Novel Measurement Method of Total Emissivity by Using Guarded Hot Plate Method

S.Koyanagi[1], *J.Okajima*[2], *S.Maruyama*[3] *and A.Komiya*[2]

[1] Graduate School of Engineering, Tohoku University, Sendai, Miyagi 980-8579, Japan
[2] Institute of Fluid Science, Tohoku University, Sendai, Miyagi 980-8577, Japan
[3] National Institute of Technology, Hachinohe College, Hachinohe, Aomori 039-1192, Japan

In this study, a novel measurement method of total emissivity using Guarded Hot Plate (GHP) method was developed. Measurement of low emissivity at normal temperature leads several difficulties, and it is generally measured under high temperature condition. It is well known that the emissivity has temperature dependency. Thus, an emissivity of material used at normal temperature should be experimentally measured at normal temperature. The Stefan-Boltzmann's law shows radiation emitted by object is proportional to fourth power of surface absolute temperature. This means emissivity measurement needs to control temperature with high accuracy. The GHP apparatus for low thermal conductivity measurement has a high accuracy of temperature control. In this research, radiative heat transfer between two parallel plates having different temperatures was focused to measure total emissivity. The parallel plates can be assumed to be 1D-parallel plate model when a gap between the plates is small compared with the characteristic length of plates. The GHP apparatus was used in vacuum under 0.05 Pa for realizing a high accuracy temperature and heat flux control. Therefore, a temperature of a sample was set no more than 100 °C but near room temperature which is lower than setting temperature in some conventional methods. The proposed measurement method was validated by measuring high emissivity (0.941) sample. As a result, total emissivity was determined as a value of 0.948 and error was less than 1%. This reveals that the proposed method can measure total emissivity with accuracy. In case of low emissivity (0.03), the emissivity was obtained as a value of 0.07. It was thought that the difference was caused by partial lack of low emissivity film from the substrate and surface contamination.

1. INTRODUCTION

Thermal evaluation of building has been conducting from the viewpoint of the environmental load by air conditioner, and it is known that contribution of heat transfer by radiation is 70%. Additionally, thermal radiation influences the heat loss significantly. For this reason, radiation shield has been developing to prevent from heat loss by radiation. Thus, it is important to measure an emissivity of material having low emissivity surface, such as radiation shield, for improving and confirming its performance. However it is well known that the measurement of lower emissivity leads, the higher measurement uncertainty [1].

A precise measurement method of a surface temperature of object is required for the emissivity measurement. Radiation emitted by an object is proportional to fourth power of the surface absolute temperature. This means nowadays non-contact temperature measurement using radiation thermometer and contact temperature measurement by thermocouple installed near the surface from inside are used to conventional emissivity measurement methods. The emissivity measurement uncertainty is strongly affected by the temperature measurement methods [2].

Moreover, an emissivity has temperature dependence [3]. Hence, emissivity should be measured under the temperature condition at which the surface is used. For example, low emissivity window glass on a house was developed and is used at room temperature. However, conventional measurement method cannot measure low emissivity at less than 100 °C.

In this study, a novel measurement method of total emissivity without measuring surface temperature was proposed using Guarded Hot Plate (GHP) method [4], which is measurement method for materials having low thermal conductivity and thermal insulators. The GHP method can control temperature and heat quantity with high accuracy. This proposed method was validated by measuring high emissivity (0.941) at near the room temperature. Furthermore, a emissivity of low emissivity glass (0.03 : catalog value) was challenged to measure at near the room temperature.

2. MEASUREMNT METHOD

The GHP method is originally a typical measurement method of thermal conductivity. When a temperature of main plate is controlled to the same temperature as guard plate, a steady state one-dimensional temperature distribution in a direction of thickness can be realized. Thermal resistance is estimated from heat quantity generated by the main heater and temperature difference of sample. Thermal conductivity of the sample can be determined by dividing the thermal resistance by thickness of sample.

To determine the emissivity of sample surface, the thermal resistance of the vacuum layer shown in Figure 1 is measured instead of the thermal resistance of material. In vacuum layer between sample and cooling plate, only radiative heat transfer was realized. In this study, conduction, convection and radiation by gas were ignored because of vacuum condition. Then, the model of Figure 1 could be assumed 1D parallel plate. Additionally, considering heat transfer phenomena of conduction of hot plate and sample, radiation between sample surface and cooling plate surface and conduction of cooling plate, heat flux through the sample can be written as:

$$q = \frac{T_h - T_{wh}}{R_h} = \frac{\sigma\left(T_{wh}^{\ 4} - T_{wc}^{\ 4}\right)}{1/\varepsilon_s + 1/\varepsilon_c - 1} = \frac{T_{wc} - T_c}{R_c} \tag{1}$$

where q is heat flux through the sample. T_h, T_{wh}, T_{wc}, T_c represent the temperature of the inside the main plate, the surface of the sample, the surface of the cooling plate, and the inside the cooling plate, respectively. R_h, R_c are thermal resistance of sample and hot plate, and cooling plate, respectively. ε_s and ε_c are the total emissivity of the sample surface, and cooling plate surface, respectively. σ is Stefan-Boltzmann constant. Then, T_{wh}, T_{wc} were eliminated in Eq. (1) and the total emissivity of the sample can be expressed as:

$$\varepsilon_s = \frac{1}{\sigma\left\{(T_h - qR_h)^4 - (T_c + qR_c)^4\right\}/q - 1/\varepsilon_c + 1} \tag{2}$$

T_h, T_c and q are obtained from the result of experiment. ε_c and R_c are considered as constant. Then, the number of unknown values are two, that is to say ε_s and R_h. Thus, experiment is performed twice on the different temperature conditions of main plate, and two relations can be made from the results of experiment. The total emissivity of the sample can be obtained by finding a solution to these equations. The temperature difference of two conditions is smaller than the temperature dependencies of the emissivity and thermal resistance. Hence, the temperature dependencies of total emissivity and thermal resistance were assumed to be ignored.

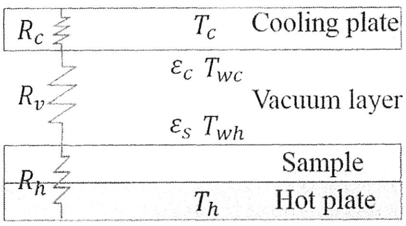

Figure 1. Heat transfer between two plates and equivalent thermal circuit

3. EXPERIMENTAL APPARATUS

Figure 2 illustrates the schematic of GHP apparatus using in this study. This apparatus is located in vacuum and experiments were performed under the condition of vacuum. The GHP system consists of a sample, hot plate under the sample and cooling plate above the sample. Then, hot plate was constructed by main plate, guard plate and Peltier module installed between main plate and guard plate [4].

Main plate was made of a pure copper with a thickness of 20 mm and a diameter of 30 mm. The temperature of main plate was measured by NTC thermistor installed in the center of that. Guard plate was also made of a pure copper with a thickness of 38.5 mm and a diameter of 70 mm. Moreover, the temperature difference between main plate and guard plate was measured by the voltage generated by Peltier module. Cooling plate is a pure aluminum and cooled by Peltier module. The temperature of cooling plate was measured with NTC thermistor.

Vacuum chamber is made of a stainless, and a diameter of that is 305 mm. That was evacuated with vacuum pomp and experiment could be conducted on the condition under 0.05 Pa.

Main heater controls the temperature difference between main plate and guard plate to be zero using PID control. The obtained values, the temperatures and heat quantity through the sample, were resisted when the voltage of main heater, the temperature of main plate and cooling plate is on steady state. In this time, the temperature difference between main plate and guard plate was kept on less than 0.05mK.

The emissivity of cooling plate should be known and uniform for measuring the sample emissivity. Thus, blackbody tape having high and uniform emissivity was put on cooling plate and the emissivity is 0.941. The thermal resistance of the cooling plate from the surface to the point of NTC thermistor was calculated considering the thermal conductivities of blackbody tape and pure aluminum. The result was 1.27 (K·m^2)/W.

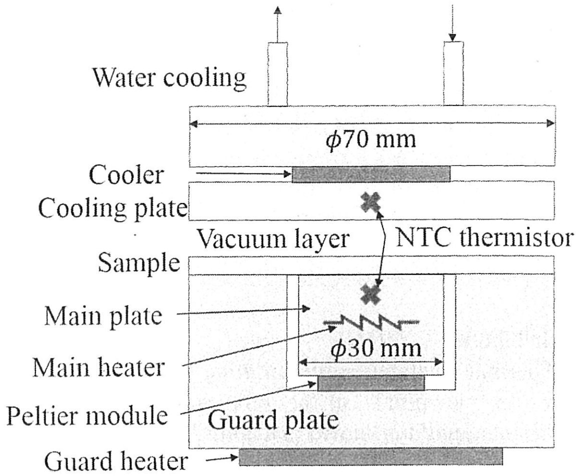

Figure 2. Schematic of GHP apparatus

In this measurement method, a sample and cooling plate were assumed as 1D parallel model. That is a model that all radiation emitted by a side reaches to another side. However, a part of radiation emitted by a sample reaches to surroundings. Therefore, the distance between a sample and the cooling plate must be considered based on the view factor to apply 1D parallel model. View factor from a sample on the main plate to the cooling plate was calculated and tabulated in Table 1.

Table 1. Calculated view factors

Distance [mm]	1	2	3	4	5
View factor	0.999	0.996	0.991	0.984	0.976

As a result, more than 99% of radiation emitted by a sample on the main plate reaches to the cooling plate when the distance is less than 3 mm. However when the distance is too close, there is a risk of making contact with a sample and cooling plate. Thus, the distance between a sample and the cooling plate was set to 3 mm.

4. RESULT AND DISCUSSION

4.1. Validation by measuring of high emissivity surface

The proposed method was validated by measuring high emissivity sample. A sample consisted of blackbody tape as a high emissivity material and a glass as a substrate. The diameter and the thickness of the sample was fixed to 70 mm and 3 mm, respectively.

As experimental condition, a temperature of the cooling plate was set to 297.15 K. In addition, two different temperatures of the main plate were set to 308.15 K and 318.15 K. The proposed method was validated on the condition above.

Figure 3 illustrates a measurement result, which shows relationship of total emissivity and thermal resistance of blackbody tape. An intersection point of two curve of 308.15 K, 318.15 K conditions was calculated and the value was 0.948. On the other hand, the total emissivity of blackbody tape was measured by FT-IR, and the value shows 0.941, showing the difference was about 0.7 %.

From the above, total emissivity can be determined by proposed method with high accuracy. The causes of the difference between the emissivity measured by proposed method and FT-IR were considered as follow: radiation from the side of sample to surroundings, heat loss from the lead wires of the main heater and NTC thermistor, and so on.

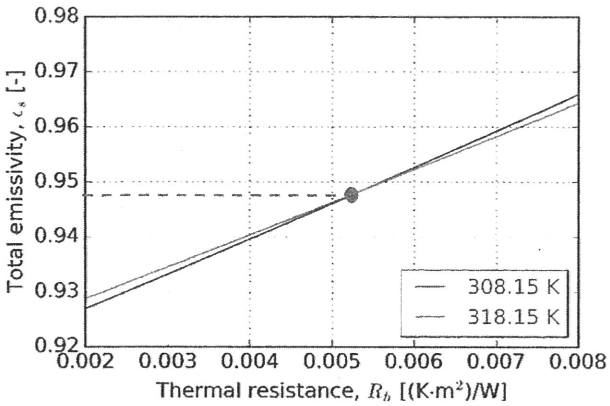

Figure 3. Relationship of total emissivity and thermal resistance of blackbody tape

4.2. Trial of low emissivity measurement

Low-e glass produced by AGC Inc. was used as a sample having low emissivity and the catalog value of total emissivity is 0.03. Low-e glass consists of thin silver film as a low emissivity material and a glass as a substrate. The diameter and the thickness of the sample was 70 mm and 3 mm, respectively.

As experimental condition, a temperature of the cooling plate was set to 293.15 K, and two different temperatures of the main plate were set to 347.15 K and 347.25 K.

Figure 4 illustrates a measurement results showing relationship of total emissivity and thermal resistance in case of Low-e glass. An intersection point of two curve at 347.15 K, 347.25 K was calculated and the result shows 0.07. This means that low emissivity was determined at lower temperature condition using the proposed method. However, the catalog value of the total emissivity was 0.03 and the difference was large compared with the result in case of high emissivity.

Figure 5 illustrates a visualization of the temperature distribution of a Low-e glass taken by IR camera. Figure 5 shows peeling part of the low emissivity film from the substrate. Moreover, oxidation or contamination of the sample surface was observed.

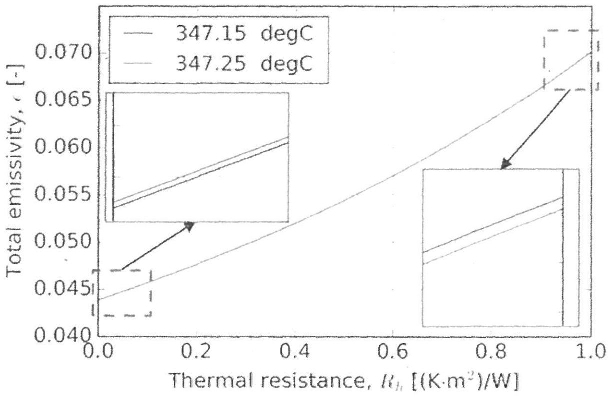

Figure 4. Relationship of total emissivity and thermal resistance of low-e glass

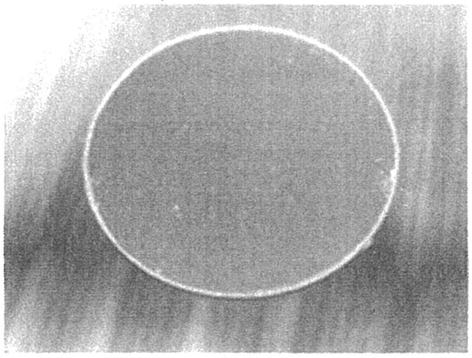

Figure 5. Visualization of the temperature distribution of a low-e glass with IR camera

5. CONCLUSIONS

In this paper, a novel total emissivity measurement method was proposed using Guarded Hot Plate method. From the validation by measuring high emissivity sample, proposed method can measure a total emissivity with high accuracy. Heat loss from the lead wire was considered as the cause of the difference 0.7 %. On the other hand, low emissivity sample was tried to measure and the result was 0.07. However, the difference compared with 0.03 was large. That reasons were considered to peeling part of low emissivity film from the substrate and dirt of the sample surface.

REFERENCES

[1] J. Ishii and A. Ono, Measurement Science and Technology, 12(2001), 2103-2112

[2] L.Campo et al, Review of Scientific Instruments, 77 (2006)

[3] K. Zhang et al, Infrared and Physics Technology, 92(2018), 350-357

[4] T. Kobari et al, International Journal of Heat and Mass Transfer, (2015), 1157-1166