SOLAR THERMOPHOTOVOLTAIC SYSTEM WITH HIGH TEMPERATURE TUNGSTEN EMITTER

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ABSTRACT

In this paper, R&D of a solar thermophotovoltaic (STPV) system is reported. Two types of TPV modules have been developed and tested under concentrated sunlight. Temperatures as high as 1800^0 C were obtained in a 12 mm dia and 15 mm length emitter, illuminated by a 0.45 m^2 pseudoparabolic facet mirror with a secondary quartz lens (4000x concentration ratio). Analysis of various parameters, influencing the overall performance of the developed STPV is presented.

INTRODUCTION

A solar thermophotovoltaic system is based on a principle of conversion of concentrated solar energy into radiation by heating an intermediate photon emitter with subsequent photovoltaic conversion of this radiation in low-bandgap photoconverters. Essential advantage of such system, compared to conventional ones, is the possibility to choose emitter material with selective emission spectrum and to use sub-bandgap photons owing to recycling process. Theoretically estimated STPV system efficiencies lay in a wide interval from 30 to 70 percent, depending on approach used [1-8]. Experimental STPV systems have been realized in [9,10], though the overall efficiency data has not been provided there. In the present paper development of a STPV system and evaluations of its performance with estimations of possible system improvements are presented.

SYSTEM DESIGN AND EXPERIMENTAL RESULTS

A solar TPV system under development consists of sunlight tracker, sunlight concentrator and STPV module. The sunlight concentrator (Fig. 1), used here, is a combination of four-segment pseudo-parabolic compound mirror (0.45 m^2 in area, 0.75 m focal length) and secondary quartz convex lens (70 mm dia, 120 mm focal length), installed in the entrance window of the STPV module. The secondary lens had an antireflection coating for the spectral range of 400-2000 nm. According to our measurements, this system gave sun concentration of about 4000X, i.e. 90% of input sunlight came to the 12 mm aperture emitter.

The TPV part of module includes a cylinder-shaped tungsten emitter, embedded in a vacuum chamber. For several experiments tantalum emitters were used instead of tungsten ones, because of easier tantalum treatment. Vacuum chamber with a quartz window for sunlight entrance was used to prevent the emitters from oxidation. Two types of the STPV modules, conical and cylindrical ones, have been developed (Fig. 2). In a conical system (Fig.2, a) thermal radiation is reflected to the PV cells by an Au coated cone-shaped mirror, and PV cells are mounted on a flat base. In the cylindrical system (Fig.2, b)

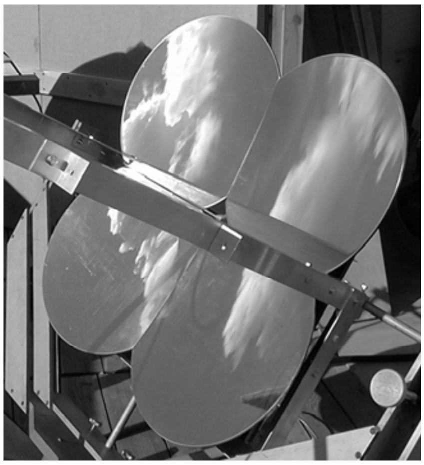

Fig. 1. Pseudo-parabolic facet concentrator made of four spherical dish mirrors installed on the sun tracker.

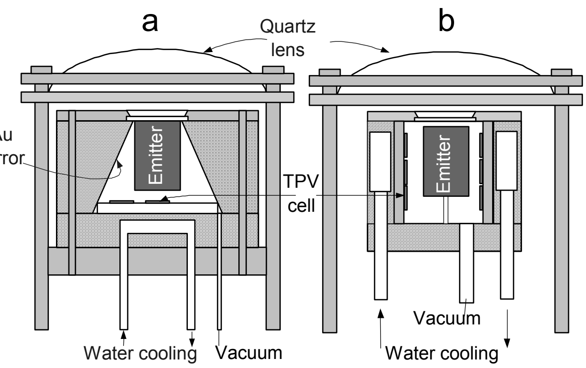

Fig. 2. Schematic drawings of the developed conical (a) and cylindrical (b) STPV modules.

PV cells surround the emitter, being mounted on the inner side of a cooled cylindrical base.

Both modules were tested outdoors under direct sun illumination. Average sun irradiation was measured to be 850 W/m^2.

Emitter temperature was registered by both pyrometer and W-Re thermocouple. Temperatures in the range of 1500-2000 K were obtained, depending on emitter size and material. 1x1 cm GaSb cells were used to evaluate system performance. In the conical system, 4.5 A/cm^2 current density was obtained with a 12 mm dia and 15 mm long tungsten emitter, while in the cylindrical one it was 1.9 A/cm^2. Overall efficiency of the developed STPV systems was estimated to be ~10%.

EFFICIENCY CALCULATION

Calculations of the STPV module efficiency have been performed in order to understand the ways for efficiency increase. In the calculations, the following assumptions were taken into account. Concentrator system consists of a broadband mirror with optical efficiency of 90%. In one's turn, 90% of concentrated solar radiation is focused inside the input aperture. Solar radiation was taken being equal to 850 W/m^2. Emitter (made from tungsten, or graphite) of a cylindrical shape with an aperture size, determined by the concentrating system (4000x), has aperture absorptance (AA) of 0.7-0.8 due to its hollow shape. Emitter temperature was calculated by solving the energy flow equation. It was varied by changing the given cylinder height. The only emitter loss considered was radiation through the input aperture. Conventional energy losses from emitter, fastened on a ceramic holder in a vacuum chamber, were considered to be negligibly low.

Almost ideal photovoltaic cells were considered (the so-called Shockley-Queisser model), i.e. all photons with energy, exceeding a band gap, are absorbed, producing photocurrent with internal quantum efficiency of 95%, and the only recombination process possible is radiative recombination. No ohmic losses were assumed, however, the current density was limited by 5 A/cm^2, which is optimal for our 1x1 cm^2 GaSb-based cells [11]. At moderate emitter temperatures, thermal radiation density was chosen to be a half of one, emitted from the emitter surface (i.e. total PV cell area was assumed to be two times larger, then emitter area), while at higher emitter temperatures, when reaching the maximum current density, the number of PV cells was increased, that reduced radiation density and limited the cell current.

In general, STPV efficiency depends on PV conversion efficiency and emitter efficiency. Our estimations of PV cell efficiency for the case of tungsten emitter have shown, that maximum efficiency for temperatures of 2000-2500K is obtained with Eg=0.6-0.7 eV. Emitter efficiency can be defined as an utilized for TPV conversion part of irradiated by an emitter energy divided by total irradiated by the emitter energy. It mainly depends on the incident light aperture and, thus, is a function of sunlight concentration ratio (CR) [12]. It appears, that emitter efficiency does not depend on aperture absorptance (AA), however, for "blacker" apertures higher temperatures can be obtained. This is illustrated in Fig. 3, where squares and triangles correspond to different emitter aperture absorptances (AA).

Combining PV and emitter efficiencies one can get a total STPV efficiency for the selected PV cell bandgap. As can be seen from Fig. 4, maximum efficiency of 12-13% can be obtained for the cells with Eg=0.5-0.6 eV. 11.5 % is expected for GaSb cells. This estimation is in a good agreement with experimental expectations. The efficiencies, calculated in such a way, are rather low. More efficient STPV systems should include definite modifications.

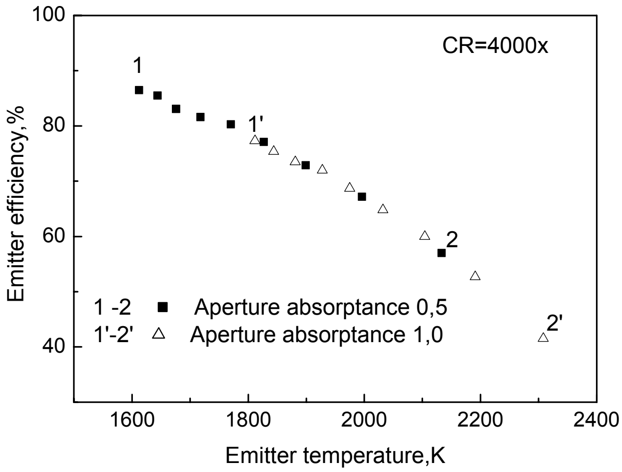

Fig. 3. Calculated emitter efficiency vs emitter temperature. Triangles and squares - calculations for the same set of cylindrical emitter height and aperture and different aperture absorptance.

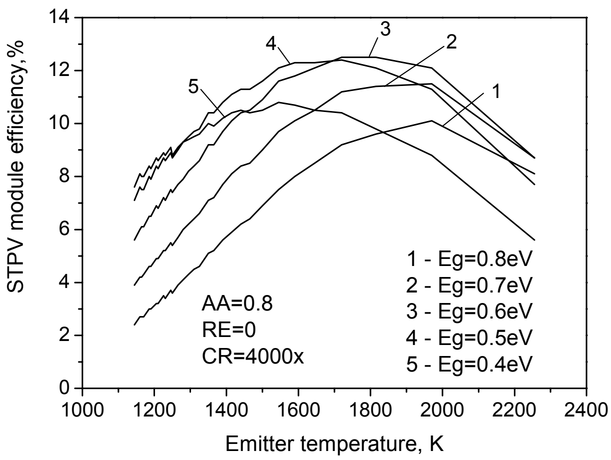

Fig. 4. Calculated overall STPV efficiency for different PV cell bandgaps with the following system parameters: aperture absorptance AA=0.8, return efficiency RE=0, concentration ratio CR=4000x.

POSSIBLE SYSTEM IMPROVEMENTS

First of all, STPV approach assumes that unused energy of sub-bandgap photons can be returned to the emitter. It can be returned by inserting a broadband metallic mirror on the PV cell backside. Experimentally measured maximum reflectance for such mirrors varies from 70 to 90 percent, depending on substrate and mirror materials used. Another way to return unused energy to emitter is to insert a selective filter between the cells and the emitter. Reflectance of dielectric mirrors, for instance, Bragg reflectors, can be more than 99%. However, they are sensitive to the light propagation direction, and are characterized by rather narrow gap, higher orders of reflectance and reduced transmittance.

Absorption coefficient for tungsten varies from 10 to 30% for the considered wavelength region assuming GaSb-based TPV system. Therefore, the unused sub-bandgap radiation cannot be totally absorbed by tungsten emitter and is again reflected to the PV cell resulting in multiple reflection cycle. Fig. 5 shows the dependence of sub-bandgap energy absorbed by the emitter as a function of return efficiency (RE) for tungsten and graphite emitters. Hereafter we use the expression "return efficiency" to indicate a part of sub-bandgap unused energy reflected back to the emitter surface. Such dependence indicates that with tungsten emitter only high values of return efficiency (> 0.85) result in more than 50% recycling of sub-bandgap photons. For the graphite emitter, this dependence is close to linear one, so that the same result is achieved with RE > 0.6.

In Fig. 6, one can see the temperature dependence of total STPV efficiency for the case of GaSb PV cells and tungsten emitter at different return efficiencies. This estimation shows, that only high enough return efficiencies produce a sensitive effect. It may be achieved by combination of backside metallized mirrors with dielectric reflecting coatings (filters), deposited on a special quartz plate, or directly on the PV cell surface.

Another factor influencing the total efficiency is absorptance of the emitter aperture. With higher values of absorptance, the part of radiation increases, that goes back through the aperture. However, higher emitter

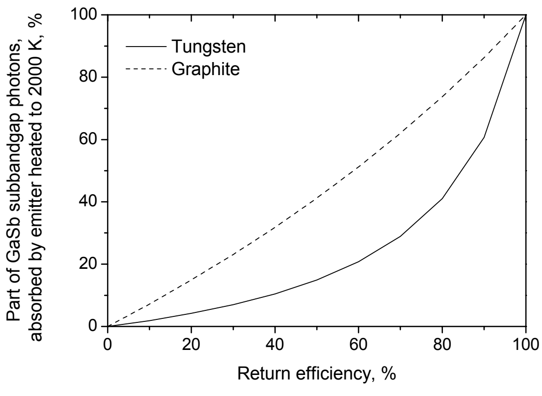

Fig. 5. Part of GaSb sub-bandgap radiation energy, absorbed by an emitter versus return efficiency. Tungsten (solid line) and graphite (dashed line) emitters are considered.

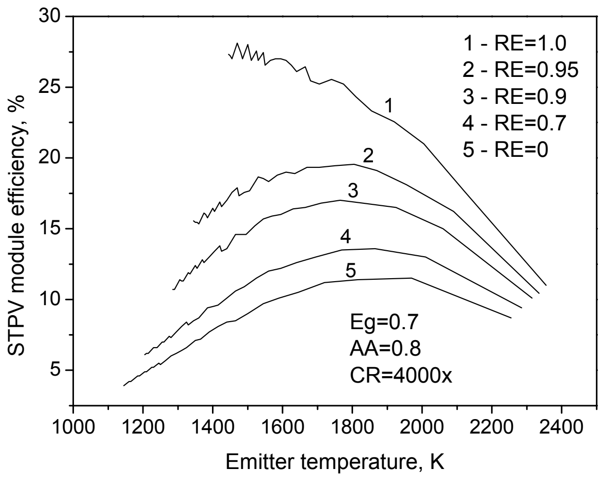

Fig. 6. Calculated STPV efficiency for GaSb cells at different return efficiencies vs tungsten emitter temperature.

temperatures are achieved, which result in more efficient energy conversion. Fig. 7 shows STPV module efficiencies using GaSb-based cells for considered sun power concentrations of 4000x for different emitter aperture absorptances. Optimization of system parameters results in 3-4 percent of overall efficiency increase. Also, the use of highly absorbing pyrolitic graphite coating inside the tungsten emitter and fabricating a higher quality facet mirror is supposed.

The overall STPV efficiency can be significantly increased by the use of selective emitters. Tungsten is a slightly selective material with emissivity increasing in the visible light spectrum, however, more selective materials would be preferable. For instance, 2D-texturized tungsten, or 3D-photonic crystals [13,14] may lead to selective increase in emissivity in a desired wavelength region (say, 1.5-1.7 μm), or materials with selective emission spectrum, such as Er or Yb doped ceramics

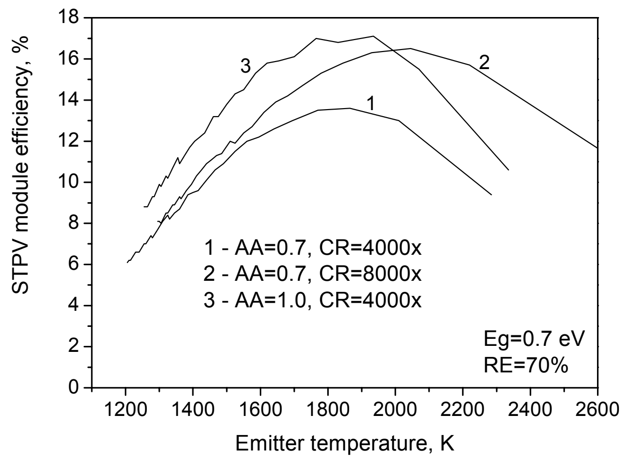

Fig. 7. Calculated STPV module efficiency as a function of tungsten emitter temperature with different sunlight concentration ratios (curves 1 and 2) and emitter aperture absorptances (curves 1 and 3).

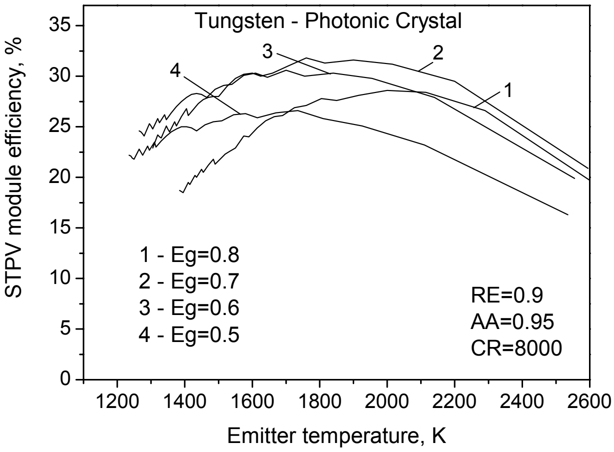

Fig. 8. Calculated STPV module efficiency as a function of emitter temperature. Emitter material- tungsten 3D photonic crystal. Other parameters: AA=0.95, RE=0.9, CR=8000x.

[9,10,13,15,16]. Fig. 8 presents STPV efficiency for the case of emitter based on tungsten 3D photonic crystal, according to the emission spectrum given in [14]. Combining the best parameters described above, efficiencies as high as 30-32 percent can be obtained in a STPV system (Fig.8).

SUMMARY

In conclusion, a solar TPV system was developed and tested. System performance was evaluated. Various factors influencing the efficiency of the developed STPV module have been examined and the ways to improve the developed STPV system performance have been proposed.

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REFERENCES

[1] W. Spirkl and H. Ries "Solar thermophotovoltaics: An assessment", *J.Appl. Phys.*, **57** (9), 1985, 4409-4412.

[2] P. A. Davies, A. Luque "Solar thermophotovoltaics: Brief review and a new look", *Solar. Energy Materials & Solar Cells*, **33**, 1994, 11-22.

[3] A. Luque, A. Marti "Limiting efficiency of coupled thermal and photovoltaic converters", *Solar Energy Material & Solar Cells*, **58**, 1999, 147-165.

[4] V. Badescu "Thermodinamic theory of thermophotovoltaic solar energy conversion", *J.Appl. Phys.,* **90**, 2001, 6476-6486.

[5] N-P. Harder, P. Würfel "Theoretical limits of thermophotovoltaic solar energy conversion", *Semicond. Sci. Technol.*, **18,** 2003, S151-S157.

[6] G.D. Cody "Theoretical Maximum Efficiencies for Thermophotovoltaic Devices", *4th Conf. on TPV Generation of Electricity*, Denver, CO USA, 11-14 Oct, 1998, pp. 58-67.

[7] V.M.Andreev, V.P.Khvostikov, V.R.Larionov, V.D.Rumyantsev, M.Z.Shvarts, S.V.Sorokina, V.I.Vasil'ev, A.S.Vlasov "Single and dual junction GaSb/InGaAsSb TPV cells" *Proc. of the 2-nd World Conf. on PVSC*, Vienna, 6-10 July 1998, p.330-333

[8] V.M.Andreev, V.P.Khvostikov, O.A.Khvostikova, V.D.Rumyantsev, P.Y.Gazarjan, A.S.Vlasov "Solar thermophotovoltaic converters: efficiency potentialities". *Proc. of the 6th Conf. on TPV Generation of Electricity,* Freiburg, June 2004, pp. 96-104

[9] K. W. Stone, N. S. Fatemi, L. Garverick "Operation and component testing of a solar thermophotovoltaic power system", *Proc. of 25th IEEE PVSC,* Washington, DC, 1996, pp. 1421-1424.

[10] H. Yugami, H. Sai, K. Nakamuro, N. Nakagama, H. Ohtsuko "Solar thermophotovoltaic using $Al_2O_3/Er_3Al_5O_{12}$ eutectic composite selective emitter" *Proc. 28th IEEE PVSC,* Anchorage, 2000, pp. 1214-1217

[11] V. Andreev, V. Khvostikov, O. Khvostikova, N. Kaluzhniy, E. Oliva, V. Rumyantsev, S. Titkov, M. Shvarts, "Low-Bandgap PV and Thermophotovoltaic cells", *WCPEC-3*, Osaka, Japan, May 11-18, 2003, 1O-B7-02.

[12] A.Ya. Ender, V.I. Kuznetsov, V.I. Sitnov, A.V. Solovyov, B.G. Ogloblin, A.N. Luppov, A.V. Klimov, "Ultra-high temperature thermionic system for space solar power applications", *11th Symp. on Space Nuclear Power and Propulsion.* 9-13 Jan. Albuquerque, NM, USA; 1994, (301) pt. 2: 861

[13] A.Gombert, "An Overview of TPV Emitter Technologies", *5th Conf. on TPV Generation of Electricity*, Rome, Italy 16-19 Sept. 2002, (653) pp 123-131.

[14] S. Y. Lin, J. Moreno, and J. G. Fleming "Three-dimensional photonic-crystal emitter for thermal photovoltaic power generation", *Appl. Phys. Lett.*, **83** (2), 2003 pp 380-382.

[15] B. Bitnar , W. Durisch, G. Palfinger, F. von Roth, U. Vogt, A. Bronstrup, D. Seiler, "Practical thermophotovoltaic generators", *Semiconductors,* **38** (8) 2004, pp 941-945.

[16] Y. Adachi, H. Yugami, K. Shibata, and N. Nakagawa, "Compact TPV Generation System Using $Al_2O_3/Er_3Al_5O_{12}$ Eutectic Ceramics Selective Emitters", *Proc. of the 6th Conf on TPV Generation of Electricity,* Freiburg June 2004, pp. 237-243