Measurement of Heat Flux on Light Condensing Spot of a Solar Simulator

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Abstract- A beam-down solar concentrator was established at the University of Miyazaki in 2012. The measurement system using the thin-film heat flux sensor can measure the instantaneous heat flux distribution on the light condensing spot of a solar concentrator that changes moment by moment. Since the heat flux sensors are manufactured in our laboratory, evaluating the absorptance on the surface of the sensor is necessary. Therefore, a calibration system was developed for measuring the absorptance on the surface of the sensor, and the absorptance was found to be approximately 0.7. The solar simulator using Fresnel lens is adopted as a simulator for the beam-down solar concentrator. This was necessary to measure the heat flux distribution on the light condensing spot of the solar simulator. It was found that the shape of the distribution on the light condensing spot of the solar simulator was similar to that of the beam-down solar concentrator in comparison with that of the obtained data by using the thin-film heat flux sensor, and the maximum heat flux value was approximately 2400 kW/m^2.

Keywords – Measurement, Solar energy, Solar concentrator, Heat flux, Solar heat

I. INTRODUCTION

Measuring the heat flux distribution at the condensing spot of a solar concentrator [1-4] is necessary to calculate the efficiency of the solar thermal application system [5-7]. This measurement has been generally performed using the Gardon heat flux sensor, which has several disadvantages. This sensor cannot correctly measure heat flux that changes moment by moment. The sensor also cannot measure heat flux while the optical receiver is working. These problems exist because the Gardon heat flux sensor measures in a steady state and cannot do so over a short time period. Conversely, the thin-film heat flux sensor is able to measure in an unsteady state and over short time periods, thus surmounting the aforementioned drawbacks. However, there are individual differences in the absorptance of the thin-film heat flux sensor. It is, therefore, necessary to calibrate for the absorptance on the surface of the thin-film heat flux sensor. We have performed the calibration of the absorptance on the surface of the thin-film heat flux sensor and the measurement of the heat flux distribution on the light condensing spot of the solar simulator over a short time period with the thin-film heat flux sensor in this paper.

II. EXPERIMENTAL DEVICES

A. Beam-down solar concentrator –

The beam-down solar concentrator [8] shown in Fig. 1 is a central tower receiver system, which has been developed by Mitaka Kohki Inc. and was installed at Miyazaki University. This concentrator is composed of heliostats and an elliptic mirror. The heliostats reflect solar radiation to the first focal point of the elliptic mirror. The elliptic mirror then reflects the radiation from the heliostats to the second focal point. The receiver is mounted at the second focal point and receives concentrated light. This system has a 16 m tower with 88 units of heliostats in an area of 60 m × 60 m on the northern side of the tower. The heat flux distribution of the condensing spot of the beam-down solar concentrator was measured by Mitaka Kohki Inc. with the Gardon heat flux sensor, as shown in Fig. 2. This system can produce approximately 70 kW of thermal energy.

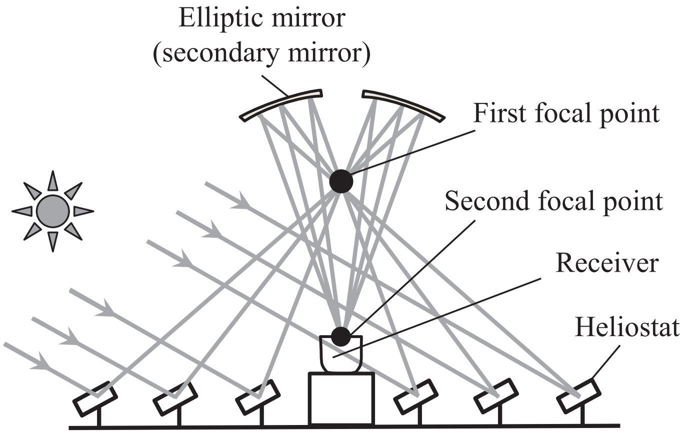

Figure 1. Beam-down solar concentrator

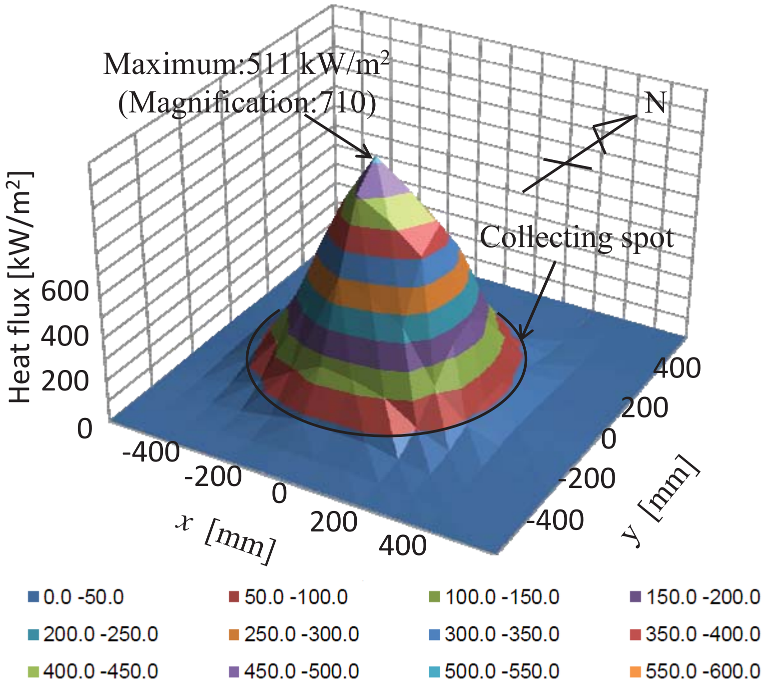

Figure 2. Heat flux distribution of beam-down solar concentrator

B. Thin-Film Heat Flux Sensor –

The thin-film heat flux sensor was developed for measuring the heat flux in engines [9]. In this study, the thin-film heat flux sensor is adapted for the measurement of the heat flux on the condensing spot of a solar concentrator. The sensor is shown in Fig. 3 and comprises a probe body, insulated wires, and a plated film. The probe body is 3.2 mm in diameter and 10 mm in length, the wires are 0.65 mm in diameter, and the plated film is 10 μm in thickness. As the probe body is thermally insulated from the outside by an insulator, i.e., the heat flux in the probe body is kept one-dimensional.

The heat flux sensor comprises two thermocouples, a surface conjunction, and an inner conjunction. The surface conjunction is connected with the surface of the probe body and the insulated wire by metal plating. The inner conjunction is spot-welded with the probe body 5 mm from its surface. From the temperature change of the surface conjunction, an unsteady state of heat flux is obtained. While from the temperature change of the inner conjunction, a steady state of heat flux is obtained. In this study, however, only the surface conjunction is used, since a steady state is unnecessary.

Finally, the output of the heat flux sensor is amplified 10000 times by a noninverting amplifier since the signal of thermoelectromotive force is weak.

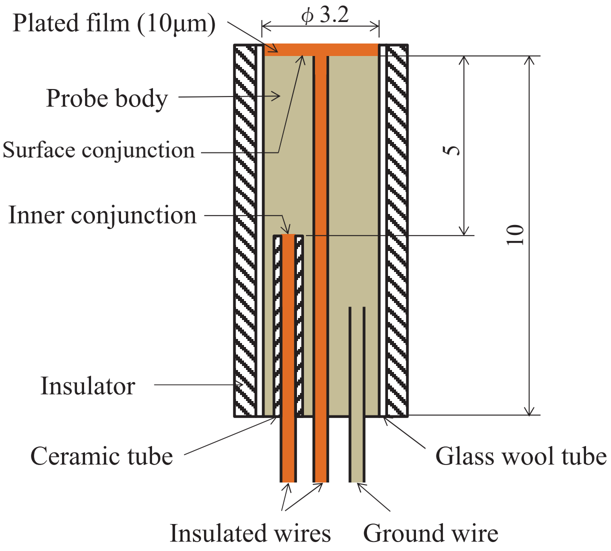

Figure 3. Thin-film heat flux sensor

C. Gardon Heat Flux Sensor –

The Gardon heat flux sensor (Fig. 4) is generally used to measure the heat flux on the condensing spot of a solar concentrator. This sensor comprises a constantan film, a copper body, and copper wires. Furthermore, this sensor comprises two thermocouples. One conjunction is connected to the center of the constantan film and the copper wire, whereas the other conjunction is connected to the constantan film and the copper body. Note that the copper body is water cooled. The heat flux is calculated from the temperature difference between the two conjunctions. The sensing part of this sensor is $2R = 10$ mm in diameter, and this sensor measures heat flux in a steady state.

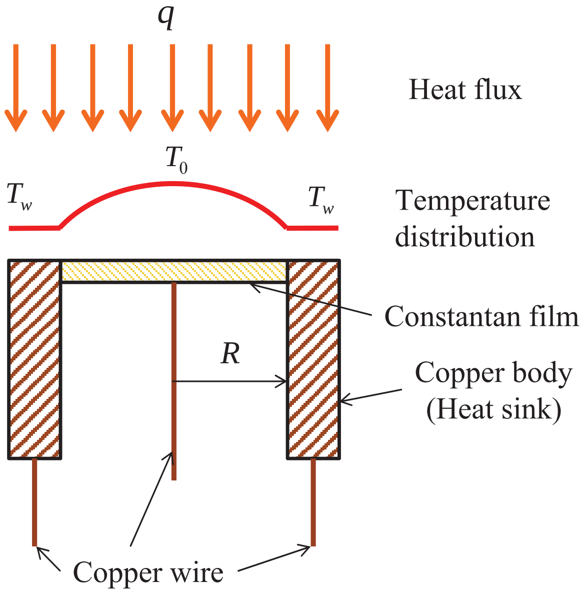

Figure 4. Gardon heat flux sensor

D. Calibration System for Absorptance –

Fig. 5 illustrates the calibration system for the absorptance of the surface of the thin-film heat flux sensor. This system is composed of a Fresnel lens, a rod lens, a chopper, and a stepping motor. The Fresnel lens concentrates the solar radiation, while the rod lens makes the concentrating solar irradiation uniform. The rod lens is used in the calibration system since uniformity on the condensing spot is necessary to correctly measure using the Gradon heat flux sensor. The Fresnel lens is 250 mm × 250 mm with a transmittance of 0.9; and the condensing spot of the calibration system is approximately 10 mm in diameter. Therefore, the heat flux at the sensor is approximately 430 times that of direct solar irradiance.

The chopper is a disc with a circular hole. When measuring by the thin-film heat flux sensor, this system performs step irradiation by revolutions of the chopper since the thin-film heat flux sensor needs temperature changes to measure the heat flux.

Conversely, when measuring using the Gardon heat flux sensor, the chopper is removed and continuous irradiation concentrates on the sensor surface, since the Gardon heat flux sensor measures heat flux in a steady state.

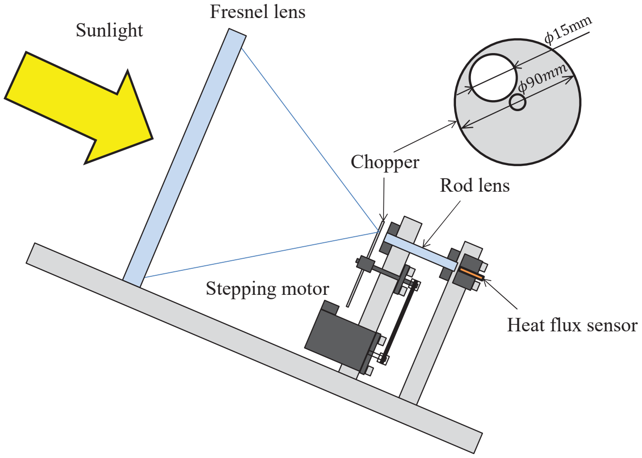

Figure 5. Calibration system for the absorptance on the surface

E. Solar Simulater –

As shown in Fig. 6, the solar simulator is used for the simulator of the beam-down solar concentrator and for the experiments of small models of solar receivers [10]. The Fresnel lens is positioned such the its normal is parallel to the direct normal solar irradiance at all time, and the size of the Fresnel lens is 1050 mm × 1400 mm. The Fresnel lens tracks the sun using a stepping motor. In this study, the condensing spot area of the solar simulator is 40 mm in diameter.

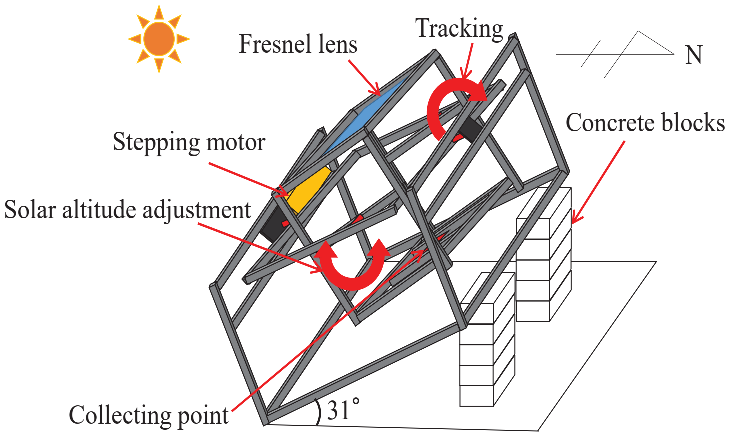

Figure 6. Solar simulator

F. Traverse Equipment –

The traverse equipment is shown in Fig. 7. Here, the surface conjunction of the thin-film heat flux sensor measures the unsteady component of the heat flux. When the intensity of input light is constant, an equipment is needed to change the intensity. The traverse equipment was manufactured for this purpose. It comprises an arm, a stepping motor, a sunshade, and a photo coupler. The arm performs revolutions using the stepping motor. Five thin-film heat flux sensors are attached to the arm every 10 mm with numbering, as shown in Fig. 7. The sensors are moved together over the condensing spot of the solar simulator by the revolution of the arm. The instant at which the arm passes the center of the condensing spot is obtained by a signal from the photo coupler. From this signal, the position of the sensor at each point in time is calculated. The sunshade prevents the concentrating light from irradiating to the photo coupler. Painted with a heat-resistant coating, the sensor holders are composed of resin to insulate the sensors. Water-cooling is unnecessary since the time period over which the sensor receives incident radiation is short.

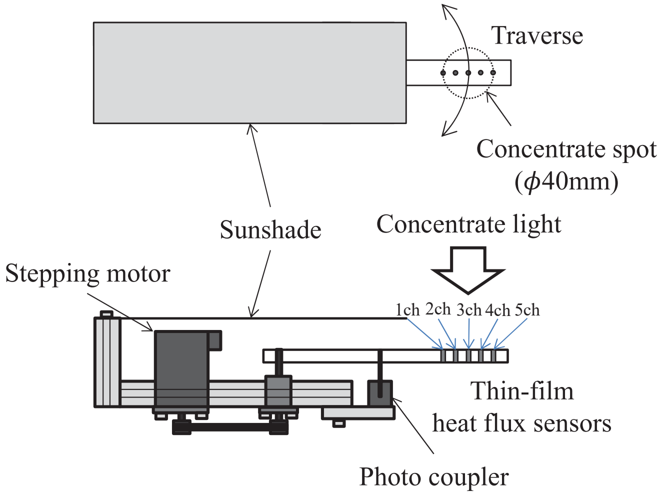

Figure 7. Traverse equipment

III. EXPERIMENTAL METHOD

A. Calibration of Absorptance –

In this experiment, the absorptance of the surface of the thin-film heat flux sensor [11] is measured. In this experiment, we used a Gardon heat flux sensor, a thin-film heat flux sensor, and a calibration system for the absorptance. The thin-film and Gardon heat flux sensors measured the condensing spot of the calibration system. These two sets of measurements were then compared, and the absorptance of the surface of the thin-film heat flux sensor was calculated by using this comparison.

When the measurements are taken with the thin-film heat flux sensor, the chopper is attached to the calibration system. The calibration system tracks the sun such that concentrated light irradiates on the sensor. The chopper turns at 60 rpm for 10 s with the irradiation concentrating on the sensor 10 times during this time interval. The mean value of these 10 times is used as the result.

When the measurements are taken with the Gardon heat flux sensor, the chopper is removed from the calibration system. Again, the calibration system tracks the sun such that concentrated light irradiates on the sensor. The measurements are conducted after the output of the Gardon heat flux sensor stabilizes; such measurements are taken 10 times every 1 s. As above, the mean value of the 10 times is used as the result.

Note that the measurements are performed for 10 s since the direct solar irradiation is measured as a mean value over a 10 s period. Moreover, the magnification of solar concentration is calculated by dividing the mean value by the direct solar irradiation. It is assumed that the magnification of the solar concentrator measured by the Gardon heat flux sensor is exact. Therefore, the absorptance of the surface of the thin-film heat flux sensor is calculated by comparing them.

B. Heat Flux Measurement for the Solar Simulator–

In this experiment, the heat flux distribution on the light condensing spot of the solar simulator is measured and compared with that of the beam-down solar concentrator. In this experiment, we used a solar simulator, a thin-film heat flux sensor and traverse equipment. The traverse equipment was mounted on the solar simulator to pass the 3 ch of the sensor at the center of the condensing spot. The revolving speed of the arm was 180 deg./s, and peripheral velocity of the 3 ch of the sensor was 0.63 m/s. The five sensors were moved together on the condensing spot at a high speed, and measurements of the heat flux distribution were taken within 1 s. The measurement results were calibrated to the absorptance of each heat flux sensor.

IV. RESULTS AND DISCUSSION

The absorptances of the thin-film heat flux sensors were approximately in the range of 0.7 to 0.8, as summarized in Table 1. The heat flux distribution on the light condensing spot of the solar simulator measured with the thin-film heat flux sensor is shown in Fig. 8. The differences of absorptance in Table 1 are considered to be different conditions of oxidation of the surface of the thin-film heat flux sensor. In Fig. 8, positive directions of the x- and y-axis represent the east and north, respectively. The sampling interval of the data was 50 μs. Furthermore, duration of 0.2 s was required to measure the condensing spot of the solar simulator. The shape of the distribution of the solar simulator was similar to that of the beam-down solar concentrator, the maximum value was approximately 2400 kW/m^2, and the maximum magnification was approximately 2500. It is found that the solar simulator can be used to simulate the beam-down solar concentrator since their shapes of heat flux distribution are similar. The maximum value of the solar simulator is very large. This is considered to be the effect of the aberration of the Fresnel lens.

Table -1 The absorptance of thin-film heat flux sensors

Heat flux sensor in Fig. 7	Absorptance
1ch	0.79
2ch	0.79
3ch	0.71
4ch	0.77
5ch	0.73

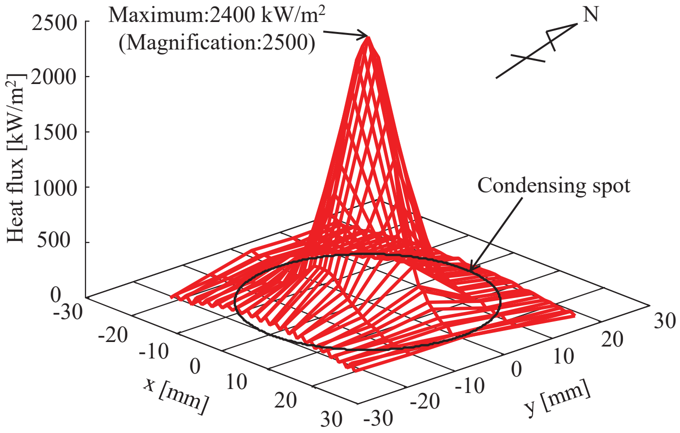

Figure 8. Heat flux distribution on light condensing spot of solar simulator

V. CONCLUSION

In this study, a calibration system was developed for measuring the absorptance on the surface of a thin-film heat flux sensor, and the absorptance was measured. The heat flux distribution of the light condensing spot of the solar simulator was measured using thin-film heat flux sensors and calibrated to the absorptance. This system was able to measure the heat flux distribution of the light condensing spot of a solar concentrator over a short time period, thus surmounting the drawbacks of the Gardon heat flux sensor. The future issues of this study are a measurement of a quantity of heat obtained at the condensing spot of a solar concentrator and the three-dimensional measurement of heat flux.

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