Development of A Floating Solar Thermoelectric Generator Using A Dome Shaped Fresnel Lens for Ocean Application

Seong-Hoon Kim[1], Jeung-Sang Go[2*]

〈Abstract〉

To solve the problem that photovoltaic panels can not harvest electrical energy at a cloudy day and night, a floating solar thermoelectric generator (FSTEG, hereafter) is studied. The FSTEG is consisted of a dome shaped Fresnel lens to condense solar energy, a thermoelectric module connected with a heat sink to keep temperature difference, a floating system simulating a wavy ocean and an electrical circuit for energy storage. The dome shaped Fresnel lens was designed to have 29 prisms and its optical performance was evaluated outdoors under natural sunlight. Four thermoelectric modules were electrically connected and its performance was evaluated. The generated energy was stored in a Li-ion battery by using a DC-DC step-up converter. For the application of ocean environment, the FSTEG was covered by the dome shaped Fresnel lens and sealed to float in a water-filled reservoir. The harvested energy shows a potential and a method that the FSTEG is suitable for the energy generation in the ocean environment.

Keywords : Energy Harvest, Floating, Solar, Thermoelectric, Fresnel Lens

1 enParticle Co. Ltd.
E-mail: shkim@enparticle.com
2* Corresponding author, Professor, School of Mechanical Engineering, Pusan National University
E-mail: micros@enparticle.com

1. Introduction

Many researches on energy harvesting from nature have been widely carried out. In particular, the floating photovoltaic energy generating systems have been in the spotlight due to the advantage of efficient cooling, compared with the ground energy harvesting systems. However, they have critical problem on efficiency degradation resulted from sea water wave and wind in an ocean environment.

Recently, to solve the problem and to improve the reliability of the systems in the ocean environment solar thermoelectric energy generation has been introduced [6-10]. The thermoelectric material transforms solar thermal energy into electrical energy by using the temperature difference between the hot junction heated up by sunlight and the cold junction cooled by ambient air of the thermoelectric material. This method has also advantages of infinite life expectancy, non-moving parts, and eco-friendly [6,8,9].

The solar thermoelectric energy generator has been introduced by Lauryn L. Baranowski et al [8]. The concentrated solar thermoelectric generator was placed in a vacuum to use solar radiation to heat up the hot junction and the cold junction was cooled with the natural convection of air. It may be overheated due to the increased temperature of the cold junction. As a result, it is difficult to maintain the temperature difference constantly.

Also, Daniel Kraemer et al utilized the planar condensing Fresnel lens to condense the solar energy onto the hot junction of the thermoelectric element [9]. It improved the efficiency of the energy generation. However, it was inconsistent because the focusing area could change along the sun path. Thus, it required an automatic solar tracker to focus the condensed light consistently on the thermoelectric element.

In this work, the floating solar thermoelectric generator, FSTEG sealed with the dome shaped Fresnel lens is presented. The FSTEG can use the temperature difference between air and ocean water even at a cloudy weather and night. Also, it can condense sunlight on the thermoelectric element regardless of the sun path. In addition, a heat sink is attached to the cold junction of the thermoelectric element and immersed in the water. Hence, the water cooling by ocean water flow can increase the temperature difference more than the natural air convection cooling. Fig. 1 shows the conceptual image of the FSTEG with a dome shaped Fresnel lens, which can

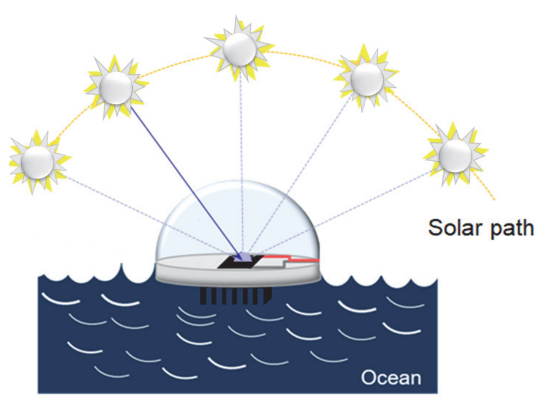

Fig. 1 Conceptual drawing of the FSTEG

focus solar energy along the sun path with higher efficiency of cooling.

2. System Design and Fabrication

The FSTEG with a dome shaped Fresnel lens is consisted of the solar condensing system, thermoelectric module, energy storage circuit and floating substrate, respectively. The solar condensing system was designed to enhance the multi-degree solar condensing ability of the Fresnel lenses. The thermoelectric module was designed to maximize temperature difference. The energy storage circuit was designed to storage electrical energy in a Li-ion battery and it converts the fluctuating output voltages stable. Finally, the floating substrate was designed to keep the system stability in the ocean environment.

Leutz proposed the dome shaped Fresnel lens to condense the solar energy without the automatic solar tracker [11]. It showed higher light condensing efficiency than conventional convex lenses [11-14]. Also, the shape can be changed more freely than the conventional convex lenses. However, the attachment of dusts on the prism patterns lowered the condensing efficiency and the thin thickness made structural weakness.

To this end, the Fresnel lens with the patterned prism inside the dome was designed in order to prevent the contact of the ocean water to the prism and the attachment of the dusts on the patterns. Also, the dome shaped Fresnel lens can disperse external forces effectively. Fig. 2 shows the design of the dome shaped Fresnel lens with the inside prism patterns. Due to transparency, the lens was made of PMMA(polymethyl methacrylate). The PMMA has a lower thermal conductivity than glass so that it has been used for lens fabrication. The properties is advantageous to keep the high temperature at the hot junction. Also, it has a longer life in the environment exposed to sunlight [9].

The angle of the prism was calculated by using Snell's law.

$$\theta_{ref} = \arcsin\left(\sin\theta_{\in c}\frac{n_{air}}{n_{PMMA}}\right) \quad (1)$$

where θ_{ref} is the refracted angle, $\theta_{\in c}$, the incident angle, n_{air}, the refractive index of air, and n_{PMMA}, the refractive index of PMMA, respectively. The 29 prisms were patterned on the inner surface of the dome by the ray-tracing method.

Fig. 2 shows the light refraction in each prism for two incident lights with an angle

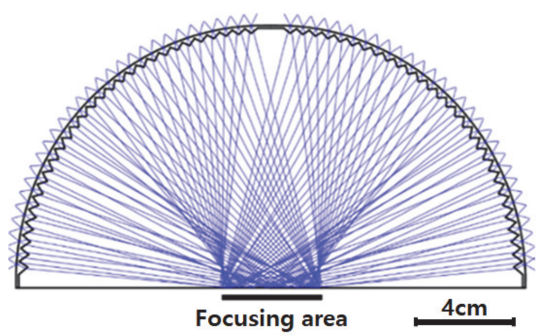

Fig. 2 2-D design of the dome shaped Fresnel lens of $\pm 30^{o}$. The two incident lights were refracted through the prism and focused on the area with a size of 4 cm in a diameter, which means the effective solar condensing area.

Based on the simulation, the dome shaped Fresnel lens was fabricated by machining PMMA to a half hemisphere and the 29 prisms were machined on its inner surface. Fig. 3 shows the fabricated dome shaped Fresnel lens with the prisms.

To evaluate its solar condensing performance, the ceramic plate was coated with black body paint (Flat Protective Enamel, RUST-OLEUM) and placed inside the lens. The size of the ceramic plate was 3.5 cm x 3.5 cm, which is the same with the size of the thermoelectric element. The surface temperature was measured by using a K-type thermocouple outdoors from 11 am to 2 pm.

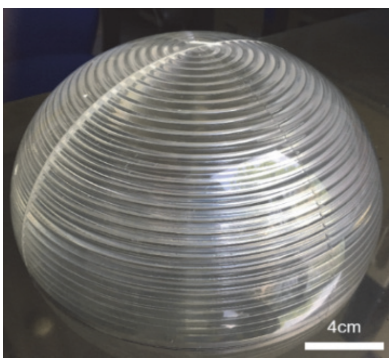

Fig. 3 Image of the fabricated dome shaped Fresnel lens

Fig. 4 visualizes the solar condensing performance of the dome shaped Fresnel lens in a colour. The center of the area is hotter than other parts, indicating that the sunlight can be condensed by the dome shaped Fresnel lens efficiently in the center area where the thermoelectric module will be placed.

In Fig. 5, the average temperature of the center area is compared with that of the total area. Their maximum temperature difference was measured to be 15 ℃.

The thermoelectric material can transform heat into electrical energy and it is explained by Seebeck effect. The output voltage is expressed as,

$$V_c = \alpha \triangle T \qquad (2)$$

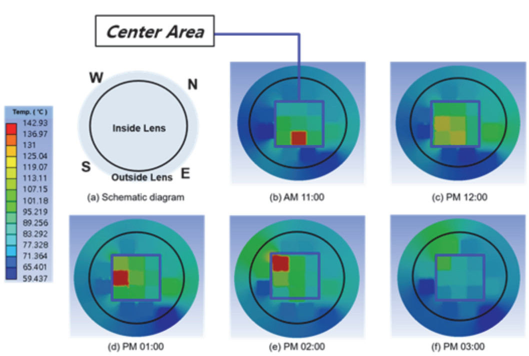

Fig. 4 Solar condensing performance of the dome shaped Fresnel lens

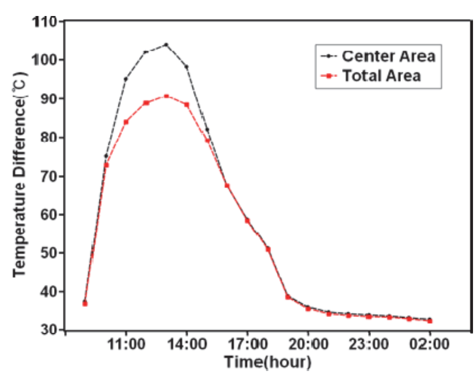

Fig. 5 Comparison of the average temperature in center and total area

where V_c is the output voltage, a, the Seebeck coefficient, and DT, the temperature difference between the hot junction and the cold junction, respectively.

For the experimental evaluation, the Bi_2Te_3 thermoelectric material (TE-MOD-5W 5V-35S, TEGpro) was used since it shows the highest thermoelectric performance under 100 ℃ [15].

Also, it is suitable to apply for the FSTEG in which its hot junction operates at less than 100 ℃. By considering the size of the solar condensing area, four thermoelectric elements were connected in series.

The hot junction of the thermoelectric module was heated up to 60 ℃ by using a cartridge heater(MicaStrip, Marathon Heater Inc.), and the cold junction was cooled by water filled in a reservoir. For a temperature difference of 4.5 ℃, two thermoelectric elements connected in series showed the highest voltage of 1V. In the experiment, four thermoelectric elements were interconnected in series and fitted onto the floating substrate.

Also, the heat sink (655-53AB, Wakefield Inc.) was bonded on the cold junction by using the thermal interface material with a thermal conductivity of 8.1 W/m℃ (PK-Zero, Prolimatech Inc.). Then, the energy harvesting performance of the thermoelectric module was evaluated. The hot junction was heated up to 180 ℃ by using a cartridge heater (MicaStrip, Marathon Heater Inc.) and the cold junction was cooled naturally in water.

The output voltage and the current were measured for the temperature difference and the corresponding power by multiplying them was calculated. Fig. 6(a) shows that the voltage and current increases for the increased temperature difference and Fig. 6(b) is the calculated power. At the temperature difference of 4 ℃, the output voltage and the current were measured to be 0.3 V and 13 mA, respectively. Also, at the temperature difference of 11.8 ℃, the voltage of 1.09 V and the current of 33 mA were measured, and the power was obtained to be 36 mW.

The energy storage circuit (hereafter, ESC) was fabricated to store the generated energy and it also adjusted the irregular voltage to

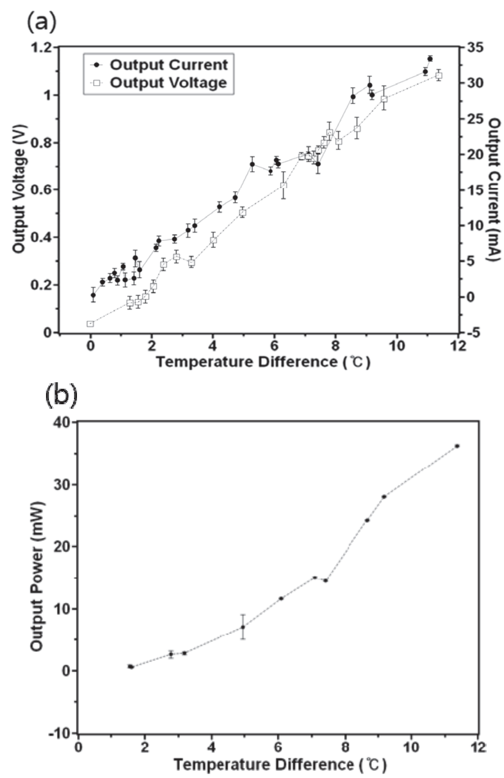

Fig. 6 Evaluation of thermoelectric module: (a) Output voltage and current (b) Output power

the regular voltage of 3.3 V by using the DC-DC converter (TPS61200EVM-179, Texas Instrument). To evaluate the ESC performance, the voltage ranging from 0 to 5 V was applied by using Arduino (Arduino MEGA, Arduino).

The output voltage of the ESC was measured as shown in Fig. 7(a). Fig. 7(b) shows that the stable step-up voltage was 3.3 V even for the application of a low voltage of less than 0.3 V and less than 10 mA was measured. It indicates that the ESC can operate over an output voltage of 0.3 V.

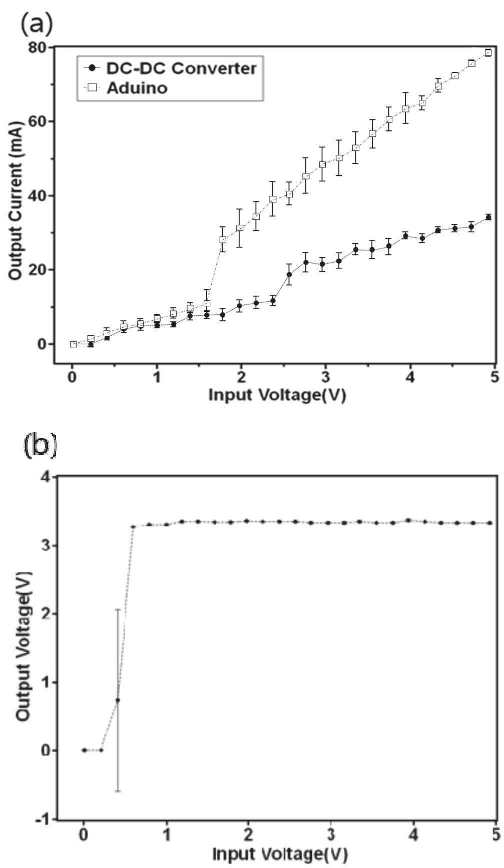

Fig. 7 Evaluation of the ESC: (a) Output current and (b) Output voltage

3. Stable Floating Solar Thermoelectric Generator(FSTEG)

For the ocean application, the stability of the FSTEG was also investigated. In general, the stable equilibrium is reversible from disturbance when the center of gravity is designed to position below the center of buoyancy.

In Fig. 8, the floating substrate was assembled with the thermoelectric module, the dome shaped Fresnel lens and the ESC. It was made of PMMA with a thickness of 10 mm. The total weight of the FSTEG was 0.7 kg. The immersed volume of the FSTEG was 6.8 x 10^{-4} m^3 and the height was 0.023 m from the bottom of the floating substrate.

The center of gravity of the object, the center of buoyancy and the meta center were analyzed for changing the tilting angle. It was predicted that the FSTEG could keep the stability for the tilting angle of less than 95°. In the experiment, a reservoir with the size of 43 cm x 43 cm x 20 cm was filled

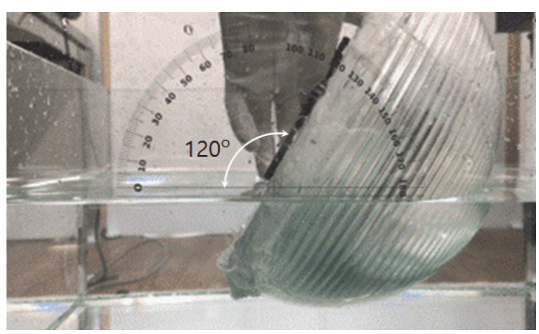

Fig. 8 Experimental setup with the input of the halogen light

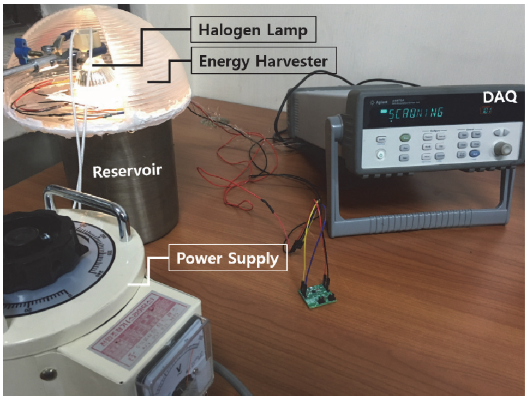

Fig. 9 Experimental setup for controlled energy harvesting performance under the halogen light

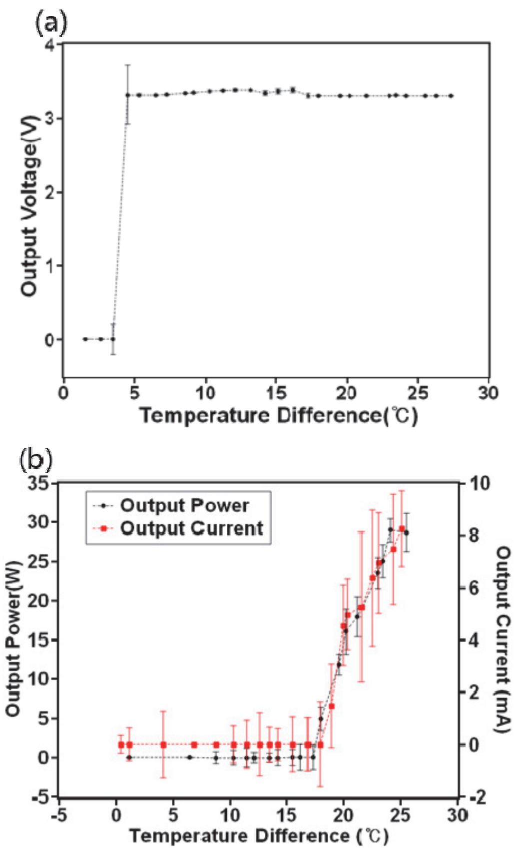

Fig. 10 Electrical performance measurement: (a) Output voltage, (b) Output power and current

with water and the FSTEG was floated. The height of the immersed part was measured to be about 2 cm, which showed a good agreement with the calculation. The FSTEG was tilted from 30° to 150°. At the tilting angle of 120°, the FSTEG was overturned. So, the fabricated FSTEG can keep the stability to external disturbance such as wave and wind in ocean.

Before testing the energy generating of the FSTEG under the sunlight, the energy generating performance was examined under the controlled light input. To apply constant light energy, a halogen of 50 W was installed to heat the hot junction up as shown in Fig. 9. The voltage obtained from the FSTEG was applied to the ESC as input and the charged electrical output was measured.

Fig. 10 shows that the voltage of the ESC was boosted to be 3.3 V at a temperature difference of 4 ℃. However, the electrical power was not charged sufficiently under the temperature difference of 17 ℃ but the electrical power increased linearly over 17 ℃.

To examine the capability of the energy generating of the FSTEG in the ocean, the performance evaluation was carried out by

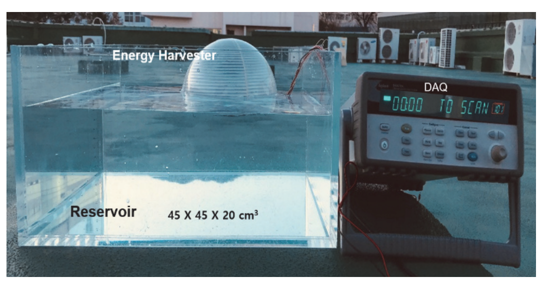

Fig. 11 FSTEG floated in the water reservoir

floating FSTEG in the reservoir filled with water as shown in Fig. 11.

The temperature difference and the output voltage were measured from 9:30 to 18:00 under the sunlight and the measurement was conducted on August 2nd, 2018. Fig. 12 shows the measured temperature difference and output voltage, respectively. The temperatures were measured at each junction and in the water. During the experiment time, the minimum and maximum atmospheric temperatures were measured 27 ℃ and 34 ℃, respectively.

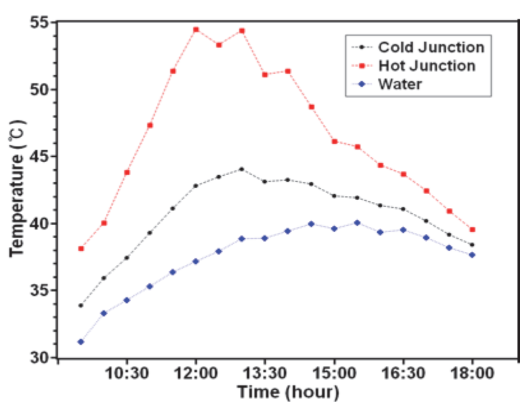

Fig. 12 Temperature measurement

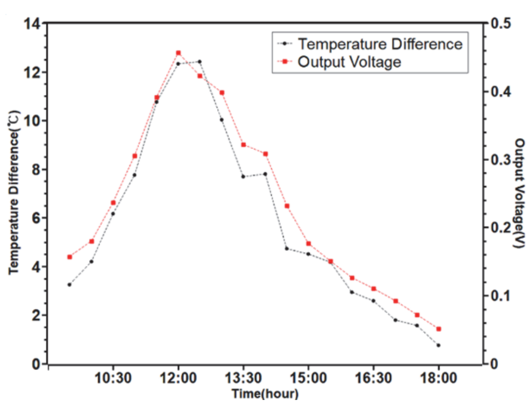

Fig. 13 Output voltage and temperature difference

At 12 pm, the maximum temperature difference was obtained as 13 ℃ and the output voltage was 0.45 V as shown in Fig. 13. Therefore, the measured temperature difference was enough to boost the ESC, but the battery was not charged sufficiently because it was smaller than 17 ℃.

In general, the thermal mass is a property which enables to store heat and it is proportional to the volume of the water. The water filled with a height of 15 cm in the reservoir is negligibly small compared with the ocean. Thus, it could not keep the water temperature cold in the reservoir like ocean. As a result, the temperature of the cold junction was increased so that the temperature difference was not enough to charge the battery. However, it can be improved simply by floating the FSTEG in the ocean when considered its infinite thermal mass.

4. Conclusions

The FSTEG sealed with a dome shaped Fresnel lens was developed for the ocean application. Four important components of the dome shaped Fresnel lens, the thermoelectric module, the floating substrate and the energy storage circuit were designed and fabricated. Specifically, the dome shaped Fresnel lens was designed to focus the sunlight onto the condensing area with 29 prisms patterned on the inner surface. Also, in order to maximize the electrical energy from the condensing area, four thermoelectric elements were connected in series. The stability of the FSTEG was designed. Finally, to keep constant output voltage, the energy storage circuit was constituted.

The energy generation was measured under the controlled light by using the halogen lamp. The output voltage in the ESC was boosted at a temperature difference of about 4 ℃ and the boost voltage was 3.3 V. Also, the outdoor energy generation of the FSTEG floated in the water filled reservoir was measured under the sunlight from 9:30 to 18:00. The maximum temperature difference was measured 13 ℃ at noon. The ESC was not charged sufficiently in the small reservoir which was easily warmed by sunlight with infinite thermal mass. However, it can be improved by floating it in the ocean with infinite thermal mass.

Different from the conventional photovoltaic solar energy generation, the FSTEG can convert energy with the presence of the temperature difference. In the ocean, because there always exists the temperature difference between air as the hot junction and ocean water as the cold junction, the FSTEG can generate the electrical energy even in a cloudy day or at night.

Acknowledgements

This work was supported by a 2-Year Research Grant of Pusan National University.

References

[1] P. Sclavounos, C. Tracy, and S. Lee, "Floating offshore wind turbines: Responses in a seastate pareto optimal designs and economic assessment," Proc. of ASME 2008 27th Int. Conf. on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers, Vol. 6, pp. 31-41, (2008).

[2] W. Shi, H. C. Park, C. W. Chung, H. K. Shin, S. H. Kim, S. S. Lee, and C. W. Kim, "Soil-structure interaction on the response of jacket-type offshore wind turbine," Int. Journal of Precision Engineering and Manufacturing-Green Technology, Vol. 2, No. 2, pp. 139-148, (2015).

[3] B. Drew, A. R. Plummer, and M. N. Sahinkaya, "A review of wave energy converter technology," Proc. of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, Vol. 223, pp. 887-902, (2009).

[4] N. M. Tri, P. C. Binh, and K. K. Ahn, "Power take-off system based on continuously variable transmission configuration for wave energy converter," Int. Journal of Precision Engineering and Manufacturing-Green Technology, Vol. 5, No. 1, pp. 89-101, (2018).

[5] A. Sahu, N. Yadav, and K. Sudhakar, "Floating photovoltaic power plant: A review," Renewable and Sustainable Energy Reviews, Vol. 66, pp. 815-824, (2016).

[6] M. Telkes, "Solar thermoelectric generators," Journal of Applied Physics, Vol. 25, No. 6, pp.765-777, (1954).

[7] T. Atalay, Y. Köysal, A. E. Özdemir, and E. Özbaş, "Evaluation of energy efficiency of thermoelectric generator with two-phase thermo-syphon heat pipes and nano-particle fluids," Int. Journal of Precision Engineering and Manufacturing-Green Technology, Vol. 5, No. 1, pp. 5-12, (2018).

[8] L. L. Baranowski, G. J. Snyder, and E. S.

Toberer, “Concentrated solar thermoelectric generators,” Energy & Environmental Science, Vol. 5, No. 10, pp. 9055-9067, (2012).
[9] D. Kraemer, B. Poudel, H. P. Feng, J. C. Caylor, B. Yu, and X. Yan, and K. McEnaney, “High-performance flat-panel solar thermoelectric generators with high thermal concentration,” Nature materials, Vol. 10, No. 7, pp. 532, (2011).
[10] D. Kraemer, Q. Jie, K. McEnaney, F. Cao, W. Liu, L. A. Weinstein, and G. Chen, “Concentrating solar thermoelectric generators with a peak efficiency of 7.4%,” Nature Energy, Vol. 1, No. 11, pp. 16153, (2016).
[11] R. Leutz, A. Suzuki, A. Akisawa, and T. Kashiwagi, “Design of a nonimaging fresnel lens for solar concentrators1,” Solar energy, Vol. 65, No. 6, pp. 379-387, (1999).
[12] K. Araki, T. Yano, and Y. Kuroda, “30 kW concentrator photovoltaic system using dome-shaped Fresnel lenses,” Optics express, Vol. 18, No. 101, pp. A53-A63, (2010).
[13] A. Akisawa, M. Hiramatsu, and K. Ozaki, “Design of dome-shaped non-imaging Fresnel lenses taking chromatic aberration into account,” Solar Energy, Vol. 86, No. 3, pp. 877-885, (2012).
[14] P. M. Viera-González, G. E. Sánchez–Guerrero, E. Martínez-Guerra, and D. E. Ceballos-Herrera, “Design of a segmented nonimaging Fresnel dome for nontracking solar collection,” Optical Engineering, Vol. 56, No. 7, pp. 075103, (2017).
[15] L. E. Bell, “Cooling, heating, generating power, and recovering waste heat with thermoelectric systems,” Science, Vol. 321, No. 5895, pp. 1457-1461, (2008).

(Manuscript received November 16, 2023;
revised November 25, 2023; accepted December 06, 2023)