Measurement of Thermal Conductivity of Ice Slurry for Ice Storage by Transient Hot Wire Method

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An ice storage system is excellent for the cold thermal storage. We have been studying on an ice slurry as a new thermal storage material for the system. When designing the ice storage system using the ice slurry, the thermal conductivity of the ice slurry is essential. The purpose of this study is to measure a thermal conductivity of ice slurry with good fluidity. In this paper, two types of ice slurries were objects to be measured. One was the ice-water slurry made from water with a small amount of additive by cooling with stirring. A silane-coupler was used as the additive. The other was ice-oil slurry made by adding silicone oil to ice particles formed before. Both slurries had good fluidity. Those thermal conductivities were measured by a transient hot wire method. And then, the relationship between thermal conductivity and IPF (Ice Packing Factor) was clarified. Moreover, the uncertainty of measurement of the thermal conductivity was estimated. From experimental results, it was found that the experimental results agreed well with the results calculated by Cheng et al. equation to estimate thermal conductivity of emulsion or suspension. Thermal conductivities of those ice slurries increased linearly with increase of IPF, respectively. Those thermal conductivities were approximated by a liner function of IPF, respectively. The uncertainty of measurement of thermal conductivity was within ĕ 3%.

1. Introduction

A peak cut and peak shift of demand of an electric power can be realized by the spread of ice storage system using a midnight electric power. In addition, discharge of CO_2 gas can be cut down because of characteristic of the midnight electric power. Therefore, the spread of ice storage system can lead to reduction of environmental load.

An equipment in the ice storage system can be smaller because an amount of thermal storage per unit volume of ice is lager than that of other thermal storage material, for example, water. Especially, in a dynamic type system since an ice slurry (suspension) is used as the thermal storage material, it has good fluidity, therefore a large amount of cold energy can be transported with less pumping work. The system of dynamic type can respond quickly to change of heat load because the ice particles have a large surface area.

Authors reported that high IPF (Ice Packing Factor) ice slurry such as snow could be formed by cooling and stirring a mixture of 10vol% silicone-oil and 90vol% water with a small amount of additive (silane-coupler) in a vessel without adhesion of ice to a cooling wall [1]. Ice particles in the high IPF ice slurry such as snow remained granular and dispersed state after the ice slurry was preserved for a long time in a freezing state. Moreover, authors reported that at a very small depression of freezing point all water of the mixture could be frozen because the additive was combined with ice by hydrogen bonding [2].

When the ice storage system using the ice slurry is designed, the value of thermal property of the ice slurry, especially, thermal conductivity, is very important. The purpose of this study is to measure a thermal conductivity of ice slurry with good fluidity. In this paper, two types of ice slurries were objects to be measured. One is the ice-water slurry made from water with a small amount of silane-coupler by cooling with stirring. The other is ice-oil slurry made by adding silicone oil to ice particles formed before. Both ice slurries had good fluidity. Those thermal conductivities were measured by a transient hot wire method. In order to examine the experimental apparatus the measurement of thermal conductivity of water was carried out before measurements of both ice slurries. And then, the relationship between thermal conductivity of ice slurry and IPF (Ice Packing Factor) was discussed. Moreover, the uncertainty of measurement of the thermal conductivity was estimated.

Nomenclatures

I_1: electric current passing hot wire [A]
I_2: electric current passing hot wire [A]
L: length of hot wire [m]
C'_i :value of IPF [%]
R: electric resistance [ɯ]
R_1: fixed electric resistance [ɯ] (=1ɯ)
R_2: variable electric resistance [ɯ]
R_3: fixed electric resistance [ɯ] (=1.2kɯ)
R_4: fixed electric resistance [ɯ] (=1.2kɯ)
R_5: variable electric resistance [ɯ]
R_6: fixed electric resistance [ɯ] (=1ɯ)
R_D: variable electric resistance [ɯ]
T: Temperature [K]
t: time [s]
ε V: voltage variation in Fig.7 [V]
ε V_1: non-equilibrium voltage in Fig.5 [V]
ε V_2: voltage variation in Fig.5 [V]

Greek symbols
щ: coefficient of electric resistance [K^{-1}]
Ｉ: thermal conductivity [W/(m ã K)]
ʃ : diameter of hot wire [m]

Subscripts
0: value for initial temperature
L: long hot wire
S: short hot wore

2. Two types of experimental apparatuses

2.1 Test section An test section and one of two kinds of circuits were designed with reference to Saito et al.[3]. The test section of transient hot wire method is shown in Fig.1. A Pt wire with ʃ = 30 ɻ m is strained vertically in a test tube with the length of 165 mm and inner diameter of 14mm. A coefficient of electric resistance for the hot wire α was measured. The Pt wire is coated with fluorine-polymer to insulate electrically. A cupper wire (lead wire) connected with the Pt wire is also coated with fluorine-polymer. An electrical resistance of cupper wire is much smaller than that of Pt wire. And the cupper wire is supported by a resin rod.

2.2 Measurement samples Two types of ice slurries were used to measure those thermal conductivities. One is an ice-oil slurry. High IPF ice slurry such as snow made from a mixture of 10vol% silicone-oil and 90vol% water with a small amount of silane-coupler (4mass%), is shown in Fig.2. There is little

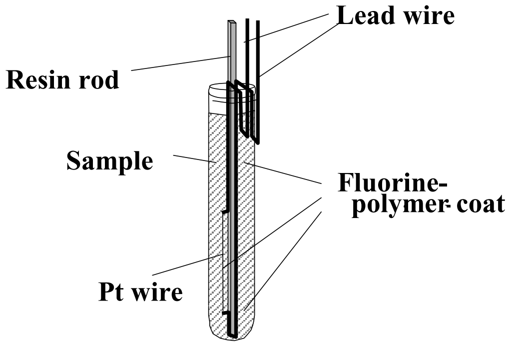

Fig.1. Measurement section.

Fig.2. High IPF ice slurry such as snow.

moisture in the ice slurry and it has not fluidity. The ice slurry is kept in the freezer at - 20 ī for over 24 h. In order to let the ice slurry have fluidity, the silicone oil with temperature controlled is added to the ice slurry. The formed ice-oil slurry with a good fluidity is shown in Fig.3 (IPF=28%). The other is an ice-water slurry. The ice-water slurry was made from water with 4 mass% silane-coupler. The ice-water slurry has a good fluidity when its IPF is small (IPF=20%), as shown in Fig.4.

In the case of ice-oil slurry, the thermal conductivity was measured for IPF = 18%, 28%, 37%, and 46% and T=-8 and -5 ī , while, in the case of ice-water slurry, for IPF=20%, 27%, 34%, 42% and 49%. Temperature difference of the ice-water slurry between 20% and 49% is less than 0.4 ī , the average temperature of the ice-water slurry from 20 to 49% is about -1.6 ī .

Where, IPF is defined as follows;

Fig.3. Ice-oil slurry with fluidity (IPF=28%).

Fig.4. Ice-water slurry with fluidity (IPF=20%).

IPF = (mass of ice)/(total mass) Ĝ 100 (%)

2.3 Measurement circuits and governing equations

2.3.1 In the case of ice-oil slurry Ice-oil slurry has a good fluidity, therefore, the bridge circuit shown in Fig.5 is effective to cancel effect of convection. Two test tubes are set in the bridge circuit. The lengths of 115 and 30 mm Pt wires are strained vertically in those two tubes, respectively. Ice-oil slurries of 22 ml are put into two test tubes with hot wires, respectively. The R_L and R_S shown in Fig.5 correspond to the resistances of long and short wires, respectively. And when the constant voltage (=5V) is applied on this circuit, the non-equilibrium voltage εV_1 is caused. And, the εV_2 is the voltage variation generated on the electric resistance R_1. The R_D is the variable resistance for making the electric current stable. And then, governing equation for calculating thermal conductivity is as follows.

$$\frac{d\dfrac{\Delta V_1}{\Delta V_2}}{d(\ln t)} = \frac{\alpha(R_{L0}-R_{S0})}{(8\pi\ R_1)\lambda}\frac{(R_L-R_S)I_1^{\ 2}}{(L_L-L_S)} \qquad (1)$$

In this circuit, by adjusting the value of R_5,

$$\frac{\alpha(R_{L0}-R_{S0})}{(8\pi\ R_1)}\frac{(R_L-R_S)I_1^{\ 2}}{(L_L-L_S)} = \text{Constant}$$

Therefore, from Eq.(1), thermal conductivity of ice-oil slurry λ can be obtained by measuring values

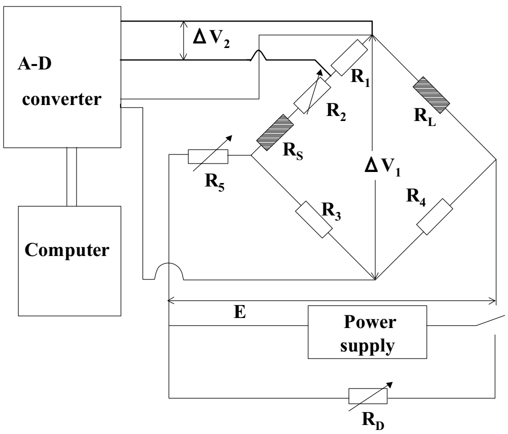

Fig.5. Measurement circuit (with bridge).

of d($\varepsilon V_1/\varepsilon V_2$)/d(ln *t*). Measurement time is 4 sec. A typical example of measurement for $\varepsilon V_1 / \varepsilon V_2$ and ln*t* is shown in Fig.6. From Fig.6, since the value of $\varepsilon V_1 / \varepsilon V_2$ increases linearly with increase of the value of ln*t*, the straight line as approximate line can be obtained. Therefore, thermal conductivity J can be calculated by the inclination of the straight line as shown in Fig.6.

2.3.2 In the case of ice-water slurry Ice-water slurry has also a good fluidity, however, it is difficult that the value of IPF in the test tube with the long Pt wire is made to be equal to that with the short Pt wire. Therefore, in this case, the measurement circuit was not the bridge circuit but the circuit with a single hot wire shown in Fig.7. The length and electric resistance of hot wire are 115mm and *R*, respectively. Ice-water slurry of 22 m*l* is put into the test tube with the hot wire. The R_6 is the fixed resistance for measuring the electric current passing the hot wire. The R_D is the variable resistance for making the current stable in the same manner as Fig.5. When the constant electric current I_2 (=50 mA) passes in the hot wire, the relationship between the voltage variation εV and ln*t* is as follows.

$$\frac{d\Delta V}{d(\ln t)} = \frac{\alpha R_0 R I_2^3}{(4\pi L)\lambda} \tag{2}$$

In this circuit,

$$\frac{\alpha R_0 R I_2^3}{4\pi L} = \text{Constant}$$

Therefore, from Eq.(2), thermal conductivity of ice-water slurry J can be obtained by measuring $d\,\varepsilon V/d(\ln t)$. Measurement time is 5 sec. Though, the figure is omitted here, a relationship between εV and ln*t* is a straight line in the same manner as Fig.6.

3. Experimental results and discussion

Before measurement of ice slurry, two types of experimental apparatuses with different circuits were corrected, respectively, using water as measurement sample. Experimental results obtained by the bridge circuit shown in Fig.5 agreed with the reference data [4] within 0.8%. And, for experimental results by the circuit shown in Fig.7, difference between experimental results and the reference data [4] was within 1.5%. Therefore, it could be thought that two types of experimental apparatuses had reliability.

3.1 In the case of ice-oil slurry Experimental results of thermal conductivity for T=-5 and -8 ī are shown in Figs.8 and 9, respectively. Experiments were repeated 4~5 times for each IPF. Measurement value corresponds the symbol Ĝ. The average value for measurement value (symbol Ĝ) is shown as symbol Ĺ. And, the symbol Ŀ corresponds to the value calculated by an equation of Cheng et al.[5,6]. The equation is used for estimation of thermal conductivity of an emulsion or a suspension. When we use this equation, effect of silane-coupler on thermal conductivity was neglected because of its very small quantity, and for thermal conductivities of silicone oil and ice, the measurement value and reference value at 0 ī were used, respectively.

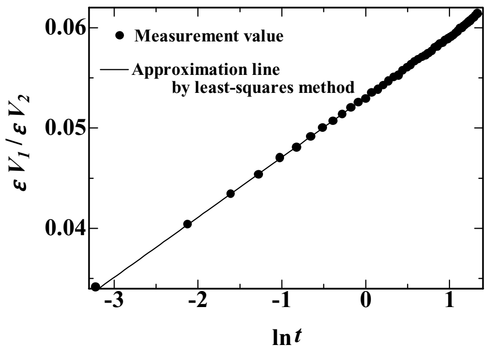

Fig.6. An example of relation between $\varepsilon V_1 / \varepsilon V_2$ and ln*t*.

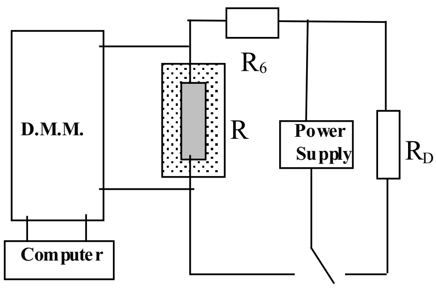

Fig.7. Measurement circuit (without bridge).

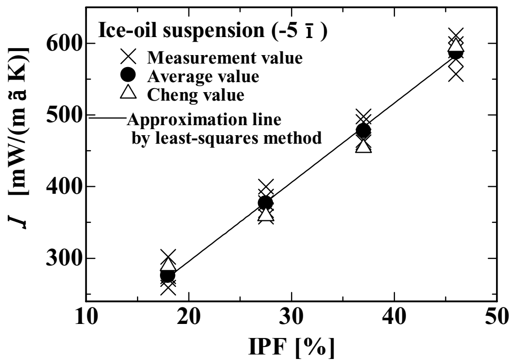

Fig.8. Relation between thermal conductivity of ice-oil slurry(suspension) and IPF (-5 ī).

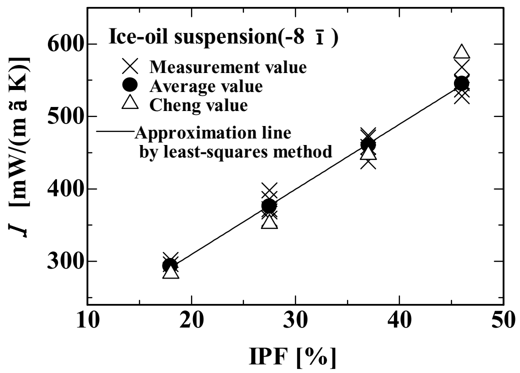

Fig.9. Relation between thermal conductivity of ice-oil slurry (suspension) and IPF(-8 ī).

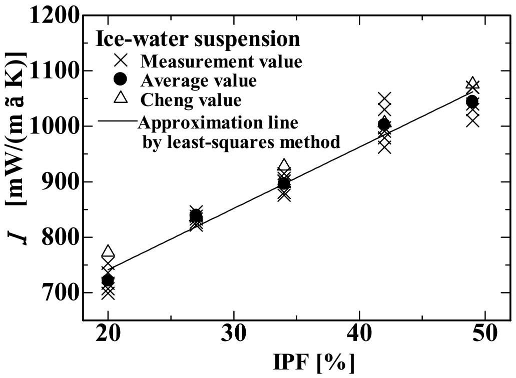

Fig.10. Relation between thermal conductivity of ice-water slurry (suspension) and IPF.

From results of Figs. 8 and 9, both dispersions of measurement values for each average value were about ě 5%. And then, both average values agreed with estimation values by the equation of Cheng et al. within 8%. Thermal conductivities of those ice slurries increased linearly with increase of IPF, respectively. Those thermal conductivities were expressed as a liner function of IPF, respectively. The liner functions correspond to the straight lines in Figs.8 and 9, respectively. Moreover, difference between -5 and -8 ī was very small because of small temperature difference.

As an example, the liner function for -8 ī is shown as follows.

λ = 8.4 C_{i} ę 124.5 [mW/(m ã K)]
(18% Ģ $M_{\%}$ Ģ 46%) ć 3 Ĉ

3.2 In the case of ice-water slurry Experimental results for ice-water slurry are shown in Fig.10. Experiments were repeated 5~6 times for each IPF. Meaning of symbols in Fig.10 and treatment of Cheng's equation are the same as in Figs.8 and 9.

From Fig.10, a dispersion of measurement values for the average value was about ě 4%. And then, average value agreed with estimation value by the equation of Cheng et al. was within 7%. Thermal conductivity of the ice slurry also increased linearly with increase of IPF. The thermal conductivity was expressed as a liner function of IPF. The liner function is shown as follows.

λ = 11.05 C_{i} ę 520.0 [mW/(m ã K)]
(20% Ģ C_{i} Ģ 49%) ć 4 Ĉ

4. Uncertainty of measurement

4.1 In the case of ice-oil slurry The uncertainty of measurement of thermal conductivity λ was discussed. Physical quantities, which effect the measurement value of λ, in the case using the circuit shown in Fig.5 are d($\varepsilon V_1/\varepsilon V_2$)/d(ln t), ɰ, R_1, $(R_{L0}-R_{S0})/(L_L-L_S)$ and $(R_L-R_S)I_1^2$. The uncertainty for d($\varepsilon V_1/\varepsilon V_2$)/d(ln t) was estimated at ě 1.6 İ on the base of over 40 measurement values in one experiment. Those for ɰ and $(R_L-R_S)I_1^2$ were estimated at ě 0.9 İ and ě 0.4 İ , respectively. Those for R_1 and $(R_{L0}-R_{S0})/(L_L-L_S)$ could be neglected. Therefore, if all physical quantities are the same sign, the total uncertainty is estimated at ě 2.9 İ .

4.2 In the case of ice-water slurry The uncertainty of measurement of thermal conductivity *J* was also discussed. Physical quantities in the case using the circuit shown in Fig.7 are d ε *V*/d(ln*t*), *щ*, R_0/L, I_2 and RI_2^2. The uncertainty for d ε *V*/d(ln*t*) was estimated at ĕ 1.6 İ on the base of over 40 measurement values in one experiment. Those for *щ*, I_2 and RI_2^2 were estimated at ĕ 0.9 İ , ĕ 0.02 İ and ĕ 0.08 İ , respectively. It for R_0/L could be neglected. Therefore, if all physical quantities are the same sign, the total uncertainty is estimated at ĕ 2.6 İ .

5.Conclusions

We have reached the following conclusions:

(1) Thermal conductivities for ice-oil and ice-water slurries could be measured with uncertainties of ĕ 2.9 İ and ĕ 2.6 İ , respectively.

(2) It was clarified that thermal conductivities of both slurries increased linearly with increase of IPF.

(3) Thermal conductivities of both slurries could be expressed as liner functions, respectively.

Those functions are as follows;

ice-oil slurry;

J = 8.4 *C*ʹ İ ę 124.5 [mW/(m ã K)]

(18% Ģ *M*% Ģ 46%, at -8 ī)

ice-water slurry;

J = 11.05 *C*ʹ İ ę 520.0 [mW/(m ã K)]

(20% Ģ *C*ʹ İ Ģ 49%)

Acknowledgements

Authors wish to thank Mr. Hara, Mr. Yoshida, Mr. Izumi and Mr. Eizawa who were students of Chuo University, for their co-operation in this experiment.

References and Notes

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