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Study of different heat exchange technologies influence on the performance of thermoelectric generators

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ABSTRACT

A key challenge in thermoelectric power conversion is to create a significant temperature difference (ΔT) across the thermoelectric generator (TEG). And one approach to create a larger temperature difference is to enhance heat transfer of the hot side of TEG. Thus, when a thermoelectric generator has been designed and manufactured, it is found that the heat exchangers of the thermoelectric device determines its performance. This paper investigated the differences as well as the advantages and disadvantages of three typical heat exchangers in a thermoelectric setup, and the power consumed by the auxiliary equipment to improve the thermoelectric performance were taken into account. For this purpose, a mathematical model has been developed. The accuracy of this model was verified via the experiments, by constructing and testing the prototypes. The results illustrate the net power output performance of thermoelectric devices with three different type of heat exchangers. The air cooling exchangers are shown a minimum auxiliary consumption whereas the heat pipe cooling exchanger are shown to be the most effective. At last, this article gets an economic analysis, and a new evaluation index associated with the power consumption of the auxiliary equipment is proposed. The results provided some practical guidelines for the design and application of practical thermoelectric power generations.

1. Introduction

With the rapid development of the industry and economy, issues relating to that of environment and energy become more serious. As a result, exploring new sources of energy and managing conventional energy in an environmentally friendly manner become a hot spot in countries around the world. However, there are still plenty of difficult and technical obstacles in the utilization of renewable energy. Therefore, a valuable alternative approach to improve the overall energy efficiency is to capture and recover the 'waste heat' [1–3]. Considering today's energy crisis, the conversion of thermal energy to electricity has garnered interest in recent years due to the abundance of low cost waste-heat.

Because of no chemical reaction, no noise, no gas emissions, no moving parts, reliability, environment-friendly and maintenance-free, the thermoelectric generators have good potential applications and many advantages for the conversion of low level thermal energy directly into electricity for improving the efficiency of energy utilization based on the Seebeck effect [4]. The TEG has many practical applications that range from microelectronics heat utilization to large scale thermal power plant waste-heat recovery, from renewable energy to traditional industrial waste heat. For example [5–8], investigated waste heat recovery of solar system using thermoelectric generator to improve solar utilization efficiency [9–12]. investigated thermoelectric system efficiency using vehicle heat exhaust. Lv et al. [4] proposed a thermoelectric wearable helmet for the collection and use of human heat loss. Tsai et al. [13] recycled the waste heat of a high-power light emitting diode to self-sufficiently support for an electrical fan. Kimet al. [14] experimentally investigated waste heat recovery performance of a thermoelectric generator. Many studies such as [15–18] investigated TEG systems for industrial waste-heat recovery applications. However, the low thermoelectric conversion efficiency is a major barrier to wide spread application of TEG. Considerable works have been done in the optimization of material [19–23], geometry [24–28] and thermal management of TEGs [29–33] to improve the efficiency thermoelectric generation, which mainly could be grouped into two categories: (1) the

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Nomenclature

A_{teg}	area of TE module, m^2
C_{fx}	local friction coefficient
C_p	specific heat, kJ/(kg·K)
D	equivalent diameter of the water tube, m
H	the height of the heat sink, m
h_{covf}	coefficient of convection heat transfer of the thermal slug, W/(m^2·K)
h_x	heat transfer coefficient along the length of the thermal slug at the location of a convective, W/(m^2·K)
I	current, A
$k_{heatsink}$	thermal conductivity of the thermal slug, W(m·K)
k_{air}	thermal conductivity of air, W(m·K)
k_{teg}	thermal conductivity of TEG, W/(m·K)
L	the length of the heat sink, m
l_{teg}	length of TEG, m
$\dot{m}$	flow rate of cooling water, m/s
n	numbers of PN junction
Nu	Nusselt number
P	electric power, W
P_{max}	maximum electric power output, W
Pr	Prandtl number
Q_h	energy that passed in hot side of the TEG, J
Q_c	energy that passed in cold side of the TEG, J
r_{teg}	electrical resistivity of a P or N leg, Ω·m
R_L	external load of circuit, Ω
R_{ct1}	thermal contact resistance between heat pipe and heat sink, K/W
R_{ct2}	thermal contact resistance between heat pipe and heat sink, K/W
R_{ct3}	thermal contact resistance between heat pipe and heat sink, K/W
R_{teg}	thermal resistance of the thermoelectric generator, K/W
$R_{heatsink}$	thermal resistance of the heat sink, K/W
$R_{heatpipe}$	thermal resistance of heat pipe, K/W
R_{con}	resistance of the heat conduction in thermal slug, K/W
R_{covf}	thermal resistance of convection heat transfer between thermal slug and ambient air, K/W
Re	Reynolds number
S_1	the cross section area of the heat sink, m^2
S_2	the total area of the thermal slug, m2
St	Stanton number
T_h	hot side temperature of TEG, K
T_c	cold side temperature of TEG, K
T_{amb}	temperature of ambient, K
T_{hs}	hot side temperature of the thermocouple, K
T_{cs}	cold side temperature of the thermocouple, K
$T_{water-o}$	temperature of heated water, °C
$T_{water-i}$	temperature of cooling water, °C
U	open circuit voltage, V
UA	over-all heat exchanger coefficient, W/K
U_hA_h	heat exchanger coefficient of hot side, W/K
U_cA_c	heat exchanger coefficient of cold side, W/K
u_∞	air flow rate, m/s
u_f	cooling water flow rate, m/s
W_{auw}	electric power consumption of the auxiliary equipment, W
W_e	electric power produced by TEG, W

Greek symbols

α_{teg}	Seebeck coefficient of TEG
α_u	uncertainties associated with the experimental facilities
ΔT	temperature difference between two side of TEG, °C
ΔP	pressure difference, Pa
ρ	density of air, kg/m^3
ρ_f	density of water, kg/m^3
μ	kinematic viscosity, m^2/s
α	thermal diffusivity, m^2/s
ν	dynamic viscosity, N·s/m^2
η_{net}	net efficiency of the complete TEG system
η_{teg}	electrical efficiency of TEG
δ	the kinetic energy correction factor

improvement of thermoelectric materials and structures; (2) the improvement of thermal management to create a larger temperature difference across TEG In recent years, significant progress has been made on improving thermoelectric materials. But when a new thermoelectric generator design has been planned and produced, the key challenge in thermoelectric power conversion is to create a significant temperature difference across the thermoelectric module. A lot of research aimed to maximize the power output of commercially available thermoelectric modules by improving heat exchangers on the hot side of TE module has been conducted. The most-used cooling methods to dissipate the heat produced on the hot side of the TE devices are air cooling, liquid cooling, heat pipe cooling and phase change material cooling and so on [34–37]. Meng et al. [35] presented a thermoelectric power generation recover the heat of blast furnace slag flushing water and analyzed water heat exchanger flow passage length on the performance of the TE device. Date et al. [37] put forward a heat pipe cooled thermoelectric generators. Thermoelectric generators are passively cooled using the heat pipes which offers high heat transfer coefficient. The results shows that for a flux of 50,000 W/m^2 a temperature difference of 75 °C across the thermoelectric generator can be achieved and an open circuit voltage of 3.02 V can be generated for each thermoelectric generator. Sundarraj et al. [38] proposed theoretical models of a hybrid solar thermoelectric generator with forced convection cooling and evaluated the performance of it by theoretical and experimental investigations.

Although a lot of work has been done in this area, most of these studies would remain incomplete for neglecting the power consumed by the auxiliary equipment [39]. It is obvious that the improvement in the performance of a heat exchanger usually entails the increase of pressure losses, which in turn leads to higher power consumption of auxiliary equipment. And the higher pressure drop, the bigger the energy consumption. In addition, apart from efficiency, cost is equally important to power output or efficiency for the adoption of waste heat recovery thermoelectric system. Another big obstacle prevented wide spread application and commercialization of thermoelectric generators lies in the cost of the waste heat recovery thermoelectric system, which should be approximately 1 $/W [40] to be competitive with currently used power technologies to foster market penetration. And [41] demonstrated that heat exchanger costs most often dominate the overall TE system costs.

Consequently, to address these problems, this paper presented an analytical multi-element component TEG models for three typical types of cooling methods on the TEG heat recovery system. The model considers not only the influence of different cooling modes on the thermoelectric performance, but also the cost of the overall system heat exchange improvement. The accuracy of this analytical models was experimentally verified, by constructing and testing the prototypes. The performances of the thermoelectric heat recovery system with different cooling methods are evaluated by the thermal and electrical characteristic of the TEG. In addition, a new evaluation index associated with the power consumed by the pumps or fans is proposed to assess the comprehensive performance of different cooling methods on TEG. The optimal TE heat recovery systems' performances were compared