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Experimental study on low-temperature waste heat thermoelectric generator

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ABSTRACT

In order to further studies on thermoelectric generation, an experimental thermoelectric generator unit incorporating the commercially available thermoelectric modules with the parallel-plate heat exchanger has been constructed. The experiments are carried out to examine the influences of the main operating conditions, the hot and cold fluid inlet temperatures, flow rates and the load resistance, on the power output and conversion efficiency. The two operation parameters such as the hot fluid inlet temperature and flow rate are found to significantly affect the maximum power output and conversion efficiency. A comparison of the experimental results with those from the previously published numerical model is also presented. The meaningful results obtained here may serve as a good guide for further improving the numerical model and conducting a system level optimization study in the next step. Also, the present study shows the promising potential of using this kind of thermoelectric generator for low-temperature waste heat recovery.

1. Introduction

Thermoelectric generator (TEG) theoretically may offer many advantages such as being highly reliable, having no moving parts, and being environmentally friendly, when compared with conventional electric power generators. Owing to these advantages, there have been considerable emphases on the development of the small TEGs for a variety of aerospace and military applications over the past years. More recently, there is a growing interest for waste heat recovery TEG, using various heat sources such as combustion of solid waste, geothermal energy, power plants, and other industrial heat-generating processes [1,2].

In the case of TEG for waste heat recovery power generation, there have been many conceptual designs of a power conversion system which are potentially capable of obtaining application in this area [3–5]. These designs involve the consideration of the maximum power output and conversion efficiency with different thermoelectric heat exchanger. Furthermore, performance evaluations of the thermoelectric generators have been theoretically carried out by modeling approach. The results show that the thermoelectric generators are promising devices for waste heat recovery. Although the economic viability of a TEG may be improved significantly when used for waste heat recovery, desirable TEG technologies for waste heat recovery are those that could reduce the device cost and increase the conversion efficiency of a device. Therefore, one of the more attractive options for waste heat recovery is to construct the TEG device by incorporating the relatively simple parallel-plate heat exchanger with the commercially available thermoelectric modules.

In the previous study, the authors presented a numerical model to evaluate the performance of thermoelectric generator with the parallel-plate heat exchanger [6]. As the second step, we expand that study to develop a low-cost, simple configuration TEG unit with commercially available Bi_2Te_3 based thermoelectric modules for an anticipated maximum power generation of about 150–200 W level. This study also aims at validating the previously published numerical model and providing some guidelines for the model modifications. This work would further the development of TEG for its intended large-scale application in waste heat recovery.

2. TEG experiment setup

The schematic diagram of an experiment setup of TEG for low-temperature waste heat recovery is shown in Fig. 1. The system consists of the heat exchanger/thermoelectric converter, the cold fluid loop, the hot fluid loop and a data acquisition system. The cold and hot fluid loops include fluid baths with temperature controlled electrical heaters, pumps and air cooler. The glycol/water mixture fluids (60:40 by mass) are employed in the system to carry the thermal energy. A temperature controller is used to control the inlet temperatures of the cold and hot fluids within 0.1 °C with PT 100 sensors.

The TEG unit with two-fluid, counter/parallel flow type, multilayer plate heat exchangers/thermoelectric modules is shown schematically in Fig. 2. The plate heat exchangers are made of thin red copper plates with the thickness of 1 mm. For the exchanger

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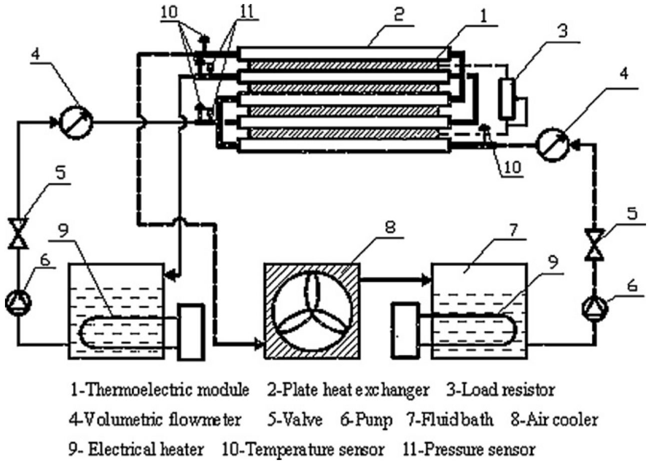

Fig. 1. The schematic diagram of an experimental setup of TEG.

geometry, the rectangle passages of the cold and hot fluids have a length of 600 mm and a cross-sectional area of 40 mm × 8 mm in each layer. The commercially available Bi_2Te_3 based thermoelectric modules with a module size 40 mm × 40 mm × 4.2 mm, a matrix of one hundred and twenty seven thermoelectric couples (p- and n-type), a maximum cooling rate of 42.8 W and maximum temperature difference of 68 °C are used in the thermoelectric converter. For the major thermoelectric properties of this kind of modules measured by manufacturer at room temperature, the appropriately averaged Seebeck coefficient, electrical resistivity and thermal conductivity are $\alpha = 2.0 \times 10^{-4}\,\mathrm{V\,K^{-1}}$, $\rho = 9.5 \times 10^{-6}\,\Omega\,\mathrm{m}$ and $\lambda = 1.7\,\mathrm{W\,K^{-1}\,m^{-1}}$. Total fifty six thermoelectric modules are sandwiched between the hot and cold fluid passages in terms of four separate layers, which are aligned tightly without open space in each layer, and all connected electrically in series. Three cold fluid passages and two hot fluid passages are isolated by these thermoelectric panels, in which the cold and hot fluids flow in the opposite or same direction as a counter/parallel flow type for the whole system. This configuration makes the system more compact and suitable for the large-scale power generation, and the thermal energy can be efficiently recovered. In addition, thermal grease is placed between all of the thermoelectric modules/fluid passages interfaces in order to minimize the thermal contact resistance. In order to reduce side heat losses from the heat exchanger/thermoelectric converter, the fully assembled unit is surrounded on the outside by insulation board with the thickness of 10 mm. For the TEG configuration in the present study, the approximate dimension of the assembled TEG unit is 600 mm × 90 mm × 62 mm.

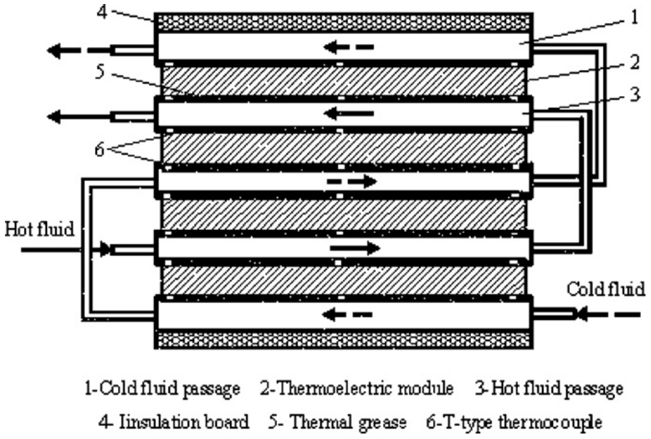

Fig. 2. The schematic diagram of TEG.

Temperature measurements are made using PT 100 sensors at the inlet and outlet of the cold and hot fluid passages. In addition, twenty four T-type thermocouples are placed at the appropriate locations of the ceramic surfaces of each layer thermoelectric modules for the temperature measurement of the hot and cold sides as shown in Fig. 2. All the temperature-measuring devices have accuracy of 0.1 °C. The cold and hot fluids volume flow rates are measured by volumetric flow meters located at the inlets of the cold and hot fluid passages, respectively. The total capacity of the fluid flow meter is 0.2–1.2 $\mathrm{m^3\,h^{-1}}$. The manufacturer's listed accuracy is 0.5% of the full scale. The pressure sensors within ±0.5% accuracy at the inlet and outlet of the hot fluid passage are used to measure the hot fluid flow pressure drop. The power outputs of TEG are obtained by measuring the TEG voltage outputs on the adjustable load resistor at various load resistances. The voltage and resistance measurements are all taken using an Agilent 34401A digital multimeter with both voltage and resistance accuracy of 0.2%. Combined standard uncertainty in measuring the overall measurement uncertainty of the power output is predicted at about 3.2%, and that in calculating the heat rate through the heat exchanger is 3.5%. The maximum uncertainty in the conversion efficiency is 6.7%. In addition, the relative heat loss from TEG is estimated to be approximately 3.5% or less based on the insulation conductivity and thickness.

Experimental performance evaluation of the TEG system is carried out on the basis of data derived from tests. Temperature, pressure, volume flow rate and power output are the main parameters measured during experimentation. All experiment data are collected by Agilent data acquisition system, model 34970A.

3. Experiment results and discussion

The performances of the TEG are evaluated by calculating the power output and the conversion efficiency. The power output is given by

$$\dot{W} = \frac{V_l^2}{R_l} \tag{1}$$

where R_l is the load resistance, V_l is the output voltage.

The heat input to the thermoelectric converter is calculated as

$$\dot{Q}_h = G_{fh}\rho_{fh}C_{fh}\Delta t_{fh} \tag{2}$$

where G_{fh} is the hot fluid volume flow rate, ρ_{fh} is the hot fluid density, C_{fh} is the specific heat capacity of hot fluid at constant pressure and Δt_{fh} is the temperature drop of hot fluid in the fluid passage.

In this case, the power conversion efficiency can be obtained as

$$\eta = \frac{\dot{W}}{\dot{Q}_h} \tag{3}$$

Experiments are conducted for a range of operating conditions as follows: the hot fluid inlet temperature t_{fh} is between 50 °C and 150 °C, the cold fluid inlet temperature t_{fc} is between 20 °C and 30 °C, and the ranges of both cold and hot fluid flow rate G_{fh} and G_{fc} are between 0.2 $\mathrm{m^3\,h^{-1}}$ and 0.6 $\mathrm{m^3\,h^{-1}}$.

Fig. 3 shows the temperature variation on the hot and cold ceramic surfaces of the thermoelectric modules along fluid passages at fixed fluid inlet temperatures, fluid flow rates and the external load resistance (basically matching the calculated total internal resistance of the modules). As it can be seen in Fig. 3, the two curves of temperature on the hot and cold sides display the approximate linear variations in temperature, and the temperature difference across the thermoelectric modules is basically consistent. This indicates this kind of multi-layered thermoelectric

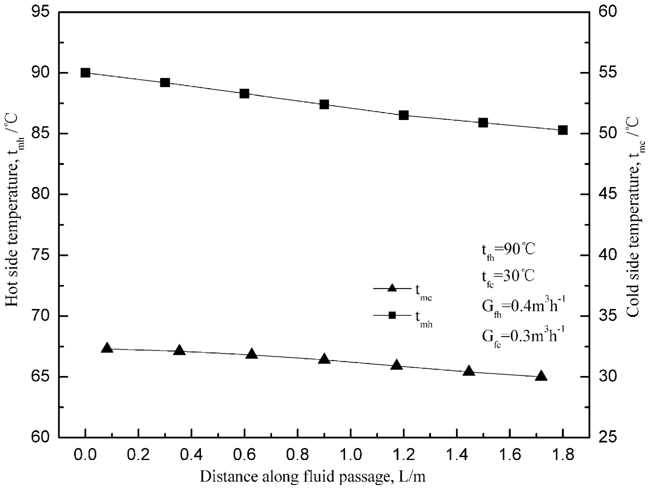

Fig. 3. Temperature variation on the hot and cold ceramic surfaces of the thermoelectric modules along fluid passages.

converter gives a homogeneous temperature difference over the whole thermoelectric panel length. Thus, it may have the potential of the larger power output by increasing the number of thermoelectric panels [7].

Fig. 4 illustrates the variation of the open circuit voltage V_{oc} with the temperature difference ΔT_f between the hot and cold fluid inlet sides at the cold fluid inlet temperature t_{fc} of 20 °C, 25 °C and 30 °C. It can be seen in Fig. 4 that the open circuit voltage increases linearly with the increase in the temperature difference ΔT_f. As well known, the open circuit voltage is directly related to the effective temperature difference between both junctions of the thermoelectric modules. The effective temperature difference, ΔT_{mj}, between the hot junction and the cold junction can be estimated through the equation for open circuit voltage, $V_{oc} = 2\alpha N_c N_m \Delta T_{mj}$, where N_c is the number of couples in the module, N_m is the number of modules in the TEG. The estimations of the resultant temperature difference ΔT_{mj} is also displayed as a function of ΔT_f in Fig. 4. It can be observed that an increase of ΔT_{mj} closely follows an increase of ΔT_f. But, the degree of increase of ΔT_{mj} decreases apparently with an increase of ΔT_f. This may not be the real case for the actual ΔT_{mj} imposed on the modules. The possible main reason for this case is that ΔT_{mj} is just estimated by taking the Seebeck coefficient α as a constant. In practice, all thermoelectric properties of the modules vary with temperature. In the present experiment, the measurement of the resultant electrical resistance R of the TEG modules is made in the operating temperature range. Fig. 5 shows the measured values of R at different hot and cold fluid inlet temperatures. As can be seen, increasing the average operating temperature for TEG will result in an increase of R. Although the Seebeck coefficient and the thermal conductivity are not measured in this experiment, the measured R indicates the influence of the temperature on the thermoelectric properties, in particular, above room temperature, cannot be neglected. Thus, the variation in the thermoelectric properties with temperature should be taken into consideration in modeling the TEG device performance.

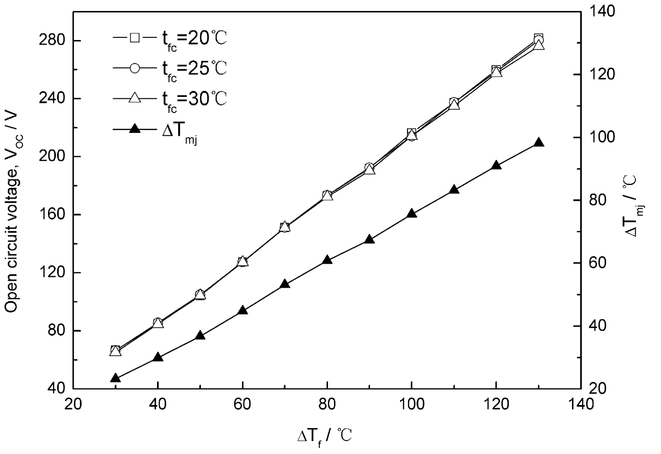

Fig. 4. The variation of the open circuit voltage V_{oc} with the temperature difference ΔT_f.

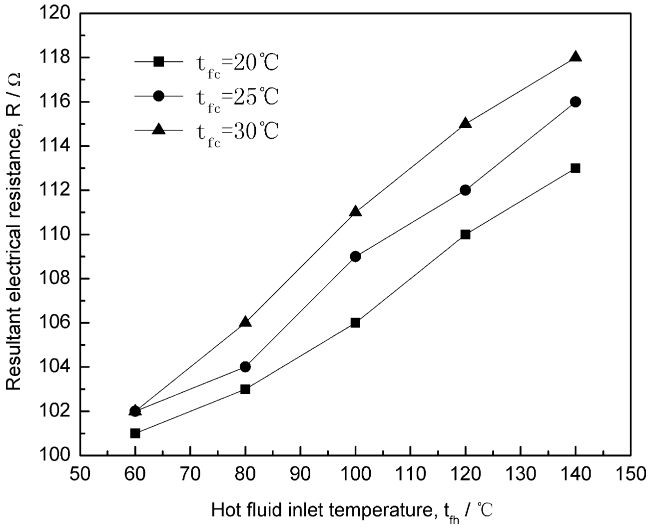

Fig. 5. The measured values of R at different hot and cold fluid inlet temperatures.

For a given TEG construction design, the power output $\dot{W}$ and conversion efficiency η are related to the cold and hot fluid conditions as well as the external load resistance. Fig. 6 shows typical measured power output curves with varying the external load resistance at a range of hot fluid inlet temperature and the fixed cold fluid inlet temperature as well as fluid flow rates. It can be seen that the power output increases with increasing the inlet temperature of hot fluid at different load resistance. Furthermore, the peak of the measured power curves occurs where the load resistance is in the range of about 100–120 Ω. Actually, previous studies have reported that the maximum power of a thermoelectric module is achieved when load resistance equals the effective internal resis-

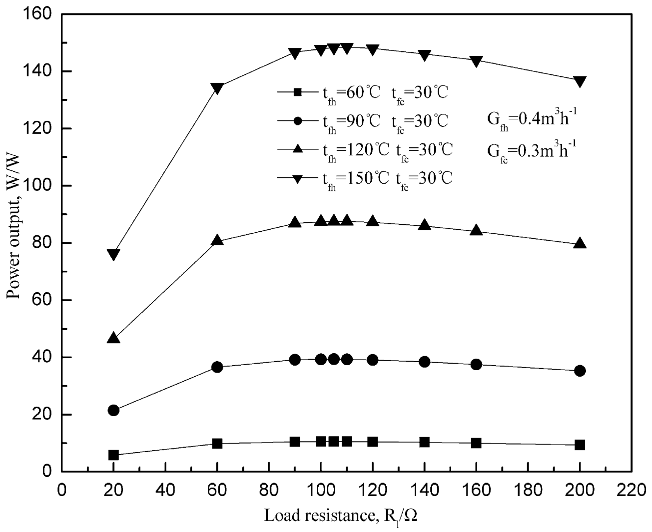

Fig. 6. The variation of power output with the load resistance.

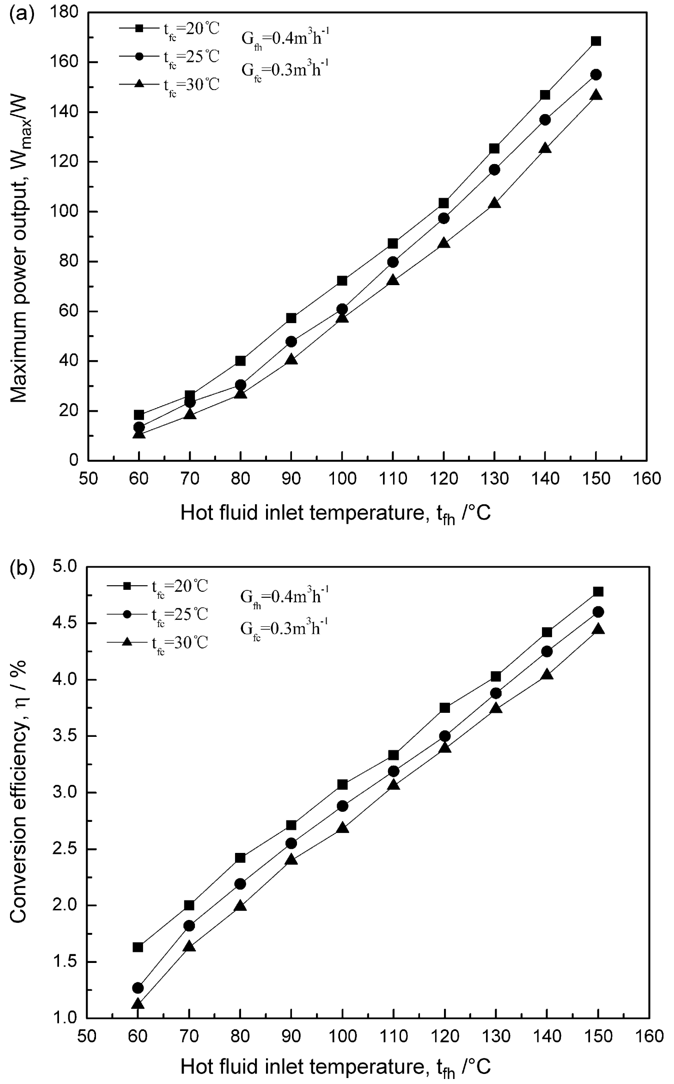

Fig. 7. (a) Maximum power output and (b) conversion efficiency as a function of fluid inlet temperatures.

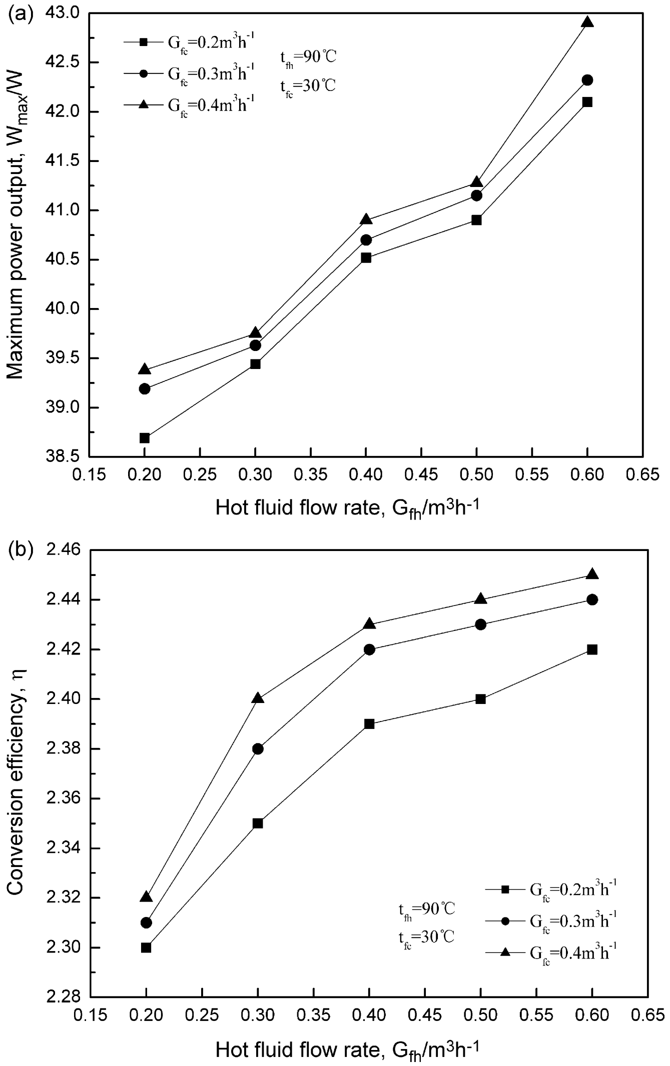

Fig. 8. The variation of (a) maximum power output and (b) conversion efficiency with respect to the fluid flow rates.

tance of the module [5]. Therefore, the output power of TEG can be optimized by balancing the internal and external resistance in practice.

Experimental results of the maximum power output and corresponding conversion efficiency of TEG are shown in Fig. 7 for different fluid inlet temperatures. As can be seen from the Fig. 7, for fixed cold and hot fluid flow rates, the maximum power output and conversion efficiency increase with increasing hot fluid inlet temperature as well as with decreasing cold fluid inlet temperature. For the fluid inlet temperatures, such as $t_{fh} = 150\,^\circ\mathrm{C}$ and $t_{fc} = 30\,^\circ\mathrm{C}$, the TEG produces a maximum power output of 146.5 W, a conversion efficiency of 4.44%.

Fig. 8 shows the variation of maximum power output $\dot{W}_{max}$ and conversion efficiency η with respect to the fluid flow rates. It is seen that for the given fluid inlet temperatures, the maximum power output and conversion efficiency increase with increasing the fluid flow rates. This is because an increase in fluid flow rates results in higher hot side temperature t_{mh} and lower cold side temperature t_{mc} of the thermoelectric modules along fluid passages, as shown in Fig. 9. When the mean temperature difference across the thermoelectric modules is increased, an increase in the maximum power output and conversion efficiency can be obtained. It is further seen that the effect of the hot fluid flow rate is greater than that of the cold fluid flow rate. This indicates the significance of increasing the fluid flow rate on the hot side of TEG.

However, it is well known that increasing the flow rate also increase the pressure drop of the fluid flowing in a heat exchanger which increases the power consumption of pumping the fluid. Especially for TEG, the net power output will be the total power output minus the pump consumption, and thus the most appropriate pair of values for the pressure drop and the temperature difference across the thermoelectric modules should be designed [8]. The variation of the hot fluid pressure drop in the TEG, ΔP, with the flow rate G_{fh} is shown in Fig. 10. It can be seen that the pressure drop increases with increasing the flow rate as well as the hot fluid inlet temperature. It is further seen that in the case of lower hot fluid inlet temperature, the pressure drop has a greater value. This is due to an increase in friction loss coefficient for the flow with decreasing the fluid mean temperature. According to the Fig. 8, the power consumption is estimated to be about 3.5 W at the present experimental conditions. In total, the power consumptions are relatively small compared with the maximum power outputs of the present TEG. In a practical large-scale application, however, the pressure drop needs consideration because taking into account the total system cost and net energy output.

Data obtained from the experiment has been used to validate the numerical model of the present TEG developed in our previ-

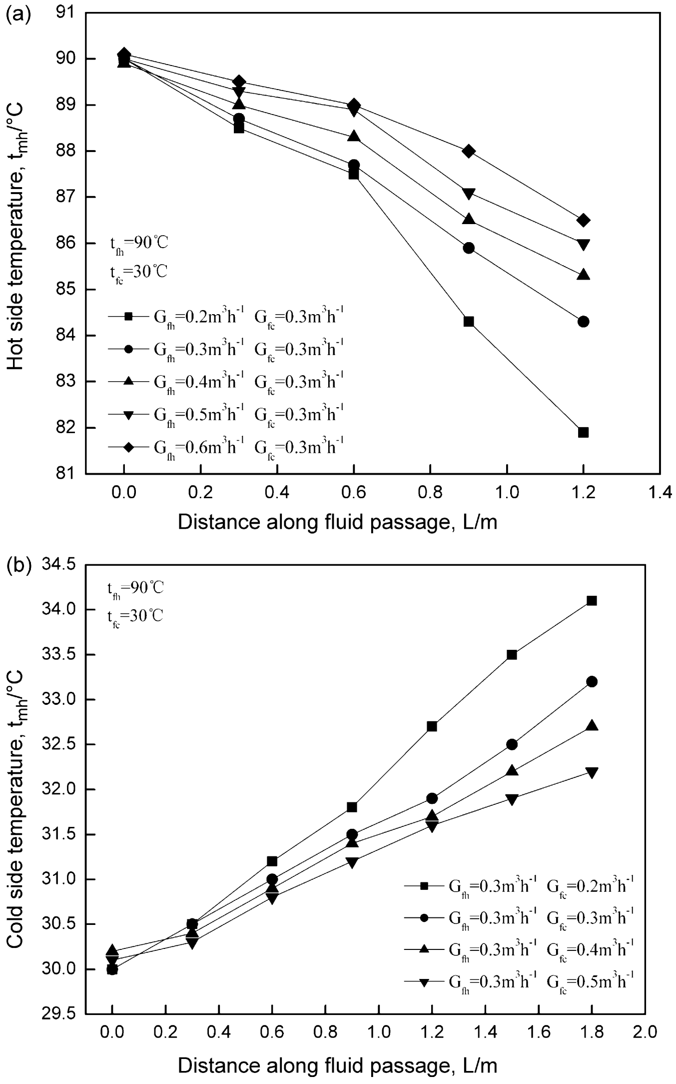

Fig. 9. The variation of the (a) hot and (b) cold side temperature of the thermoelectric modules with respect to the fluid flow rates.

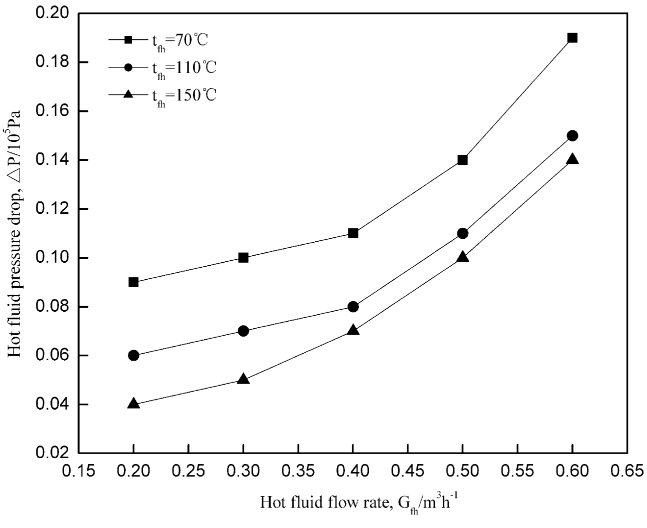

Fig. 10. The variation of the hot fluid pressure drop with the flow rate.

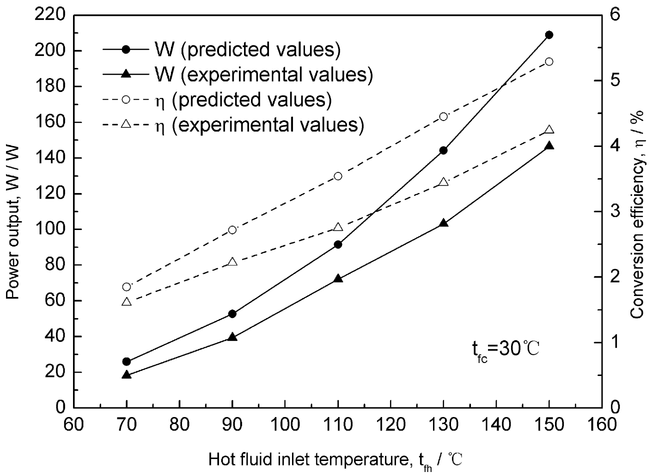

Fig. 11. Comparison between predicted and measured results for the TEG performances.

ous research. Fig. 11 compares the predicted and measured power delivered into a matched load, and the corresponding conversion efficiency, as a function of the hot fluid inlet temperature, for a cold fluid inlet temperature of 30 °C. It can be seen that the numerical model over-predicts performances of TEG over the entire range of the hot fluid inlet temperature. At low temperatures, there is relatively good agreement between the predicted performances and the measurements. However, at high temperatures, the deviation of the prediction arises largely with increasing hot fluid inlet temperature. The discrepancy between the predicted and experimental values may be due to the fact that the heat losses are not taken into account in the numerical model. In fact, the heat losses that have been observed experimentally increase significantly with increasing hot fluid inlet temperature, although the TEG is thermally insulated outside. On the other hand, the properties of the thermoelectric materials are assumed to be of constants in the model, whereas this assumption has been found to introduce errors into the model as mentioned previously. Therefore, in the case of the TEG which involves a high operating temperature, the effects of the heat losses and variable thermoelectric properties are noticeable and should be taken into consideration in the model to avoid overestimation of the device performance. Moreover, more tests will be necessary to precisely determine the heat losses, and for modeling these losses in the predictions. Also, additional studies are needed to investigate about variable thermoelectric properties of commercially available thermoelectric module.

4. Conclusion

In this study, a TEG unit has been designed, built and tested for low-temperature waste heat power recovery. The results derived from the experimental measurements are reported for the different operating conditions. The results show that both the maximum power output and the corresponding conversion efficiency are greatly affected by the operating conditions, especially the hot fluid inlet temperature and flow rate. Preliminary validation for the previously published numerical model is also presented. The comparison indicates that the level of agreement between the numerical model and the measured data is encouraging, and gives guidelines for further improving the numerical model. It is believed that taking into account the heat losses and variable thermoelectric properties in a revised model, the predicted and experimental results would be in good agreement. Further experiments are in progress to identify suitable modifications regarding the heat losses and variable thermoelectric properties. Further work is also planned to conduct a systems level optimization study and develop an appropriate manufacturing process in a more effective manner for the potential of TEG waste heat power recovery.

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