4 Analytical results of radiative thermal conductivity against the particle diameters for temperature condition of 77–300 K based on REM^2.

The database of extinction coefficient against the wavelength and particle diameter was made from the refractive index and used for the radiative analysis. The analysis results indicated that the radiative thermal conductivity is not proportional to the cube of temperature in contrast to the analysis based on diffuse approximation. The results suggested the preferred particle diameter for the temperature conditions: normal-temperature condition, high-temperature condition, and cryogenic condition. Figure 4 shows the analytical results of radiative thermal conductivity against the particle diameters for temperature condition of 77–300 K based on REM^2. It indicated that the design guide of vacuum insulation panels based on the radiation element method using ray emission model to realized the reduction of radiative thermal conductivity was established.

Chapter 7: General conclusion

In chapter 7, the conclusions obtained from the each chapter were summarized, which will contribute to clarification of the heat transfer in insulation materials and design of insulation materials. The obtained conclusions were as follows.

1. The solid thermal conductivity, gaseous thermal conductivity, and radiative thermal conductivity were separately estimated and discussed from the temperature dependence of effective thermal conductivity for various porous insulation materials based on diffuse approximation.
2. An accurate and precise guarded hot plate method was development for measurement of effective thermal conductivity of thermal insulation materials.
3. Using developed guarded hot plate method, effective thermal conductivity of commercial vacuum insulation panels was measured and discussed.
4. Design method for vacuum insulation panel with core material of perlite, which has high thermal insulation performance and low cost, was made based on radiative heat transfer analysis.