Enhancement of cooling design on the performance of thermoelectric Generator

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Abstract: Thermoelectric generators(TEG) is considered as a promising technology for utilizing low-grade thermal energy, while the cooling system plays a key role in TEG. A two-dimensional numerical model of jet impinging jet cooling is developed based on the commercial code FLUENT. The influences of several factors on thermoelectric conversion efficiency are observed. The factors include the air inlet velocity, the TE legs height, and the fins. The results show that the air inlet velocity is one of the most important factors for the cooling performance, the convection heat transfer efficiency and conversion efficiency significantly increases with the improvement of the air velocity. Higher TE legs height can influence the TEG performance effectively, 5~7mm legs height is recommended in this study. And fins can effectively increase the TEG efficiency, the thermoelectric conversion efficiency with 1mm×1mm fins is 6.73% which was 2.4 times higher than without fins.

Introduction

With the increase of the global energy consumption, energy saving and emissions have become world wide problems to global sustainable development. Hendricks and Choate[1] reported that about 1/3 of the manufacturing industrial energy was discharged directly to the atmosphere or cooling systems as heat. With development of waste heat recovery technologies, the high temperature waste heat have already been utilized to generate electricity or heat to increase the energy utilization efficiency, while most of this lost energy is "low quality" and not practical or economical to recover, in order to expand the waste heat recovery to low grade waste heat, a new type of thermoelectric generators (TEG) based on Seebeck effect has become a popular research topic recently which can convert thermal energy into electricity directly without any moving components. TEG technology have been proposed for some applications such as solar energy, Geothermal and some sort of industrial waste heat.

As a green technology, TEG have showed advantages in low grade waste heat recovery[2-4], Compared with the conventional methods, TEG technology has the advantages of compact, quiet, highly reliable and environmentally friendly, and the advancements in thermoelectric materials with high figure of merit have highlighted the TEG's energy efficiency and commercial potential.

The most widely study of TEG technology is used for automotive exhaust gas, Bass et al. [5-6] applied an array with 72 pieces of TEG on a diesel truck. and energy conversion efficiency of 4.5% was achieved when the temperature of hot and cold sides of TEGs maintaining 230 °C and 30 °C respectively, Thacher et al.[7]attached HZ-20 (Bi_2Te_3) to a light truck engine. The whole system can produce up to 330 W power. In addition, Champier and co-workers [8] applied TE modules on biomass cook stoves to generate electricity to power the fan and light. Crane et al. [9] used hot water as a heat source and air as a heat sink to simulate an exhaust thermoelectric generator.

Dan et al. [10] presented a liquid metal based TEG system which had the efficiency of 2%. Gou et al. [11] proposed some advices, like increasing the waste heat temperature, expanding heat sink surface area in proper range and enhancing cold-side heat transfer capacity, to enhance the TEG performance.

As the source that TEG utilizes is low grade waste heat, cheap or free, and there is no consume of fresh fuel for electricity production, it will be able to obtain additional benefits in terms of an improved overall efficiency. In addition, the energy conversion efficiency is quite attractive when the TEG works in a parasitic mode.

According to the Seebeck effect of thermoelectric, the higher the temperature difference between hot and cold side of the TE material, the power generation is higher which means the heat transfer plays an important role in the TEG system. The hot side is usually determined by the waste heat resources, so in order to increase the temperature difference, high heat transfer performance should get to reduce the temperature at the cold side as lower as possible. Effective exhaust heat exchanger design is critical for improving TEG performance, and some novel types of heat exchanger structures, such as roll cake structure[12], multi-layer plates[13], microchannels[14], and heat pipes[15] have been used for TEG. In this study ,a Jet Impinging Cooling of TEG is studied.

Mathematical model and control equations

Physical model

A TEG module is composed by some pairs of N-legs and P-legs that are thermally connected in parallel and electrically connected in series by metal electrodes. The simplified 2D physical model of jet impinging cooling TEG is shown in Fig. 1. In this study Bi_2Te_3-based thermoelectric materials was used.

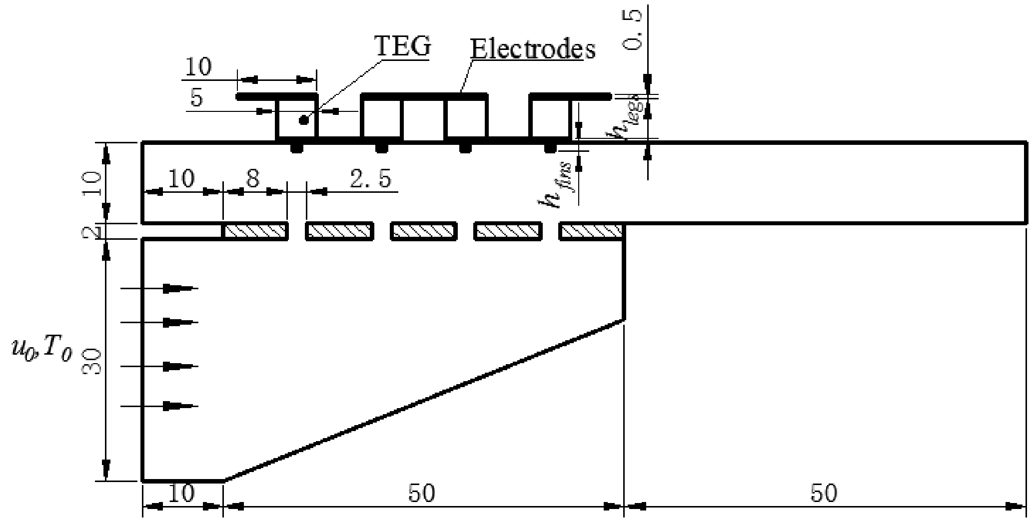


Fig.1 Physical model of TEG simulation (unit in mm)

The relevant parameters used are provided in Table 1.

Table 1 Operating conditions and model parameters used in simulations

Parameters	Unit	symbol	Values
Air inlet velocity	m/s	u_0	3,**5**,10,15
Air inlet temperature	K	T_0	300
TEG legs height	mm	h_{legs}	3,**5**,7,9
Cold side fin height	mm	h_{fins}	**0**,1
TEG Hot side temperature	K	T_h	600

The boldface values represent nominal parameters.

Mathematical model

The TEG cooling process can be described by the following equations of continuity, momentum, and energy closed by the realizable k-ε turbulence model.

Continuity equation: $\frac{\partial}{\partial x_i}\left(r u_i \right) = 0$

(1)

Momentum equation: $\frac{\partial}{\partial x_j}\left(r u_i u_j \right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\left[m\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{2}{3} m \frac{\partial u_l}{\partial x_l} d_{ij} \right)$ (2)

Energy equation: $\nabla \cdot (r c_p T) = \nabla \cdot (l_e \nabla T)$

(3)

In the solid region like TEG legs, electrodes and middle plates, the energy equation can be written as:

$$\frac{\partial}{\partial x_i}\left(k \frac{\partial T}{\partial x_i} \right) + S_E = 0 \tag{4}$$

Where *k* is the thermal conductivity of TEG legs, electrodes or middle plates, For electrodes and middle plates, the energy source term S_E=0, while for TEG legs, the source term of Joule heat can be written as

$$S_E = \frac{I^2 r}{A^2} \tag{5}$$

And the electromotive force *E* and electric current *I* is

$$E = \int_{T_c}^{T_h} \left(a_P(T) - a_N(T) \right) dT \tag{6}$$

$$I = \frac{E}{R_L + R_{P-leg} + R_{N-leg}} \tag{7}$$

Where *α* is Seebeck coefficient and *ρ* is the electrical resistivity. T_h and T_c is the temperature at the hot and cold side respectively, and R_L, $R_{P\text{-}leg}$ and $R_{N\text{-}leg}$ is the load resistance, P-legs resistance and N-legs resistance respectively, the leg resistance of TE legs can be calculated as follows:

$$R_{leg} = \sum \int_0^{h_{TE}} \frac{r}{A} dy \tag{8}$$

It has been found that the model based on variable TE properties is superior to that based on constant material properties[16]. The variable TEG Seebeck coefficient, thermal conductivity and electrical resistivity are listed in Table 2.

Table 2 The variable TE material properties

Parameters	Unit	Equations
Seebeck coefficient	μV/K	$a_p = -490.14 + 4.42T - 8.24\times10^{-3}T^2 + 4.03\times10^{-6}T^3$ $a_n = 351.37 - 3.74T + 7.62\times10^{-3}T^2 - 4.51\times10^{-6}T^3$
Thermal conductivity	W/(m·K)	$k_p = 9.88 - 5.79\times10^{-2}T + 1.21\times10^{-4}T^2 - 7.27\times10^{-8}T^3$ $k_n = 11.42 - 6.86\times10^{-2}T + 1.49\times10^{-4}T^2 - 9.53\times10^{-8}T^3$
Electrical resistivity	Ω·m	$r_p = 2.75\times10^{-5} - 2.42\times10^{-7}T + 8.47\times10^{-10}T^2 - 7.74\times10^{-13}T^3$ $r_n = 5.08\times10^{-7} - 4.84\times10^{-9}T + 1.93\times10^{-10}T^2 - 2.53\times10^{-13}T^3$

The subscript *p* and *n* means the TEG P-legs and N-legs respectively.

Boundary conditions

Boundary conditions are expressed as follows:

(1) Inlet: $T = T_{in}, u = u_0$ (9a)

(2) Outlet: $P = P_0$, $\frac{\partial \overset{\mathbf{r}}{v}}{\partial x} = \frac{\partial T}{\partial x} = 0$ (9b)

(3) Hot side of TEG legs: *T*=600 K (9c)

Numerical method

The commercial software FLUENT (Version 6.3) based on finite-volume method is utilized to solve all of the governing equations, together with the boundary conditions. The SIMPLE algorithm is used for the pressure-velocity coupling. The inlet boundary condition is velocity inlet. And the outlet is modeled as a pressure outlet. The C codes of the source terms were compiled and linked with FLUENT by user defined function (UDF).

The model was meshed using the quadrilateral grids. The mesh near the wall were refined using boundary layer and y^+ of the first grid point is less than unity. And mesh independence tests have been performed to ensure that the solution does not vary with the number of computational elements,

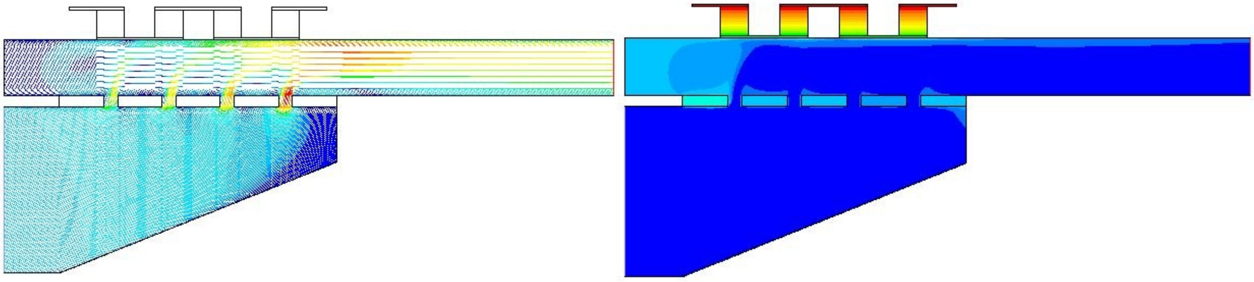
The important characteristics for TEG modules are the thermoelectric conversion efficiency which is defined as follows:

$$h = \frac{P_0}{Q_h} \times 100\% = \frac{I^2 R_L}{(a_P - a_N) I T_h - 0.5 I^2 R_i + \int_{T_c}^{T_h} \left(\frac{A_P k_P}{h_{TE}} + \frac{A_N k_N}{h_{TE}} \right) dT} \times 100\% \qquad (10)$$

Results and discussion

Velocity vector and temperature field

Fig. 2 shows the temperature field and the velocity vector. The velocity vector and temperature field of TEG cooling process when the inlet velocity is 10m/s and TEG hot side temperature is 600K. It can be seen that air velocity increased with the decrease of the section area along the x direction, and the jets create when the air flow through the holes which made the air velocity near the TEG cold side larger than the inlet velocity and make a more effective heat transfer performance. And the flow boundary layer and thermal boundary layer can be found near the TEG cold side which means that improving the flow and heat tranfer performance near the cold side can get more higher TEG conversion efficiency.



(a) Velocity vectors (b) Temperature field

Fig.2 The velocity vectors and temperature field

Effect of inlet velocity

For jet impinging cooling, the inlet velocity play a key role in the TEG conversion efficiency because it can influence the TEG cold side temperature. Fig. 3 shows the result with different inlet velocity ranged from 3m/s ~15 m/s while the TEG leg height (h_{legs}) is 5mm.From Fig. 3, the cold side temperature decreased and the thermoelectric conversion efficiency increased with the increase of inlet velocity. Higher velocity generates higher turbulence and thiner flow and thermal boundary layer, and then results in higher convection heat transfer coefficient and higher conversion efficiency. However, the improvement of applied inlet volcity is limited by driven power to overcome the pressure drop.

Effect of TEG legs height

The effect of TEG legs height is shown in Fig. 4. The plot shows that higher legs resulted in larger efficient conversion rate. This is because the thermoelectric materials can not be considered as heat insulator for the thermal conductivity of P-type and N-type materials is about 1.3~2.8 W/(m.K) and 1.6~3.1 W/(m.K) respectively at the temperature range of 30~300℃. At the same cooling conditions, the shorter legs will lead to smaller temperature gradient in legs and lower conversion efficiency, while higher TEG legs needs more semiconductor material which means more cost and lower economics, so the suitable legs height of 5~7mm is recommended in this study.

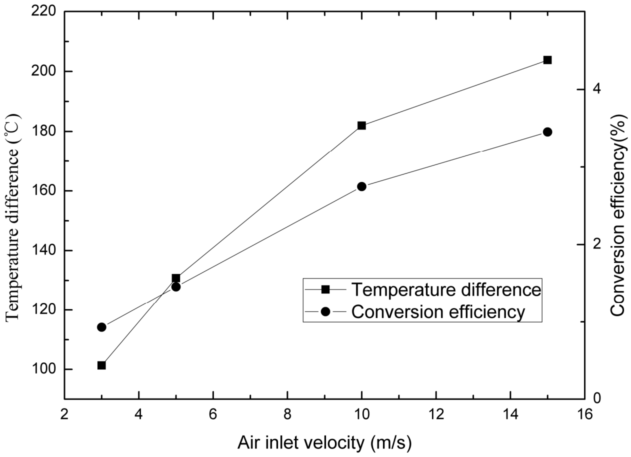


Fig.3 Effects of air inlet velocity

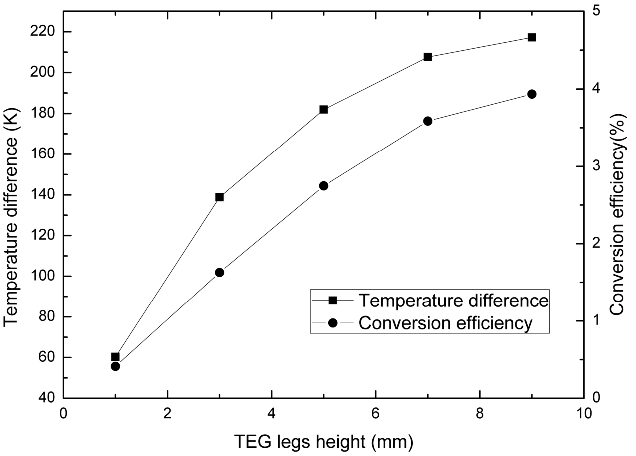


Fig. 4 Effects of TEG legs height

Effect of Fins

Finned surface are widely used in compact heat exchangers to improve heat transfer performance, usally it is considered that the role of fins is to increase heat transfer area, and effectively destroyed the boundary layer to enhance the ability of fluid to be turbulence. 1mm height and 1mm width fins are used to increase the cooling performance. The comparision between system with fins and without fins are listed in Table 3.

Table 3 The comparision of TEG performances between system with fins and without fins

Systems	Cold side temperature	Temperature difference	Conversion efficiency
Without fins	145.1℃	182.0℃	2.75%
With fins	43.9℃	283.1℃	6.73%

As seen in Table 2, using the fins on the electrodes can effecitively increase the performance of TEG. The cold side temperature at TEG legs droped from the 145.1℃ to 43.9℃ which means the temperature difference between the TEG hot sides and cold sides increased from 182.0℃ to 283.1℃,and the thermoelectric conversion efficiency with fins is 6.73% which was 2.4 times higher than that without fins.

Conclusions

This study developed a two-dimensional numerical model of TEG coupled with jet impinging cooling system. The effects of air inlet velocity, TEG legs height and fins surface were investigated. The conclusions can be drawn as below.

(1) The air inlet velocity plays a key role for cooling performance and TEG efficiency. The temperature difference between TEG hot and cold side and the conversion efficiency increased with the increase of air velocity.

(2) With the increase of TEG legs height, the temperature difference and efficiency is increased, but taking into account the cost and the economy, 5~7mm height is recommended in this study.

(3) Finned surface can effectively enhance the heat transfer rate and then results in higher efficiency, and the thermoelectric conversion efficiency with 1mm×1mm fins was 2.4 times higher than without fins.

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