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Thermoelectric module design strategy for solid-state refrigeration

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ABSTRACT

In this paper, a new characterization factor for thermoelectric module design in thermoelectric refrigeration is presented with guidelines for practical design strategy. It has been general practice to optimize the geometric factor (G-factor), the ratio of the area to the leg length of a thermoelectric leg, and the number of leg pairs simultaneously to gain a minimum refrigeration temperature from a module for a refrigeration system. However, the B-factor, which is defined as the ratio between the leg length and the fill factor (ratio of the area filled with thermoelectric materials to the module area), allows for module optimization with only one parameter. To demonstrate, a theoretical model of a module was created with energy conservation equations. While disregarding electrical contact resistance, the number of leg pairs did not affect the obtainable maximum temperature difference or the power consumption of a module when utilizing the B-factor. The effects of contact resistance on the optimum B-factor were also evaluated and avoided when the leg length was increased. It was then found that using fewer legs in a module would produce a temperature difference that was less sensitive to a varying input current. The present theoretical approach was validated with experimental evidence.

1. Introduction

Thermoelectric refrigerators are widely known to be environmentally friendly, quiet, and have low power consumption in small size refrigerators [1]. Additionally, they can be fabricated rather easily and work effectively if a properly designed thermoelectric module is used. When designing a thermoelectric module for a refrigerator, it is crucial to consider the module's geometric parameters, as well as its material properties. Unfortunately, it is difficult to find a simple model for choosing or designing thermoelectric modules for thermoelectric refrigeration. Furthermore, a characterization factor for module design has yet to be found with a set of guidelines for temperature control strategy in thermoelectric refrigeration.

The design process of a thermoelectric module takes into consideration different module aspects to gain the maximum temperature difference across the module. Typically, the properties of thermoelectric materials, such as the Seebeck coefficient (α), electrical resistivity (ρ), and thermal conductivity (k), are important to the module's performance. These properties can be combined into a figure-of-merit (ZT) for thermoelectric modules, which can be increased to improve module performance [2]. Many research activities focus on material development and the figure-of-merit for thermoelectric modules; however, not many works on system design are readily available [3].

One of the most widely adopted models for thermoelectric modules suggests an optimum current value as a function of only ZT under two main assumptions: 1) the temperatures of the hot and cold sides of the module are not affected by the input current; and 2) no heat is gained from the environment when the cold side of the module reaches its minimum temperature [4]. The derivation process to find the optimum current that allows for the maximum temperature difference begins with equation (1), as shown in Table 1. Setting the derivative of equation (1) equal to zero creates an equation for the optimum current, as shown in equation (2). This can be substituted back into equation (1) to gain equation (3), the maximum cooling power of the module [4]. By finding the optimum current and maximum cooling power in this way, the effects of the input current, such as Joule heating and the Peltier effect, on the temperatures of the hot and cold sides of the module are neglected. This causes the equations provided by the traditional model for the optimum input current and maximum cooling power to be inconsistent with actual results. Moreover, the traditional model suggests the maximum temperature difference of the module will occur when the maximum cooling power is equal to zero ($q_{C,max} = 0$), which is how equation (4) may be derived from

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Table 1
The equations used in the various methods of modeling a thermoelectric refrigerator.

Method	Equations	
Traditional method		
	$q_C = (\alpha_p - \alpha_n)IT_C - K(T_H - T_C) - \frac{1}{2}I^2R$	(1)
	$I_{opt} = \frac{(\alpha_p - \alpha_n)T_C}{R}$	(2)
	$(q_C)_{max} = \frac{(\alpha_p - \alpha_n)^2 T_C^2}{2R} - K(T_H - T_C)$	(3)
	$(T_H - T_C)_{max} = \frac{(\alpha_p - \alpha_n)^2 T_C^2}{2KR} = 1/2\, ZT_C^2$	(4)
	$Z = \frac{(\alpha_p - \alpha_n)^2}{KR}$	(5)
Numerical determination by energy conservation		
	$q_H = SIT_H - K(T_H - T_C) + \frac{1}{2}I^2R = \frac{T_H - T_\infty}{\Psi_H}$	(6)
	$q_C = SIT_C - K(T_H - T_C) - \frac{1}{2}I^2R = \frac{T_\infty - T_C}{\Psi_C + \Psi_{ins}}$	(7)
Modification of energy conservation using G-factor		
	$q_H = 2N\alpha IT_H - 2NkG(T_H - T_C) + \frac{I^2N}{G}\left(\rho + \frac{2\rho_c}{L}\right) = \frac{T_H - T_\infty}{\Psi_H}$	(8)
	$q_C = 2N\alpha IT_C - 2NkG(T_H - T_C) - \frac{I^2N}{G}\left(\rho + \frac{2\rho_c}{L}\right) = \frac{T_\infty - T_C}{\Psi_C + \Psi_{ins}}$	(9)
Modification of energy conservation using the fill-factor and leg length		
	$q_H = 2N\alpha IT_H - \frac{kA_{mod}FF}{L}(T_H - T_C) + \frac{1}{2}I^2\left(\frac{4N^2L\rho}{A_{mod}FF} + \frac{4N\rho_c}{A_c}\right) = \frac{T_H - T_\infty}{\Psi_H}$	(10)
	$q_C = 2N\alpha IT_C - \frac{kA_{mod}FF}{L}(T_H - T_C) - \frac{1}{2}I^2\left(\frac{4N^2L\rho}{A_{mod}FF} + \frac{4N\rho_c}{A_c}\right) = \frac{T_\infty - T_C}{\Psi_C + \Psi_{ins}}$	(11)

equation (3). In reality, there will always be heat gained from parasitic heat transfer from the environment when the cold side of the module is maintained at a lower temperature than ambient temperature. Therefore, there will always be heat transfer at the cold side of the module, and the maximum temperature difference occurs when the parasitic heat transfer is equal to the heat transfer at the cold side of the module. Hence, the traditional optimum working conditions are deemed inadequate for the purposes of analyzing a thermoelectric refrigerator, where the consideration of parasitic heat transfer is crucial (see Table 1).

In order to avoid the assumptions made in the traditional method, energy conservation equations must be used to determine the temperature on each side of a module used in thermoelectric refrigeration. Energy conservation equations can be derived by matching the heat transfer on each side of the thermoelectric module. The heat transferred through the module can be modeled based on the system shown in Fig. 1. While the heat transfer on the cold side of the module is matched with the parasitic heat transfer into the refrigerator, the heat transfer on the hot side of the module is matched with the heat dissipated through the heat sink (equations (6) and (7) in Table 1). The energy conservation equations are functions of the module properties and system parameters [5]. The module properties can be defined with material properties and module geometries:

$$S = 2N\alpha \tag{12}$$

$$K = \frac{2NkA_c}{L} \tag{13}$$

$$R = \frac{2N\rho L}{A_c} + \frac{4N\rho_c}{A_c} \tag{14}$$

where N is the number of pairs of negative and positive legs in the module, α is the average absolute Seebeck coefficient of the n-type and p-type legs (½$(\alpha_p - \alpha_n)$), k is the thermal conductivity of the leg material, A_c is the cross-sectional area of one thermoelectric leg, L is the leg length, ρ is the electrical resistivity of the leg material, and ρ_c

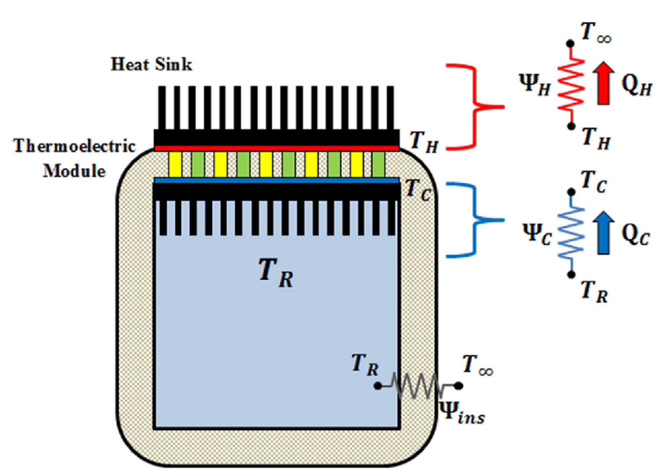

Fig. 1. A schematic of the heat transfer in a thermoelectric refrigerator. Ψ_H is the thermal resistance on the hot side of the module, Ψ_C is the thermal resistance on the cold side of the module, and Ψ_{ins} is the thermal resistance of the refrigerator's insulation.