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Experimental investigation on thermoelectric generator with non-uniform hot-side heat exchanger for waste heat recovery

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ABSTRACT

In typical gas-to-liquid thermoelectric generators for waste heat recovery, the stream-wise gas temperature drop in the hot-side heat exchanger leads to the decrease of power output of the whole system. Denser fins are usually arranged on the downstream of the hot-side heat exchanger to improve the uniformity of temperature field and thus the total power output performance of thermoelectric generators when the steam-wise temperature drop is small, but it is not benificial when the steam-wise temperature drop is large. This work investigates the effect of configuration of winglet vortex generators on the performance of thermoelectric generator system. Three sets of hot-side heat exchangers, including a heat exchanger with smooth channel, a heat exchanger with uniform configuration of winglet vortex generators and a heat exchanger with non-uniform configuration of winglet vortex generators, are tested in a gas-to-liquid thermoelectric generators experimental system. The hot-side Reynolds number ranges from 3000 to 6400 and the hot-side inlet temperature is within 523–553 K. The experimental results show that the total and net power output of thermoelectric generator under matched load resistance with uniform heat exchanger can respectively outperform that with smooth heat exchanger by 97.5% and 77.7% in average, whereas that with non-uniform heat exchanger by 189.1% and 177.4% in average. Since the uniform and non-uniform heat exchangers have the same number but different configuration of winglet vortex generators, this kind of active cascade control of heat transfer enhancement elements is proved to be effective in improving the power output of thermoelectric generator system without increasing pumping power.

1. Introduction

The thermoelectric (TE) power conversion system directly converts thermal energy into electric power by using TE materials based on the principle of Seebeck effect [1]. It has become one of the promising technologies to recover waste heat released from energy and power engineering systems. For instance, the waste heat in the micro-miniature power generators can be reutilized by thermoelectric modules embedded recuperated Brayton cycle [2]. The placement of thermoelectric modules on water tube walls inside a boiler can effectively recover the waste heat at coal-fired power plants [3]. Also, the waste heat recovery by thermoelectric modules in automobile engine systems is a hot issue and has been widely investigated [4]. The thermoelectric generator (TEG) has the nature of heat engine governed by the laws of thermodynamics and the efficiency of energy conversion is limited by Carnot efficiency [5]. Although the energy conversion efficiency of the TEG is quite low at present, the waste heat serving as heat source for the TEG is virtually free and the low efficiency is no longer a major concern [6]. Besides, the thermoelectric conversion technology also provides many advantages including low cost, no noise, no pollution, high reliability and easy scale-up and down. Also, since the TEG is a direct solid-state energy conversion system, it is relatively simple to be integrated into the existing thermodynamic cycles compared to the energy conversion systems based on mechanical moving components and traditional gas or liquid working fluids.

A typical TEG is consisted of the hot-side heat exchanger, the TE module and the cold-side heat exchanger. The hot-side heat exchanger transfers the thermal energy of hot-side fluid to the hot-side surface of TE modules. The cold-side heat exchanger removes heat from the cold-side surface of TE modules into the cooling fluid. The temperature difference between the hot-side and cold-side surface across the TE modules is the driving force to convert heat energy into electric power. In the system-level perspective, the electric power output of the TEG is not only determined by the TE material's performance, but also relies on the hot-side and cold-side heat transfer performances [7]. At present, the commercially available TE materials such as Bismuth-Telluride (Bi_2Te_3) have a figure of merit, *ZT*, of 0.8–1.0 [8]. But the laboratory-developed TE materials with higher *ZT* still need a long time to put into

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Nomenclature

A	heat transfer area, m^2
c_p	specific heat capacity, J/(kg·K)
d_{eq}	hydraulic diameter, m
d_{leg}	distance between two adjacent thermoelectric legs, m
h	heat transfer coefficient, W/(m^2·K)
h_{leg}	height of thermoelectric legs, m
H	height, m
H_{TEM}	height of a single thermoelectric module, m
H_{VG}	height of rectangular winglet type of vortex generator, m
I	electric current, A
K_{TE}	thermal conductance of thermoelectric module, W/K
l_{leg}	length of thermoelectric legs, m
L	effective length of heat exchange in hot-side heat exchanger, m
L_{TEM}	length of a single thermoelectric module, m
L_{VG}	length of winglet vortex generator, m
n	number of thermoelectric couples in a single module
N_{VG}	number of winglet pairs along hot-side heat exchanger
p	pressure, Pa
P_l	longitudinal distance of two adjacent pairs of winglets, m
P_{net}	$P_{out} - P_V$, net power output in thermoelectric generator, W
P_{out}	total power output in thermoelectric generator, W
P_t	transverse pitch of two adjacent pairs of winglets, m
P_V	pumping power, W
q_m	mass flow rate of air, kg/s
q_v	volume flow rate of air, m^3/s
Q	heat transfer rate, W
R_L	electric load resistance of circuit, Ω
R_{TE}	internal electric resistance of a thermoelectric module, Ω
Re	Reynolds number
t	thickness of conductive metal strip, m
t_w	wall thickness, m
T	temperature, K
u	velocity, m/s
U	electric voltage of thermoelectric generator, V
V	volume occupied by fluid, m^3
W	width of heat exchanger, m
W_{TEM}	width of a single thermoelectric module, m
W_{VG}	width of rectangular winglet type of vortex generator, m
x	stream-wise direction along heat exchanger, m
y	transverse direction across thermoelectric module, m
ZT	figure of merit for thermoelectric material

Greek symbols

α_{TE}	Seebeck coefficient of thermoelectric module, V/K
β	attack angle of winglet vortex generator, °
Δp	static pressure drop, Pa
ΔT	temperature difference, K
Δx	distance, m
λ	thermal conductivity, W/(m·K)
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3

Subscripts

c	cold-side surface
f	working fluid
fc	cold-side working fluid
fh	hot-side working fluid
h	hot-side surface
i	i_{th}, i = 1,2,3…
max	maximum
opt	optimum
TEM	thermoelectric module
VG	vortex generator
work	working condition

market [9]. Further, when the TE modules are integrated into a TE system, the conversion performance of TE system is even worse than that of the intrinsic TE material because of the insufficient consideration of the hydraulic-thermal-electric multiphysics interplay of the whole system [10]. Hence, the system-level design and optimization for TEG is of great importance to offset the margin between conversion performances of TE material and TE system.

Many investigations are focused on design and optimization of single TE modules. Hsiao et al. [11] employed experiment and one-dimensional (1-D) thermal resistance model to study the feasibility of improving fuel efficiency of internal combustion (IC) engine by mounting the TE module on exhaust pipe and radiator. A heater was used to offer continual energy to the hot side and a water-cooling heat sink was used to remove the energy. Jang et al. [12] numerically and experimentally studied the optimized spreader thickness for a TEG in waste heat recovery. The heat transfer coefficients were specified to hot-side and cold-side thermal boundaries in the numerical model. The results showed that the optimized design of spreader was also strongly dependent on the heat transfer coefficient of exhaust gas. Hu et al. [13] established a three-dimensional (3-D) numerical model for a Bi_2Te_3-based TE module by considering the temperature-dependent physical properties of TE material and verified the model with experimental setup. Kossyvakis et al. [14] numerically and experimentally investigated the influence of hot-side temperature non-uniformity and heat loss for a commercial TE module. Shi et al. [15] established a real-sized TE module and found that under ideal condition of constant heat input, higher height, larger cross-sectional area and fewer amount of TE couples could obtain an excellent output performance under matched load resistance. Li et al. [16] investigated the heat transfer and fluid flow of tube-and-fin heat exchangers as hot-side channels in a TEG. The results showed that the tube-and-fin heat exchanger was more compact but with lower pressure endurance ability than the tube heat exchanger. Wang et al. [17] constructed a metal foam-filled plate heat exchanger-TE module setup, where the TE module with various pairs of legs with Bi_2Te_3 TE materials was tested. Li et al. [18] studied the temperature distribution of a TEG composed of a Bi_2Te_3-based TE module and two-fluid heat exchangers. The results showed that the influence of fluid velocity on temperature distribution was weak and Peltier effect was limited when the velocity was slow. Also, when hot-side temperature was up to 473 K, the Peltier effect should be taken into consideration.

However, since the TEG in exhaust gas-based waste heat recovery is mostly consisted of multiple TE modules. Each TE module along the heat exchanger subjects to different working temperatures due to the stream-wise temperature gradient. Also, heat utilization by one TE module at upstream affects the thermal field for the subsequent TE modules at downstream. Thus, the working condition and corresponding optimization for a single TE module does not necessarily correspond to multiple TE module sequences, particularly when the stream-wise temperature of exhaust gas appreciably changes. Some investigations are conducted to enhance the power output performance in a system-perspective. Stevens et al. [19] established a model to study the theoretical limit of electrical power generation for a given exhaust stream and system configuration under optimal electrical loading condition. The analysis showed that the simple isothermal modeling approach often applied to individual TE leg pair was not sufficient to