Thermoelectric Generation Using Water Lens

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Abstract

A solar light concentrator is designed, which is composed of water and plastic transparent film. This flexible lens can trace the solar movement with the control of tensile stress and amount of water, and concentrate the solar energy to the thermoelectric module surface. The water lens was experimentally constructed and the concentrated intensity was monitored by the photodiode as the function of x-z positions. For example, when 3.0 kg of water was filled and a tension of 69.0 N/m was applied to the transparent vinyl sheet, the concentration ratio was evaluated as the maximum of 28.0 at a depth (657 mm) from the water lens bottom surface. TE generation was tested to show the validity of water lens and the surface condition of receiver was critical.

Keywords: *Thermoelectric power generation, solar light concentration, optical lens*

1 INTRODUCTION

Thermoelectric (TE) generation based on the Seebeck effect can directly convert heat into electricity. A TE generation system has the advantage of not requiring a large-scale system and has been studied as a way to recover unused heat, such as waste heat from automobiles [1], fuel cells [2], and marine engines [3], as well as solar heat [4,5]. The solar light generation using silicon photoelectric cell covers a wide range of wave length of the solar radiation, but energy from the longer waves in the infrared area is not converted completely, and the residual component of infrared ray was not satisfactorily used. Because the energy density from the sun is low for thermal utilization, the light concentrators such as convex and Fresnel lens are needed. The parabolic mirror is also effective to concentrate the solar energy. However, these light concentration device and its ray tracking mechanism were complex and not cost-affordable; the precise mechanical control of heavy concentrators requires the mechanical power and the materials such as expensive glass or gold mirror.

Because the conversion efficiency of TE generation systems is generally as low as a few %, it is necessary to rise the hot side temperature of TE modules by the large concentration of solar energy. The concentration ratio, *C*, is defined as the ratio of receiver surface area to the lens surface area. For example, C is required to be 50 to obtain the temperature difference, ΔT, as 100 K when the p-n elements with 3.0 mm length of Bi_2Te_3 can be used [6]. The higher C is effective to get the larger ΔT and the larger power, because the performance is proportional to the square of ΔT. When we consider the applicable maximum temperature for the high-performance material Bi_2Te_3 at room temperature, C should not exceed 150 to protect the melting of welding at the joints [6].

Fig.1 proposes a solar power generation system using water lens array. The water in the plastic bags plays as the lens to concentrate the solar light onto the TE module, whose cold surface is cooled by a thermal fluid such as natural water. By feeding water to the lens, the thickness of water lens becomes variable. We expect that the flexible lenses may focus the solar light adjusting with the solar movement during a day and with the seasonal change. If the motion of TE modules to receive the light can be limited in only a horizontal plane, it becomes much easier to control the receiver position mechanically.

Fig.2 shows another idea of application using water lens. The water is filled in an array of plastic film to form the half cylindrical lens, and the concentrated light focus on a line of the pipe surface in which the coolant flows. The heated fluid is introduced to the heat exchanger equipped with TE modules. Using this kind of TE module, we may reduce the number of TE modules, and resultantly the electric parts and the internal resistance are reduced. A small number of TE modules can work efficiently to generate the electricity by cooling with fresh water.

Because our project that the water lens can assist the concentration of solar energy has just started, a fundamental confirmation of water lens was carried out experimentally in this paper. The calculations of lens shape and of ray tracing are reported separately [7].

The purpose of this work is to examine the light condensation behavior due to water lens and to find the workability as the lens in a TE power plant. Although the merit of water lens is the flexibility by using the transparent and soft plastic film to support the liquid water, two dimensional modeling was introduced to simplify three dimensional flexibility. A half cylindrical lens was studied mainly whether it could condense the light perpendicular to the water surface.

2 APPARATUS

Several types of experimental setup and plastic sheet have been tested. Here two types of experimental setup are reported using a vinyl chloride sheet with 0.1 mm thickness and 416 mm wide. This sheet is popular in the agricultural field as the green house material. To maintain a half cylindrical shape with water, wall sheets were set at two edges of the cylinder. The mass of water was typically 3.0 kg, which could stabilize the water surface against the breeze.

Fig.3 and 4 illustrate the side views of the metallic frames used for the experiments. The height of the frame was 1900 mm. The water lens was supported by the two aluminum rods (40 mm in diameter) where the vinyl sheet was winded, as shown in Fig. 5. One rod was fixed with the frame. Another was free for rotation and expanded with the tension at two terminals given by two digital suspension gauges (max 250 N). The solar light irradiated to the water surface and the refracted light into the water lens went out from the plastic film at the bottom side. Under the water lens, a photodiode (2x2 mm) and a variable electric resistance (500Ω max.) were mounted on a board as the photo sensor. This sensor can move smoothly on the rails along x-axis. The height of sensor can be changed by a jack. The output voltage was monitored continuously and recorded in a computer.

As shown in Fig.4, the pin-spot light for the theater (650W halogen lump) was mounted at the top of metallic frame, and 396 mm above the lens. The light passes through the metallic slits to allow the light to irradiate perpendicular to the lens.

TE module used in this study was made by Aisin Seiki Ltd. (Type: EP3-06E046RTO, 8.2 X 6.0mm, 1.7 mm thick), which based on Bi_2Te_3 elements. The temperatures in the systems were monitored by J-type thermocouples, and the water cooled copper plate was used to cold side of TE module. The hot side was coated by carbon fine powder.

3 RESULTS AND DISCUSSION

3.1 SOLAR IRRADIATION

Fig. 6 shows an example of water lens under solar light. The size of floor tile is 100 mm square. For simplicity, the tension gauges were removed. 3.0 kg of water was filled in the transparent sheet, and the positions of two rods were artificially optimized to obtain the condensed light on the floor. As shown in Fig. 6, the main ray was condensed as a brilliant image, but some portion of reflected light entered the camera, and the other portion was refracted to another direction under the lens. The intensity measurement of refracted beam is essential to discuss the performance of water lens.

Fig. 7 shows the concentration ratio, *C*, which was here defined as the ratio of the electromotive force (EMF) of photodiode to that under the solar light without the lens. A good linearity of EMF value against illuminance was separately confirmed using an illuminometer. The measured EMF, *E* (V), was related with the illuminance, *I* (lx) as,

$$I = 6.77\text{x}10^5\, E + 9.66 \text{ x } 10^2 \qquad (1)$$

The outdoor measurement was done on 19 October 2011, at 13:00 to 14:30. The incident angle of solar light was about 45 degree. The water surface was 214 x 369 mm and located at 541 mm over the floor level. The distance between the upper surface of water lens and sensor are indicated in Fig. 7. The horizontal position of the sensor was measured from the center of water lens.

As indicated in Fig. 7, the concentration ratio *C* was varied as a function of position of sensor. The maximum *C* was about 4. The condensed beam was not symmetrical and had some waves close to the strong peak.

3.2 INDOOR IRRADIATION

Under the solar light with the fixed lens parameters, the movement of the sun disturbed the reproducible measurements. Especially the behavior of the wavy refracted light and the maximum concentration ratio were sensitive with the incident beam, and the experimental setup was moved to inside of the building. As shown in Fig. 4, the stable light source was used hereafter.

The light source can offer a parallel beam suitable for the theater, but the metallic thin plates were inserted as the parallel slits to ensure the cut-off of diverse light. Using 3.0 kg of water and tensions in the range of 47.8-77.3 N per 1 m width, the concentration effect of water lens was examined as a function of x and z, where x and z are defined as the horizontal position from the center of water lens and the distance between the bottom of water lens and photodiode, respectively.

The measured EMF values were summarized in three-dimensional space as shown in Fig. 8. The direct beam without the water should be measured to normalize the EMF value in order to show the concentration ratio, C, as shown in Fig.7. However, the frequent water change causes a slight difference in water lens shape, and we sometimes skipped to measure the direct beam when the height of sensor was varied. Therefore, the measured EMF was shown and it was not normalized.

Several subpeaks existed close to the main peak, as shown in Fig.8(a), (b) and (c). Non-symmetrical results against x may be due to the off-central irradiation from the lens center. It is noted that the horizontal position x of the main peak was commonly shifted off the center by about 10 mm. This deviation could not be adjusted to the center, and it is taken as the experimental error for parallel beam with the perpendicular irradiation.

Fig.8 (a) shows some waves, and the several strong peaks exist at various distances from the lens. No clear focusing point was found in this tension. Fig. 8 (b) also shows a splitting of refracted beam. Because the tensile stress is close to the optimal condition, a small deviation from the optimal position darkens the concentration. EMF value without water was 2.28 mV at the tensile stress of 51.8 N/m, and the concentration ratio, C, was evaluated as 13.6 at the maximum position. Fig. 8 (c) shows the maximum of C, C_{max}, as 14.9 at (x, z)=(-12 mm, 601 mm). The lens with the larger tension could concentrate the light effectively as shown in Fig. 8 (d), and C_{max} was 28.0 at (x, z)=(-8 mm, 657 mm). This condition was not stable and the small effort to the mechanical adjustment caused the drastic decrease in C_{max}.

Fig. 9 shows the relationship among the tensile stress, f, the maximum concentration ratio, C_{max}, and the distance from the lens, z to obtain C_{max}. Because the tension increases, the thickness of water lens becomes smaller, and the focusing point is farther from the lens.

When the amount of water decreased too little, the meniscus bends the flat surface of water at the edges and a good concentration effect was not obtained. The size effect of water lens was numerically calculated [7, 8], but the surface tension was not considered. The experiments will be reported later on the size effect of water lens.

3.3 TE GENERATION UNDER INDOOR IRRADIATION

3.0 kg of water with the tension f = 55.2 N/m was taken as the experimental conditions. The pin-spot light irradiates perpendicular to the water surface, and the TE module was placed at the focusing position with water cooling. The hot side temperature was stabilized after 180 s and a constant temperature difference was obtained. By varying the external resistance, the generated voltage from TE module and the circuit current were measured. Fig. 10 (a) shows the linear relationship between the voltage on the external resistance and current, as seen commonly in the serial circuit. This is because the temperature difference given to TE module was enough small to be able to neglect the temperature dependency of the materials properties. The output power at the external resistance was evaluated and shown in Fig. 10 (b). The parabolic behavior is shown by evaluating it from the linear dependency in Fig. 10(a).

When the fine carbon powder is pasted on the ceramic top plate of TE module, the outer surface temperature of TE module increased. Temperature difference, ΔT, between two surfaces of TE module was only 1.1 K when carbon powder was not pasted. ΔT increased to 7.0 K and the obtained electric power became 7.7 times larger as indicated in Fig. 10 (b). This can be explained by the improvement of heat absorbing capacity due to the black powder coating.

4. CONCLUSIONS

A solar light concentrator is designed, which is composed simply by water and plastic transparent film. We expect that the flexible lens such as water can trace the solar movement with a small mechanical control, and that it can concentrate the solar energy to the thermoelectric (TE) module surface. As the first step of water lens project, the incident light perpendicular to the water lens is analyzed by the the experiments.

The half cylindrical water lens was constructed using the plastic sheet with 3.0 kg of water. The solar light could be concentrated as C=4. The spot light for the theater stage irradiated the photodiode, and its EMF was monitored as the function of x-z positions. When we applied 0.69 N/m as the tensile stress to the plastic sheet, C_{max} was 28.0 at 657 mm from the water lens.

These analyses encouraged us to apply the water lens to convert the light energy to electricity. The typical relationship among current, voltage and power was monitored, and the black surface painted by carbon powder was effective to obtain the solar heat on the hot surface of TE module. The emissivity of TE surface, the receiver size of TE module, the coolant temperature and the shadow of thermocouple for surface temperature monitoring significantly affect the TE power as well as the external resistance. The further optimization is planed by assistance of optical path calculation [7,8].

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Figure Captions

Fig. 1 Conceptual image of water lens array and TE power generation cooled by thermal fluid. The water level in the plastic bags/trays is controlled to trace the solar movement.

Fig. 2 Half cylindrical water lens array to heat the thermal fluid, which is carried to the heat exchanger equipped with TE modules.

Fig. 3 Experimental setup for the solar light.

Fig. 4 Experimental setup using pin-spot light.

Fig. 5 Cylindrical lens.

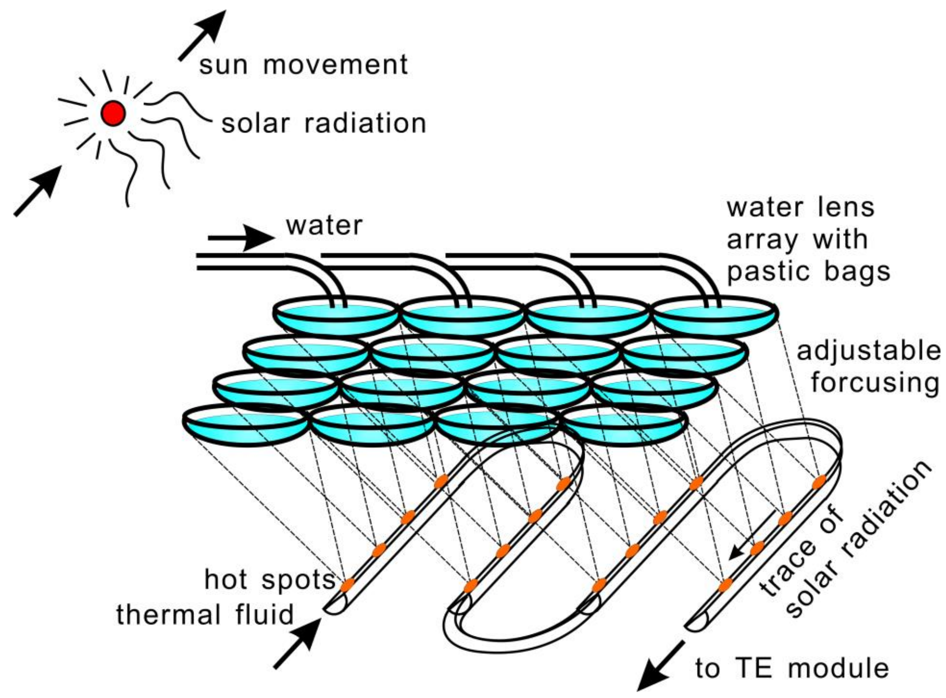
Fig. 6 Water lens under solar light.

Fig. 7 Concentration ratio of the water lens under solar light. y : distance between the sensor and the upper surface of water lens.

Fig. 8 EMF of photodiode as the function of distance from the water lens center, x, and the distance between lens bottom and photodiode, z. The tensile stress was (a) 47.8 N/m, (b) 51.8 N/m, (c) 55.2 N/m and (d) 69.0 N/m.

Fig. 9 Maximum concentration ratio and its distance from the lens, where 3.0 kg of water and the light perpendicular to water surface were used.

Fig. 10 (a) Relationship between current and voltage, and (b) relationship between current and power.



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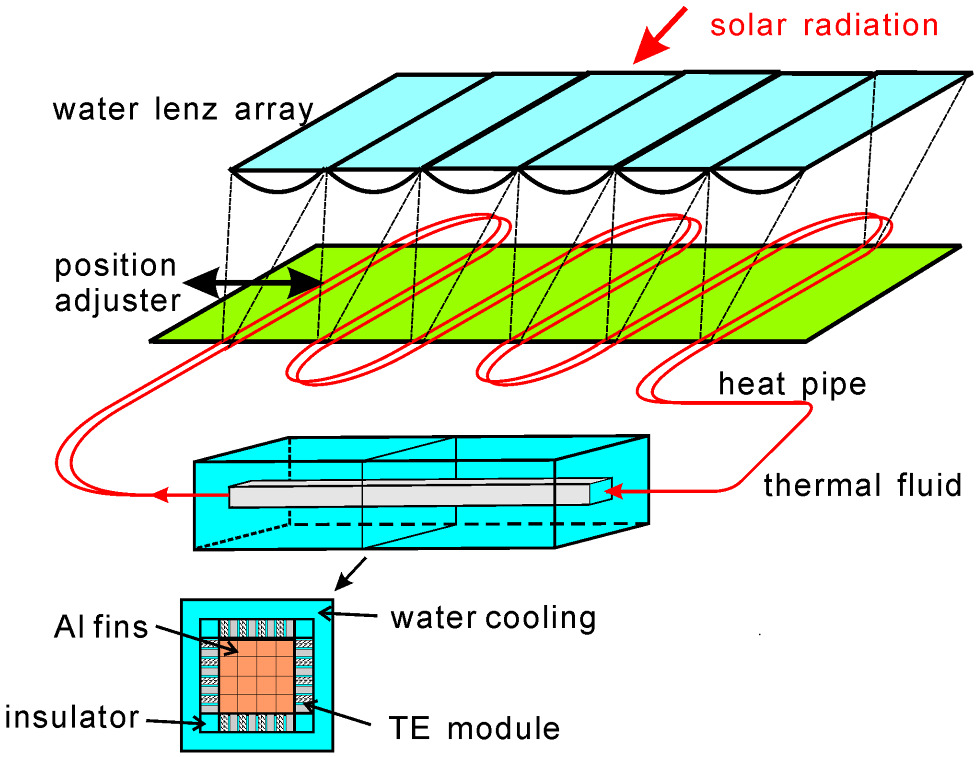

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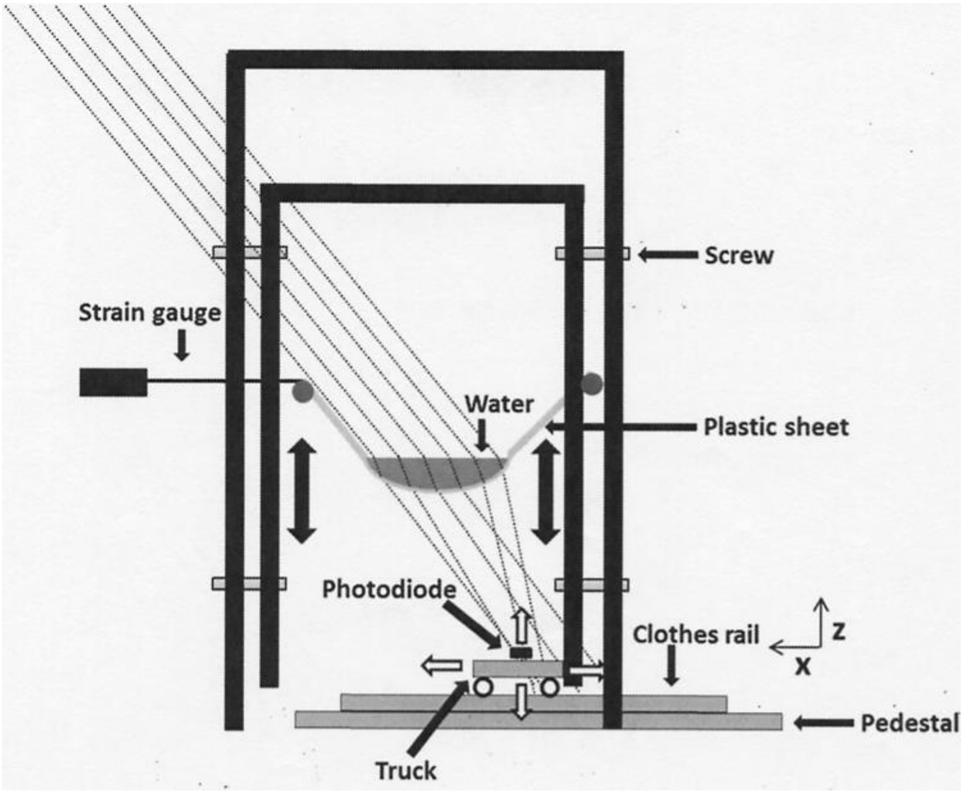

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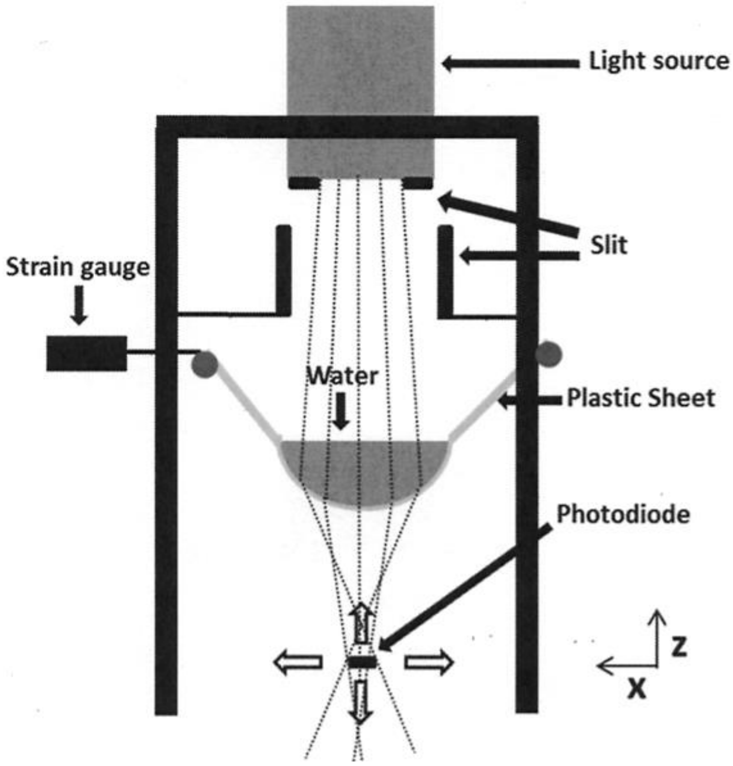
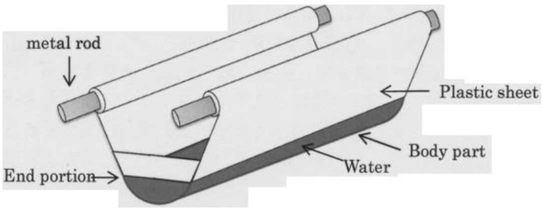


Fig. 4 Experimental setup using pin-spot light.



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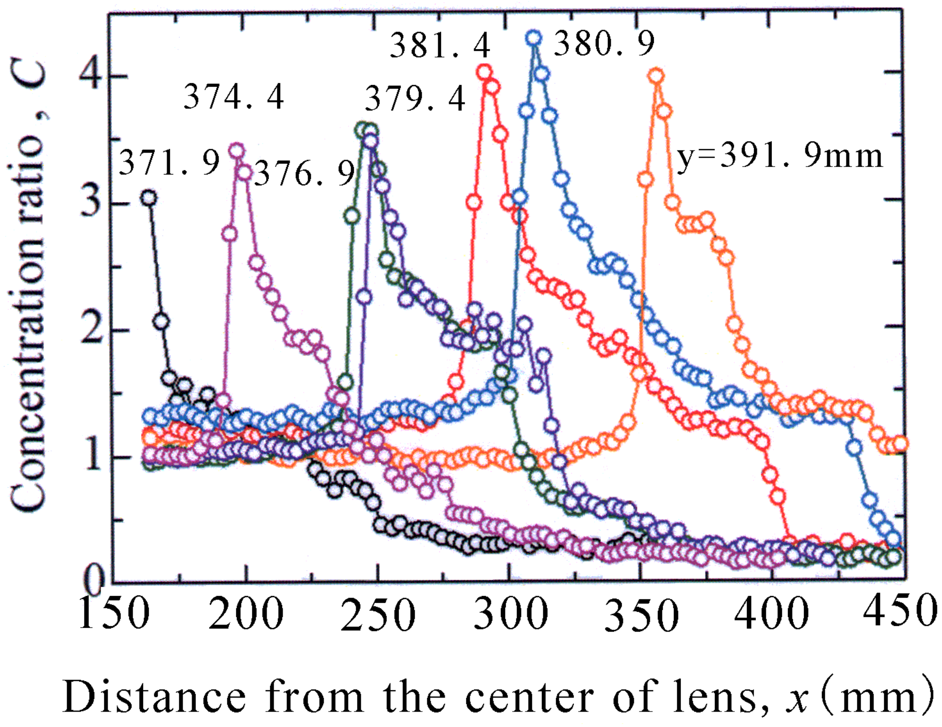
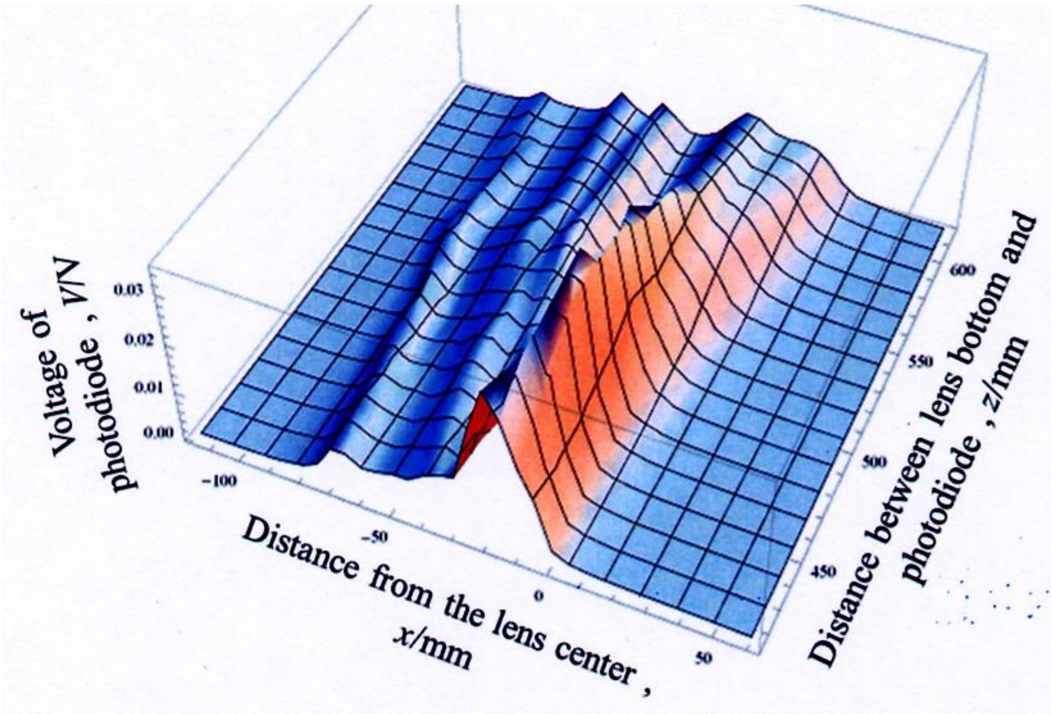
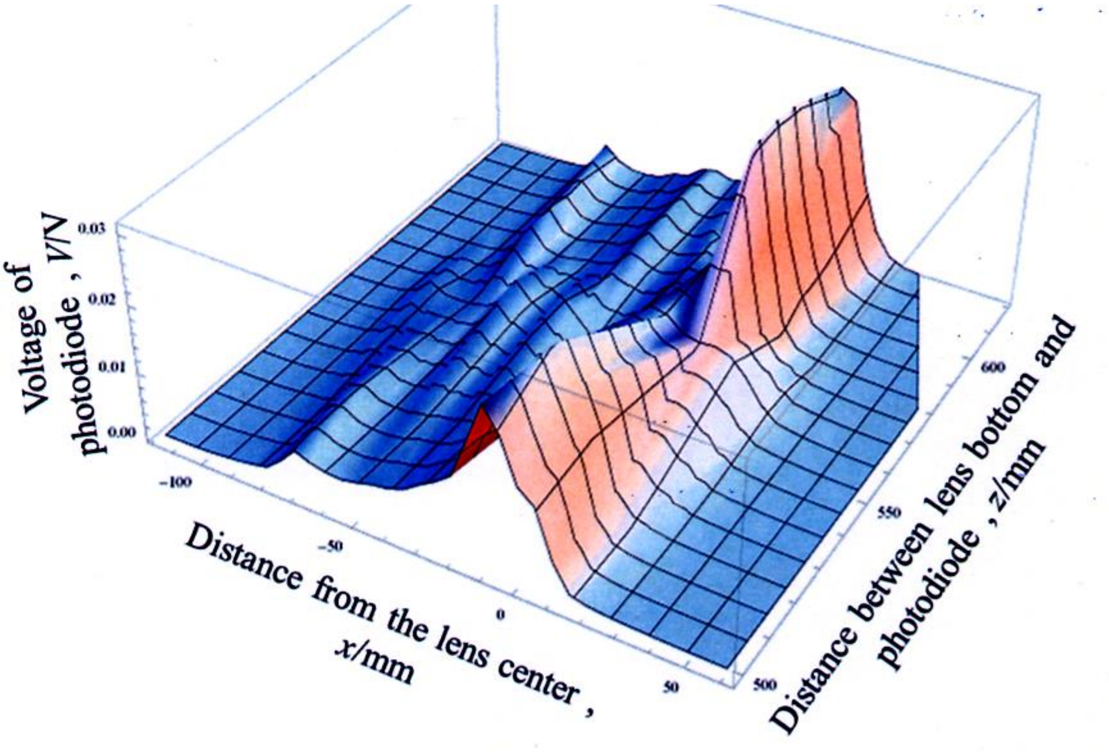


Fig. 7 Concentration ratio of the water lens under solar light.

y : distance between the sensor and the upper surface of water lens.


Voltage of photodiode , V/V
0.03
0.02
0.01
0.00
-100
-50
0
50
Distance from the lens center , x/mm
450
500
550
600
Distance between lens bottom and photodiode , z/mm

(a)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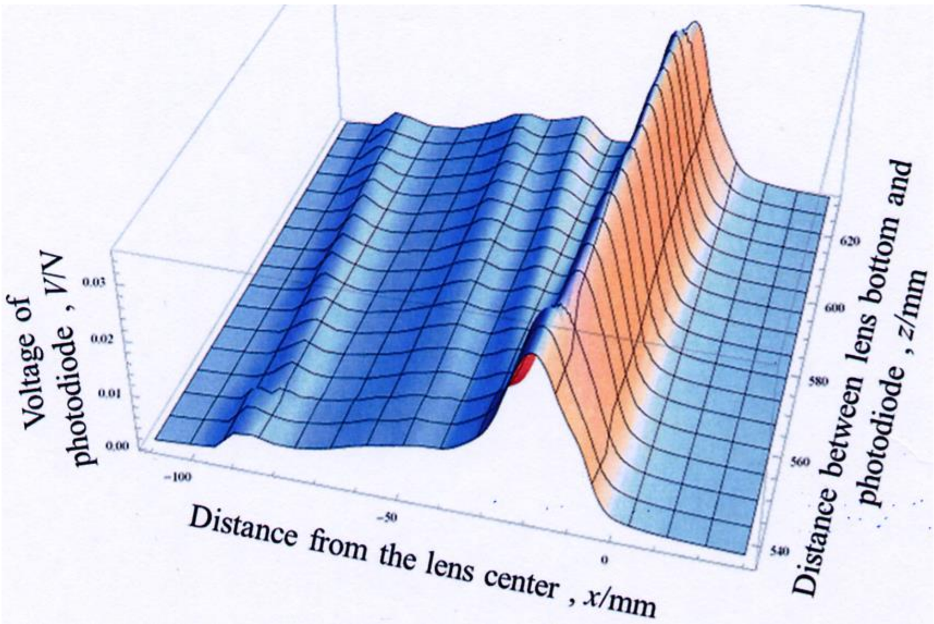
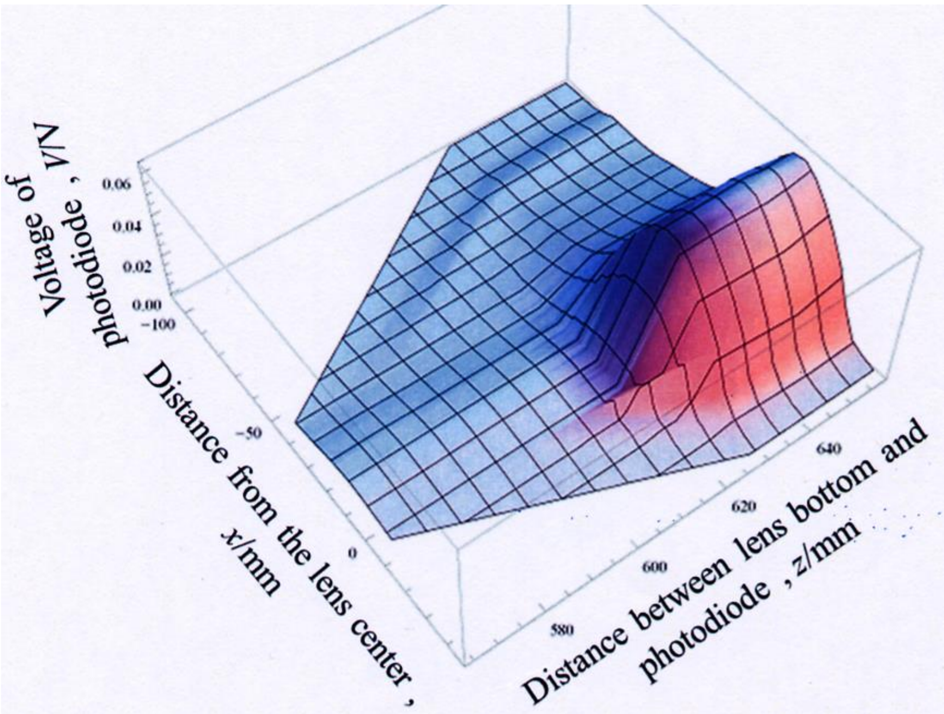
(b)

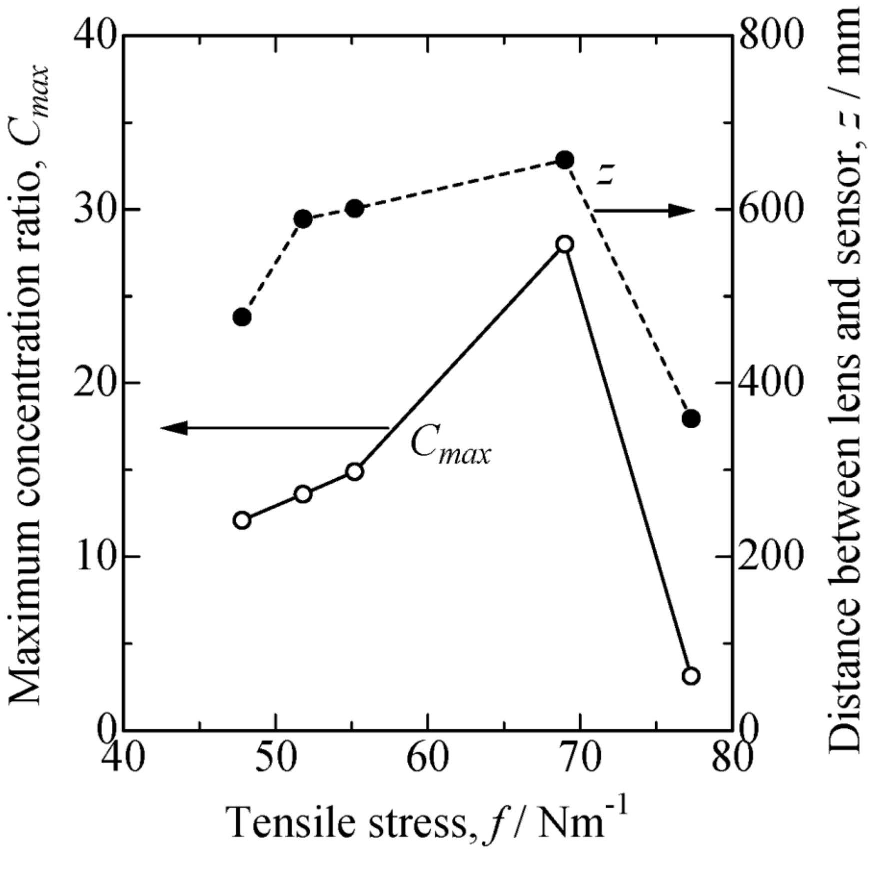


(c)



(d)

Fig. 8 EMF of photodiode as the function of distance from the water lens center, *x*, and the distance between lens bottom and photodiode, *z*. The tensile stress was (a) 47.8 N/m, (b) 51.8 N/m, (c) 55.2 N/m and (d) 69.0 N/m.



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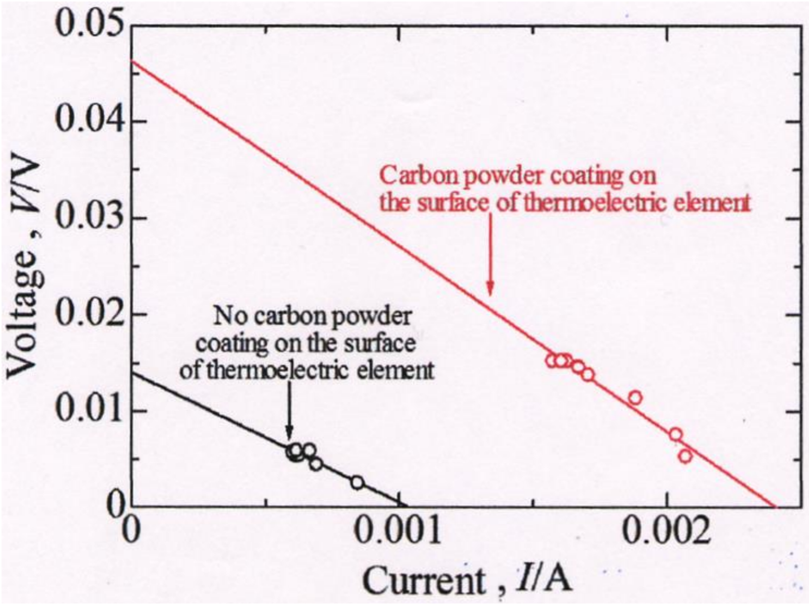
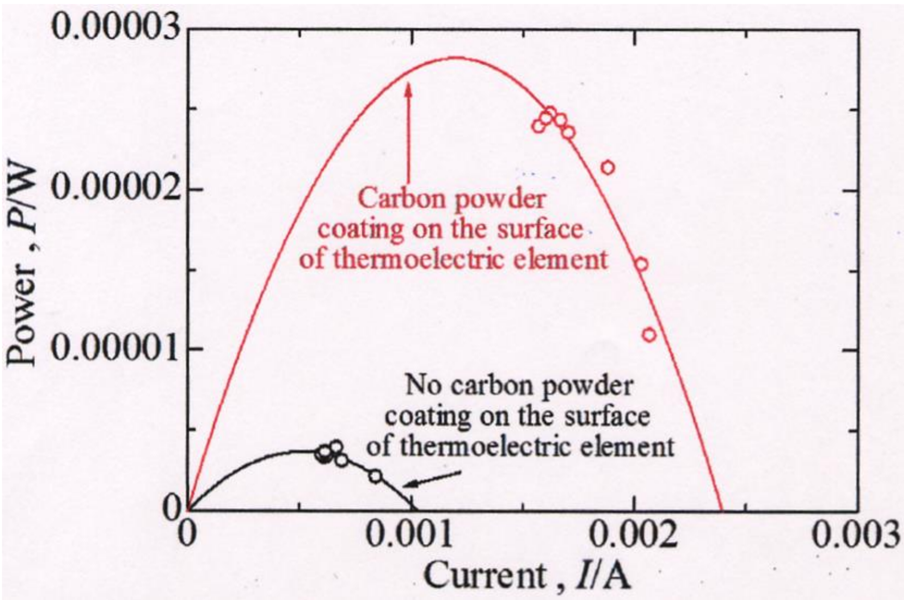


(a)



(b)

Fig. 10 (a) Relationship between current and voltage, and (b) relationship between current and power.