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Hybrid Operating Modes of Thermoelectric Modules

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It is suggested that thermoelectric coolers designing should not be limited to the extreme modes of their operation. In some cases, it is convenient to use the so called hybrid modes — a combination of the extreme mode of maximum coefficient of performance for large temperature differences and a general cooling mode for small ones. The proposed hybrid mode makes it possible to control the cooling capacity of the module and not to confine this value to that under the extreme operating conditions, the maximum coefficient of performance in particular.

Keywords: Thermoelectric module, hybrid mode, cooling capacity per pellet.

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1. Introduction

In a steady-state operation of a thermoelectric module two modes are commonly used: the mode of the maximum coefficient of performance (COP) $\varepsilon_{\max}$ and the mode of the maximum cooling capacity $Q_{0\max}$ [1,2]. The key difference of these modes is electric current value. However, the mode of the module operation determines the design of the heat sink on its hot side, therefore the changing of the operating mode does not only involve the tuning of the current, but requires redesigning of the heat sink. Such relation between the operating modes of the module and its design means that it is not always reasonable to be limited to these two extreme modes. It is especially noticeable in the $\varepsilon_{\max}$ mode as the temperature difference ΔT on the module approaches 0. In this case, although the COP ε grows inversely proportional to ΔT, the cooling capacity $Q_{0\varepsilon}$ tends to 0 in proportion to ΔT.

In the $Q_{0\max}$ mode at $\Delta T \to 0$ the value $\varepsilon \to 0.5$, and the cooling capacity approaches the maximal value $Q_{\max}$ in this mode.

This paper considers the so-called *hybrid* operating modes of a thermoelectric module and shows possible areas of their application.

2. Hybrid Modes Investigation

The main task in thermoelectric cooling is to ensure the specified value of Q_0 at the given value ΔT [3]. In the extreme modes the module current is determined by ΔT, the geometry of the pellets and their thermoelectric characteristics, whereas the required value of Q_0 is provided by the number of pellets in the module. In Fig. 1 the curves Q_0 give an idea of the cooling capacity of a thermoelectric pellet in the extreme modes in the units of $Q_{\max}$.

From Fig. 1 we see that as the temperature difference across the module decreases, the discrepancy between the values Q_0 in the mode $\varepsilon_{\max}$ and $Q_{0\max}$ grows. In this case, the ratio $Q_{0\varepsilon\max}/Q_{0\max}$ approaches zero as ΔT decreases. To provide the required cooling capacity of the module at $\Delta T \to 0$ in the $\varepsilon_{\max}$ mode, the number of pellets in the module should evidently tend to infinity. Regarding this, the $Q_{0\max}$ mode is significantly better; however, the power consumption and heat rejection will be significantly higher than in the mode $\varepsilon_{\max}$.

Let us consider the hybrid operation modes of a pellet, providing Q_0 in the interval between the cooling capacities in the modes $\varepsilon_{\max}$ and $Q_{0\max}$. Since there are no extreme conditions, they can be replaced by any other. For example, the desired dependences can be set as:

$$\varepsilon = f(\Delta T), \tag{1}$$

i.e. the mode of a given coefficient of performance. You can also set the desired cooling capacity:

$$Q_0 = Q_{\max}\phi(\Delta T). \tag{2}$$

In Eq. (1) and (2) $f(\Delta T)$ and $\phi(\Delta T)$ are arbitrary dimensionless functions and $Q_{\max}$ is the maximum cooling capacity of a pellet:

$$Q_{\max} = \frac{\alpha^2 T^2}{2R}. \tag{3}$$

Of course, these functions must satisfy the conditions:

$$\varepsilon_{\max}(\Delta T) \geq f(\Delta T) \geq \varepsilon_{Q_0\max}(\Delta T), \tag{4}$$

$$Q_{0\max}(\Delta T) \geq Q_{\max}\phi(\Delta T) \geq Q_{\varepsilon\max}(\Delta T), \tag{5}$$

where $\varepsilon_{Q_0\max}(\Delta T)$ is COP in the mode $Q_{0\max}$, and $Q_{\varepsilon\max}(\Delta T)$ is the cooling capacity in the mode $\varepsilon_{\max}$.

Let us consider Q_0 and ε under condition (1). The heat rate equation at the cold end of the pellet with temperature T_0:

$$\alpha I T_0 - \frac{1}{2} I^2 R - K\Delta T = Q_0, \tag{6}$$

where α is the Seebeck coefficient of a pellet, I is electric current, R is electric resistance, K is thermal conductance of the pellet, Q_0 is the pellet cooling capacity.

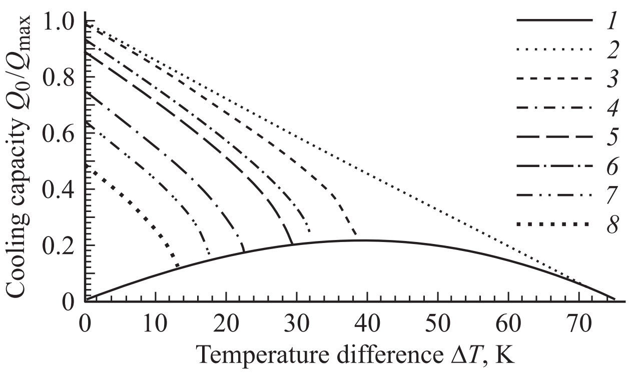

Figure 1. Dependence of the ratio Q_0 to Q_{max} at $Z = 0.003\,K^{-1}$ for the extreme and hybrid modes at varying ε: *1* — mode ε_{max}; *2* — mode $Q_{0\,max}$; $\varepsilon = 0.6$ (*3*), 0.85 (*4*), 1 (*5*), 1.5 (*6*), 2 (*7*), 3 (*8*).

Using the definition of COP $Q_0 = \varepsilon(IR + \alpha\Delta T)I$ [1], substituting in Eq. (6) the corresponding value and solving Eq. (6) with given values ΔT, $f(\Delta T)$ and the hot side temperature T we obtain:

$$I = I_{q\,max}F, \tag{7}$$

where $I_{q\,max}$ is electric current in the mode $Q_{0\,max}$ at $\Delta T = 0$:

$$I_{q\,max} = \frac{\alpha T}{R}, \tag{8}$$

and the factor F is equal to

$$F = \frac{1 - (\Delta T/T)\big(1 + f(\Delta T)\big)}{1 + 2f(\Delta T)} \times \left[1 + \sqrt{1 - \frac{\Delta T}{T}\,\frac{2\big(1 + 2f(\Delta T)\big)}{ZT\Big(1 - (\Delta T/T)\big(1 + f(\Delta T)\big)\Big)^2}}\right], \tag{9}$$

where Z is Figure-of-Merit $Z = \frac{\alpha^2}{RK}$.

The cooling capacity Q_0 equals:

$$Q_0 = 2Q_{max}\varepsilon[F^2 + (\Delta T/T)F]. \tag{10}$$

The root in expression (9) turns into 0 at the values $f(\Delta T)$ corresponding to the maximum COP, because the values $f(\Delta T)$ exceeding ε_{max} for a given $\Delta T/T$, do not make sense in accordance with inequation (4).

Expressions (9) and (10) are valid not only for a pellet, but also for couple, if $I_{q\,max}$, Q_{max} and ZT mean the corresponding values for the pair of pellets.

As an example, let us take the case $f = \text{const}$. The results calculated by formula (10) for different values ε are shown in Fig. 1.

The figure shows that the calculated curves for the hybrid modes branch from the curve $\varepsilon_{max}(\Delta T)$. The second reference point for the curves, at $\Delta T = 0$ and the corresponding value of F, is the cooling capacity Q_{00}, the value of which can be obtained from Eq. (10):

$$Q_{00} = Q_{max}\frac{8\varepsilon}{(2\varepsilon + 1)^2}. \tag{11}$$

Fig. 1 also shows that the calculated curves cover the entire range of values Q_0 between $Q_{0\varepsilon\,max}$ and $Q_{0\,max}$. Therefore, for temperature differences larger than $\Delta T_{\varepsilon\,max}$, where $\Delta T_{\varepsilon\,max}$ corresponds to the temperature difference at which the maximum is reached on the cooling capacity curve in the mode of maximum COP the cooling capacity coincides with $Q_{0\varepsilon\,max}$, and when $\Delta T < \Delta T_\varepsilon$ max, the expression for the cooling capacity is given by general Eq. (10).

Fig. 2 shows the corresponding dependences of COP for extreme and hybrid modes of the operation. It proves that the use of hybrid modes can significantly increase the cooling capacity for small temperature differences, while keeping ε at an acceptable level.

Let us consider the operation of a pellet in the mode of a given cooling capacity (2). It is this approach that allows us to solve the problem with insufficient cooling capacity in the mode ε_{max} and to provide the pellet operation at $\varepsilon < \varepsilon_{max}$, but with quite a higher cooling capacity. In this case the factor F instead of (9) is given by F_1:

$$F_1 = \frac{T_0}{T}\left(1 - \sqrt{1 - \frac{2}{ZT_0^2}\left(\Delta T + \frac{Z}{2}T^2\phi(\Delta T)\right)}\right). \tag{12}$$

Let us take the simplest case when ϕ depends on ΔT linearly. Let the maximum cooling capacity in the mode of the maximum COP be Q_{0m} and correspond to ΔT_m and the cold side temperature T_{0m}. If the Figure-of-Merit $Z = 0.003\,K^{-1}$ the value $\Delta T_m = 39.61$ K and $Q_{0m} = 0.212159\,Q_{max}$. The

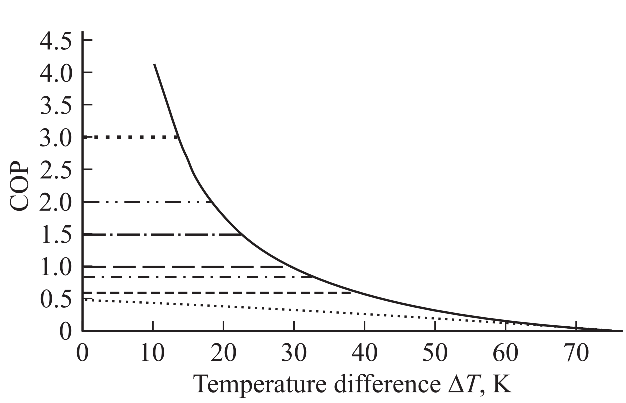

Figure 2. The dependences of COP ε for $Z = 0.003\,K^{-1}$ on temperature difference for the extreme and hybrid modes with a fixed value ε. For the temperature differences to the right from the intersection of the curves the mode ε_{max} is applied, and to the left — the mode of the fixed ε. The designations are the same as in Fig. 1.

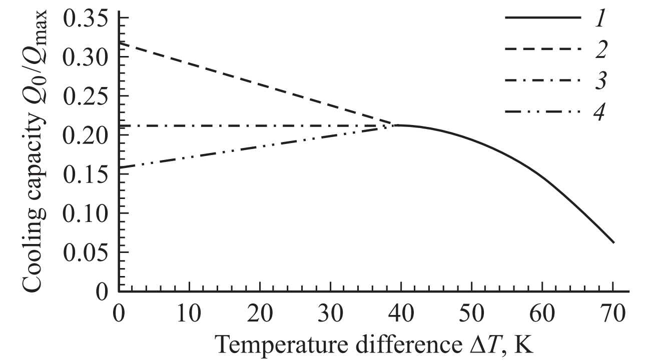

Figure 3. The cooling capacity in the units $Q_0/Q_{\max}$ for $\Delta T > \Delta T_{\varepsilon\max}$ in the mode of the maximum COP, and for $\Delta T < \Delta T_{\varepsilon\max}$ in the mode of linearly varying cooling capacity at $Z = 0.003\,\mathrm{K}^{-1}$. The operation modes: *1* — the mode of $\varepsilon_{\max}$; *2* — $Q_0 = 1.5Q_{0m}$, *3* — $Q_0 = Q_{0m}$, *4* — $Q_0 = 0.85Q_{0m}$.

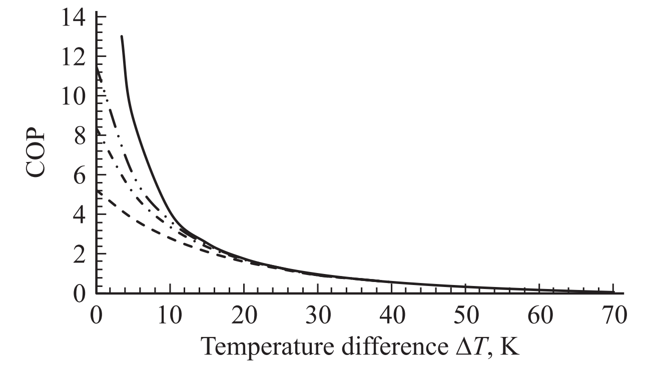

Figure 4. COP for different cooling conditions. The designations are the same as in Fig. 3.

expression ϕ becomes the following:

$$\phi = \frac{Q_{0m}}{Q_{\max}}\left(1 + k\left(1 - \frac{\Delta T}{\Delta T_m}\right)\right), \tag{13}$$

where k is some coefficient of proportionality. From Eq. (13) it follows that at $\Delta T = 0$, $Q_{00} = Q(1+k)_{0m}$, which makes it possible to easily calculate COP at $\Delta T = 0$ by Eq. (11). At $k = 0$ the value Q_{0m} does not depend on temperature and equals $0.212159\,Q_{\max}$ in our case.

For case (13) the expression for F_1 allowing for $Q_{0m} = Q_{\max}\frac{\Delta T_m}{T^2}\frac{2(M_mT_{0m} - T)M_m}{(M_m+1)(M_m-1)^2}$ [1,3], has the form:

$$F_1 = \\ = \frac{T_0}{T}\left(1 - \sqrt{1 - \frac{2}{ZT_0^2}\left(\Delta T + \frac{\left(1+k(1-\Delta T/\Delta T_m)\right)Z\Delta T_m(M_mT_{0m}-T)M_m}{(M_m+1)(M_m-1)^2}\right)}\right), \tag{14}$$

where $M_m = \sqrt{1 + Z\left(T_m + \frac{\Delta T_m}{2}\right)}$, and COP for $\Delta T < \Delta T_m$:

$$\varepsilon = \frac{\Delta T_m(M_mT_{0m} - T)M_m\left(1 + k(1 - \Delta T/\Delta T_m)\right)}{T^2\left(F_1^2 + \frac{\Delta T}{T}F_1\right)(M_m+1)(M_m-1)^2}, \tag{15}$$

and electric current is $I = I_{q\max}F_1$.

The calculated results are given in Fig. 3 and 4.

From Fig. 3 and 4 we see that the mode of the given cooling capacity supplements the mode of the given cooling coefficient and provides wider possibilities for cooling in the area $\Delta T < \Delta T_m$.

3. Conclusion

The proposed hybrid mode makes it possible to control the cooling capacity of a pellet (module) without relating this value to the values under the extreme operating conditions. It is useful when designing modules to operate at low temperature differences.

Moreover, hybrid modes make us free in choosing the value ε. That can be useful for the optimization of the design by some other parameters, for example, by weight, dimensions or cost.

Conflict of interest

The authors declare that they have no conflict of interest.

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