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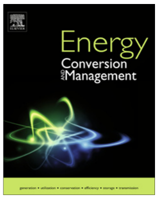

The practical performance forecast and analysis of thermoelectric module from macro to micro

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ABSTRACT

The practical operating conditions of thermoelectric products, such as the input power source and the thermal resistance of hot side heat exchanger, are different from the theoretical study. Thus the equations, which are used to estimate the practical maximum cooling performance just according to the datum in datasheet of commercial thermoelectric module (TEM), are given. The nested loop method is adopted to solve the numerical model. This study provides a method to choose a suitable TEM for thermoelectric product to meet the application requirement. It finds that the minimum cold side temperature increase and the voltage for achieving the minimum cold side temperature step decrease with the increase of thermal resistance of hot side heat exchanger, respectively. The maximum temperature difference increase and the voltage for achieving the maximum temperature difference step increase with the increase of thermal resistance of hot side heat exchanger, respectively. According to the dimension, three kinds of thermoelectric module, bulk TEM, miniature TEM and micro TEM, are studied. The novel scale effect are discovered by comparing these TEMs. It found that the step-change phenomenon become more and more obvious with the decrease of the dimension of thermoelectric module. The influence ratio of thermal resistance of hot side heat exchanger on the maximum cooling performance increases and the influence ratio of input power source decreases from macro to micro, respectively. It forecasts that there exists a critical value for the dimension of thermoelectric module, when the dimension of thermoelectric module is smaller than this critical value, the maximum voltage or current of thermoelectric module is constant and does not change with the thermal resistance of hot side heat exchanger.

1. Introduction

More and more researchers focus on studying the thermoelectric cooling (TEC) system, because TEC system does not use CFCs as working fluids and does not contain moving part. Thermoelectric modules (TEMs) have been widely used for cooling and heating in the military, aerospace, commercial devices, and industry fields for its compact size and environmental friendly [1]. There are many commercial thermoelectric devices, such as thermoelectric refrigerator [2], thermoelectric air-conditioner [3,4], thermoelectric dehumidifier [5] and cooling equipment for optoelectronic device [6]. While the user of thermoelectric refrigeration is faced with somewhat different problem. It is usually a matter of selecting one or more available commercial modules from the range offered by a manufacturer to meet a specific requirement [7].

At present, the datasheet of commercial thermoelectric module just give a table of maximum characteristic parameters (i.e. maximum temperature difference, the maximum cooling capacity, the maximum working voltage, and the maximum electric current), a set of design curves and a dimension of TEM. But these values and such curves are based on the assumption that all modules works under ideal condition, the thermal resistance of hot side heat exchanger is equal to 0 (namely the hot side temperature of TEM maintains at constant), the input source is current source.

In fact, in many practical applications, the thermal resistance of hot side heat exchanger is not equal to 0, and the input power source generally adopts voltage source [8]. This is because TEM cannot work without the hot side heat exchanger, which is used to release the hot side heat generation of TEM to the environment, and it has an important influence on heating and cooling performance of TEM. Furthermore, the dissipation performance of heat exchanger can be presented by thermal resistance, which is the function of heat flux and temperature. The smaller thermal resistance is, the better dissipation performance is achieved. While

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Nomenclature

R_h	thermal resistance of hot-end heat exchanger (°C W^{-1})
R	electrical resistance of thermoelectric module (Ω)
K	thermal conductivity (W m^{-1} K^{-1})
Q_c	cooling capacity (W)
T	temperature (°C)
ΔT	the temperature difference between hot side and cold side (°C)
I	electric current (A)
U	voltage (V)
$\Delta T_{\max}$	the maximum temperature difference between hot side and cold side (°C)
$U_{\Delta T\max}$	the voltage for achieving the maximum temperature difference between the hot side and the cold side (V)
$T_{c\min}$	the minimum cold side temperature (°C)
$U_{Tc\min}$	the voltage for achieving the minimum cold side temperature $T_{c\min}$ (V)
$\Delta T_{\max}(U)$	the maximum temperature difference under voltage source (°C)
$\Delta T_{\max}(I)$	the maximum temperature difference under current source (°C)
$T_{c\min}(U)$	the minimum cold side temperature under the voltage source (°C)
$T_{c\min}(I)$	the minimum cold side temperature under the current source (°C)
$U_{Tc\min}(U)$	the voltage for achieving the minimum cold side temperature $T_{c\min}$ under the voltage source (V)
$U_{Tc\min}(I)$	the responding voltage for achieving the minimum cold side temperature $T_{c\min}$ under the current source (V)
$U_{\Delta T\max}(U)$	the voltage for achieving the maximum temperature difference under the voltage source (V)
$U_{\Delta T\max}(I)$	the responding voltage for achieving the maximum temperature difference under the current source (V)
$I_{Tc\min}(U)$	the responding current for achieving the minimum cold side temperature $T_{c\min}$ under the voltage source (A)
$I_{Tc\min}(I)$	the current for achieving the minimum cold side temperature $T_{c\min}$ under the current source (A)
$I_{\Delta T\max}(U)$	the responding current for achieving the maximum temperature difference under the voltage source (A)
$I_{\Delta T\max}(I)$	the current for achieving the maximum temperature difference under the current source (A)

Greek letter

α	Seebeck coefficient of thermoelectric module (V K^{-1})

Subscripts

c	cold side of the thermoelectric module
h	hot side of the thermoelectric module
a	ambient

thermoelectric products design is varying heat source/sink temperatures over hot/cold sides of the thermoelectric modules [9]. Therefore, the maximum cooling performance of TEM varies with the change of thermal resistance. In addition, Shen et al. [10] showed that there is some difference between the voltage source and current source. They found that the current source neglect the interaction between the current and temperature in the TEM, but the voltage pulse explicitly takes the interaction into consideration. Therefore, its not feasible to choose TEMs for thermoelectric product just according to the datasheet of TEM.

In the previous studies, there is no open report on the above practical conditions to choose a suitable TEM for thermoelectric product to meet the application requirement. Therefore, three kinds of commercial TEMs, bulk TEM, miniature TEM and micro TEM are introduced in this study. A model is established to investigate the practical maximum cooling performance of commercial thermoelectric modules just according to the datasheet. Several critical application issues and novel phenomena related to the TEC system, such as the voltage $U_{Tc\min}$ for achieving the minimum cold side temperature $T_{c\min}$, the voltage $U_{\Delta T\max}$ for achieving the maximum temperature difference $\Delta T_{\max}$, the step-change phenomena under practical conditions, are addressed. The possibility of micro TEM approaching critical phenomena is forecasted under practical condition.

2. Numerical model

The cooling capacity (Q_c) of TEM at the cold side, and the heat generation (Q_h) of TEM at the hot side can be obtained by use of Eqs. (1) and (2) respectively [11].

$$Q_c = \alpha I T_c - 0.5 I^2 R - K(T_h - T_c) \tag{1}$$

$$Q_h = \alpha I T_h + 0.5 I^2 R - K(T_h - T_c) \tag{2}$$

The difference of the ideal and practical working condition are listed in Table 1, to better present the difference of different input power source and the influence of hot side heat exchanger on the maximum cooling performance, we introduced voltage (U) and thermal resistance of hot side heat exchanger (R_h) as the variables into the mathematical models. Where I in Eqs. (1) and (2) can substitute with the following equation:

$$I = (U - \alpha(T_h - T_c))/R \tag{3}$$

the heating generation (Q_h) of TEM at the hot side releases to the environment is given by

$$Q_h = (T_h - T_a)/R_h \tag{4}$$

where α (V K^{-1}) is the Seebeck coefficient of the TEM, I (A) is electric current, U (V) is the voltage, R (Ω) is the electrical resistance of the TEM, K (W K^{-1}) is thermal conductance of the TEM, T_a (K) is the ambient temperature. T_c (K) and T_h (K) are the cold side and hot side temperatures of TEM respectively. However, α, R and K can be calculated according to the datasheet [12].

$$\alpha = U_{\max}/T_h \tag{5}$$

$$R = \frac{U_{\max}}{I_{\max}} \frac{(T_h - \Delta T_{\max})}{T_h} \tag{6}$$

$$K = \frac{U_{\max} I_{\max} (T_h - \Delta T_{\max})}{2 T_h \Delta T_{\max}} \tag{7}$$

Table 1
The ideal and practical working condition of thermoelectric cooling.

	Ideal condition	Practical condition
Input power source	Electric current (I)	Electric voltage (U)
Thermal resistance of hot side heat exchanger	$R_h = 0$ °C W^{-1}	$R_h > 0$ °C W^{-1}