Energy 91 (2015) 84–90

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Exergetic analysis of a solar thermoelectric generator

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ARTICLE INFO

Article history:
Received 20 April 2015
Received in revised form
22 July 2015
Accepted 15 August 2015
Available online 3 September 2015

Keywords:
Combined heat and power (CHP)
Heat transfer analysis
System optimization
Exergy

ABSTRACT

Recently, thermoelectric modules have been considered as possible replacement to solar photovoltaic system due to its potential for combined heat and power. In the designs of solar thermoelectric cogeneration systems, a careful compromise has to be made between thermal energy and electrical power. For practical purposes, electrical power is preferred over heat energy. However, due to the current low conversion efficiencies of thermoelectric materials, increasing electrical power generation causes the overall combined efficiency to suffer. This study proposes an exergetic analysis of combined heat and power solar thermoelectric systems to maximize exergetic efficiency. The modeling is based on the previously investigated design of a solar thermoelectric generator for residential combined heat and power generation. The working conditions (cold side reservoir temperature and solar concentration) are varied to maximize exergetic efficiency without sacrificing too much electricity generation. The module geometry for thermal load matching is also suggested.

1. Introduction

Solar thermoelectric generation (STEG) systems have been studied for their potential for distributed electricity production at low maintenance cost and capability of combined heat and power. Several researchers have published optimization studies on solar thermoelectric systems, most of which focused on maximizing power output from thermoelectric modules [1–5]. However, the STEG systems often require high power cooling systems to maintain a large temperature differences across the modules. The power needed to cool the STEG system was rarely taken into consideration and can exceed the power generated from the modules. In our previous work [6], we presented an optimization work of a combined heat and power solar thermoelectric system, and proposed working conditions for maximizing combined efficiency rather than maximizing electrical power generation by thermoelectric modules. The modeling work was also supported by experimental demonstration. Although our experimental setup have demonstrated up to 32% of combined efficiency and potential of further improvement by 8%, the amount of power generation was much less than the values presented by other researchers. Higher combined efficiencies can be reached only when more heat (and less electricity) was generated at lower temperature, which does not economically justify the use of thermoelectric modules. Moreover, heat collected at a lower temperature can hardly benefit any thermal system. In practical application, electrical energy has a higher quality than the same amount of heat, and rejected heat at a higher temperature has higher availability (or exergy). Therefore rather than engineering a solar thermoelectric system for maximum power or maximum combined efficiency, an exergetic analysis should be made to make the solar thermoelectric system competitive to other solar energy conversion technique.

There have been a few previous exergetic studies of thermoelectric power generation [7–9]. Shu et al. and Fontes et al. both presented exergetic analyses of non-solar thermoelectric generation systems. Shu demonstrated a maximum exergetic efficiency of 46% for a wasted heat recover system and Fontes et al. developed and tested a 1.5 kw cogeneration system which reached 10.4% exergetic efficiency. Eswararmoothy and Shanmugan also presented their design of a solar parabolic dish thermoelectric generator with an exergetic analysis reaching energy efficiency of 2.8% and an exergetic efficiency of 3.0%. Yazawa and Shakouri also presented an exergetic analysis of a waste heat recover system, in which they provide thermal engineering strategies for cogeneration. However, these past studies relied on various assumptions to define the temperatures (hot/cold/source/sink) of their system. In reality these temperatures of the system change due to the amount of heat being absorbed/rejected and the current generated within the module. Various approaches have used empirically found

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http://dx.doi.org/10.1016/j.energy.2015.08.030
0360-5442/

relations [9,10], or assumed a constant source/hot side/cold side module temperature [5,8,11–13].

Fontes et al., and Eswararmoothy and Shanmugam presented exergetic analyses based on empirically found relationships. Through various tests, Eswararmoothy and Shanmugam were able to apply a second order polynomial fit to their data to predict the receiver temperature and the power output of their system. While simple to follow and use, empirical models use fitting parameters only constrained to the systems tested and will lose accuracy when the same relationship is used on another system with different working conditions [9,10]. Other previous exergetic studies [11–13] are based on the traditional load matching approach as suggested by Angrist [14]. This approach is accurate only when the temperatures at the cold and hot sides of the thermoelectric materials are known and kept constant. In practical application, these temperatures change due to Joule heating and Peltier cooling that occurs within the module. Due to these oversights, the traditional load matching conditions overestimate amount of power generation. Moreover, the hot source temperature (solar receiver temperature) changes based on how much heat is drawn. In low power energy harvesting, the reservoir temperature change is negligible due to the small amount of heat drawn from the module compared to the thermal mass of the source/sink. However in larger power generation systems, or when the source/sink has a smaller thermal mass, the source/sink temperature can change drastically necessitating solving for the temperature before the analysis can be carried out. Recent system level studies have considered Joule heating and Peltier effect on thermoelectric material temperatures [15–17], but none of these presented a full exergetic analysis nor considered the change in the hot source temperature.

This paper presents a design strategy of a combined heat and power solar thermoelectric generation system for higher exergetic efficiency. Exergetic analysis offers the benefit of quantifying the quality of electricity and heat produced, which will help to determine suitable end-usage application temperatures and balance heat and electricity generation. The modeling done in this study is performed under practical conditions detailed in our earlier work [6]. Energy conservation equations, which are not based on the constant temperature assumption, are applied throughout the system to determine power generation, heat rejection, and exergetic efficiency, with respect to different working conditions (solar concentration, working fluid temperature, and module geometry).

1.1. System overview/modeling approach

The exergetic analysis in this study is based on the combined heat and power solar thermoelectric system first proposed in our previous work [6]. The proposed system collects solar radiation used to generate electrical power and captures rejected high-grade heat for an absorption chiller. Fig. 1 shows a schematic of the system. Solar energy is collected using a concave dish mirror and a silicon carbide cavity receiver, where thermoelectric modules are attached. The collected solar energy in the receiver is then either passed onto the module or lost via radiation and convection. After electrical conversion, the rejected heat is passed onto heat exchangers attached on the cold side of the thermoelectric modules. The heat is then transferred to an external thermal usage, in this study an absorption refrigerator. Like many past studies, the model is conducted at steady state and assumes 1-Dimensional heat transfer through the module and constant properties. Heat losses in the system are only considered at the receiver, with the rest of the system being well insulated. The material properties along with various other working conditions can be seen in Table 1, which was characterized experimentally as described in our earlier work [17]. The material properties in the table were derived from the bulk averaged module properties of commercially available Bismuth Telluride based module. Actual values of high temperature materials are different from the values used in this study, but the constant properties assumption was used to understand the system level behavior for simplicity. Furthermore, the number of pairs of thermoelectric legs was restricted for this study and obtained using a typically commercially available fill factor (30%) and extrapolating the number of pairs of its module to the larger sized module needed for the receiver contact area in the system.

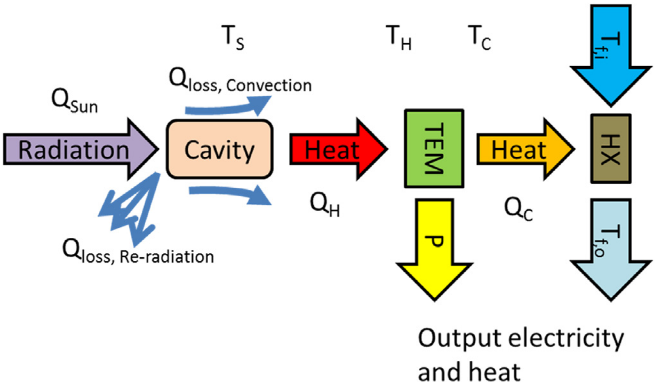

Fig. 1. Schematic view of the thermoelectric cogeneration system.

Modeling of the system begins with the energy conservation equation on the receiver: absorbed solar radiation is matched with the heat transferred to the thermoelectric module or lost by re-radiation or convection [18]:

$$Q_{sun} - Q_H - Q_{loss,radiation} - Q_{loss,convection} = 0 \tag{1}$$

where Q_{sun} is the total solar radiation into the cavity, Q_H is the heat transferred into the thermoelectric modules, $Q_{loss,\ radiation}$ is the heat re-radiated from the cavity to the surroundings, and $Q_{loss,\ convection}$ is the heat loss from the cavity to the surroundings by convection. Substituting temperature relationships for the different heat transfers results in:

$$\varepsilon A_R n_C q''_{sun} - \frac{T_R - T_H}{\psi_H} - \varepsilon\sigma A_R\left(T_R^4 - T_\infty^4\right) - UA_R(T_R - T_\infty) = 0 \tag{2}$$

where T is temperature, ε is the emissivity, $\boldsymbol{\sigma}$ is the Stefan–Boltzmann constant, n_c is the concentration ratio, A_R is the area of the receiver, q''_{sun} is the solar radiative flux, UA_R is the overall convective heat transfer coefficient of the receiver, and Ψ_H is the hot side thermal resistance. Subscripts R and H denote the receiver and hot side of the thermoelectric module respectively. Q_H is related to the temperature difference between the receiver and the hot side thermoelectric and the thermal resistance (Ψ_H) between the two bodies.

At the hot side of the modules, energy conservation is applied to match the heat transferred from the receiver to the heat at the junction of the thermoelectric materials seen in traditional modeling [14]. This equation can be modeled by [14]:

$$Q_H = SIT_H + K(T_H - T_C) - \frac{1}{2}I^2R \tag{3}$$

where S is the Seebeck coefficient of the module, I is the current generated within the module, K is the thermal conductance of the module, and R is the internal resistance of the module. Subscript C denotes the cold side of the module. The module properties can