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热电制冷的应用与优化综述

吴 雷 高 明 张 涛 周媛媛

(南京理工大学能源与动力工程学院 南京 210094)

摘 要 热电制冷(TEC)是以温差电现象为基础的制冷方式,是基于帕尔贴效应的固态环保型制冷技术。与其他制冷方式相比,热电制冷具有体积小、结构简单、可靠性高、制冷迅速等优点。本文通过研究国内外的相关文献,主要从热电制冷的应用及性能优化两方面综述了热电制冷近年来的研究进展和成果。对热电制冷在热电冰箱、热电空调和电子器件冷却等方面的应用及相关研究进行了归纳分析,并对热电制冷与太阳能、蒸气压缩以及蒸发冷却等复合系统应用进行了分析阐述。在热电制冷性能优化方面,总结了在材料已定时提升热电制冷的性能优化方法,包括热电制冷器结构、工作参数及热端散热等,并在工作参数优化过程中分析了近年来研究较多的脉冲电流研究进展。

关键词 热电制冷;性能优化;复合系统;散热;脉冲电流

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Thermoelectric Cooling Application and Optimization: A Review

Wu Lei Gao Ming Zhang Tao Zhou Yuanyuan

(School of Energy and Power Engineering, Nanjing University of Science and Technology, Nanjing, 210094, China)

Abstract Thermoelectric cooling is a type of solid-state, environmentally friendly cooling technology based on thermoelectric phenomenon. The thermoelectric cooling system has advantages over other refrigeration methods including small volume, simple structure, high reliability, rapid cooling, and simple operation. This study reviewed recent advances in thermoelectric cooling from two main aspects: thermoelectric cooling applications and performance optimization. In this study, developmental history, principle, characteristics, and research direction of thermoelectric cooling were briefly introduced. Next, thermoelectric cooling applications were summarized, including the application of thermoelectric refrigerators, thermoelectric air conditioning, heat dissipation of electronic devices, and a composite system, particularly for thermoelectric cooling using solar energy and other cooling systems in the composite system. Finally, to improve a thermoelectric cooling system's performance, many optimization methods have been described, including the structure of a thermoelectric cooler, working parameters, and hot end heat exchangers. In addition, the research progress of pulse currents has been added to working parameters. It is expected that this study will be beneficial to thermoelectric cooling system application and optimization.

Keywords thermoelectric cooling; performance optimization; composite system; heat dissipation; pulse current

热电制冷(TEC)完全不同于蒸发压缩式制冷和吸收式制冷,是以温差电现象为基础的制冷方式,是帕尔贴效应(Peltier effect)在制冷方面的应用,可以直接将电能转化为温度梯度从而进行制冷[1]。

热电制冷最早始于 19 世纪,德国科学家赛贝克发现不同导体接头处存在温差时会产生电势——赛贝克效应(Seebeck effect)。而后帕尔贴又发现不仅温差会产生电势,电势也会产生温差的帕尔帖效应,由此开始了热电制冷的研究。随后,热力学创始人之一的汤姆逊从理论方面展开了对于热电制冷的研究,发现了影响热电制冷的另一种可逆的汤姆逊效应(Thomson effect)。热电制冷由这 3 种可逆效应和不可逆的焦耳效应(Joule effect)及傅里叶效应(Fourier effect)组成[2]。

热电制冷的原理如图 1 所示。热电制冷器内部由多对 P、N 型半导体联结的热电偶组成。受帕尔贴效应影响,通电情况下热电偶会产生一端吸热,另一端放热的现象。这种热电制冷器具有体积小、结构简单、可靠性高、制冷迅速和操作简单等优点[3],但也存在制冷效率低的问题,同时对于材料的高度依赖性、制造成本高等因素也制约了其发展。

近年来,热电制冷除了应用于军工、航天、医

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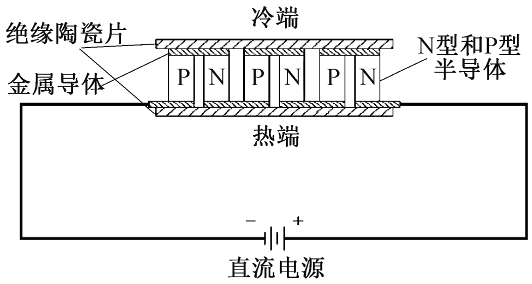

图 1 热电制冷原理

Fig.1 The principle of thermoelectric cooling

疗[4-5]以及科学研究等传统方面,也逐渐与人们的生活变得越来越密切,越来越多的热电制冷被研究用于商业化的汽车[6]、冰箱[7]、空调[8]等方面。

对于热电制冷的研究,目前主要集中在高优值系数(ZT)热电材料的研究与制造、基于已定热电材料的性能优化及应用推广[9-10]等方面。尽管近年来热电材料已有较多的研究成果,使优值系数有了相应提高,但一些高优值系数的材料目前仍处于实验室阶段,存在复制和大规模制造困难等问题,商业化的高优值系数材料依然有待发展[11]。因此如何对现有的热电材料进行优化和应用,挖掘其"潜力",成为具有现实意义的重要研究方向。本文从近些年热电制冷的应用和优化两方面出发,对热电制冷的研究进展进行了相应的分析总结,希望可以为热电制冷在实际应用中的推广及其性能提升提供参考和帮助。

1 热电制冷的应用

随着电子器件的不断发展以及人们对于高品质生活的追求,热电制冷以其体积小、重量轻、控温准确以及制冷迅速等优势,在生产生活的各领域应用越来越广泛[12-13]。为发挥热电制冷的优势及弥补制冷效率低的问题,近年也形成了很多热电制冷与其他系统复合的形式。复合系统的出现及材料性能和制造技术的不断提升,使得大功率的热电制冷模块阵列在大型负荷场所也得到越来越多的应用。

1.1 热电冰箱

在家用热电冰箱领域,D. Astrain 等[14-15]采用新型热管散热,以优化散热方式提高了热电冰箱的 COP。后针对热电冰箱制冷效率低和蒸气压缩式温度波动大的缺点,又提出并改进了一种热电制冷与蒸气压缩式相结合的混合式冰箱[16-17],该冰箱既能精准控制冰箱内部温度又有较高的 COP,对高级食材和药物的保存起到了较好的帮助。在户外旅行和汽车领域,Dai Y. J. 等[18-19]利用普通电池和太阳能光伏电池都能直接供电的特性,对太阳能电池驱动的便携式热电冰箱进行了实验和理论研究,并改善了其应用性能。S. A. Abdul-Wahab 等[20]设计制造了一台便携式热电冰箱并对其进行了性能检测,结果表明热电冰箱的制冷速度很快,但 COP 仅约为 0.16。在医疗领域,对于疫苗、血清以及其他生物产品的运输和保存有着严格的温度控制要求,对此 He Rongrong 等[21]研制了一种便携式热电制冷冰箱,该热电冰箱既能够稳定的保持药物所需温度,也具有较好的便携性,相比传统制冷冰箱优势显著。

1.2 热电空调

S. B. Riffat 等[22]就热电空调与传统的蒸气压缩式空调、吸收式空调进行对比,结果表明热电空调制冷 COP 仅在 0.38~0.45 范围内,远低于传统空调。Shen Limei 等[23-24]为提升热电空调的性能,先后提出并改进了一种热电辐射空调系统(TE-RAC)。主要以热电模块阵列作为辐射板来代替传统的水合板,改进后的热电辐射空调制冷 COP 能够达到 0.78~1.07,相比传统热电空调有了很大改善。Á. G. Miranda 等[6]对电动汽车用的热电空调进行了可行性研究,以热电模块为负载、太阳能电池为可再生能源、高功率锂离子电池为储能装置设计了一套热电空调系统。A. Attar 等[25]指出使用热电空调系统可以灵活冷却指定区域,而非所有空间,能够有效降低由于热电空调 COP 低所导致的电能浪费。此外他们还对汽车用热电空调进行了优化设计和实验验证[26],模拟与实验结果也表明优化后车用热电空调制冷 COP 能够达到 1.7。

在热电空调的舒适性方面,K. Irshad 等[27-28]对热电风管空调系统(TE-AD)进行了研究,结果表明在热带气候地区,热电风管空调系统在舒适性方面显示出了对于传统空调的良好替代性。在此基础上 K. Irshad 等[29]研究了在房间外墙的南面设立太阳能与 TE-AD 相结合的空调系统,结果表明该系统可有效降低室内热负荷,提高系统制冷功率及 COP,为建筑节能提供了有利条件。

1.3 电子设备冷却

在电子设备的冷却方面,S. O. Tan 等[30]研究表明电脑在热电冷却下的性能优于空冷和水冷,对其温度测定结果也表明热电冷却下的电脑温度平均约为 33 ℃,远低于其他冷却方式的下平均温度。Liu Di 等[31]将微型热电制冷器与微型热管相结合用于 CPU 的散热,有效抑制了 CPU 功率过大时温度的大幅上升。扶新等[32]将热电制冷用于 CPU 散热时考虑了结露问题,并对热电制冷器的冷量控制进行了设计。在半导体激光器的温度控制方面,Zhang Wei 等[33]指

出激光器的性能与其热控制系统关系密切,在不使用热电制冷器降温的情况下,激光器内光学芯片的温度会高达 227 ℃,而热电制冷器的应用能够有效地将芯片温度控制在 30~40 ℃,使得激光器能够更稳定、更高效的工作。根据国内医疗成像的实际问题,傅明星等[34-38]研制了一套热电制冷摄像机,通过热电制冷器为成像器件创造了恒定的低温环境,有效提高了摄像器件的信噪比及摄像机品质。

在微电子领域,传统块状热电制冷器体积较大,与微电子制造工艺不兼容,这使其应用受到很大限制。而平面薄膜热电制冷器[39]的出现,以其微型化特性及与标准集成电路(IC)的良好兼容性,被广泛的集成到了微电子电路中。Su Yu 等[40]对用于芯片冷却的薄膜热电冷却器进行了实验与模拟研究,分析了接触电阻和热阻对其性能的影响。刘光裕[41]基于通信用激光器的散热,研究了一款薄膜热电制冷器,以控制激光器的内部温度。刘向阳等[42-43]基于热电材料的进步,分别对小型、微型热电器件的研究和应用进行了总结,为热电制冷的相关研究提供了帮助。

1.4 热电复合系统

1.4.1 热电制冷与太阳能

太阳能作为一种长效清洁能源与热电制冷系统相结合具有非常好的季节和昼夜匹配性。且太阳能可以解决热电制冷的电源问题,热电制冷也可以提高光伏发电效率。所以各种热电制冷与太阳能形成复合系统的应用越来越广。

S. Soltani 等[44-45]发现光伏电池板的发电效率受面板温度影响很大,随着面板温度的升高,光伏组件的输出功率下降,且电池退化加速,降低了光伏组件的效率和寿命。因此,A. Kane 等[46]设计研究了用于降低光伏发电腔温度的热电制冷器,结果表明在一定温度和光照范围内,该装置能有效提高发电能力、延长光伏组件寿命。

Liu Zhongbing 等[47]在零耗能建筑的研究中指出太阳能热电辐射空调系统和太阳能蓄能空调系统的 COP 分别可达 1.90 和 1.22,均优于常规热电制冷系统。Shen Limei 等[48]在零耗能建筑的研究中将热电制冷(TEC)和热电发电(TEG)与太阳能相结合,TEC 用于热电辐射顶板和一次空气处理装置中,为室内提供良好的热舒适和新鲜空气,TEG 则与太阳能光伏电池板相结合,用于改善发电效率。在电源方面,M. A. Muñoz-García 等[49]利用太阳能驱动热电制冷模块进行冷凝集水,用于干旱地区幼树的灌溉方面。热电制冷与太阳能复合系统还包括太阳能热电制冷背包[50]及太阳能热电冰箱等。

1.4.2 热电与蒸气压缩式复合制冷系统

陈波等[51-52]提出利用热电制冷来提高蒸气压缩式制冷系统的过冷度,降低节流损失,从而提高系统的整体制冷性能。在与家用空调的复合制冷系统方面,金听祥等[53]研究表明用热电制冷器提高冷凝器出口的过冷度,可以明显提高系统的制冷量和系统性能系数。J. Sarkar 等[54-55]在提升 CO_2 跨临界制冷性能的研究中指出,在 CO_2 制冷系统中使用热电制冷器进行过冷,不仅可以提高制冷 COP 和系统的容积冷却能力,还能降低系统的高侧压力、压缩机压力比和压缩机排气温度。S. Jamali 等[56]对热电与跨临界 CO_2 复合制冷系统进行了优化改进,利用两级热电发电机从气体冷却器的余热中产生电能。与简单的 CO_2 制冷循环对比表明,该复合系统的 COP 提高约 19%。

1.4.3 热电与蒸发冷却复合制冷系统

蒸发冷却是一种高效、经济和环保的冷却方式,在空气调节方面有着非常广泛的应用,但蒸发冷却在温和潮湿环境中,冷却能力受到很大限制。且外界空气条件不稳定时,单一的蒸发冷却不能保证性能的稳定。孙哲等[57]提出将蒸发冷却与热电制冷相结合的复合制冷系统,并对蒸发冷却与半导体制冷相结合的分体式蒸发空调器进行了实验研究。

孙哲等[58-59]指出通过蒸发冷却技术既可制取冷风也可制取冷水,但制取的空气和冷却水的温度只能理论上接近被处理空气的湿球温度或露点温度,不能满足较高需求场合的要求。而在热电与蒸发冷却复合系统中,通过热电制冷对蒸发冷却制取的冷水进一步冷却,即可达到较高温度要求。这种复合系统[60]的优势在于,热电制冷对蒸发冷却有着补充和辅助调节的作用,蒸发冷却制取的接近湿球温度的水可为热电制冷的热端进行散热,使热电制冷性能得到提升。

1.4.4 其他复合系统

在复合热泵系统中,Zhu Lin 等[61]将热电制冷器与空气源热泵相结合,通过热电冷却器的冷端进行制冷剂的过冷,热端作为辅助加热,充分利用热电模块的冷热能,有效提高了热泵机组的性能。在复合系统除湿领域,郑宇薇等[62]建立了热电制冷与固体除湿相结合的除湿装置,基于固体除湿剂的除湿特性,使热电制冷器的冷端温度可以不低于露点的温度进行除湿,且利用热端的热量帮助固体吸湿材料进行再生。复合系统也包括热电制冷与膜蒸馏相结合[63]、热电制冷与相变储热相结合[64]等多方面应用。

1.5 其他方面的应用

熔融材料的成型质量对温度的要求非常高,温度

较高则材料成型过程中易产生拉丝,而温度较低则容易干裂和变形。吕逸飞[65]将控温准确、冷热转换方便的热电制冷技术用于熔融材料温度的控制。等电聚焦装置(IEF)在科学研究中,特别是在蛋白质组学中有着广泛的应用。由于装置工作时会产生许多焦耳热,对蛋白质分离有不利影响,温度控制是 IEF 运行的关键。Hu H. M. 等[66]将热电制冷器应用于等电聚焦装置中,以达到快速、精确控制温度。为保证微纳米测量的准确性,蔡震[67]基于热电制冷研制了一套高精度温度控制系统,以控制温度的稳定。基于热电制冷具有体积小、工作稳定等特点,郭宗坤等[68-69]研制了一种基于热电制冷技术的除湿装置,用于改善电柜内湿度过高、凝露等问题。此外还有便携式淡水发生器[70]、饮料冷却器[71]、热电汽车座椅[72]、热电制冷头盔[73]等多方面的应用。

2 热电制冷性能优化

热电制冷的性能评判标准除决定材料的优值系数(ZT)外,还包括制冷量(Q_c)、制冷系数(COP)及冷端温度(T_c)等。由于热电优化一般不能使其整体性能同时达到最优[74],所以热电制冷优化通常是针对部分性能进行。本文也将从热电制冷的结构、工作参数及热端散热等方面阐述热电制冷的性能优化。

2.1 热电制冷结构优化

热电制冷器的核心是热电模块,而热电制冷的结构优化目前主要集中在热电模块内的 P、N 型热电元件及热电制冷器两部分,所以本文将从这两部分阐述热电制冷的结构优化。

热电元件的结构优化主要集中在热电元件的臂长(L)、面积(A)及对数等方面。Min Gao 等[75]通过模拟的方式,研究了热电元件臂长对于热电制冷的影响,结果表明,COP 会随热电元件 L 的减小而减小,而制冷量随 L 减小而逐渐增加,直到达到其最大值。K. Pietrzyk 等[76-79]对热电元件的几何因子 G($G=L/A$)、热电元件对数(N)以及 B 因子等进行了优化研究,以获得更低的冷端温度。Wang Tianhu 等[80]为提升热电制冷的整体性能,对热电制冷进行了较为完整的参数分析和优化设计,如两级热电模块中的臂长比($\lambda=L_1/L_t$)[81],P、N 型热电元件所占面积比($\varphi=A_p/(A_p+A_n)$),填充因子($\gamma=(A_p+A_n)/A_{pair}$)[82]以及两级热电对数比($\zeta=N_1:N_2$)[83-84]等。Lü Hao 等[85-86]研究了变截面的热电元件,以改进热电制冷的瞬态冷却,如图 2 所示。Lin Shumin 等[87]做了关于变截面的梯形热电元件优化研究,以获得更高的 COP 和更大的制冷量,值得注意的是此两级热电制冷模块没有中间陶瓷板存在,有效降低了两级间的热阻,如图 3 所示。

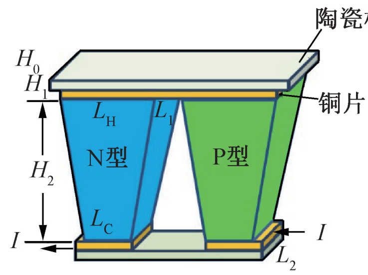

图 2 变截面热电元件

Fig.2 Variable section thermoelectric element

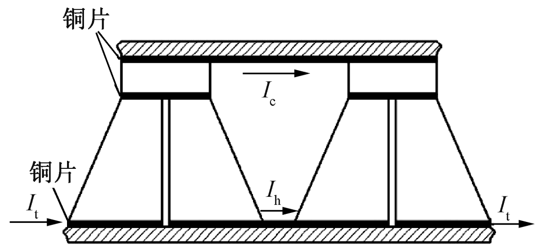

图 3 梯形热电偶

Fig.3 Trapeziodal thermocouple

热电制冷器结构优化,一部分集中在不同的级数和形式方面。因为不同级数的热电制冷器本身就是一种优化,H. Nami 等[88]综合热力学和经济学两方面对比了单级和两级热电制冷器,结果分析表明两级热电制冷器具有更大的能效和㶲效,能达到更大的温差,但单级热电的结构更简单,成本更低。在多级制冷器方面,G. Karimi 等[89]研究了热电制冷器级数(S)及热电对数比对于热电制冷性能的影响。结果表明靠近热端的热电元件对数越多越有利于热量的排出,可以达到的冷端温度也越低。考虑各级臂长对于排热量的影响,Yang Ronggui 等[90-91]对多级热电制冷器的各级臂长进行了相应研究,结果表明靠近热级的臂长越短越利于热端散热。为适应不同的应用,热电制冷器核心的热电制冷模块形状也包括了环形、波纹形和薄膜形等不同的结构形式[92-93]。

热电制冷器结构优化的另一部分主要集中在热电制冷器的热管理方面。为此许多学者对冷热端的热导分配比($x=K_hA_h/KA$)[94-97]、冷热端面积分配比($f=A_c/A_h$)[98-99]以及冷热两端热阻匹配(R_h/R_c)[100]等方面进行了优化研究,通过调节吸热量与排热量的平衡,使热电制冷器更高效运行。

2.2 工作参数优化

由于电流的增大不仅会使帕尔贴冷增加,也会使焦耳热增大,所以制冷量和 COP 并非一直随电流的

增加而增加。对于只有一个工作电源的情况,电流大小只存在一个最优电流 I_{opt},分别使 COP、制冷量或冷端温度最优。而对于分离电流,由于使用了两个或多个工作电流,所以系统最优工况是多个电流耦合作用的结果。

Xuan X. C. 等[101]对不同电流连接形式下的两级热电制冷模块,如串联[102]、并联[103]及分离电流[104]进行了研究,如图 4 所示。结果表明在相同几何结构下,串联电流比并联电流的最大温差更大,而通过将串联电流改为分离电流则可进一步提高最大温差。

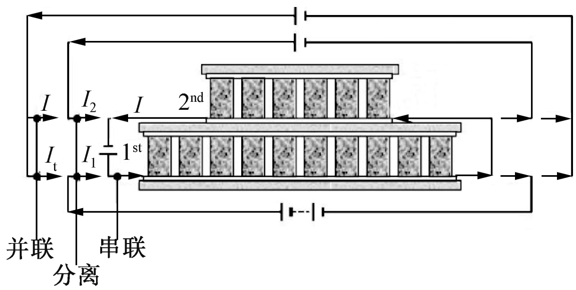

图 4 不同电流连接形式的两级热电模块

Fig.4 TTEC with different current connection forms

针对热电制冷的瞬态效应,越来越多研究人员[105-107]意识到施加脉冲电流相比于稳态操作可以获得更低的冷端温度,在较小冷热端温差下可以明显提高制冷效率等制冷强化作用。Lü Hao 等[105]对单级和两级热电制冷模块的脉冲电流影响进行了研究对比,结果表明相比于单级热电制冷器,两级热电制冷器在脉冲电流作用下得到的冷端温度更低,过冷持续的时间更长且引起的过冲也更小。对于脉冲电流的波形而言,Lü Hao 等[108-109]对 t^0、$t^{1/2}$、t^1、t^2、t^3、t^4、t^5 这 7 个波形的脉冲电流进行了深入研究,并指出最优的脉冲波形与多种因素有关,如到达最低冷端温度的时间 t_{min} 和脉宽 τ 等。Ma Ming 等[110-112]对脉冲电流的幅值(I_p)和脉宽(τ)进行了相关优化研究,尝试通过对脉冲电流参数的积极控制来提高瞬态过冷性能。由于过冷现象总是伴随着温度的过冲, Ma Ming 等[113-114]模拟了在脉冲电流或连续脉冲电流作用下热电模块的温度过冲特性。值得注意的是 Shen L. M. 等[115]指出,脉冲电流的幅值超过一定界限后将不会产生过冷效应,因为焦耳热影响会变得非常大,这也是热电制冷器无法通过脉冲电流无限制降低冷端温度的原因。

2.3 热端散热优化

热电模块冷热端温差的增大会使热电元件内的 Fourier 导热和 Seebeck 电势增加,对热电制冷性能产生很大的不利影响,所以优化热端散热,对降低温差、提升制冷性能至关重要。

2.3.1 翅片散热

翅片散热[116]是最普遍的一种热端散热方式,因形式简单、易于安装、价格低等优点被广泛用于各种实际应用和实验研究。Cai Yang 等[117-118]对用于电子器件冷却的翅片散热热电制冷器进行了相关研究,灵活的特性使其方便用于热电制冷器的热端。但该种散热方式的散热能力有限,且受环境温度影响非常大,所以常用于热流密度较小的场所。

2.3.2 循环流体散热

循环流体冷却散热方式[102]利用了液体具有较高热容的优点,在热电制冷的实验研究方面应用广泛。Huang H. S. 等[119-120]运用循环流体散热进行热电制冷的相关实验研究,通过调节流体温度和流速,研究了热端传热系数对于热电制冷性能的影响。这类散热方式虽然散热能力强、调节灵活,但其配套设施需要水泵、水箱、控制阀门、流体侧换热器等一系列设备,不利于实际应用。

2.3.3 高效散热器散热

热管是利用相变特性带走大量潜热的高效换热装置,近年来在热电制冷器热端散热方面的应用越来越广泛。Lee J. S. 等[121]通过实验与模拟的方法研究了热端热管散热效果,结果表明热端的传热系数可达 5 400 W/(m^2·K)。Shen Limei 等[24, 122]研究了热管对热电制冷器性能的影响,结果表明热管能够有效强化热端散热效果,整体提升了热电制冷性能。

微通道散热器是一类结构紧凑、轻巧、高效的换热器,具有单位体积传热效率高的特点。Chein R. 等[123-124]研究了将微通道用在热电制冷器的热端散热,结果发现对于体积小、热流密度大的热端散热有很好的效果,有效降低了热端热阻。

2.3.4 纳米流体散热

纳米流体是近年来较为热门的研究方向,主要是向水、醇等流体中加入一定的纳米粒子,以增加流体的导热性能,在强化散热领域有着非常广泛的应用。S. K. Mohammadian 等[125]为强化循环流体的换热,研究了纳米流体对热电制冷器性能的影响,结果表明在低 *Re* 下,在热交换器中加入低体积分数的纳米粒子,可显著提高热电模块的性能系数,降低总熵的生成。T. Yousefi 等[126]对使用了纳米流体的微型热管散热器的散热性能进行了研究,结果表明此类热管在体积缩小下,依然有较好的散热性能。N. Ahammed 等[127]通过纳米流体微通道换热器进一步强化了对

热电制冷器热端的散热作用。

2.3.5 相变材料(PCM)散热

Zhao Dongliang 等[128]提出通过相变材料(PCM)来降低工质温度,为热电制冷器热端散热的方法,也达到很好的热端散热效果。主要方式是使冷却工质通过相变材料形成的腔体,利用相变材料相变使工质降温,然后将此冷却后的工质供给热端进行散热[129]。对于相变后的相变材料,夜晚环境温度下降后,相变材料散发热量可以再次回归固体状态供给白天高温时使用。

表 1 热电制冷器的不同研究方向

Tab.1 Different research directions of thermoelectric coolers

文献	热电制冷器结构		主要研究参数	脉冲电流相关参数	热端散热方式	工作流体
	级数	电流连接方式				
G. Min 等[75]	单级	串联	L	—	—	—
K. Pietrzyk 等[76]	单级	串联	G;N;B	—	翅片/热管	—
Meng Jinghui 等[77]	单级	串联	I	—	翅片	空气
Liu Di 等[122]	单级	串联	I;f;U_hA_h	—	热管	空气
Wang Tianhu 等[80]	两级	分离	λ;γ;ϕ;ΔT;ζ	—	—	—
Lin Shumin 等[102]	两级	串联	I;t;Q_l;q	I_p;τ	循环流体	水
Ma Ming 等[103]	两级	并联	I;λ;L_t	—	—	—
Lü Hao 等[105]	两级	串联	ζ;λ	I_p;τ;形状	—	—
Xuan X. C.[130]	多级	串联/分离	—	—	—	—
G. Karimi 等[89]	多级	串联	S;I;ζ_m	—	—	—

根据以上的热电制冷性能优化,本文主要有以下几方面的概括:

1)热电对数以及工作电流都是制冷与产热达到热平衡的重要参数,过多的热电对数和过大的工作电流虽然会使帕尔贴冷量增加但同时也使内部产生的焦耳热增加,所以对于热电对数和工作电流均有其最优值。不同级数之间的热电对数比和电流比将决定热级产生的热量能否被冷级有效带走,从而不对系统产生恶劣影响。

2)冷热端热导分配比、面积比及热阻匹配是关于热电制冷器吸热和放热之间的热平衡设计。合理的冷热端热导分配能够有效平衡吸热量和散热量,使系统既能最大的吸收热量又不至使热量集聚无法排出,从而提升系统的 COP 和制冷量。变截面的热电模块研究结果也表明,增加热侧热电元件的截面积对于冷热端的热平衡有很大帮助,将更有利于热端散热,提高 COP 和制冷量。

3)不同的热电制冷结构优化、工作参数优化、散热优化实质上均可概括为对热电制冷器的冷热平衡优化,即使热电制冷器冷端的制冷量、自身产热能够和散热量之间达到优化平衡。

3 结论和展望

本文以热电制冷技术近十年来的发展为基础,首先对热电制冷的发展、背景和原理进行了回顾,其次从热电技术的应用和优化两个方面的发展进行了梳理,主要得到以下结论:

基于热电制冷性能的改善以及对于制冷环境的更高要求,热电制冷的应用越来越广泛,由此也推动了热电制冷更多更深入的研究。本文基于近年来热电制冷在热电冰箱、热电空调、电子设备冷却及复合系统等方面的应用,介绍了热电制冷近些年的发展和研究成果。在热门的电子散热领域,热电制冷在温度控制和结构匹配方面的优势显著。热电制冷与太阳能的复合系统,在季节和昼夜匹配性、热电制冷电源及发电效率等方面有很好的发展前景。在其他制冷系统的结合方面,热电制冷充分发挥了其独特优势,弥补了其他制冷方式的缺点,形成了各种优势互补的复合系统。复合系统可能会成为热电制冷未来最广阔的发展方向之一。

热电制冷由于材料发展的限制,使得各种优化成为了热电制冷器性能提升的主要方式。制冷量、COP

和冷端温度等多个方面使热电制冷性能优化有着丰富的研究内容。热电元件和热电制冷器的优化,使热电制冷的性能基础可以更高。运行工况的电流优化,使热电制冷具有更好的性能以满足不同需求,其中脉冲电流的使用扩展了热电制冷的研究方向,也为瞬态冷却提供了思路。高效的散热方式和散热器使热端的散热能力更强,可以整体提升热电制冷器的性能,也是热电制冷性能优化的重要方向。

虽然热电制冷的应用和优化研究已有很多成果出现,但同时也存在着脱节现象。即热电制冷的应用不能很好的利用成熟的优化成果,如优化热端散热、进行热导分配和选择更合适的热电模块等。很多优化研究忽略了热电制冷目前应用的可行性,如新型结构热电制冷器的生产制造。所以在应用与优化两者结合方面还存在很多研究空间,值得研究者们更深入的探索和研究。

目前商用热电材料的优值系数仅约为 1,热电制冷已经有了较大的发展,相信随着越来越多高性能材料的市场化,热电制冷技术会越来越完善,有更多的发展空间。且随着世界对于绿色环保、节能减排的倡导,热电制冷以其安静无污染等特性将会对生活品质和生存环境产生更多的积极作用。

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通信作者简介

周媛媛,女,博士,讲师,南京理工大学能源与动力工程学院, 18652080509,E-mail:zhouyy@njust.edu.cn。研究方向:制冷与低温系统热物理过程基础理论及制冷空调节能技术。

About the corresponding author

Zhou Yuanyuan, female, Ph. D., lecturer, School of Energy and Power Engineering, Nanjing University of Science and Technology, +86 18652080509, E-mail: zhouyy@njust.edu.cn. Research fields: basic theory of thermophysical process in refrigeration and cryogenic system and energy-saving technology of refrigeration and air conditioning.