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A review of thermoelectric cooling: Materials, modeling and applications

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HIGHLIGHTS

- Thermoelectric cooling has great prospects with thermoelectric material's advances.
- Modeling techniques for both thermoelement and TEC have been reviewed.
- Principle thermoelectric cooling applications have been reviewed and summarized.

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ABSTRACT

This study reviews the recent advances of thermoelectric materials, modeling approaches, and applications. Thermoelectric cooling systems have advantages over conventional cooling devices, including compact in size, light in weight, high reliability, no mechanical moving parts, no working fluid, being powered by direct current, and easily switching between cooling and heating modes. In this study, historical development of thermoelectric cooling has been briefly introduced first. Next, the development of thermoelectric materials has been given and the achievements in past decade have been summarized. To improve thermoelectric cooling system's performance, the modeling techniques have been described for both the thermoelement modeling and thermoelectric cooler (TEC) modeling including standard simplified energy equilibrium model, one-dimensional and three-dimensional models, and numerical compact model. Finally, the thermoelectric cooling applications have been reviewed in aspects of domestic refrigeration, electronic cooling, scientific application, and automobile air conditioning and seat temperature control, with summaries for the commercially available thermoelectric modules and thermoelectric refrigerators. It is expected that this study will be beneficial to thermoelectric cooling system design, simulation, and analysis.

1. Introduction

Thermoelectric cooling, commonly referred to as cooling technology using thermoelectric coolers (TECs), has advantages of high reliability, no mechanical moving parts, compact in size and light in weight, and no working fluid. In addition, it possesses advantage that it can be powered by direct current (DC) electric sources, such as photovoltaic (PV) cells, fuel cells and car DC electric sources. The main disadvantages of thermoelectric cooling are the high cost and low energy efficiency, which has restricted its application to cases where system cost and energy efficiency are less important than energy availability, system reliability and quiet operation environment. Though thermoelectric cooling effect was discovered in the 19th century, it hadn't come to rapid development until 1950s when the basic science of thermoelectric materials became well established [1].

Thermoelectric module is a solid-state energy converter that consists of a bunch of thermocouples wired electrically in series and thermally in parallel. A thermocouple is made of two different semiconducting thermoelements, which generate thermoelectric cooling effect (Peltier–Seebeck effect) when a voltage in appropriate direction applied through the connected junction. Thermoelectric module generally works with two heat sinks attached to its hot and cold sides in order to enhance heat transfer and system performance. For a specific module and fixed hot/cold side temperatures, there exists an optimum current for maximum

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Nomenclature

A	cross-sectional area, m^2
COP	coefficient of performance
C_p	heat capacity, J kg^{-1} K^{-1}
E	electric field, V m^{-1}
f	thermoelectric module packing fraction covered by thermoelement
h	convective heat transfer coefficient, W m^{-2} K^{-1}
I	electric current, A
j	electric current density, A m^{-2}
k	thermal conductivity, W m^{-1} K^{-1}
K	thermal conductance, W K^{-1}
l	thermoelementlength, m
N	number of thermocouples
P	electrical power supply, W
q	energy in thermoelement scale, W
Q	energy in thermoelectric module scale, W
R	electrical resistance, Ω
t	time, s
T	temperature, °C
x	length, m
X	slenderness ratio
ZT	dimensionless figure-of-merit

Greek symbols

α	Seebeck coefficient, V K^{-1}
β	ratio of the Thomson heat to the thermal conduction
ΔT	temperature difference between hot and cold sides, K
ε	emissivity
φ	ratio of temperature difference to the hot side temperature
θ	non-dimensional temperature
ξ	non-dimensional length
ρ	electrical resistivity, Ω m
ρ	density, kg m^{-3}
γ	combination heat transfer coefficient of radiation and convection in Eq. (8) W m^{-2} K^{-1}
γ	ratio of the Joule heating to the thermal conduction in Eq. (12)
σ	electrical conductivity, S m^{-1}
σ_b	Stefan–Boltzman constant, 5.67 × 10^{-8} W m^{-2} K^{-4}
τ	Thomson coefficient, V K^{-1}
ϕ	electric scalar potential, V

Subscripts

c	cold side
con	conduction
e	thermoelement
h	hot side
m	mean/average
max	maximum
n	n-type thermoelement
p	constant pressure
p	p-type thermoelement
∞	ambient

Overbar

	temperature independent value

coefficient of performance (COP) as shown in Eq. (1) [2]. Fig. 1 shows the cooling COP variation of a thermoelectric module under optimum current with fixed hot side temperature of 300 K.

$$(\mathrm{COP})_{\mathrm{c,\,max}} = \frac{T_\mathrm{c}}{T_\mathrm{h} - T_\mathrm{c}} \frac{\sqrt{1 + ZT_\mathrm{m}} - \frac{T_\mathrm{h}}{T_\mathrm{c}}}{\sqrt{1 + ZT_\mathrm{m}} + 1} \tag{1}$$

where, ZT_m is the thermoelectric material figure-of-merit at average hot and cold side temperature T_m.

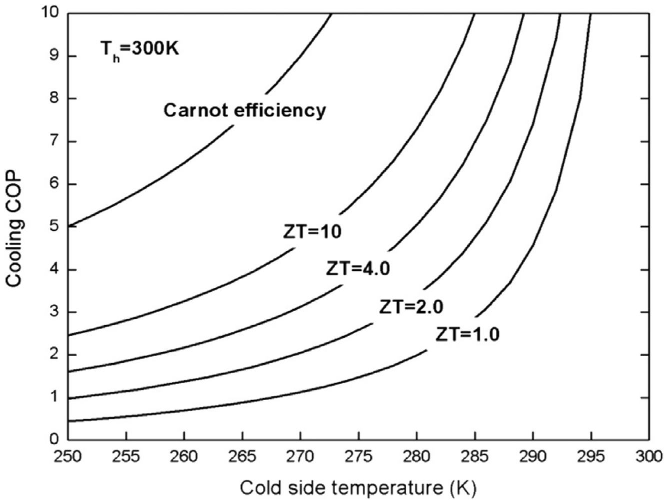

Fig. 1. Cooling COP of a thermoelectric module under optimum electrical current with fixed hot side temperature of 300 K.

Besides its applications in military, aerospace, industrial and scientific work, thermoelectric cooling is gradually getting more involvement into people's daily life. Thermoelectric cooling devices are widely used for electronic cooling such as PC-processors, portable food & beverage storages, temperature-control car seats and even thermoelectric air-conditioners. Scientific community has placed huge amount of efforts on thermoelectric cooling research.

There are good review papers on thermoelectric technologies and applications, including modeling and analysis of thermoelectric modules [3], solar-based thermoelectric technologies [4], cooling, heating, generating power, and waste heat recovery [5,6]. Riffat and Ma [2] presented a review of COP improving for thermoelectric cooling systems in 2004. Recent research provides two possible paths that may lead to significant progress in thermoelectric cooling [4]: 1) to improve the intrinsic efficiencies of thermoelectric materials, and 2) to improve thermoelectric cooling system's thermal design and optimization based on currently available thermoelectric modules. This review work focuses on the development of thermoelectric cooling in recent decade with particular attention on advances in materials, modeling and optimization approaches, and applications.

2. Development of thermoelectric materials

Reviews have summarized progress on thermoelectric materials [7–10], bulk thermoelectric materials [11,12], and low-dimensional thermoelectric materials [1,13–15].

As shown by the primary criterion of merit $ZT = \alpha^2\sigma T/k$, a good thermoelectric material should have high Seebeck coefficient, high electrical conductivity (or high power factor), and low thermal conductivity. However, since these three parameters are interrelated, following the Wiedemann–Franz law [16], researches have to