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Thermal characteristics of combined thermoelectric generator and refrigeration cycle

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ABSTRACT

A combined thermal system consisting of a thermoelectric generator and a refrigerator is considered and the effect of location of the thermoelectric generator, in the refrigeration cycle, on the performance characteristics of the combined system is investigated. The operating conditions and their influence on coefficient of performance of the combined system are examined through introducing the dimensionless parameters, such as $\lambda(\lambda = Q_{HTE}/Q_H$, where Q_{HTE} is heat transfer to the thermoelectric generator from the condenser, Q_H is the total heat transfer from the condenser to its ambient), temperature ratio ($\theta_L = T_L/T_H$, where T_L is the evaporator temperature and T_H is the condenser temperature), r_C ($r_C = C_L/C_H$, where C_L is the thermal capacitance due to heat transfer to evaporator and C_H, is the thermal capacitance due to heat rejected from the condenser), θ_W ($\theta_W = T_W/T_H$, where T_W is the ambient temperature), θ_C ($\theta_C = T_C/T_H$, where T_C is the cold space temperature). It is found that the location of the thermoelectric generator in between the condenser and the evaporator decreases coefficient of performance of the combined system. Alternatively, the location of thermoelectric device in between the condenser and its ambient enhances coefficient of performance of the combined system. The operating parameters has significant effect on the performance characteristics of the combined system; in which case temperature ratio (θ_L) within the range of 0.68–0.70, $r_C = 2.5$, $\theta_W = 0.85$, and $\theta_C = 0.8$ improve coefficient of performance of the combined system.

1. Introduction

Increasing energy demand and environmental pollution lead to development of new technologies towards utilizing renewable energy sources. The recent developments in scientific research enable to demonstrate utilization of the solid state devices, to produce direct electricity from the waste heat resources, is one of the alternative solutions for the waste heat recovery. Thermoelectric generators are the solid state devices and they are one of the potential candidates for renewable energy conversion from the waste heat sources. Their environment friendly nature, simple design, and easiness of operation are the driving forces for their current interest in electricity production despite their low efficiency. Advancements in thermoelectric materials enhance the device efficiency through improving the figure of Merit. The proper arrangement of the device geometric configurations minimizes thermodynamic losses during the operation while improving the device performance considerably. Although thermoelectric generators can find applications in industry, domestic applications are limited because of their low efficiency. However, the overall performance of the thermal system can be further improved through integration of thermoelectric generators in the system. One of the practical systems is the refrigeration cycle, which is widely used in households for the food storage purposes. The waste heat from the refrigeration cycle can be utilized by the thermoelectric generators; however, thermal load of the system changes with the addition of such device while modifying thermal characteristics of the system. Therefore, investigation of thermal integration of thermoelectric generator in the refrigeration cycle for improved system performance becomes essential.

Considerable research studies were carried out to examine thermal performance of thermoelectric generators. Optimization of power and efficiency of thermoelectric devices with asymmetric thermal contacts was carried out by Yazawa and Shakouri [1]. They presented a generic formula of the maximum power output and obtained optimum device geometric configuration resulting the maximum power. The maximum power and efficiency of an irreversible thermoelectric generator with a generalized heat transfer law were investigated by Chen et al. [2]. They demonstrated that the external heat transfer did not affect the device characteristics and the optimum performance of the thermoelectric device could

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Nomenclature

C_L	heat conductance between low temperature reservoir and evaporator (W/K)
C_H	heat conductance between high temperature reservoir and condenser (W/K)
Q_H	heat transfer rate from the condenser (W)
Q_{HTE}	heat transfer rate from condenser to the thermoelectric generator (W)
Q_L	heat transfer rate to the evaporator (W)
Q_{LTE}	heat transfer rate between thermoelectric generator and evaporator (W)
r_C	conductance ratio, C_L/C_H
T_{ave}	average temperature in the thermoelectric generator (K)
T_C	temperature of low temperature reservoir (K)
T_H	condenser temperature (K)
T_L	evaporator temperature (K)
T_W	temperature of high temperature reservoir (K)
W_C	power input to the compressor (W)
W_{TE}	power output of the thermoelectric generator (W)
Z	figure of Merit ($Z = \sigma S^2/\lambda$, where S is Seebeck coefficient, λ thermal conductivity, □ and σ electrical conductivity) (1/K)
β	coefficient of performance
η_{TE}	efficiency of the thermoelectric generator
λ	fraction of heat rate to the thermoelectric generator, Q_{HTE}/Q_H
θ_C	dimensionless temperature of the low temperature reservoir, T_C/T_H
θ_L	dimensionless evaporator temperature, T_L/T_H
θ_W	dimensionless condenser temperature, T_W/T_H

be achieved for proper selection of device parameters such as the figure of Merit. The possible increase of cycle efficiency of thermal plants through integration of thermoelectric devices was investigated by Sarnacki et al. [3]. They showed that integration of thermoelectric devices improved the overall efficiency of marine diesel propulsion systems and a microgas turbine. Solar thermoelectric generator for micropower applications was examined by Amatya and Ram [4]. They indicated that using novel thermoelectric materials, a conversion efficiency of 5.6% can be achieved for a solar thermoelectric generator. Energy conversion efficiency of a hybrid solar system incorporating photovoltaic, thermoelectric, and waste heat was studied by Yang and Yin [5]. They showed that energy conversion efficiency depended on the solar irradiation, ambient temperature, and water flow temperature; moreover, the hybrid system had a higher efficiency than that of the traditional photovoltaic system. Performance characteristics of a multi-element thermoelectric generator with radiation heating source were examined by Meng et al. [6]. They indicated that the maximum electrical current decreased with the increase of the number of thermoelectric elements while it increased with the increase of the generator heat source temperature. Thermal control of exhaust-heat-thermoelectric generation was investigated by Brito et al. [7]. They demonstrated that the current commercial thermoelectric modules were temperature limited, so they were unable to be in direct contact with the exhaust gases for electricity generation. Energy and exergy analysis of a double-pass thermoelectric solar air collector were carried out by Khasee et al. [8]. They showed that exergy efficiency of the thermal system varied from the minimum of 7.4% to the maximum of 8.4%. Parametric and exergetic analysis of waste heat recovery system based on thermoelectric generator and organic Rankine cycle were carried out by Shu et al. [9]. They demonstrated that the thermoelectric-organic Rankine cycle system was suitable to recover waste heat from engines because of the fact that thermoelectric generator could be operated at extend temperature range of heat source and thereby improved the fuel economy. Effect of linear and non-linear components in the temperature dependences of thermoelectric properties on the energy conversion efficiency was investigated by Yamashita [10]. He demonstrated that that the temperature dependences of thermoelectric properties of the generator had a significant influence on the thermal efficiency of the device. Thermoelectric-hydraulic performance of a multistage integrated thermoelectric power generator was studied by Reddy et al. [11]. They indicated that the addition of modules in the device resulted in a significant improvement in power output; however, a reduction in produced electric current and efficiency was observed. The analysis of thermoelectric energy conversion efficiency with linear and non-linear temperature dependence in material properties was carried out by Wee [12]. He suggested that the accurate inclusion of the Thomson effect was essential to understand even the qualitative behavior of thermoelectric energy conversion.

Thermoelectric power generator can operate with the combination of other thermal systems. In this case, the combined system performance can be improved due to utilization of rejected heat by the thermoelectric generator. Although thermal analysis of thermoelectric power generation was studied previously [13–18], the main focus was to investigate the effects of geometric configuration on the device performance and characteristics including efficiency, output power, and thermal stress states. However, thermal analysis in relation to practical application of the thermoelectric generator, such as in refrigeration cycle, is left obscure. Therefore, in the present study, thermal analysis of combined cycle, consisting of a refrigerator and thermoelectric power generator, is presented. The influence of the location of thermoelectric generator, in the combined system, on the cycle performance as predicted by coefficient of performance of the thermal system is investigated. The analysis is extended to include various operating parameters, such as temperature ratio, heat fraction ratio, and thermal capacitance ratio, for the assessment of thermal system performance and characteristics.

2. Thermodynamic analysis of combined system

The coefficient of performance of a refrigeration cycle may be increased by using thermoelectric generator in a proper arrangement. Therefore, the waste heat can be utilized by the thermoelectric device to generate electrical power, which can be used as a supplement to the compressor of the refrigeration cycle. This arrangement reduces the external power required to run the compressor; which in turn yields a high coefficient of performance of the combined system consisting of a thermoelectric generator and a refrigerator.

The thermal efficiency of the thermoelectric generator depends on the temperature difference between across the thermoelectric generator. Therefore, as a first trial, consider placing the thermoelectric generator between the condenser and the evaporator of the refrigeration cycle as shown in Fig. 1. Here, λ in Fig. 1 indicates the fraction of the heat rejected from the condenser at temperature T_H which is used by the thermoelectric device to generate electricity. The remaining of the heat rejected from the condenser is released to the surrounding at temperature T_W.