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Theoretical and experimental study on heat pipe cooled thermoelectric generators with water heating using concentrated solar thermal energy

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Abstract

This paper presents the theoretical analysis and experimental validation on the transient behaviour of a proposed combined solar water heating and thermoelectric power generation system. The proposed system consists of concentrated solar thermal device that provides a high heat flux source for thermoelectric generators. Thermoelectric generators are passively cooled using the heat pipes that are embedded inside a heat spreader block. The heat pipe condenser is immersed in a water tank. The immersed liquid cooling technique offers high heat transfer coefficient for cooling of the thermoelectric generators as well as a way to scavenge the heat through water heating that can be used for domestic or industrial purpose. Theoretical analysis develops the governing equations for the proposed system. Results from a scaled down lab setup are used to validate the theoretical analysis. For a flux of 50,000 W/m^2 a temperature difference of 75 °C across the thermoelectric generator can be achieved and the hot water can be heated up to 80 °C which can be used for domestic or industrial applications. With 75 °C temperature difference across the TEG hot and cold side, an open circuit voltage of 3.02 V can be generated for each thermoelectric generator with dimensions of 40 mm × 40 mm.

Keywords: Thermoelectric generators; Passive cooling; Heat pipes; Water heating

1. Introduction and background

Solar water heating systems are a mature technology that is well established and being widely used in many countries. The very first hot water system was introduced in the United States in 1871 by Clarence M. Kemp (Butti and Perlin, 1981). During the early 1900s many researchers focused on research related to solar water heating. Around 1909 a thermosyphon was used for the first time in solar water heating systems (Butti and Perlin, 1979). Until 1930 most of the domestic water heating was supported by coal fired boilers (Kalogirou, 2009). Solar water heating systems became real commercial products towards the 1960s (Best and Riffat, 1995). The 1973 oil crisis gave a major initiative to boost research in the field of solar water heating systems in the United States (Best and Riffat, 1995).

Solar water heating systems are becoming more well-known and now contribute significantly to global energy capacity (Global status report, 2013). China currently dominates the solar thermal market globally, in terms of total global share and also in terms of the annual growth in the global share of solar water heating. Apart from China, countries like Germany, Turkey, Brazil and India

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Nomenclature

q''_{in}	solar radiation flux incident of Fresnel lens (W/m^2)
$\dot{q}_h$	concentrated solar radiation on the target (W)
$\dot{q}_l$	heat loss rate from the water storage tank (W)
$\dot{q}_{l-tar}$	heat loss rate from the target of solar concentration (W)
$\dot{W}_{TEG}$	power generated by thermoelectric generator (W)
A_{lens}	aperture area of the lens (m^2)
$A_{hp-cond}$	outer surface area of condenser section of a heat pipe (m^2)
η_{lens}	optical efficiency of lens
t	time (s)
$q''_{w_{hp}}$	heat flux at the inter face of heat pipe and water in tank (W/m^2)
$\dot{q}_w$	heat input to the hot water in the storage tank (W)
$\dot{q}_l$	heat lost from the hot water storage tank (W)
m	mass of water in the storage tank (kg)
c_p	specific heat of water (kJ/kg K)
T_w	temperature of water in the tank (°C)
T_a	ambient temperature (°C)
T_i	initial temperature of water in the tank (°C)
T_c	temperature of the cold side of the thermoelectric generator (°C)
T_h	temperature of the hot side the thermoelectric generator (°C)
T_{h-cond}	temperature of heat pipe condenser (°C)
T_{h-evap}	temperature of heat pipe evaporator (°C)
UA	rate of heat loss from the storage tank per unit temperature difference (W/°C)
R_w	thermal resistance for heat transfer from heat pipe to water (°C/W)
R_{hp}	thermal resistance offered by the individual heat pipe (°C/W)
N_{hp}	number of heat resistance (°C/W)
$R_{contact}$	contact thermal resistance (°C/W)
R_{TEG}	thermal resistance of each thermoelectric generator (°C/W)
N_{TEG}	number of thermoelectric generators

have got the leading share in global usage of solar water heating systems (Global status report, 2013) (see Fig. 1).

Broad categorization of solar water heating systems is presented by Raisul Islam et al. (2013) in his review paper. He categorizes solar water heating systems in 5 types as follows, thermosyphon systems (passive systems) Kalogirou, 1997; Gupta and Garg, 1968, integrated collector storage system (passive) (Smyth et al., 2006), direct circulation system (active) (Li et al., 2010), indirect water heating system (active) (Chaturvedi et al., 1998), and Air system (active) (Xu et al., 2006).

All the solar hot water systems presented by Raisul Islam et al. (2013) in his review paper are mature

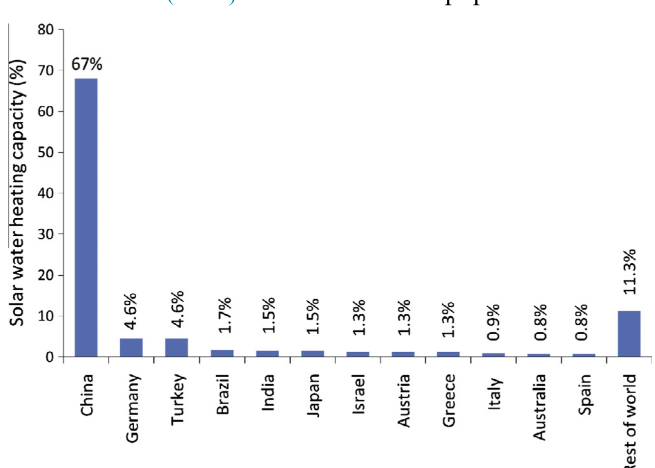

Fig. 1. Global share of the countries in 2011 for installed and operative solar water heating capacity (Global status report, 2013).

technologies and able to heat the water close to its boiling temperature at atmospheric pressure. There have been attempts made in the past to utilise this thermal energy from the solar heated water to solely generate electricity or combine it with power generation and hot water supply. Hu et al. (2010) has demonstrated the use of solar energy to assist power generation in conventional coal fired power generation plants. Whereas Quoilin et al. (2011) has presented a design to utilise solar thermal energy with an organic Rankine cycle solely for power generation. Few researchers have investigated using the hot water from the evacuated solar collector with thermoelectric generators and using an active water cooling system to generate power (Date et al., 2014). The hot water after circulating over the thermoelectric generator can be used for domestic hot water needs. This system has a limit on the hot side temperature of the thermoelectric generator since the water can be heated at maximum to 100 °C under atmospheric pressure in the evacuated tube solar collectors. Zheng et al. (2014) has proposed an active system with thermoelectric cogeneration for domestic purpose using the thermal energy from the water heating boiler and solar energy.

Significant amount of work research has been done on the photovoltaic thermal technology since 1970s (Chow, 2010) and low concentrated photovoltaic thermal technology during last decade (Yadav et al., 2013). Photovoltaic thermal system converts the small part of light energy directly to electrical energy while harvesting the large amount to thermal energy that can be easily stored and used for low grade energy applications such as space or