Development of an energy-saving module via combination of solar cells and thermoelectric coolers for green building applications

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A solar-driven thermoelectric cooling module with a waste heat regeneration unit designed for green building applications is investigated in this paper. The waste heat regeneration unit consisting of two parallel copper plates and a water channel with staggered fins is installed between the solar cells and the thermoelectric cooler. The useless solar energy from the solar cells and the heat dissipated from the thermoelectric cooler can both be removed by the cooling water such that the performance of the cooling module is elevated. Moreover, it makes engineering sense to take advantage of the hot water produced by the waste heat regeneration unit during the daytime. Experiments are conducted to investigate the cooling efficiency of the module. Results show that the performance of the combined module is increased by increasing the flow rate of the cooling water flowing into the heat regeneration water channel due to the reductions of the solar cell temperature and the hot side temperature of the thermoelectric coolers. The combined module is tested in the applications in a model house. It is found that the present approach is able to produce a 16.2 °C temperature difference between the ambient temperature and the air temperature in the model house.

1. Introduction

Under the inevitable influence of the energy shortage and the rise of environmental awareness, promising energy sources to satisfy the world’s growing energy demand has received increasing attention in the past several decades. In recent years, energy conservation is achieved through efficient energy consuming or energy-saving methods, in which energy use is decreased while achieving a similar outcome, or by reduced consumption of energy services. For these purposes, renewable energy coming from natural resources such as sunlight, wind, tides, and geothermal heat are of great interests to the energy technology researchers. Moussazadeh et al. [1] showed that covering 0.16% of the land on earth with 10% efficient solar conversion systems would provide 20 TW of power, nearly twice the world’s consumption rate of fossil energy. Therefore, solar cells are one of the promising technologies to convert the incident solar radiation into electric power by the photovoltaic (PV) effect [2]. The development of the solar cell seems from the researches of the French physicist César Becquerel in 1839, but the first solar cell was built by American inventor Charles Fritts, who coated the selenium with thin layer of gold to form the junctions with 1% conversion efficiency. In planning for the future scaling-up photovoltaic power generation, it is essential to carefully choose the semiconductor materials. Recent development seemingly indicates that GaAs is most materials for promising PV technologies; however, since the cost of the GaAs solar cells is relatively more expensive than those made of crystalline silicon, over 80% of the world’s solar cells and module productions are currently made of sliced single crystal or polycrystalline silicon cells [3]. However, a lot of issues, considering the long term stability and temperature effect on the cells, need to be clarified prior to commercial breakthrough of the technology [4]. The operating cell temperature greatly affects its efficiency through the functional dependence of the different physical parameters, such as short-circuit current, open-circuit voltage, light absorption and the fill factor, on the cell temperature [5,6]. In general, the voltage output and life expectancy of a solar cell will be decreased with increasing temperature. Therefore, controlling the operating temperature is an important factor for the solar cells [7].

Thermoelectric material can be used to directly convert heat into electricity, or vice versa. It can be used in two major operating
models: thermoelectric generator (TEG) [8] and thermoelectric cooler (TEC). Thermoelectric cooler is a solid-state active heat pump which transfers heat from the cold side of the device to the hotter side against the temperature gradient, with consumption of electricity. A numerical model for simulation of transient, three-dimensional thermal characteristics of the thermoelectric coolers was presented by Cheng et al. [9]. Different from the vapor-compression refrigeration systems, the thermoelectric cooler does not require the components like compressor, expansion valve, evaporator, condensers, or solution pumps. Moreover, it does not require working fluids or utilize any moving parts. Because of the advantages such as high reliability, flexibility in packaging and integration, and low weight, the thermoelectric coolers are regarded as clean and active cooling methods which have been widely used in military, aerospace, instrument, and industrial products. When a TEC is used for cooling purposes, the TEC must be designed based on required cooling capacity at a proper coefficient of performance (COP) [10,11]. In practices, the performance of the TECs is strongly dependent on several operating parameters, namely, the temperatures of the TEC cold and hot sides [12], thermal and electrical conductivities of TEC elements [13], thermal contact resistance between the TEC cold side and the cooled device surface, thermal resistance of the heat sink placed on the TEC hot side [14], and the applied electric current [15].

Furthermore, a number of studies have been performed to investigate the performance of the combined systems of the thermoelectric cooler and the solar cells. Hara et al. [16] installed the solar cell-driven thermoelectric coolers at the front of a headgear to cool the forehead for outside personal cooling device, and Mei et al. [17] studied a solar-assisted automobile thermoelectric air conditioner. Lately, Bansal and Martin [18] compared the relative performance among the vapor-compression refrigeration system, the solar cell-driven thermoelectric cooler, and the absorption refrigerators.

Recently, global increasing demand for air conditioning for buildings led to production of more electricity and consequently more release of CO2 all over the world. A recent report of Xi et al. [19] indicated that the energy consumption for air-conditioning systems is estimated to 45% of the whole households and commercial buildings. It is recognized that the thermoelectric coolers and the solar cells combined system can be used for the air-conditioning applications, and the technology actually meets the demand for energy conservation and environment protection. Chein and Chen [20] presented an expression for the heat transfer rate at the hot side of a thermoelectric cooler:

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Q_h = 2N[\alpha T_{tech} + \frac{1}{2} \beta \rho - KG(T_{tech} - T_1)]
\]  

where \(N\) is number of thermoelectric element pairs, \(\alpha\) is the Seebeck coefficient, \(I\) is the input current, \(\rho\) is the electrical resistivity of the thermoelectric material, \(G\) is the thermoelectric element geometric factor, \(K\) is thermoelectric element thermal conductivity, and \(T_1\) is the average temperature of cooling water in the heat regeneration water channel. In such combined modules, the heat at the hot side of the thermoelectric cooler must be readily rejected toward the surroundings to increase the performance, while the temperature of the solar cells should be maintained at a low level to yield a high photovoltaic efficiency, as described earlier.

To the authors’ knowledge, so far there is no efficient existing method available that may be used to meet the two requirements with the combined module. Therefore, in this study a solar-driven thermoelectric cooling module with a waste heat regeneration unit is proposed and tested. The waste heat regeneration unit consisting of two parallel copper plates and a water channel with staggered fins is installed between the solar cells and the thermoelectric cooler. The solar cells are mounted on the surface of one of the copper plates and the thermoelectric cooler is placed on the surface of another copper plate. The solar cells are used to provide the electricity for the thermoelectric cooler which is employed to absorb heat from the indoor space of the green building and then dissipate heat to the cooling water flowing in the regeneration channel. In this manner, the useless solar energy from the solar cells and the heat dissipated from the thermoelectric cooler can both be removed by the cooling water such that the solar cells are cooled to improve the photovoltaic efficiency and on the other hand the performance of the thermoelectric cooler is elevated because it also reduces the hot side temperature of the thermoelectric cooler. Moreover, it makes engineering sense to take advantage of the hot water, produced by the waste heat regeneration unit, for further application during the daytime. In this study, a model house with the combined module has been built for testing the feasibility of this approach, and the experimental results are provided in the following sections.

2. Experiments

2.1. Description of experimental apparatus

The tested combined module is divided into four major components: namely, solar cells, thermoelectric cooler, waste heat
magnitude of COP is calculated by $Q_c/W_{in}$, where $Q_c$ is the rate of heat absorbed by cold side of the thermoelectric cooler, which is determined from the difference between the ambient temperature and the cold side temperature, $T_o$.

One may expect that an increase in $T_{tecc}$ resulted from the elevation of $T_w$ leads to a decrease in both $Q_c$ and COP. Note that as the inlet cooling water temperature is increased to 36 °C, the cold side temperature reaches a value higher than the ambient temperature. As a result, the values of $Q_c$ and COP both become negative as shown in Fig. 9.

It is important to emphasize here that in this approach, the electricity consumed in the air-conditioning system of the model house is generated from the renewable energy by the solar cell installed the combined module itself. Furthermore the waste heat rejected by the solar cell and the thermoelectric cooler is utilized for water heating. Therefore, both the air-conditioning and the water heating demands can be satisfied without consuming any electricity provided from the external source.

4. Concluding remarks

In this study a solar-driven thermoelectric cooling module with a waste heat regeneration unit is proposed and tested. The solar cells are used to provide the electricity for the thermoelectric cooler which is employed to absorb heat from the indoor space of the green building and then dissipated heat to the cooling water flowing in the regeneration channel. A model house with the combined module has been built for testing the feasibility of this approach, and the experimental results are provided. The conclusions reached in the present study are listed as follows:

1. Cooling the solar cell is an important factor to improve the performance of our energy-saving module because it can easily raise the output power of solar cell. It is found that the steady-state temperature of the solar cell is decreased by increasing the flow rate of the cooling water. For the particular case considered in this study, when the flow rate is 2500 ml/min, the steady-state temperature of the solar is reduced to 30.5 °C. However, the flow rate of the cooling water may not exceed 750 ml/min since at a flow rate of 750 ml/min, the solar cell temperature is still reduced to 33.2 °C.

2. It is observed that the heat dissipated from the hot side of the thermoelectric cooler can also be efficiently removed by the cooling water to elevate the performance of the thermoelectric cooler. It is found that in the case without the cooling water the hot and the cold side temperatures of the thermoelectric cooler may be higher than 44 °C and 34 °C, respectively. Nevertheless, when the cooling water is allowed to flow through the heat regeneration water channel, the steady-state temperatures at the hot and cold sides of the thermoelectric cooler are reduced to 25 °C and 22.5 °C, respectively.

3. Furthermore the waste heat rejected by the solar cell and the thermoelectric cooler is utilized for water heating. Therefore, both the air-conditioning and the water heating demands can be satisfied without consuming any electricity provided from the external source.

4. Based on the model house tests, it is found that the present approach is able to produce a 16.2 °C temperature difference between the ambient temperature and the air temperature in the model house. This implies that the combined module is capable of cooling down the indoor air of the model house.

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References


