液氢温区两级全同轴型脉管制冷机

庞晓敏^{1*}, 戴巍², 马素霞¹, 王晓涛²

1. 太原理工大学电气与动力工程学院, 太原 030024;

2. 中国科学院理化技术研究所, 北京 100190

* 联系人, E-mail: pangxiaomin@tyut.edu.cn

2020-12-17 收稿, 2021-02-02 修回, 2021-02-03 接受, 2021-02-04 网络版发表

中国博士后科学基金(2019M661061)和国家自然科学基金(5197061222)资助

摘要 同轴型脉管制冷机因其结构紧凑的优势在空间探测等领域具有重要应用潜力. 然而, 同轴布置的两部件(如回热器和脉管)仅依靠不锈钢薄壁间隔, 相同轴向位置时温度不一致会造成二者之间的径向热交换, 影响整机制冷性能. 本文基于液氢温区两级脉管制冷机, 针对不同结构冷指中存在的径向换热进行分析, 发现两级全同轴型冷指不仅能够大幅提高冷指紧凑性, 而且经由低温级脉管壁面的径向换热能够有效改善其温度分布, 降低低温级脉管损失, 提高膨胀效率, 进而提高制冷性能. 相比于无径向换热的两级冷指(U型或直线型冷指), 全同轴型冷指在20 K时的制冷量提高了50%以上. 设计研制了一台液氢温区全同轴型两级脉管制冷机, 在20 K时可获得1.2 W冷量, 以声功计相对卡诺效率达到7.34%.

关键词 两级脉管制冷机, 同轴型, 径向换热, 温度梯度, 膨胀效率

液氢温区的小型低温制冷机在低温超导、低温电子学、红外探测等众多领域都有广泛应用. 不断提高的技术需求在推动小型低温制冷机发展的同时, 也对其提出了更严格的要求, 如高效率、高可靠性、高功率密度、低振动等. 在现有的液氢温区小型低温制冷机中, 斯特林型脉管制冷机采用无油直线压缩机驱动, 采用脉管结构隔离冷端与室温环境, 在脉管热端利用阻力元件如惯性管、小孔气库等调节内部声学阻抗分布, 在低温端无运动部件, 因而具有结构简单、振动小、可靠性高等优势^[1,2], 极具发展潜力, 成为目前的研究热点之一.

脉管制冷机根据回热器与脉管相对位置的不同, 可以分为直线型、U型和同轴型. 对于直线型脉管制冷机, 回热器和脉管沿轴向在同一直线布置, 冷头位于二者之间, 不方便冷量的提取和利用. 对于U型脉管制冷

机, 回热器和脉管并列布置, 通过U型管连接, 冷头位于系统末端. 对于同轴型脉管制冷机, 回热器和脉管呈同轴型布置, 系统结构最为紧凑, 且同轴布置带来系统紧凑的优势随着冷指数增加越发明显, 在空间探测器等领域具有重要的应用潜力. 同轴型制冷机中, 回热器和脉管仅依靠不锈钢薄壁间隔, 二者轴向温度分布不一致势必会引起两者之间的径向热交换^[3], 对制冷性能产生影响. 部分学者针对回热器与脉管之间的径向热交换展开了研究. Radebaugh等人^[4]通过理论分析发现, 当回热器被冷却时有利于制冷性能的提高. Johnson和Ross^[5]的实验研究也表明了类似的结论. 但是, 上述研究均没有以实际同轴冷指为模型, 且未针对回热器与脉管之间的热量传递进行分析. Wang等人^[6]的研究表明, 通过合理匹配回热器和脉管的轴向温度分布, 可提高同轴型制冷机的制冷性能.

引用格式: 庞晓敏, 戴巍, 马素霞, 等. 液氢温区两级全同轴型脉管制冷机. 科学通报, 2021, 66: 2629–2634

Pang X M, Dai W, Ma S X, et al. A completely co-axial two-stage pulse tube cooler working at liquid hydrogen temperatures (in Chinese). Chin Sci Bull, 2021, 66: 2629–2634, doi: 10.1360/TB-2020-1614

工作于液氢温区的脉管制冷机大多采用两级结构,从耦合方式上可以分为热耦合型和气耦合型.热耦合制冷机每级工质流动相互独立,方便优化^[7].2017年,蒋燕阳^[8]基于两级热耦合同轴型制冷机进行研究,表明低温级脉管通过与回热器的径向换热可得到冷却,脉管内时均焓流增加,冷指制冷量也随之增大.实际上,对工作于液氢温区的脉管制冷机,脉管内损失已经与净制冷量相当^[9],为制约液氢温区脉管制冷机性能的主要因素之一.浙江大学植晓琴^[10]研究表明,利用上级冷头的冷量预冷低温级脉管可有效降低脉管焓损失,进而提升制冷性能.但是,热耦合制冷机独立进气流程使得配气系统复杂化,同时低温热桥也会增加不可逆损失.气耦合两级制冷机取消了预冷制冷机,能够提高系统功率密度,但系统内工质流动相对复杂.两级气耦合制冷机通常采用U型结构^[11].目前,国内外关于同轴布置对气耦合两级制冷机性能影响的研究相对较少.

本文针对不同结构形式两级冷指中存在的径向热交换效应及其对系统温度分布与制冷性能的影响进行了详细数值分析,随后搭建了两级全同轴型脉管制冷机实验平台,开展了相关实验研究.

1 数值模拟

制冷机结构参数如表1所示.一级回热器采用不锈钢丝网填充,二级回热器采用磁性蓄冷材料 HoCu_2 填充.本文主要采用Sage软件^[12]进行模拟,针对4种情形分别进行了数值分析. Case A: 无径向换热(对应U型或直线型冷指); Case B: 一级回热器与一级脉管呈同轴型

表1 制冷机结构参数(单位: mm)

Table 1 Main parameters of the pulse tube cooler (unit: mm)

名称	结构参数
一级回热器	长度60.5, 等效直径20.0
一级脉管	长度74.0, 等效直径14.6
二级回热器	长度50.0, 等效直径12.6
二级脉管	长度148, 直径7

布置(对应一级同轴、二级U型冷指); Case C: 二级脉管低温段与二级回热器呈同轴型, 高温段与一级回热器呈同轴型(对应一级U型、二级同轴冷指); Case D: 一级脉管位于一级回热器与二级脉管之间, 三者呈同轴型布置, 此外二级脉管低温段还与二级回热器呈同轴型(对应两级全同轴型冷指). 4种工况结构示意图如图1所示.

当两级冷指均不存在径向换热时, 回热器和脉管内气体的轴向温度分布如图2所示. 一级回热器和二级回热器的温度分布基本趋于线性, 但是脉管内气体温度分布呈现非线性趋势. 尤其是低温级脉管, 其温度跨度较大, 为20~300 K, 且脉管较长, 其轴向温度分布严重偏离线性. 对应于一级冷头的位置, 二级脉管内气体温度高达230 K, 比一级冷头温度高将近190 K. 如果构建同轴型结构, 这样大的温差势必会导致径向换热.

为了更直观地表达径向换热对温度分布的影响, 不同工况下回热器和脉管内气体轴向温度分布如图3所示. 径向换热对回热器温度分布影响较小, 主要影响脉管内气体轴向温度分布. 对于Case B, 一级冷指呈同轴型结构, 一级回热器和一级脉管之间存在径向换热.

图1 (网络版彩色)两级冷指结构图

Figure 1 (Color online) Schematic of a two-stage cold head

图 2 (网络版彩色)无径向换热时回热器和脉管内气体轴向温度分布

Figure 2 (Color online) Axial temperature distributions of the regenerators and pulse tubes without radial heat transfer

相比于Case A, 一级脉管被一级回热器冷却, 一级脉管与一级回热器在相同轴向位置的最大温差由20 K下降至不足10 K, 二级回热器和脉管内气体温度分布基本没发生变化. 对于Case C, 二级冷指呈同轴型结构, 二级脉管低温段与二级回热器存在径向换热, 高温段与一级回热器存在径向换热. 相比于Case A, 一级脉管温

度几乎没有变化, 二级脉管受到两级回热器的冷却, 其温度显著降低, 对应于一级冷头位置, 二级脉管的温度为110 K, 二者温差由190 K降低至65 K左右. 对于Case D, 两级冷指呈全同轴型结构, 一级脉管与一级回热器、二级脉管高温段均存在径向换热, 二级脉管低温段与二级回热器存在径向换热. 一级脉管和二级脉管温度均有所降低, 相同轴向位置时, 一级脉管与一级回热器在相同轴向位置的最大温差降至5 K左右; 对应于一级冷头位置, 二级脉管与其温差降低至75 K.

图4给出了不同工况下, 系统内不同部件的焓损失. 径向换热主要影响回热器、脉管内的焓损失. 一级回热器与脉管的径向换热降低了一级脉管的焓损失, 但是一级回热器的焓损有所增加, 整机焓损基本不变. 二级脉管与其他部件的径向换热能够有效降低二级脉管的焓损, 整机焓损也降低, 提高了制冷性能.

表2进一步给出了径向换热对系统性能、两级脉管性能的影响. 无径向换热时, 一级回热器与一级脉管的温度梯度相差较小, 一级冷指同轴型布置带来的径向换热对其温度梯度及脉管内时均焓流的影响也较小, 一级脉管膨胀效率(表征脉管冷端焓流转化为声功的能力)略有改善. 但是, 二级脉管与其他部件之间的径向换热会影响其膨胀效率及整机制冷性能, 二级脉管存

图 3 (网络版彩色)4种冷指结构回热器和脉管内气体轴向温度分布

Figure 3 (Color online) Axial temperature distributions of the regenerators and pulse tubes in four cases

图 4 4种工况不同部件焓损失

Figure 4 Exergy losses distribution in the system of four cases

在径向换热时(Case C和Case D), 其膨胀效率均由70%提高到85%以上, 制冷量也由1.27 W提高至近2.0 W. 径向换热导致二级脉管冷端时均焓流增加, 制冷性能也随之增加. 模拟结果显示, 对于多级制冷机, 低温级冷指同轴型布置带来的径向换热效应能够有效改善低温级脉管内温度分布, 降低靠近脉管冷端的温度梯度, 从而减少其热损失, 有助于提高制冷性能.

2 实验系统与结果

模拟结果表明, 两级全同轴型冷指可以获得与一级U型、二级同轴冷指相当的制冷性能. 此外, 两级全同轴型冷指还能够大幅提高冷指紧凑性. 本文搭建了两级全同轴型制冷机系统, 实验系统包括直线压缩机、全同轴型冷指、测量系统等. 压缩机采用中科力函生产的双活塞压缩机. 制冷机结构参数如表1所示, 采用冷却水对室温换热器进行冷却, 调相机机构采用阶

梯形室温排出器调相. 测量系统包括传感器及信号采集设备, 制冷性能的测量参数包括制冷温度和制冷量, 一级冷头采用铂电阻温度计(Pt100)测量, 精度为0.1 K, 二级冷头采用Lakeshore公司生产的Cernox电阻温度计(CX-1050-SD)测量, 精度为0.01 K, 制冷量通过在冷头缠绕康铜加热丝进行测量.

该制冷机冷指实物图如图5所示. 在设计工况, 系统运行频率30 Hz, 充气压力3.0 MPa, 随着输入声功从130 W增加到223 W, 无负荷温度由18.5 K降低至14.6 K. 223 W输入声功时, 20 K可获得1.2 W制冷量, 以声功计相对卡诺效率达到7.34%, 整机相对卡诺效率达到5.42%. 制冷机实验性能与模拟性能对比如图6所示, 实验结果与模拟结果变化趋势类似, 但相同工况下模拟性能优于实验性能. 仔细对比实验和模拟中系统内各参数分布, 发现该工况一级冷端温度为62.8 K, 远高于模拟中一级冷端温度45.9 K, 这可能是由一级脉管采用环形结构所导致. Sage模型是准一维计算模型, 环形脉管损失^[13,14]在模型中未能考虑. 此外, 各部件内流动及温度不均匀性损失、同轴型冷头流道弯折带来的阻力损失等在模型中均没有体现, 这些都可能致实

图 5 (网络版彩色)两级全同轴型冷指实物图

Figure 5 (Color online) Photo of the completely co-axial two-stage cold head

表 2 两级冷指径向换热对系统性能影响

Table 2 Effect of radial heat transfer on the system performance in a two-stage cold head

工况	输入声功(W)	20 K制冷量	一级脉管膨胀效率(%)	二级脉管膨胀效率(%)	一级脉管换热量(W)	二级脉管换热量(W)
Case A	223	1.27	78.9	69.3	0	0
Case B	223	1.29	82.7	69.3	2.547	0
Case C	223	2.06	79.2	86.7	0	2.833
Case D	223	2.00	81.3	85.6	3.215	2.12

图6 不同输入声功下的制冷性能。(a) 无负荷制冷温度; (b) 20 K制冷量

Figure 6 Cooling performance with different PV power input. (a) No-load cooling temperature; (b) cooling power at 20 K

验性能与模拟性能的差距。

3 结论

本文通过数值模拟指出, 同轴型冷指中径向热交换作用会对系统性能产生重要影响。两级冷指中, 低温级脉管温度跨度较大、长度较长, 导致其温度分布严

重偏离线性分布。采用同轴型布置可以有效改善其温度分布, 脉管膨胀效率可由70%提高至85%以上, 有利于提高制冷性能。全同轴型冷指相比于其他结构冷指, 其紧凑性大幅提高。进一步搭建了两级全同轴型制冷机, 开展了实验研究。研究表明, 223 W输入声功时, 20 K可获得1.2 W制冷量。

参考文献

- 1 Radebaugh R. Pulse tube cryocoolers for cooling infrared sensors. In: Andresen B F, Fulop G F, Strojnik M, eds. Infrared Technology and Applications XXVI. Proc SPIE, 2000, 4130: 363–379
- 2 Radebaugh R. Cryocoolers: The state of the art and recent developments. J Phys Condens Mater, 2009, 2116: 164219
- 3 Ki T, Jeong S. Study for coating effect of various materials in pulse tube of pulse tube refrigerator. Cryogenics, 2012, 52: 518–522
- 4 Radebaugh R, Marquardt E D, Gary J, et al. Regenerator behavior with heat input or removal at intermediate temperatures. In: Ross R G, ed. Cryocoolers 11. Boston: Kluwer Academic/Plenum Publishers, 2001. 409–418
- 5 Johnson D L, Ross R G. Cryocooler coldfinger heat interceptor. In: Ross R G, ed. Cryocoolers 8. New York: Plenum Press, 1995. 709–717
- 6 Wang L B, Dang H Z, Wu Y N, et al. Theoretical and experimental investigation on the axial temperature mismatch and its optimization for coaxial inertance pulse tube cryocoolers. In: Miller S D, Ross R G, eds. Cryocoolers 16. Boulder, CO: ICC Inc, 2011. 193–200
- 7 Tang K, Chen G B, Gunter T. 13 K thermally coupled two-stage Stirling-type pulse tube refrigerator. Chin Sci Bull, 2005, 16: 144–146
- 8 Jiang Y Y. Research on key technology of 20 K cryogenic temperature two-stage pulse tube cooler (in Chinese). Doctor Dissertation. Beijing: University of Chinese Academy of Sciences, 2017 [蒋燕阳. 20 K深低温双级脉管制冷机关键技术研究. 博士学位论文. 北京: 中国科学院大学, 2017]
- 9 Li Z P, Gan Z H, Chen J, et al. Investigation of high frequency regenerator characteristics at liquid helium temperature (in Chinese). J Eng Thermophys, 2010, 31: 1449–1452 [李卓裴, 甘智华, 陈杰, 等. 液氦温区回热器高频损失特性研究. 工程热物理学报. 2010, 31: 1449–1452]
- 10 Zhi X Q. Investigation on the refrigeration mechanism and loss characteristics of stirling pulse tube cryocooler at low temperature (in Chinese). Doctor Dissertation. Hangzhou: Zhejiang University, 2014 [植晓琴. 深低温区斯特林脉管制冷机理及损失特性研究. 博士学位论文. 杭州: 浙江大学, 2014]
- 11 Qiu L. A separate two-stage pulse tube cooler working at liquid helium temperature. Chin Sci Bull, 2005, 50: 1030–1033
- 12 Gedeon D. Sage User Guide, 2007
- 13 Pang X, Chen Y, Wang X, et al. Numerical and experimental study of an annular pulse tube used in the pulse tube cooler. IOP Conf Ser-Mater Sci Eng, 2017, 278: 012145
- 14 Pang X, Dai W, Wang X, et al. CFD investigation on the characteristics of annular pulse tube. Int J Refrig, 2020, 114: 181–188

Summary for “液氢温区两级全同轴型脉管制冷机”

A completely co-axial two-stage pulse tube cooler working at liquid hydrogen temperatures

Xiaomin Pang^{1*}, Wei Dai², Suxia Ma¹ & Xiaotao Wang²¹ College of Electrical and Power Engineering, Taiyuan University of Technology, Taiyuan 030024, China;² Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China* Corresponding author, E-mail: pangxiaomin@tyut.edu.cn

Pulse tube coolers, which work at liquid hydrogen temperature, are widely used in applications such as cooling infrared sensors and superconducting devices because of the advantage of no moving parts at low temperatures. Pulse tube coolers can be divided into three types according to their shape: In-line type, U-type, and co-axial type. In-line type and U-type pulse tube coolers separate the regenerator and the pulse tube, both of which are only connected through the cold end heat exchanger. For co-axial pulse tube coolers, the regenerator normally has an annular cross section surrounding the pulse tube. They are becoming increasingly popular in practice for their compactness, but the thermal contact between the regenerator and the pulse tube may affect the system performance. Few studies have been conducted on the influence of radial thermal contact, most of which are based on a single-stage pulse tube cooler and deviate from an actual co-axial type pulse tube model.

For pulse tube coolers working at liquid hydrogen or a low temperature, two-stage cold heads are commonly used. In this study, theoretical analyses are conducted on the basis of a two-stage gas-coupled pulse tube cooler to investigate the influence of radial heat transfer. Based on the simulations, a completely co-axial two-stage pulse tube cooler is set up and experimental studies are carried out.

Four models (corresponding to different shapes of cold heads) are constructed to theoretically analyze the mechanism based on the Sage software. Without radial thermal contact (corresponding to a two-stage U-type cold head), the temperature distributions along the pulse tubes are nonlinear, especially the 2nd stage pulse tube due to the large temperature span. Corresponding to the position of the 1st cold end, the temperature of the 2nd stage pulse tube is high to 230 K; at the same axial location, the temperature difference between the 2nd stage regenerator and the pulse tube is approximately 190 K. Radial heat transfer on the 2nd stage pulse tube (corresponding to 1st stage U-type and 2nd stage co-axial type cold head or the completely co-axial two-stage cold head) can cool down the 2nd stage pulse tube effectively; at the same axial location, the temperature difference between the 2nd stage regenerator and the pulse tube decreases to 60 K with the 1st stage U-type and 2nd stage co-axial type cold head; such a difference also decreases to 75 K with the completely co-axial two-stage cold head. Radial heat transfer increases the enthalpy flow in the 2nd pulse tube, and the expansion efficiency of the pulse tube increases from 69% to approximately 85%. The cooling performance is also improved. Meanwhile, the radial heat transfer between the 1st stage regenerator and the pulse tube (corresponding to 1st stage co-axial type and 2nd stage U-type) has a relatively minor effect on the system performance. Exergy losses are also investigated with different models. Therefore, a well-matched geometrical arrangement of the co-axial configuration is essential for achieving the optimal performance. The completely co-axial two-stage cold head not only improves the compactness but also the cooling performance. Experiments are then performed. As a result, a completely co-axial two-stage pulse tube cooler is built. A cooling power of 1.2 W at 20 K is obtained with 223 W PV power input.

two-stage pulse tube cooler, co-axial, radial heat transfer, temperature gradient, expansion efficiencydoi: [10.1360/TB-2020-1614](https://doi.org/10.1360/TB-2020-1614)