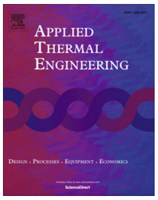
Applied Thermal Engineering 118 (2017) 742–747

Contents lists available at ScienceDirect

Applied Thermal Engineering

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



Research Paper

The temperature distribution and electrical performance of fluid heat exchanger-based thermoelectric generator

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HIGHLIGHTS

- A fluid heat exchanger-based thermoelectric generator system has been build up.
- The temperature difference is mainly generated on the thermoelectric module.
- Temperature distribution is weakly affected by fluid velocity and Peltier effect.
- Attention must be paid to the contact electrical resistance induced by soldering.
- Peltier effect should not be ignored in design optimization of the generators.

ARTICLE INFO

Article history:
Received 26 October 2016
Revised 4 January 2017
Accepted 3 March 2017
Available online 8 March 2017

Keywords:
Thermoelectric generator
Fluid heat exchanger
Temperature distribution
Output power

ABSTRACT

Thermoelectric generator (TEG) has great potential in waste heat recovery. In this paper a TEG system has been build up which consists of a Bi_2Te_3-based thermoelectric module and two fluid heat exchangers. The temperature distribution, electrical performance and heat components of the system have been investigated via both experiment and numerical simulation. It is revealed that the influence of fluid velocity on the temperature distribution is weak until the velocity is very slow, and the influence of Peltier effect on the temperature distribution is also limited in this system. Furthermore, attention should be paid to the contact electrical resistance induced by soldering, especially when the hot side temperature of the Bi_2Te_3 module is expected up to 473 K. Besides that, heat component analysis suggests that Peltier effect should not be ignored in optimization analysis of thermoelectric module.

1. Introduction

In the wake of the environmental and energy crisis, sustainable energy technologies are attracting significant attention. Among them there is substantial interest in technologies for generating electricity from waste heat. TEG is solid state heat engine, which generates a voltage out of a temperature gradient due to material's Seebeck effect. Practical TEGs consist of hot and cold side heat exchangers and thermoelectric (TE) modules. The module consists of many individual p and n junctions wired in series and placed in parallel along the heat flow direction. TEG offers unique advantages including no mechanical movement and low maintenance cost, making it attractive for a wide variety of applications, such as automotive and industrial waste heat recovery [1–6]. LeBlanc et al. performed cost and efficiency analysis at the TEG system level [7,8], indicating that certain bulk materials are clearly promising for the mid- to high-temperature applications.

However, optimizing these devices for maximum power production can be difficult due to the many heat transport mechanisms occurring simultaneously within TEG. In previous research, the thermal resistance model was widely used to investigate TEG performance [4,9–11], and is still most frequently adopted so far. It excludes heat exchangers and supposes the hot and cold end temperatures of the TE module fixed, and the constant or temperature-averaged materials properties are assumed. This kind of model can derive analytical expressions of the output power and conversion efficiency, thus provide guidance for material exploration and device design optimization. However, the Peltier effect occurring at the ends of TE module tends to decrease the temperature difference in practice, and in some cases even makes it difficult to build large temperature deference. In addition, the pumping power required by convection cooling should be subtracted from the generated power in order to calculate the net power output.

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http://dx.doi.org/10.1016/j.applthermaleng.2017.03.022
1359-4311/

As heat flux increases, the coolant flow rate must increase to be able to pump more heat, implying more pumping power consumed [1]. In this context, works on TEG systems with heat exchangers included have been carried out [1,7,8,12–14]. Yazawa and Shakouri performed cost-efficiency trade-off analysis [1]. Full electrical and thermal cooptimization yield a simple analytical expression for optimum design, based on constant property model and fixed heat source and heat sink temperatures. Suzuki and Tanaka investigated the electric power of large-scale flat TE modules exposed to two thermal fluids [14], in which Peltier and Joule effects was ignored and constant property model was used. The better heat transfer to/from the module surface and the worse thermal conductivity of the module are desired, in addition to the better figure of merit. These works are generally based on constant property model. Jinghui Meng et al. developed a numerical TE module model considering temperature-dependent properties [15]. With the two end temperatures of the module fixed, the model was compared with the classical thermal resistance model. The comparison reveals that the assumption of constant material properties leads to underestimated inner electrical resistance, and overestimated thermal conductance and Seebeck coefficient, so that the thermal resistance model predicts unrealistically high performance than the temperature-dependent properties model. Therefore it is necessary to carry out investigation on TEG system with heat exchangers included, based on temperature-dependent properties.

In this work, a TEG system has been built up which consists of a commercial Bi_2Te_3-based TE module together with hot and cold side fluid heat exchangers. The temperature distribution and electrical properties have been investigated via both experiment and numerical simulation based on temperature-dependent properties. In particular, attention has been paid on how the temperature distribution is affected by fluid velocity and Peltier effect. Besides that, the heat components occurring in the system have also been analyzed.

2. Experimental procedure and simulation model

The experimental setup of the TEG system is illustrated schematically in Fig. 1. It consists of a commercial TEC1-1270 module, hot and cold side heat exchangers, fluid circulation loops, and data acquisition system. The dimension of the Bi_2Te_3-based module is $40 \times 40 \times 4.2$ mm^3. The external dimension of the aluminum heat exchanger is $40 \times 80 \times 12$ mm^3, and its internal tubular diameter d_i is 7 mm. Water is employed as the fluid. PID controlled electrical heater is applied to control the water bath temperature (accuracy: ±0.1 K). To decrease contact thermal resistance and parasitic heat loss, the surfaces of the TE module were coated with thermal grease and sandwiched between the heat exchangers, then the TEG was wrapped with 50 mm thick adiabatic cotton and finally clamped with home-made fixture. Thin film NTC Thermistors (accuracy: ±0.1 K) were inserted to measure the hot and cold side end temperatures of the module ($T_{h\text{-}module}$ and $T_{c\text{-}module}$, subscripts h and c denote hot and cold side respectively, and the same below), as well as the external surface temperatures of the heat exchangers (T_{hw} and T_{cw}). The fluid inlet temperatures of the heat exchangers ($T_{h\text{-}inlet}$ and $T_{c\text{-}inlet}$) were measured via PT100 thermometers (accuracy: ±1 K). External load resistance R_L could be adjusted at the range of 1–100 Ω (accuracy: ±0.1 Ω), and the corresponding voltage (accuracy: $\pm10^{-3}$ V) and current (accuracy: $\pm10^{-3}$ A) data were collected. The experimental procedures were as follows: firstly under open circuit condition and fixed $T_{h\text{-}inlet}$ and $T_{c\text{-}inlet}$, fluid velocity u_b was adjusted to observe the variation of the TEG temperature distribution. Then under fixed $T_{h\text{-}inlet}$, $T_{c\text{-}inlet}$ and u_b, R_L was modulated to observe the variation of the temperature distribution and the electrical output.

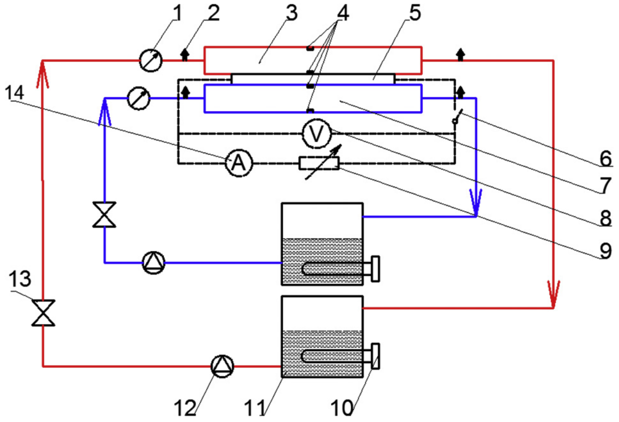

Fig. 1. Schematic illustration of the experimental setup of the TEG system. 1-flowmeter 2-PT100 thermometer 3-hot side heat exchanger 4-thin Film NTC thermistors (the temperatures from top to bottom are T_{hw}, $T_{h\text{-}module}$, $T_{c\text{-}module}$, and T_{cw}, respectively) 5-TE module 6-circuit switch 7-cold side heat exchanger 8-voltmeter 9-variable resistor 10-electrical heater 11-fluid bath 12-pump 13-valve 14-amperemeter.

Numerical simulation analysis includes two sections. Firstly the temperature distribution under open circuit condition was simulated via computational fluid dynamics (CFD). The model (shown in Fig. 2) is one fourth of the practical system, where the dimension of the TE module is $20 \times 20 \times 4.2$ mm^3 with 31 pairs of thermocouples, the dimensions of copper connector and TE leg are the same as in practice, the external dimension of the heat exchanger is $20 \times 40 \times 12$ mm^3 and its internal tubular diameter is as in practice. The materials' properties are given in Table 1. TE properties of Bi_2Te_3-based materials were measured via widely used methods in temperature range of 300–523 K [16]. Boundary conditions have been set as follows: fluid inlet is set to velocity-inlet, and fluid outlet is pressure-outlet, with the relative pressure equal to 0 Pa. The governing equations and grid independence examination are presented in supplement information. The convergence criteria adopted herein are a scaled residual under 10^{-3} for the momentum balance, 10^{-6} for the energy balance, and a relative error under 0.1% for the total energy conservation of the system. After that the electrical performance of the TEG was simulated using another model (shown in Fig. 3). The external load is electrically coupled with the electrodes of the TE module. Here the $T_{h\text{-}module}$ and $T_{c\text{-}module}$, extracted from the CFD simulation, are applied directly as the boundary conditions. The convergence criteria adopted in this simulation are a scaled residual under 4.311×10^{-5} for current balance and 1.385×10^{-4} for heat flow balance. The environmental walls of both models are set adiabatic.

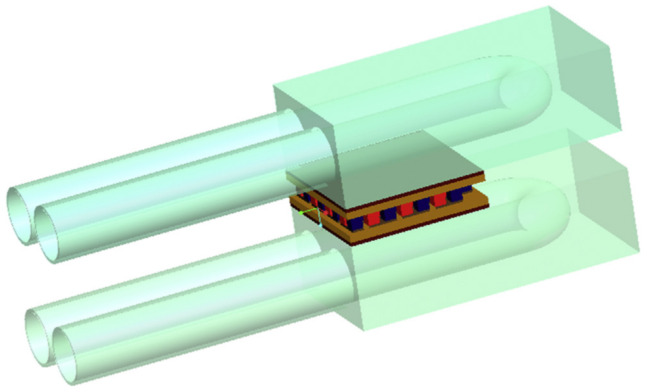

Fig. 2. The temperature distribution simulation model.