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Experimental Study on Steam Generator for Beam-Down Solar Concentrator

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Abstract- One purpose of this study is to obtain fundamental knowledge about the design of receivers for solar thermal power generation. In this study, two types of experiments were conducted. One is the measurement of temperature distribution on the inner surface of a boiler can. It was found that the maximum temperature was over 1270 °C on the bottom surface. The side wall was heated by conduction rather than concentrated sunlight and did not contribute to the photo thermal conversion efficiency. However, when using the receiver as a boiler, it is important to increase the heat transfer area. The other experiment is the measurement of the photo thermal conversion efficiency under water-filled conditions. The maximum photo thermal conversion efficiency was approximately 80% under ideal conditions, and the average throughout the experiment was approximately 60%. As a result, fundamental knowledge about the receiver for the beam-down tower type of solar concentrating plant was obtained.

Keywords – Solar Energy, Beam-Down Solar Concentrator, Steam Generator

I. INTRODUCTION

Recently, the world has begun facing fossil fuel depletion, environmental conservation problem and safety issue of nuclear power generation. Generally, it is thought that the use of the renewable energy is one of the effective solutions for these problem. Solar thermal power generation is critical from the viewpoint of effective solar heat utilization and is expected to be established in the near future. The beam-down type solar concentrator [1-3], which has a high concentration rate, is a primary area of focus and research worldwide.

Steam turbines are generally used for solar thermal power generation, wherein the steam is produced by a boiler. In this case, the boiler receives sunlight and converts light to heat energy. The receiver's performance influences the generating system's total performance. However, the optimum shape of the receiver is unique to each system. To design a high-performance receiver, it is necessary to determine the optimal shape for the beam-down type solar concentrator. This study aims to evaluate the performance of a receiver similar to a once-through boiler and to measure the temperature distribution on the receiver surface.

II. EXPERIMENTAL DEVICE

A. Beam-Down Solar Concentrator

The outline of the beam-down solar concentrator is shown in Fig. 1. This system, which was installed at the University of Miyazaki in 2012, primarily comprises heliostats and an upper reflecting mirror. Its 88 heliostats each have 10 concave mirrors that are 500 mm in diameter and are installed on the ground. The upper reflecting mirror has an elliptical shape. The principle of solar concentration is as follows. Heliostats follow the movement of the sun and reflect the sunlight to the upper reflecting mirror. This reflected sunlight passes through the primary focus of the upper reflecting mirror, which then reflects the sunlight to its secondary focus. The receiver is located at the secondary focus, where the sunlight is concentrated, so that it can be exposed to this highly concentrated sunlight.

B. Receiver

To investigate the performance of the solar collector, a receiver similar to a boiler was designed and manufactured. This receiver was manufactured by Kyushu Olympia Industry. Estimated boiler efficiency is 85% at a maximum of 0.6 MPaG, which can evaporate 100 kg of water in 1 hour. The outline of the receiver is shown in Fig. 2. Almost all of its components, excluding the insulator and the window, are made of steel. The quartz glass window, which is resistant to high temperatures, was attached to the aperture to prevent heat loss by convection. For window protection, an incombustible insulator, made from calcium silicate, glass fiber, and other materials, was set around it. The sockets for thermocouples were welded to 16 points on the side wall and 17 points on the bottom surface. The inner part of the receiver (Fig. 3) receives sunlight on the inner surface, and heat is transferred from the outer surface to the water.

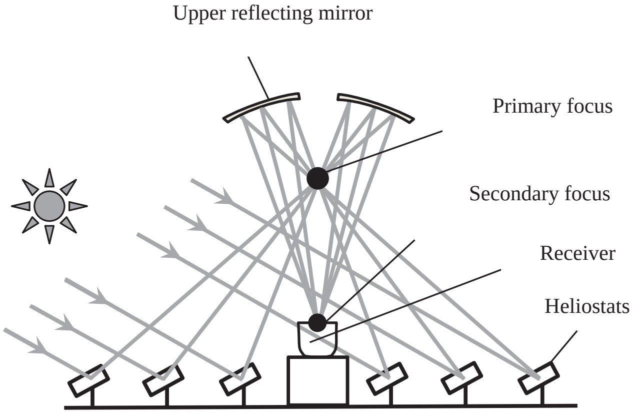


Figure 1. Beam-down solar concentrator

To measure temperature distribution when receiving concentrated sunlight, the inner part of the receiver was manufactured separately from the receiver. It is called the inner can body so as to distinguish it from the abovementioned receiver. Its shape and material are the same as the receiver, except that it does not have an exterior part. In the experiment, it was covered by a thermal insulator called ISOWOOL, which is made from ceramic fibers. It is resistant to high temperatures and its maximum allowable operating temperature is 1400 °C.

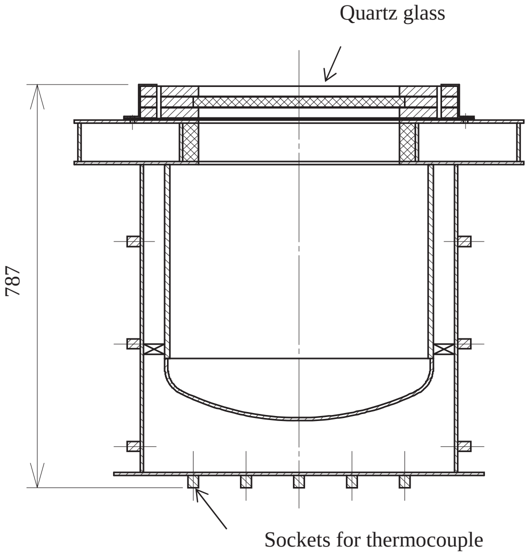


Figure 2. Outline of receiver

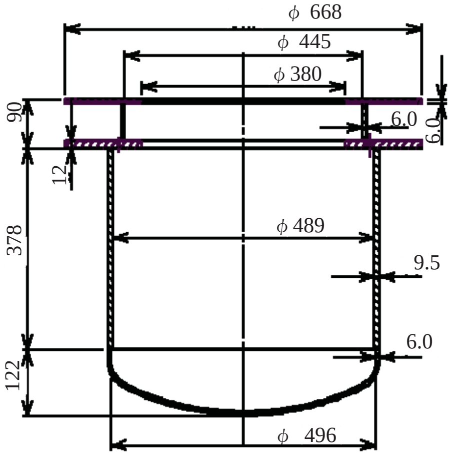


Figure 3. Inner can body

III. EXPERIMENTAL METHOD

A. Experiment for Temperature Distribution Measurements

The temperature distribution measurements on the inner surface were initially planned to be performed by thermocouples; however, such measurement was very difficult due to the high concentration of light. Therefore, the inner surface temperature of the inner can body was measured by thermopaint, and the outer surface temperature was measured by thermocouples.

Thermopaint irreversibly changes its color in a stepwise manner according to temperature. The thermopaint was applied to the inner surface of the receiver (Fig. 4). It was radially painted in eight directions from the center of the bottom to the top of the side wall as well as to the side wall in two rings orthogonal to the radial pattern.

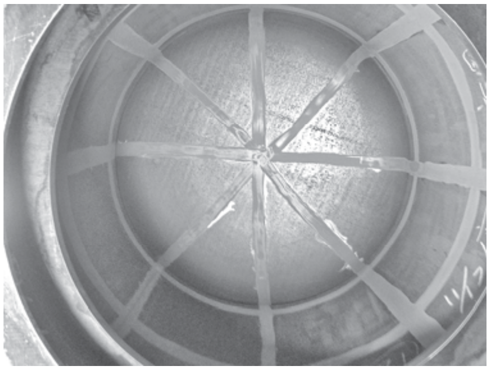
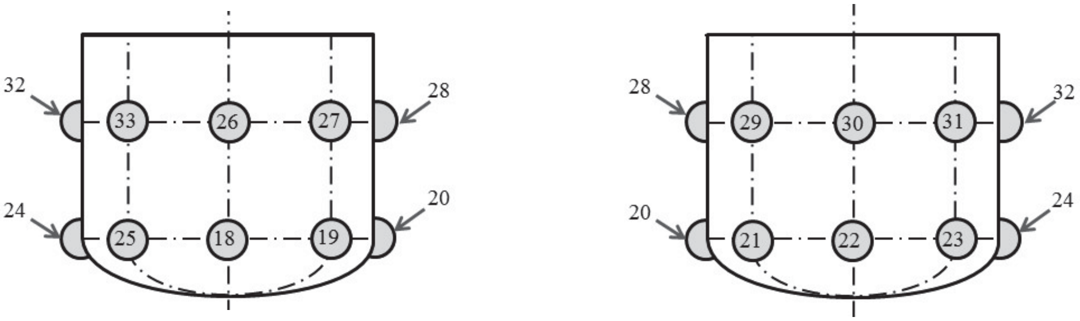


Figure 4. Inner surface of receiver

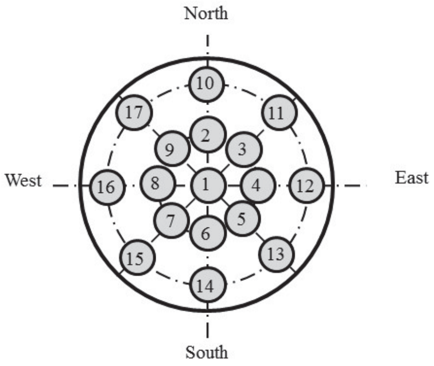
The thermocouple measuring points are shown in Fig. 5. Thermocouples were directly attached to the outer surface of the body by spot welding. The total number of measuring points was 33: 17 points on the bottom surface and 16 on the side wall.

Heliostat control started the heating by concentrated sunlight, and heating continued until equilibrium was reached. Temperature data was recorded to a data logger at intervals of 0.5 s. After cool-down, the color change was observed by comparison to the color chart.



(a) South view

(c) North view



(b) Bottom view

Figure 5. Thermocouple measuring points

B. Experiment for Steam Generation

The steam generation experiment was conducted in the same way as the temperature distribution measurements using the inner can body, except with water filling the space between the inner and outer can bodies. When the water decreased to the lower level, new water was automatically supplied to the upper level with a volume of 10 L per instance. Steam generation was conducted under 0.35 MPa in gauge pressure, which is the minimum pressure of K-100M. The generated steam was a dry, saturated vapor. Generally, the performance of a boiler is evaluated by boiler efficiency [4], and heat collection efficiency [5] is calculated as the conversion efficiency from light to heat. In this case, the total conversion efficiency from light to heat was calculated from Eq. (1).

$$\eta=G(h_2-h_1) / \int S_i I_i. \qquad (1)$$

η : Conversion efficiency
G: Mass flow rate [kg/s]
h_1: Specific enthalpy at the inlet [J/kg]
h_2: Specific enthalpy at the outlet [J/kg]
S_i: Aperture area [m^2]
I_i: Heat flux [W/m^2]

The input energy density was calculated from the heat flux measurement data from the Gardon gauge. Suppositions for this calculation are as follows:

1. During a heat flux measurement and an experiment, the state of the optical system does not change.
2. The heat flux at the second focus is directly proportional to the direct normal irradiance.

The heat flux data was measured on the horizontal plane passing through the secondary focus in intervals of 100 mm using a 25-mm-diameter Gardon gauge.

As a reference, the heat flux distribution at the secondary focus was calculated from the heat flux measurement data and the direct normal irradiation. The aperture of the receiver, which received concentrated sunlight at the secondary focus, was 380 mm in diameter. The total amount of input energy was calculated from the representative value of each area (Fig. 6). This experiment was conducted on October 12, 2012.

When the experiment for steam generation was conducted, the heat flux was calibrated at every instance with direct normal irradiation.

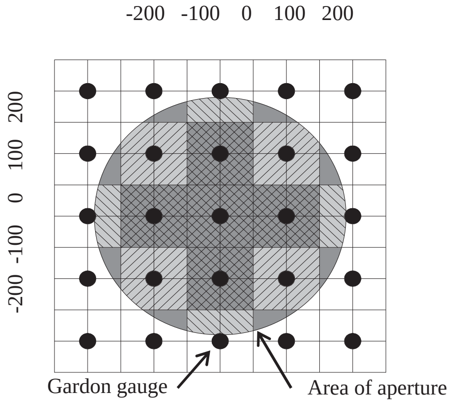


Figure 6. Heat flux distribution

IV. RESULTS AND DISCUSSION

C. Temperature Distribution

The temperature distribution measured by thermopaint is shown in Fig. 7. Border lines indicate the threshold of colors on the painted line. The temperature at the north side of the bottom wall was very high, with a maximum temperature of over 1270 °C. The temperature on the side wall was not quite as high, despite being close to the secondary focus. This implies that the angle of incidence on the wall affects the photo-thermal conversion.

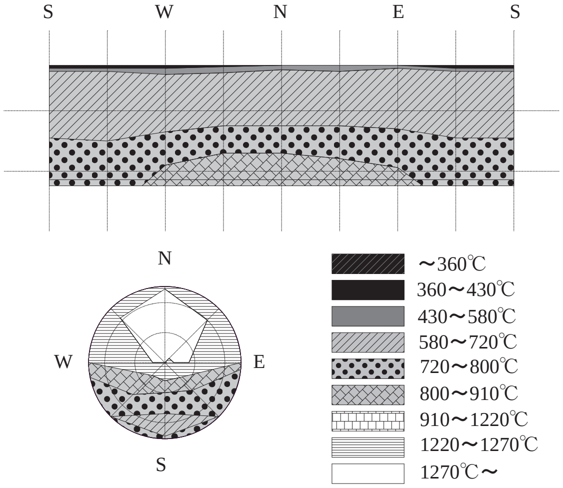


Figure 7. Temperature distribution Top: side view, Bottom left: bottom view, Bottom right: legend

The temperatures measured by the thermocouple are shown in Figs. 8 and 9. The high-temperature area was the same as in the results of the thermopaint, and the maximum temperature was over 1000 °C at point (2). The minimum temperature was below 700 °C at point (6). Temperature changes at points (1), (4) and (6) were similar, so these lines had overlap in Fig. 8. Comparing these figures, the temperature of the bottom part increased faster than that of the side wall. This suggests that the side wall was not directly heated and was influenced by the heat conduction or heat radiation from the bottom.

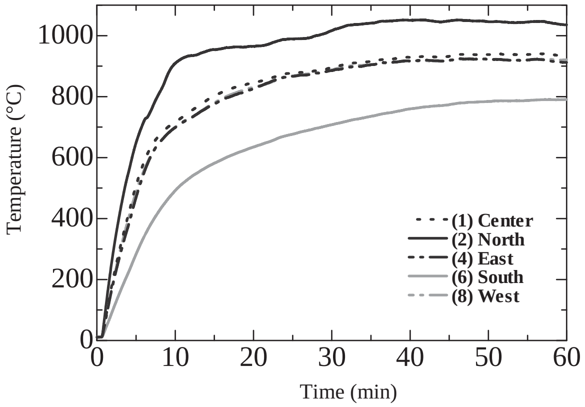


Figure 8. Temperature change on bottom

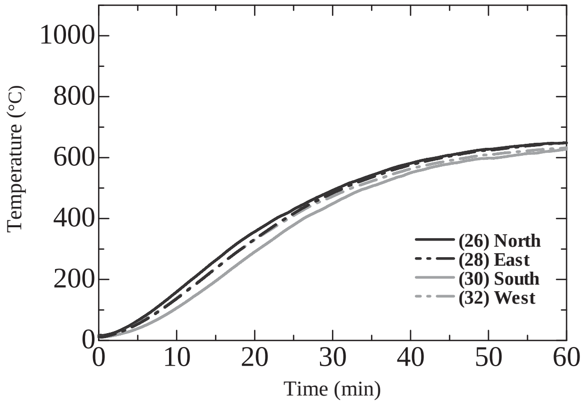


Figure 9. Temperature change on side wall

When the receiver is used as a boiler, it is expected that water would be heated downward by the inner can body. The minimum temperature of the side wall is approximately 600 °C. This area is primarily heated by heat conduction, which suggests that the heat transfer area would be wide when this receiver is used as a steam generator. In addition, the temperature would be uniform by convection because of the added water. Therefore, such a receiver shape could be suitable as a beam-down solar concentrator.

D. Steam Generation

To calculate the conversion efficiency using Eq. (1), the water consumption and supplied energy were also measured. The supplied energy was calculated from the heat flux and direct normal irradiance at each moment.

The conversion efficiency history is shown in Fig. 10. From when heating started to the first water supply, 1.5 h were required because of the heat capacity of the receiver. Efficiency increased gradually to a maximum efficiency of approximately 80% around the time of culmination, which is close to the boiler efficiency of typical small once-through boiler. After that, efficiency decreased according to solar altitude. This tendency is similar to the collection efficiency of the beam-down solar concentrator. The calculated conversion efficiency includes heat loss from the receiver. Here, the collection efficiency of the beam-down solar collector is not calibrated with solar altitude. Therefore, the actual conversion efficiency may be higher than the obtained result.

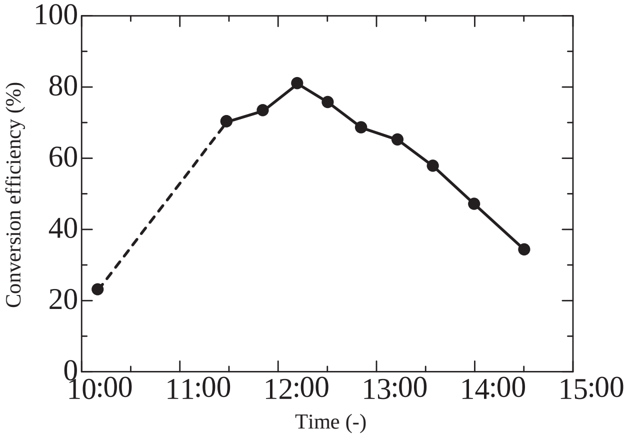


Figure 10. Conversion efficiency

V. CONCLUSION

In this paper, the following results are obtained.

1. The maximum temperature, over 1270 °C, was observed on the bottom surface.
2. The angle of incidence against the wall is important. The designed and manufactured receiver has a suitable shape for a beam-down solar concentrator.
3. A maximum conversion efficiency of approximately 80% is attained around the time of culmination. Moreover, it changes according to solar altitude.

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