MODELLING OF MODULE TEMPERATURE OF A CONCENTRATOR PV SYSTEM

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ABSTRACT: In order to estimate the electrical energy generated by a concentrator PV system and its cost, a model of the PV module temperature and its influence on the power conversion efficiency has been developed. Energy input and loss are calculated from direct solar insolation and the difference between the module temperature and atmospheric temperature. A comparison between the module temperature estimated by the model and that measured experimentally shows good agreement and the deviation estimated in terms of RMSE (Root Mean Square Error). It is found that (1) calculation values are very close to measurement values, (2) RMSE on a fine and cloudy day are 0.730°C and 0.608°C, respectively, (3) average RMSE of 7 days is 0.661°C.
Keywords: Modelling, Concentrators, PV System, Module Temperature

1 INTRODUCTION

In order to reduce the generation cost of a PV system, a concentrator PV system which has high efficiency has been developed [1][2]. In the concentrator PV system, temperature rise of module is a big problem, because the efficiency of the solar cell decreases with increasing module temperature.

From October, 2002, field tests of a concentrator PV system have been carried out in Toyohashi, Japan, and the power generation and module temperature have been measured [3]. It is found that the power conversion efficiency decreases by about 0.3% with each 1°C rise in module temperature[4]. It is important to make a calculation model of the module temperature using weather data as input data, in order to estimate the power generation and generation cost for the PV system in detail.

Influence of solar cell temperature on efficiency and a model of the cell temperature had been investigated [5][6]. In this study, the calculation model for the module temperature of the concentrator PV system was investigated. Weather data such as direct solar insolation and atmospheric temperature were input into the model. In the model, the energy input and loss were calculated from direct solar insolation and the difference between the module temperature and atmospheric temperature. Then, the module temperature was calculated from the energy input, energy loss and heat capacity of the module. Calculation values of module temperature by the model were compared with measurement values, and the model was estimated in terms of RMSE (Root Mean Square Error).

2 OUTLINE OF THE SYSTEM

Fig. 1 shows the appearance of the concentrator PV system with flat Fresnel lens. One PV module consists of 32 flat Fresnel lenses followed by glass homogenizer (optical concentration ratio : 300 X) – solar cell pairs. Homogenizer technologies give uniform flux and prevent from conversion loss that stem from chromatic aberration and surface voltage variation [7][8]. Total area of one module is 0.627 m^2. The solar cell is the InGaP/InGaAs/Ge 3 junction cell. All the cells were connected in series.

The PV system has a 2-axis solar tacking system,

Figure 1: The concentrator PV system with flat Fresnel lens

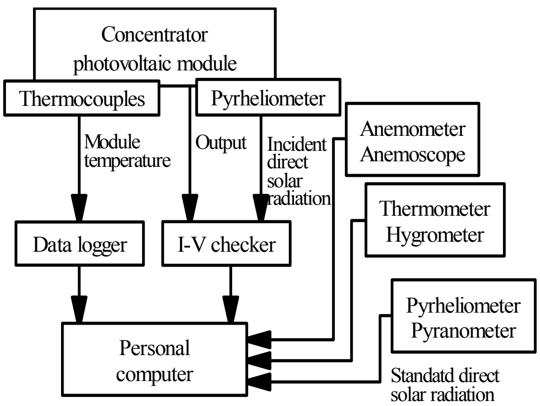

Figure 2: Arrangement of the measurement system

that controls azimuth angle and elevation angle with high accuracy. Sun tracking error (RMS) of azimuth angle and elevation angle are 0.045° and 0.027°, respectively [9].

The heat is dissipated by the module wall and no heat sinks or no external cooling utilities are used.

Maximum efficiency of this system reached 22.0%, and maximum daily average efficiency was 17.6% on November 6, 2002 [3].

3 OUTLINE OF FIELD TEST

Field tests of the concentrator PV system were carried out in Toyohashi University of Technology (Toyohashi, Japan) from October, 2002. Fig. 2 shows arrangement of the measurement system. Module temperatures were measured by thermocouples and recorded by a data logger. Direct solar radiation was measured by a pyrheliometer fixed to the module. These data were measured every 10 seconds.

Weather data such as wind speed and direction, atmospheric temperature, humidity, global solar radiation were also measured every 10 seconds.

PV module output and voltage at maximum power point were measured by an IV tracer every 60 seconds.

4 DAILY CHANGE OF MODULE TEMPERATURES

Fig. 3 and 4 show daily curves for the module temperature, atmospheric temperature, direct and global solar radiation. Fig. 3 is the result from a fine day, and fig. 4 a cloudy day. As shown in fig. 3, the module temperature rises rapidly with increasing direct solar radiation on the fine day. After 10 a.m., when direct solar radiation reaches the maximum, the module temperature saturates at about 30°C which is 20°C higher than atmospheric temperature.

In the cloudy day, the module temperature also rises rapidly when direct solar radiation increases rapidly (shown in fig. 4).

Fig. 5 shows relationship between the highest daily

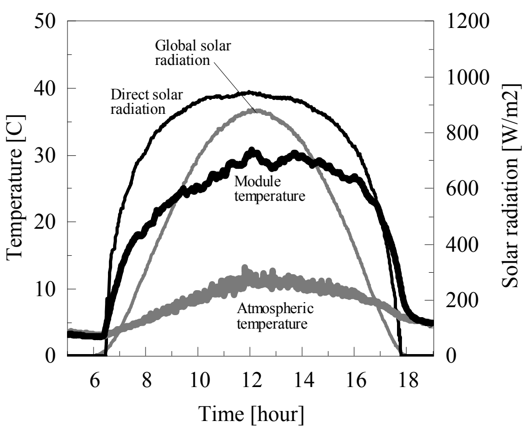

Figure 3: Daily curve for the module temperature, atmospheric temperature, direct and global solar radiation on a fine day (09/03/2003)

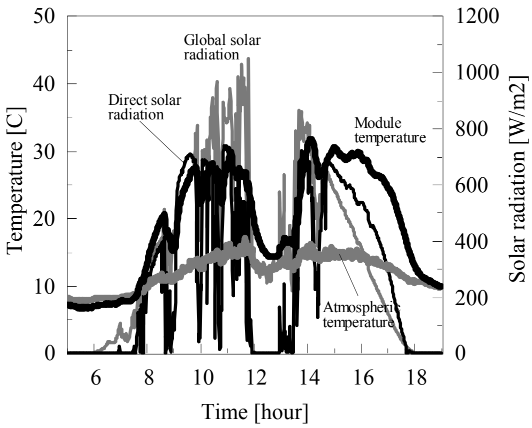

Figure 4: Daily curve of module temperature, atmospheric temperature, direct and global solar radiation on a cloudy day (17/03/2003)

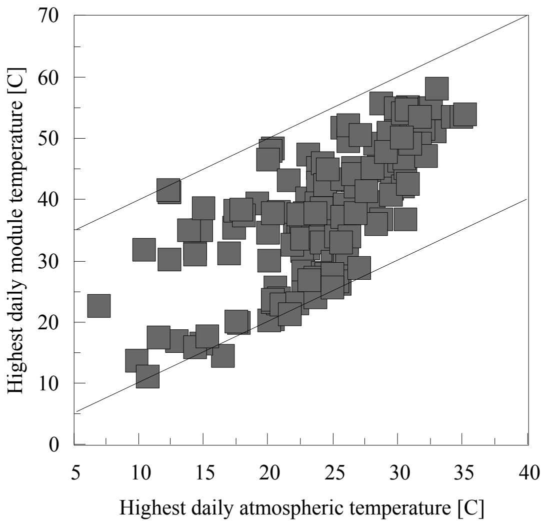

Figure 5: Highest daily temperature of the module and atmosphere

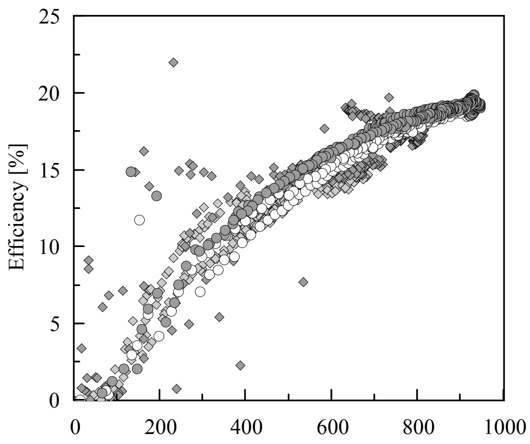

Figure 6: Relationship between direct solar radiation and generation efficiency of the system

temperature of the module and atmosphere. Highest module temperature increases with increase of highest atmospheric temperature. However, the highest daily module temperature varies even with the same highest daily atmospheric temperature, because of influence of the weather conditions and wind speed.

The difference between the highest temperature of the module and the atmospheric temperature is restrained within 30°C.

5 INFLUENCE OF MODULE TEMPERATURE ON EFFICIENCY

The relationship between module temperature and efficiency was investigated.

The efficiency of the concentrator PV system also changes in accordance with solar radiation as shown in fig. 6. Therefore, the module behaviour was investigated at specific solar radiation levels, to isolate the effects of module temperature.

Fig. 7 and 8 show the relationship between efficiency and module temperature. Fig. 7 is the case when direct solar radiation is at 600 W/m^2, and fig. 8 is at 700 W/m^2. There is a negative correlation between the module temperature and the efficiency. As a result, about 0.3% of efficiency of the system is lost when the module temperature rises by 1°C.

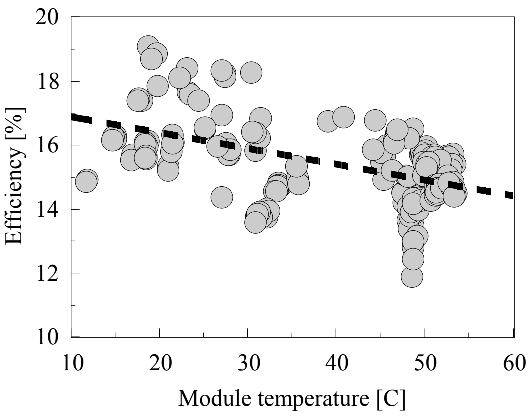

Figure 7: Relationship between efficiency and module temperature of the concentrator PV system (Direct solar radiation : 600 W/m^2)

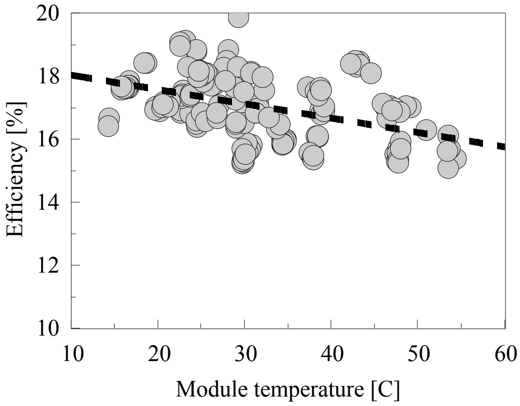

Figure 8 Relationship between efficiency and module temperature of the concentrator PV system (Direct solar radiation : 700 W/m^2)

6 MODELING OF MODULE TEMPERATURE

The calculation model for the module temperature was investigated, in order to estimate the power generation and generation cost for the concentrator PV system in detail.

The model calculates module temperature in period t_n from module temperature in period t_{n-1}, energy input and energy loss in period t_n.

The energy input is calculated from incident direct solar insolation into the module over the period t_n and transmission of lens. The energy loss is calculated from the difference between the module temperature and atmospheric temperature over the period t_n and heat transfer coefficient k_2.

Thus, the module temperature over the period t_n is calculated from the following equation :

$$T_m(t_n) = T_m(t_{n-1}) + \frac{k_1 \, I(t_n) - k_2 \, (T_m(t_n) - Ta(t_n))}{C_m} \qquad (1)$$

where,

- $T_m(t_n)$: module temperature in period t_n
- $Ta(t_n)$: atmospheric temperature in period t_n
- $I(t_n)$: direct solar insolation over period t_n
- C_m : heat capacity of the module
- k_1 : transmission factor of the lenz

$Ta(t_n)$ and $I(t_n)$ were measured in field tests. k_2 and C_m were determined to minimize calculation error (RMSE). In this study, module temperatures were calculated every 5 minutes.

Wind speed and direction influence on k_2. To eliminate such influence, seven days when average daily wind speed was lower than 3 m/s were selected for making and estimating the model.

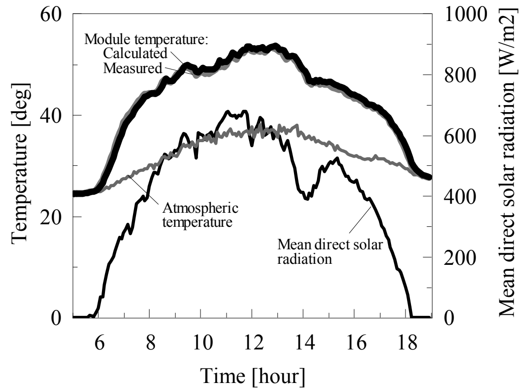

Figure 9: Comparison between the daily curve for measured and calculated module temperature on a fine day (23/08/2003)

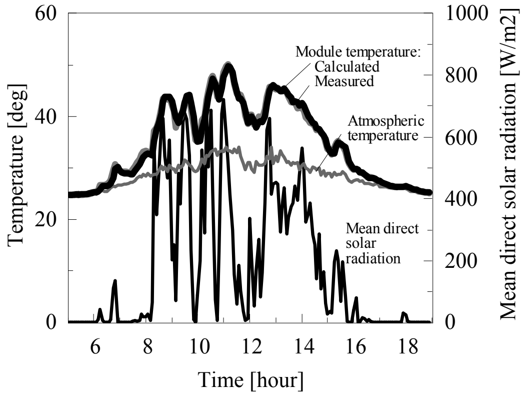

Figure 10: Comparison between the daily curve for the measured and calculated module temperature on a cloudy day (27/08/2003)

Table I: Calculation error (RMSE) of each day

	Date	RMSE
Fine day	04/08/2003	0.832
	25/08/2003	0.606
	23/08/2003	0.753
Cloudy day	14/03/2003	0.506
	31/07/2003	0.713
	07/08/2003	0.573
	27/08/2003	0.642
Average		0.667

7 REULTS

Fig. 9 and 10 show daily changes of module temperature calculated by the model and measurement values. Fig. 9 is the result from a fine day, and fig. 10 from a cloudy day. In the calculation, C_m and k_2 were set to 8.78 Wh/°C and 1.178 Wh/°C, respectively, corresponding to calculation step (= 5 minutes).

As shown in fig. 9 and 10, those calculation values are very close to measurement values for both the fine and cloudy days. RMSE of fig. 9 and fig. 10 are 0.753°C and 0.642°C, respectively.

Table I shows the RMSE of each day. The average RMSE for the cloudy day is 0.608°C and is lower than for the fine day (= 0.730°C). The average RMSE of 7 days is 0.661°C.

8 CONCLUSION

In this study, a calculation model for the module temperature of the concentrator PV system was investigated. Weather data such as direct solar insolation and atmospheric temperature were input to the model.

The module temperature calculated from the model was compared with those measured experimentally, and the model was estimated in terms of RMSE (Root Mean Square Error). As the result, it was found that (1) calculation values were very close to measurement values, (2) RMSE of fine day and cloudy day were 0.730°C and 0.608°C, respectively, (3) average RMSE of 7 days was 0.661°C.

9 ACKNOWLEDGEMENT

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