Performance Evaluation of a Prototype Solar Collector using Convex Lenses for Varying Mass Flow Rate of the Heat Transfer Fluid

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Abstract

As conventional sources of energy (especially fossil fuels) continue to deplete and pose, more and more environmental challenges day by day, there is a need to shift towards non-conventional sources of energy. Solar energy being the original form of energy, abundantly available and free from environmental hazards, attracts our attention. However, being dilute form of energy, harnessing solar energy employs the need of either solar photo-voltaic or concentrating solar power (CSP) technology. Of the two technologies, CSP is more cost efficient and suitable for a developing economy like India. In the present research paper, experimental evaluation of the performance of a prototype solar collector using convex lenses for CSP is presented. The performance was analysed for varying mass flow rate of the working fluid for five days over a span of two seasons. The experimental evaluation showed that the prototype solar collector's efficiency was more or less constant at 68.5% for all the values of mass flow rate, with maximum efficiency of 68.69% for a mass flow rate of 0.23 kg/h.

Keywords: *solar energy, concentrating solar power, convex lens, solar collector, solar collector's performance*

I. INTRODUCTION

The world today is facing challenges related to energy sources and their efficient utilisation. The challenges vary from limited supply of conventional sources (especially fossil fuels) to environmental threats posed by them. For the solution, non-conventional sources especially **sun** is in the purview. To summarise in the words of Ex. P.M. of India, Shree Manmohan Singh "Our vision is to make India's economic development energy-efficient. Over a period of time, we must pioneer a graduated shift from economic activity based on fossil fuels to one based on non-fossil fuels and from reliance on non-renewable and depleting sources of energy to renewable sources of energy. In this strategy, the sun occupies centre-stage, as it should, being literally the original source of all energy. We will pool our scientific, technical and managerial talents, with sufficient financial resources, to develop solar energy as a source of abundant energy to power our economy and to transform the lives of our people. Our success in this endeavour will change the face of India. It would also enable India to help change the destinies of people around the world [1]." Thus, the research in the field of harnessing and efficiently utilising solar energy is all the more necessary.

Solar energy is the earliest form of energy known to mankind, but perhaps the least utilised. Solar energy is globally distributed and free from depletion or embargo and present no environment problems, and is very large, inexhaustible source of energy. The power from the sun intercepted by the earth is approximately 178 billion MW, which is about 10,000 times more than the present energy demand. Thus in principal, solar energy could supply all the present and future energy needs of the world on a continuing basis. This makes it one of the most promising of the non-conventional energy sources [2-4].

Although abundant, solar energy impinging on the earth's atmosphere is relatively dilute (approx. 1352 W/m^2). Traversing the earth's atmosphere dilutes it further by attenuation, local weather phenomena and air pollution. Moreover, solar energy is received only intermittently at any point on the earth [5,6]. However, areas lying between 30 ^{0}N to 30 ^{0}S latitudes, receives maximum solar radiations. So, India (8^{0}N to 32^{0}N) is one of the few countries for having been blessed with abundant solar radiations. On an average, India's annual solar energy potential is about 7000 MJ/m^2, whose effective utilisation can provide solution to the challenges posed by conventional energy sources [7,8]

As of today, there are two technologies available to harness solar energy viz. solar photo-voltaic (SPV) and concentrated solar power (CSP). Of the two, concentrated solar power is more cost effective and can be incorporated at local level without the need of elaborate set-up as needed in the case of solar photo-voltaic. The cost effectiveness is the major criteria for selecting a technology in the case of developing economy like India, where investment in new technologies is a necessity and not a leisure. Thus, concentrated solar power can provide for the energy demand of the rural and impoverished areas of India.

Many researchers have contributed to the study of CSP using various collectors [9-23]. However, a need was felt for further research using convex lenses as solar collector to concentrate solar power. For the reason, a convex lens CSP prototype solar collector was designed and fabricated with the following objectives.

a) To experimentally evaluate the effect of varying mass flow rate of the heat transfer fluid on the outlet temperature, overall heat loss coefficient and efficiency of the prototype solar collector.
b) To experimentally verify the potentiality of the prototype solar collector.

II. MATERIALS AND METHODS

As no standard procedure was available for designing a solar collector using convex lens, the design was done by adopting the methods employed by the previous researchers [24-30]. The prototype solar collector thus developed is as shown in Plate 2.1 below.

Plate 2.1 Experimental Set-up

The prototype solar collector i.e. the experimental set-up consisted of various parts whose description and specifications are as given in Table 2.1 below.

Table 2.1 Description and Specifications of Prototype's Parts

Sr. No.	Name of the Component	Dimension
1	Solar Collector Box (Plywood)	70×14.5×21 cm^3
2	Diameter of Convex Lens (Glass)	10 cm (4 in)
3	Number of Convex Lenses	6
4	Thickness of Convex Lens	1.5 cm (at the center)
5	Focal Length of the Lens	18.5 cm
6	Diameter of Receiver Tube (Copper)	6.25 mm (1/4th inch)
7	Capacity of Supply Tank (Steel)	2 liters
8	Manual Tracking Mechanism (Iron)	90×15×200 cm^3
9	Thermocouple Wire (Iron Constantan)	1.2 m

A. *Principle of Working of the Convex Lens*

A convex lens is a converging lens. When parallel rays of light pass through a convex lens the refracted rays converge at one point (Figure 2.1) called the principal focus. The distance between the principal focus and the centre of the lens is called the focal length.

As solar energy is diluted form of energy, therefore, converging of sunrays at a focal point so as to increase the concentration is the only means to tap the diluted solar energy. The concentrated solar energy can then be used for a variety of activities from heating to running a power plant.

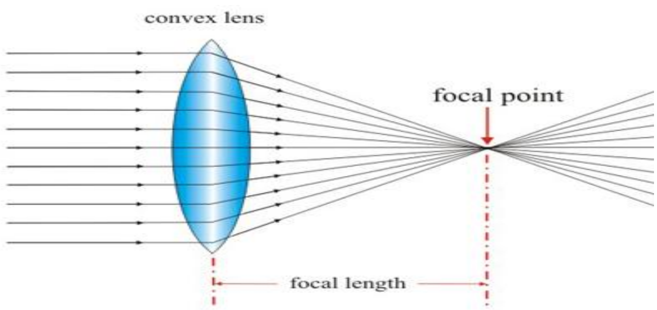

Fig. 2.1 Convex Lens

B. *Test Procedure*

The experimental evaluation consisted of using water as the heat transfer fluid. The water was chosen as for its ready availability, however, precautions were taken to use RO (Reverse Osmosis) purified water so as to make the working fluid devoid of any physical or chemical contaminations.

The experimental evaluation was performed with an aim to study the effect of mass flow rate of water on the prototype solar collector's performance. The evaluation was done for five clear sunny days, during 16th May to 17th May, 2014 (Day1 – Day2) and 21st January to 23rd January, 2015 (Day3 – Day5), on the rooftop of 90 – Abhinandan Nagar at Indore (M.P.). The experimental observations were taken for mass flow rates of 0.41 kg/h, 0.23 kg/h, 0.50 kg/h, 0.66 kg/h and 1.00 kg/h for those five days respectively.

As for the constructional similarity of the prototype solar collector's panel with the flat plate collector (FPC), the performance of the prototype solar collector was evaluated in the same manner as of FPC. The collector's efficiency is the measure of collector's performance and is defined as the ratio of the useful heat gain by the collector over any time to incident solar energy over the same period of time.

The description of various instruments used for experimental measurements is as shown in Table 2.2 below.

Table 2.2 Description of Instruments

Instrument	Make	Purpose/Meas.
Lux Meter	Lutron Electronics	Solar Intensity
Anemometer	Lutron Electronics	Wind Speed
Dig. Temp. Ind.	Perfect Electronics	Temperature
Thermometer	Omron	Temperature
Water Beaker	Hazel	Water
Stop Watch	Sony Xperia Z3	Time

III.RESULTS AND DISCUSSION

The data collected through experimental observation during the aforementioned five days, were analysed and represented in graphs as shown below.

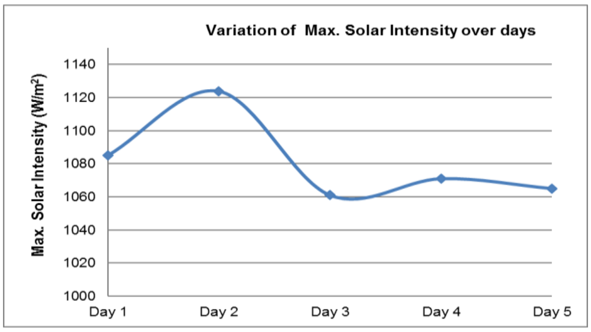

Fig. 3.1 Variation of Maximum Solar Intensity over Days

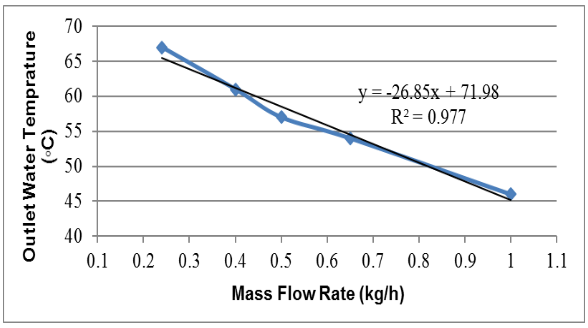

Fig. 3.2 Variation of Outlet Water Temperature with Mass Flow Rate of Water

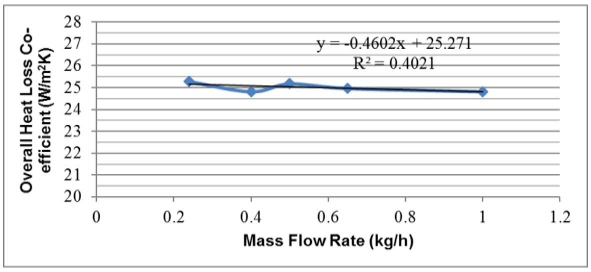

Fig. 3.3 Variation of Overall Heat Loss Co-efficient with Mass Flow Rate of Water

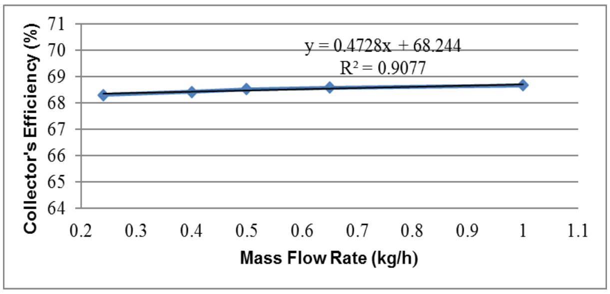

Fig. 3.4 Variation of Collector's Efficiency with Mass Flow Rate of Water

In figure 3.1, Variation of Maximum Solar Intensity is plotted against the Day. The maximum solar intensity is observed as 1125 W/m^2 on the 2nd Day of the testing i.e. 17th May, 2014. The reason for the observation is self-explanatory, as solar intensity is more during summers as compared to winters, and moreover, sky was clearer on 17th May, 2014 as compared to 16th May, 2014.

In figure 3.2, Variation of Outlet Water Temperature is plotted against the Mass Flow Rate of Water. The outlet water temperature is found to decrease from 67 ^{0}C at 0.23 kg/h to 46 ^{0}C at 1 kg/h, thus showing reduction in the outlet water temperature with increase in the mass flow rate of water, as for the obvious reasons. A regression equation y = - 26.85x + 71.95 was developed and plotted along the experimentally calculated data, having r.m.s value of R^2 = 0.997. The regression equation thus developed was calculated based on the maximum temperature obtained for the given mass flow rate. The regression curve varies slightly with the experimentally carved curve.

In figure 3.3, Variation of Overall Heat Loss Co-efficient is plotted against the Mass Flow Rate of Water. The overall heat transfer coefficient was calculated using Klein's Formula for all the values in order to study the effect of mass flow rate of water. The overall heat losses varies from 25.28 W/m^{2}K at 0.23 kg/h to 24.81 W/m^{2}K at 1 kg/h. Thus, slight decrease in overall heat loss co-efficient is observed with increase in mass flow rate of water. A regression equation y = -0.46x + 25.27 was developed and plotted along the experimentally calculated data, having r.m.s. value of R^2 = 0.402. The regression curve slightly varies with the experimentally carved curve.

In figure 3.4, Variation of Collector's Efficiency is plotted against the Mass Flow Rate of Water. The collector's efficiency varies very slightly or in other words remains almost constant at 68.5%, for all the values of mass flow rate of water. This indicates a consistent performance of the prototype solar collector. A regression equation y = 0.472x + 68.24 was developed and plotted along the experimentally calculated data, having r.m.s. value of R^2 = 0.907. The regression curve fitted well with the experimentally carved curve.

IV. SUMMARY AND CONCLUSIONS

The present research work aimed at experimentally analysing the performance of a prototype CSP solar collector using convex lens for varying mass flow rate of heat transfer fluid i.e. water in the present case. For the purpose, mass flow rate of water was varied from 0.23 kg/h to 1 kg/h, and tests were carried out over the two seasons of summer and winter. From the experimental analysis following conclusions were drawn.

a) It was found that with the increase in mass flow rate of water; the outlet water temperature decreased from 67 ^oC at 0.23 kg/h to 46 ^oC at 1 kg/h, overall heat loss coefficient decreased slightly from 25.28 W/m^2K at 0.23 kg/h to 24.81 W/m^2K at 1 kg/h, whereas, the prototype solar collector's efficiency remained nearly constant around 68.5% for all the values of mass flow rate.
b) The prototype solar collector was experimentally verified as a potential solar collector.

REFERENCES

[1] GOI. Jawaharlal Nehru National Solar Mission, Ministry of New and Renewable Energy, New Delhi, pp01-15, 2008.
[2] Rai, G. D. Non-conventional Energy Sources, Khanna Publishers, New Delhi, pp01-44, 2011.
[3] Khan, B. H. Non-conventional Energy Resources, McGraw Hill Education (India) Private Limited, New Delhi, pp01-46, 2009.
[4] Kothari, D. P., et al. Renewable Energy Sources and Emerging Technologies, PHI Learning Private Limited, New Delhi, pp01-23, 2011.
[5] Quaschning, V. Renewable Energy and Climate Change, Wiley India Private Limited, New Delhi, pp87-143, 2010.
[6] Quaschning, V. Understanding Renewable Energy Systems. Earthscan Publishers, London, pp77-180, 2006.
[7] Gehlot, D., Gawali, P. and A. C. Tiwari. Effect on thermal boundary layer by roughened surface of solar air heater duct. International Journal of Research in Engineering Technology and Management. Vol. 1, pp1-6, 2013.
[8] Gehlot, D., Gupta, A., Gawali, P. and A. C. Tiwari. Effect on thermal boundary layer caused by various roughened surface of solar air heater duct. International Journal of Innovative Research and Development. Vol.3, pp68-74, 2014.
[9] Adeff, J. A. and T. J. Hofler.. Design and construction of a solar-powered, thermos-acoustically driven, thermos-acoustic refrigerator. Journal of Acoustical Society of America. Vol. 1, pp01-10, 2000.
[10] Jing, L., Liu, H. and H. Zhao. Design of novel compound Fresnel lens for high performance photovoltaic concentrator. Report published by National Basic Research Program of China. Pp01-10, 2010.
[11] Tyagi et al. Predicted efficiency of a nano-fluid based direct absorption solar receiver. Proceedings of the 2007 ASME conference on Energy Sustainability Conference, New York, pp. 729-736, 2007.
[12] Murthy, et al. Evaluation of thermal performance of heat exchanger unit for parabolic solar cooker for off place cooking. Indian Journal of Pure and Applied Sciences. Vol. 45, pp745-748, 2007.
[13] Bello, S. R. and S. O. Odey. Development of hot water solar oven for low temperature thermal processes. Leonardo's Electronic Journal of Practices and Technologies. Vol. 14(1), pp73-84, 2009.
[14] Mo, S., Chen, Z. and P. Hu. Performance of a passively cooled Fresnel lens concentrating photovoltaic module. Solar Energy Materials and Solar Cells. Vol. 1, pp01-10, 2007.
[15] Leon, M. T., Chong, H. and M. Kraft. Design and modelling of SOI based solar thermoelectric generators. Procedia Engineering. Vol. 47, pp76 – 79, 2012.
[16] Barrera, et al. Analysis of the performance of a GAX hybrid (Solar - LPG) absorption refrigeration system operating with temperatures from solar heating sources. Energy Procedia. Vol. 30, pp884-892, 2012.
[17] Berger, et al. Solar driven cold rooms for industrial cooling applications. Energy Procedia. Vol. 30, pp904-911, 2012.
[18] Yasser, A. and A. Hadi. Simulation model of a new solar pumped laser system of Fresnel lens in Helwan of Egypt. NRIAG's Journal of Astronomy and Geophysics. Vol. 1, pp195-198, 2012.
[19] Wu, et al. Experimental characterisation of a Fresnel lens photovoltaic concentrating system. Solar Energy. Vol. 86, pp430-440, 2012.
[20] Kale, S. S. and N. N. Shinde. Design and development of CSP using convex lenses for domestic water heating and steam generation. International Journal of Mechanical Engineering and Research. Vol. 1(2), pp74-78, 2013.
[21] Mahmouda, M. S., Farraga, T. E. and W. A. Mohamed. Experimental and theoretical model for water desalination by humidification – dehumidification. Proceedings of the 2012 International Conference on Sustainable Future for Human Security, New Delhi, pp100-110, 2012.
[22] Pozivil, et al. A pressurized air receiver for solar-driven gas turbines. Energy Procedia. Vol. 49, pp498-503, 2014.
[23] Winston, R., Jiang, L. and B. Widyolar. Performance of a 23KW solar thermal cooling system employing a double effect absorption chiller and thermodynamically efficient non-tracking concentrators. Energy Procedia. Vol. 48, pp1036-1046, 2014.
[24] Pillai, R. P. and R. Banerjee. Impact of Hot Water Usage Pattern and Location on Economics of Solar Water Heating Systems. M. Tech. (Thesis). Energy Systems Engineering. Indian Institute of Technology, Bombay, India, 2010.
[25] Sterrer, R., et al. Theoretical analysis of the combination of CSP with a biomass CHP plant using ORC technology in Central Europe. Energy Procedia. Vol. 49, pp1218-1227, 2014.
[26] Whitfield, G. R., et al. The development and testing of small concentrating PV system. Solar Energy. Vol. 67(3), pp23-34, 1999.
[27] Xie, W. T., et al. Concentrated solar energy applications using Fresnel lenses: A Review. Renewable and Sustainable Energy Reviews. Vol. 15, pp2588-2606, 2011.
[28] Wang, W., et al. Design and validation of a low-cost high-flux solar simulator using Fresnel lens concentrators. Energy Procedia. Vol. 49, pp2221-2230, 2014.
[29] Shekhar, Y. R., Sharma, K. V. and M. B. Rao. Evaluation of heat loss coefficients in solar flat plate collectors. APRN's Journal of Engineering and Applied Sciences. Vol. 4(5), pp15-19, 2009.
[30] Ma, Z., Glatzmaier, G. C. and M. Mehos. Development of solid particle thermal energy storage for concentrating solar power plants that use fluidized bed technology. Energy Procedia. Vol. 49, pp898-907, 2014