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低温技术

氢气在螺旋管内流动冷凝传热特性研究

金俊中[1,2] 陶 轩[2] 徐 雅[1] 申运伟[2] 王 博[2] 甘智华[2,3]

(1 中国计量大学能源环境与安全工程学院 杭州 310018; 2 浙大城市学院低温中心 杭州 310015;
3 浙江大学 全省制冷与低温技术重点实验室 杭州 310027)

摘 要 为了满足制冷机冷却的小型氢液化装置优化设计需求,本文搭建了低温制冷机冷源系统,针对氢气在内径为1.75 mm的螺旋管内开展流动冷凝传热特性实验研究。在开展实验前,对制冷机性能进行测试,并通过数据拟合得到制冷量与冷头温度之间的函数关系。实验在3种不同饱和压力(495、665、850 kPa)和质量流率为15~40 kg/(m²·s)的工况下进行,通过敏感性分析揭示质量流率、饱和压力和温差对传热系数的影响。结果表明:在实验范围内,氢气冷凝传热系数随质量流率的增大而显著提高,整体增幅为74%~133%,且在低质量流率区间增长更为明显;在低质量流率条件下,饱和压力由495 kPa提高至850 kPa时,冷凝传热系数下降47%,而在高质量流率下压力影响明显减弱;此外,在本实验工况下冷凝传热系数区间为594~1 388 W/(m²·K)。

关键词 氢气;流动冷凝;传热特性;低温制冷机

中图分类号: TB61⁺1;TB657.5 **文献标识码:** A

Flow-Condensation Heat-Transfer Characteristics of Hydrogen in Helical Tube

Jin Junzhong[1,2] Tao Xuan[2] Xu Ya[1] Shen Yunwei[2] Wang Bo[2] Gan Zhihua[2,3]

(1. College of Energy Environment and Safety Engineering, China Jiliang University, Hangzhou, 310018, China; 2. Cryogenic Center, Hangzhou City University, Hangzhou, 310015, China; 3. Zhejiang Key Laboratory of Refrigeration and Cryogenic Technology, Zhejiang University, Hangzhou, 310027, China)

Abstract

Objective: To satisfy the optimization and design requirements of small-scale hydrogen liquefaction systems cooled by cryogenic refrigerators, this study investigates the flow-condensation heat-transfer process of hydrogen in a small-diameter helical tube. The objective is to reveal the condensation behavior and key factors influencing hydrogen under cryogenic conditions. Owing to its low viscosity, surface tension, and two-phase density ratio, the heat-transfer mechanism of hydrogen differs significantly from that of conventional refrigerants. However, existing experimental data and correlations for hydrogen flow condensation remain limited. Therefore, in this study, the effects of mass flux, saturation pressure, and temperature difference on the flow condensation heat-transfer performance of hydrogen were investigated, thus providing experimental evidence and theoretical references for the structural design and performance optimization of small-scale hydrogen liquefaction systems.

Methods: An experimental setup for hydrogen-flow condensation was established using a Gifford - McMahon refrigerator. The condenser comprises a stainless-steel helical coil (inner diameter: 1.75 mm) welded onto a copper block in close contact with the refrigerator to ensure efficient heat transfer. Experiments were conducted at three saturation pressures (495 kPa, 665 kPa, and 850 kPa) with mass fluxes ranging from 15 kg/(m²·s) to 40 kg/(m²·s). The temperature, pressure, and flow rate were measured, and the hydrogen-condensation heat-transfer coefficient was calculated using a thermal-resistance model and the heat-balance method. Prior to the hydrogen-condensation experiments, the refrigerator performance was tested, and a fitted function relating the cooling capacity to the cold-head temperature was obtained. Additionally, computational fluid dynamics (CFD) simulations were performed to verify the uniformity of the internal temperature distribution of the copper block. The results confirmed that the measured temperature represented the refrigerator cold-head temperature, thus ensuring the reliability of the heat-transfer calculations.

Results and Discussions: The condensation heat-transfer coefficient increased with mass flux, with a higher growth rate at low mass fluxes and a more gradual increase at high mass fluxes. This behavior is primarily due to the thinning of the liquid film, enhanced convective heat transfer, and reduced thermal resistance as the two-phase flow velocity increased. At low mass fluxes, increasing the

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saturation pressure decreases the condensation heat-transfer coefficient, which is attributed to liquid-film thickening, reduced thermal conductivity, and weakened film fluctuations. However, at high mass fluxes, turbulence dominates heat transfer, thereby diminishing the effect of pressure, and the heat-transfer coefficients stabilize at different saturation pressures. The condensation heat-transfer coefficient decreased with increasing temperature difference. A larger temperature difference thickened the liquid film, increased the liquid viscosity, and increased the gas-liquid density ratio, thereby increasing the thermal resistance. This trend aligns with the data reported by Ohira et al., thereby verifying the reliability of the experimental results.

Conclusions: Within the experimental range, the hydrogen-condensation heat-transfer coefficient increased significantly with mass flux, with an overall enhancement of 74%–133%. Moreover, the increase was more pronounced under low mass fluxes. Additionally, at low mass fluxes, when the saturation pressure increased from 495 kPa to 850 kPa, the condensation heat-transfer coefficient decreased by 47%, whereas the effect of pressure weakened at high mass fluxes. Under the present experimental conditions, the condensation heat-transfer coefficient ranged from 594 W/(m^2·K) to 1 388 W/(m^2·K).

Keywords hydrogen; flow condensation; heat transfer characteristics; cryogenic refrigerator

氢气作为一种清洁、高效的二次能源，具有燃烧热值高、零碳排放和来源多样等优点，被广泛认为是未来能源体系的重要组成部分[1-2]。近年来，随着氢能产业链的快速发展，已形成涵盖氢气制取、储存与运输等环节的完整体系[3]，在高压氢气、低温液氢和金属氢化物这 3 种储运方式中，液氢凭借能量密度高、加工与运输灵活等特点，展现出巨大的发展潜力[4-5]。

目前大型氢液化系统流程复杂，主要用于航天和军事领域[6-7]。相比之下，小型氢液化系统能够更灵活地服务于分布式应用，有助于推动氢能普及和液氢技术发展。小型氢液化系统通常采用外部冷却技术，例如逆布雷顿循环和 GM(Gifford-McMahon)制冷机，在换热器内实现氢气的流动冷凝[8]。该类系统结构紧凑、调节灵活，能在不同流量、温度及环境条件下高效运行，并凭借微通道与小型化设计适用于科研实验、能源站、加氢站及大型工厂预冷等多种应用场景。表 1 所示为典型的小型氢液化实验装置及其产量，图 1 所示为对应的装置照片。

与常规制冷剂相比，氢气具有更低的液相黏度、表面张力和较小的两相密度比，这使其在流动与传热特性上呈现出与常规制冷剂不同的特征。现有的氢冷凝实验研究较少且多为较大管径下的膜状冷凝[9-12]，这些实验虽然为理解氢气冷凝提供了初步参考，但与当前小型化、微通道化的液化与换热需求存在明显差距。对于以 GM 制冷机作为冷源的小型氢液化系统，其冷凝换热器通常采用小直径螺旋管结构，以在有限体积内提高单位长度的换热能力并增强换热效果。目前的低温工质冷凝实验研究多针对液氦[13]、液氖[14]、液氮[9,15-16]和甲烷[17]，结果表明其流型与传热特性与常温工质存在显著差异。已有传热关联式（如 Akers[18]、Shah[19-22]、El Hajal[23]、Zhuang[17,24]等）通常存在未充分考虑低温物性突变或在微小通道内适用性有限等问题。

本文以氢气在螺旋管内流动冷凝传热过程为研究对象，开展了低温实验研究。通过改变质量流率、饱和压力和温差等参数，测量并分析了冷凝传热系数的变化规律，可为小型氢液化装置中冷凝换热器的结构设计与运行参数优化提供实验依据，并为制冷机多台串联换热器的设计与产能提升提供参考。此外，研究成果还可为分布式能源系统中的冷凝换热器优化设计提供参考。

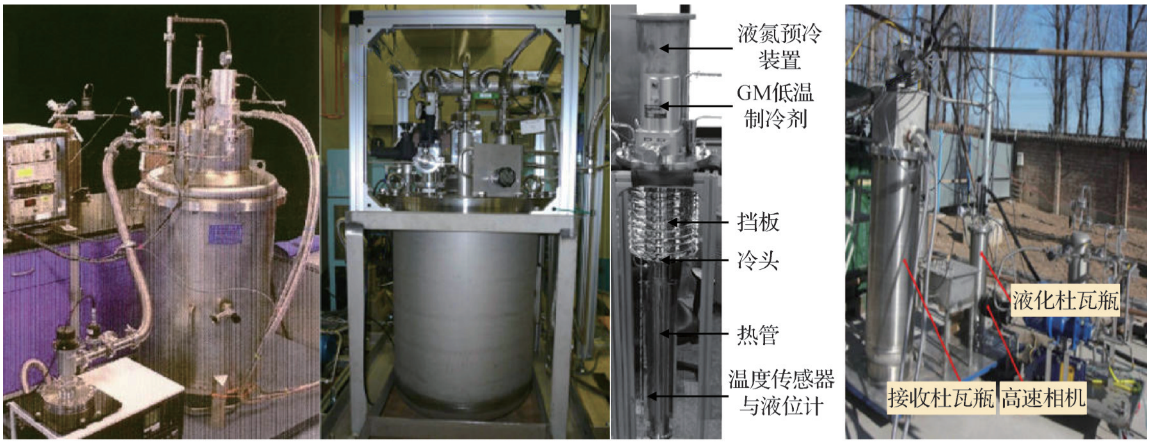
表 1 小型氢液化实验装置及产量

Tab.1 Small-scale hydrogen liquefaction experimental device and output

研究单位	氢液化方式及产量
中佛罗里达大学和NASA[25]	单级 GM 制冷机。7.2 L/d；25 L/d(液氮预冷)
日本产业技术综合研究所[26]	两级 GM 制冷机。19.9 L/d
中佛罗里达大学和韩国科学院[27-28]	单级 GM 制冷机。16.8 L/d；33.6 L/d(液氮预冷)
西安交通大学[29]	两级 GM 制冷机。10.5 L/d

1 实验装置

本文采用外部冷却的方式开展氢气流动冷凝实验，氢气流动冷凝实验系统如图 2 所示，氢气来源于高压氢气瓶，首先通过液氮预冷装置降温，再通过减压阀和刻度调节阀控制氢气进口压力和流量。随后，氢气依次经过间壁式换热器和测试冷凝器，在测试冷凝器内逐渐冷凝并进入气液两相区。冷凝后的氢气最终通过间壁式换热器低压侧进一步冷却来流的高压氢气，随后排入室外大气。实验冷源为两级 GM 制冷机，冷头与铜块紧密接触，测试冷凝器焊接缠绕在铜块上，以实现高效换热，所用氢气纯度为



(a) J. H. Baik[25] (b) A. Nakano等[26] (c) N. M. Garceau等[27-28] (d) Xie Fushou等[29]

图 1 采用制冷机(外部)冷却的小型氢液化装置

Fig.1 Small-scale hydrogen liquefaction cooled by an external refrigerator

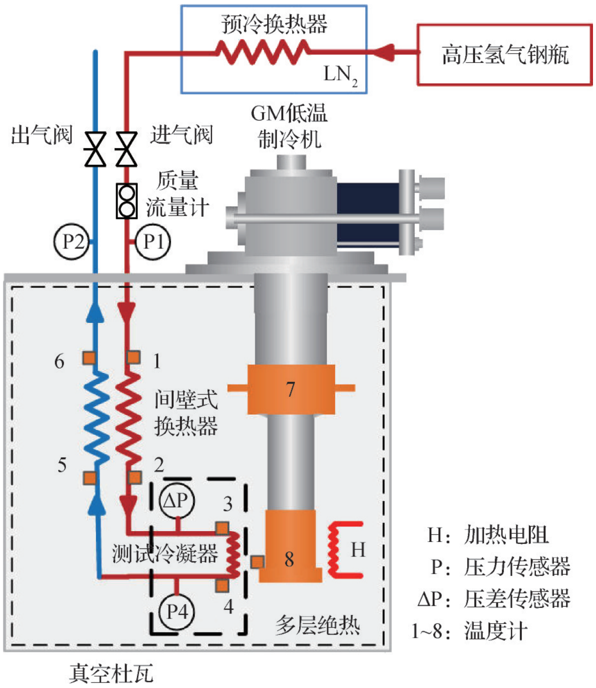


图 2 氢气流动冷凝实验系统

Fig.2 Schematic of the hydrogen flow condensation experimental system

99.999%。

制冷机和测试冷凝器均置于真空罩内，实验过程中，真空泵持续工作，使真空罩内真空度保持在 5×10^{-5} Pa 以下，此时气体的对流漏热可忽略不计，真空罩内实验装置外部包裹了 30 层绝热材料以减少辐射漏热，测试冷凝器进口引压管延伸至真空罩外并连接外置压差传感器会带来导热漏热，经计算辐射漏热和导热漏热分别为 0.18 W 和 0.03 W。

图 3 所示为实验测试系统，表 2 所示为测试仪表精度。图 3 中点 1~8 为温度计布置位置，各点所测得的温度用 T_1~T_8 表示。其中 T_1、T_2 为间壁式换热器高压侧进出口温度，T_3、T_4 为冷凝通道进出口温度，T_5、T_6 为间壁式换热器低压侧进出口温度，T_7、T_8 为制冷机一级和二级冷头温度。压力测量方面，p_1、p_2 分别测量间壁式换热器高压侧进口与低压侧出口压力，Δp 测量测试冷凝器进出口温差，p_4 测量测试冷凝器出口压力。流量由质量流量计实时测量。

2 传热模型建立

2.1 制冷量测试

本实验选取 GM 制冷机作为冷源，采用外部冷却的方式冷凝氢气，所用制冷机为南京鹏力超低温技术有限公司生产的 KDE415SA，配套压缩机型号为 KDC6000V，当压缩机供电频率为 50 Hz 时，制冷机制冷性能如图 4 所示。为保证实验顺利进行，对 GM 制冷机进行了制冷量测试。采取热平衡法测量制冷量，测试示意图如图 5 所示。

测试结果均为一级冷头未加热条件下测得的第二级制冷量，实测冷量曲线与原有冷量曲线吻合较好，该制冷机在二级冷头温度为 14~24 K 时可提供 14~22 W 冷量。为验证制冷机性能，开展了重复性实验测试结果如图 6 所示。根据实测数据拟合出制冷机第二级制冷量与温度之间的函数关系如下：

$$Q = 277.32 - 10.33T_7 - 8.71T_8 + 0.08T_7^2 + 0.04T_8^2 + 0.21T_7T_8 \quad (1)$$

式中：Q 为制冷机制冷量(换热量)，W；T_7 为制冷机一级冷头温度，K；T_8 为制冷机二级冷头温度，K。

2.2 模型建立

测试冷凝器采用一段不锈钢螺旋盘管，将其缠绕焊接在与制冷机冷头紧密接触的铜块上；该测试冷凝器外径为 3.175 mm、内径为 1.75 mm、长度为 1.2 m。实验测试段与铜块的组装如图 7 所示。

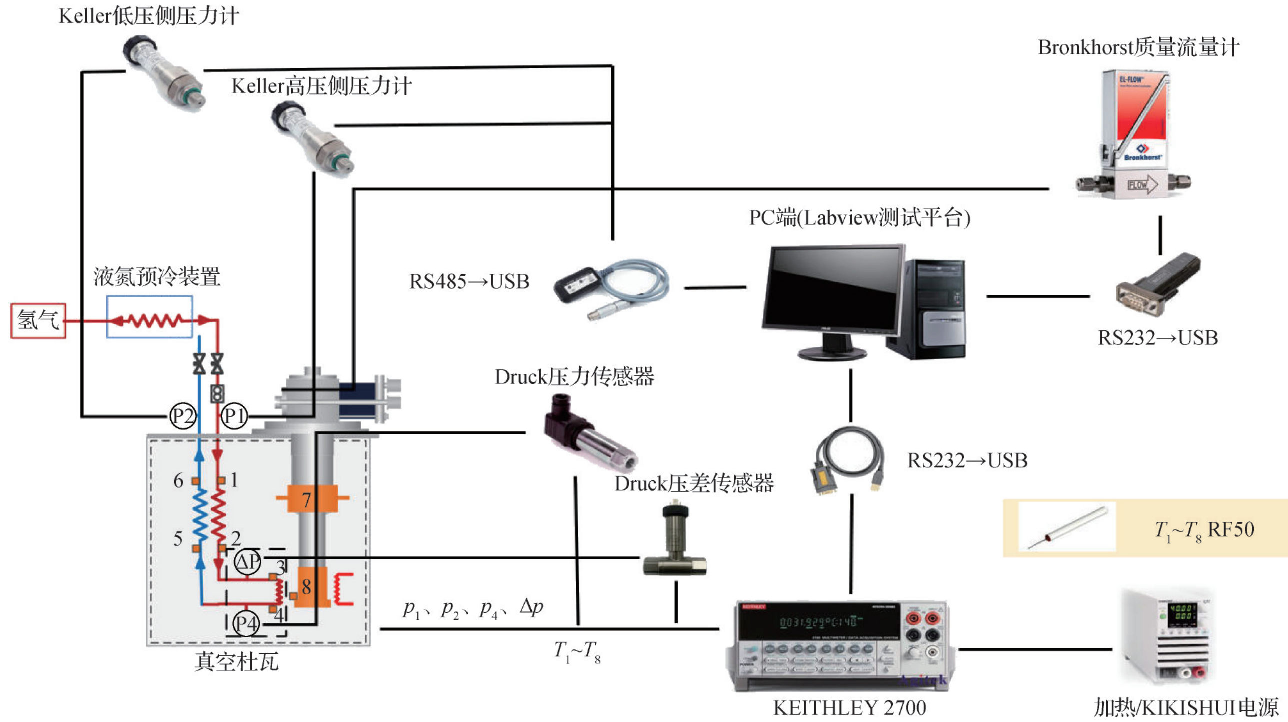


图 3 实验测试系统

Fig.3 Schematic of the experimental test system

表 2 测试仪表精度

Tab.2 Test instrument accuracy

仪器名称	精度
铑铁温度计	±0.1 K
Keller PAA-33X 压力传感器	0.05%FS
Bronkhorst F-111AC 质量流量计	0.1%FS
DRUCK PMP 5073 压差传感器	0.04%FS
DRUCK PMP 5073 压力传感器	0.04%FS

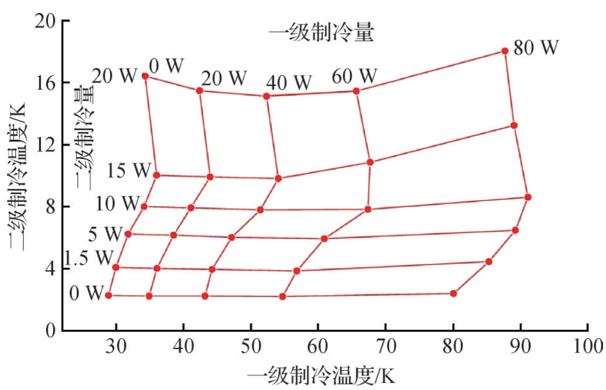


图 4 GM 制冷机性能曲线

Fig.4 Performance curve of the GM refrigerator

实验过程中，氢气通入螺旋盘管，在与低温壁面接触时发生冷凝相变，释放潜热并向壁面传热，形成氢气至冷源的多层耦合冷凝传热过程。

本实验冷凝传热过程可视为由 4 级串联热阻组成的热阻链，其传热路径依次为：氢气与不锈钢管道内壁间的对流传热、不锈钢管道壁层的热传导、不锈钢管壁与铜块焊接接触界面的热阻传热以及铜块与管接触区域到铜块测温位置的热传递过程，传热过程如图 8 所示。

各级热阻共同决定了氢气冷凝过程中热流的传递效率，稳态条件下计算氢气的冷凝传热系数可以简化为一维热传递问题，总体传热流程计算如下：

$$Q = \frac{\Delta T}{R_{总}} = \frac{T_{sat} - T_{cold}}{R_1 + R_2 + R_3 + R_4} = \frac{T_{sat} - T_{cold}}{\dfrac{1}{\alpha A_{wi}} + \dfrac{\ln(d_{wo}/d_{wi})}{2\pi k L} + R_{contact} + R_{Cu}} \quad (2)$$

$$A_{wi} = \pi d_{wi} L \theta \quad (3)$$

式中：T_{sat} 为氢气饱和温度，K；T_{cold} 为铜块测温位置温度，充当制冷机二级冷头温度，K；R_1 为氢气与不锈钢管道内壁之间的对流传热热阻，K/W；R_2 为不锈钢内外壁面的热传导热阻，K/W；$R_{contact}$ 为不锈钢管与铜块焊接界面接触热阻，K/W；R_{Cu} 为铜块与管接触区域到铜块测温位置的热传导热阻，K/W；α 为氢气冷凝传热系数，W/(m^2·K)；d_{wi}、d_{wo} 分别为管内径和管外径，m；A_{wi} 为管内壁面传热面积，m^2；θ 为测试冷凝器焊接嵌入到铜块的比例，取值为 0.45；L 为测试冷凝器长度，m；k 为不锈钢导热系数，W/(m·K)。其中 $R_{contact}$ 在本实验中无法直接测量得到，通过银钎焊工艺将测试冷凝器缠绕焊接在铜块上，这极大程度地减小接触

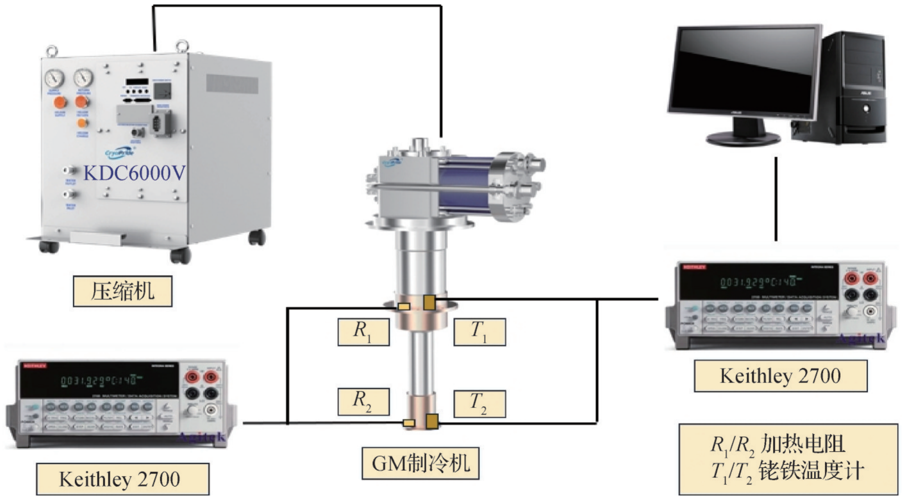


图 5 GM 制冷机性能测试示意图

Fig.5 Schematic diagram of the GM refrigerator performance test

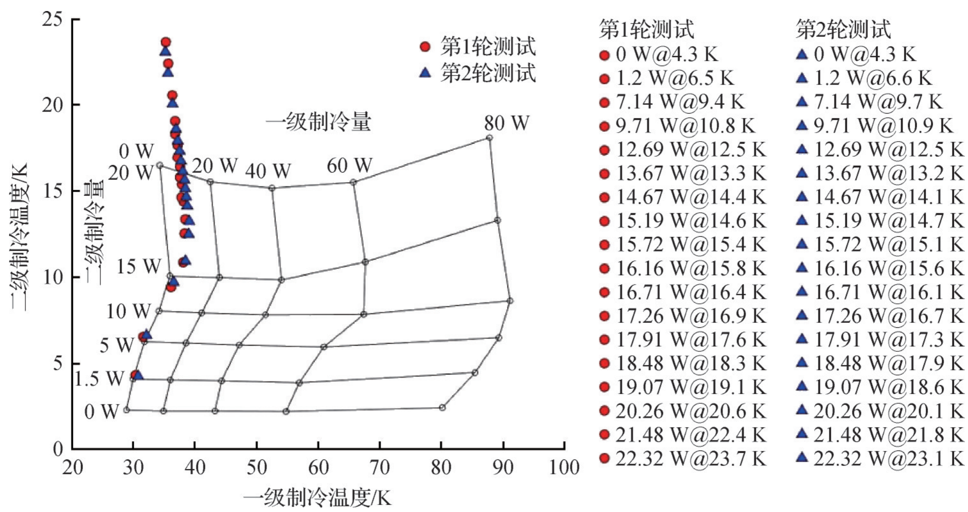


图 6 制冷机性能测试结果

Fig.6 Results of the refrigerator performance test

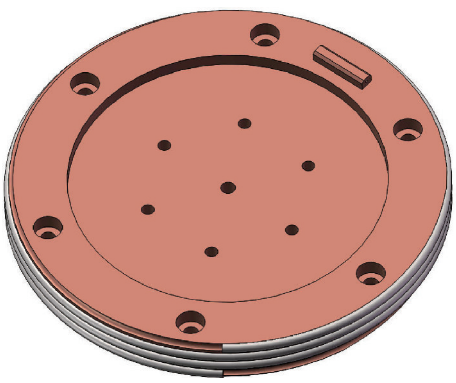


图 7 测试冷凝器与铜块组装

Fig.7 Assembly of the test condenser and copper block

热阻，根据文献报道取值约为 10^{-6}~10^{-5} K/W[30-31]，相比之下，R_1 和 R_2 的数值分别为 0.2~0.7 K/W 和 0.02~0.03 K/W，由此可见，接触热阻远小于传热过程中的主要热阻，因此在后续分析中可予以忽略。R_{Cu} 同样无法直接测得，因此需要验证铜块整体的换热性能来判断其大小，铜块传热量好整体温度一致则证明 R_{Cu} 可忽略不计。式(2)简化为式(4)。

$$Q = \frac{\Delta T}{R_{总}} = \frac{T_{sat} - T_{cold}}{\dfrac{1}{\alpha A_{wi}} + \dfrac{\ln(d_{wo}/d_{wi})}{2\pi kL} + R_{Cu}} \tag{4}$$

氢气冷凝传热系数计算如下：

$$\alpha = \frac{1}{\left[\dfrac{T_{sat} - T_{cold}}{Q} - \dfrac{\ln(d_{wo}/d_{wi})}{2\pi kL} - R_{Cu}\right] A_{wi}} \tag{5}$$

实验中在与制冷机相连的铜块上布置测点，将测得温度作为制冷机二级冷头温度，为了验证稳态条件下铜块整体温度的一致性，本文将实验中的 1 组数据进行 CFD 模拟，计算求解铜块温度变化情况，模型假设如下：1）稳态求解铜块整体平均温度变化情况；2）根据前期计算，辐射漏热和导热漏热分别为

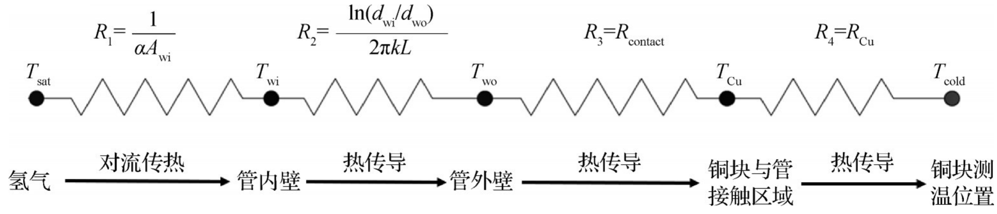


图8 氢气冷凝传热途径和热阻

Fig.8 Heat transfer path and thermal resistance during hydrogen condensation

0.18 W与0.03 W,约占制冷机制冷量的1%,因此在模型中忽略该部分漏热;3)铜材的物性参数由CMP软件查询,并经MATLAB拟合得到温度相关函数,假设在20~40 K时物性数据具有较高准确性;4)依据实验工况,制冷机制冷量为18.92 W,对应铜块测温点温度为18.7 K。假设铜块测温位置周向温度均匀,可视为等温壁面。结合制冷机与铜块接触面积,确定制冷机冷头吸热区域的热流密度为5 070.96 W/m²;冷凝器与铜块耦合区域热流密度为2 294.87 W/m²;其余区域边界条件均设为绝热界面。

CFD模拟结果表明,铜块整体温度区间为18.6~18.7 K,温度云图如图9所示,铜块温度变化范围小于0.1 K,接近温度计不确定度。可以认定铜块换热性能良好,制冷机二级冷头温度T_{cold}与铜块测温位置温度T_8相等,因此R_{Cu}忽略不计,氢气冷凝传热系数计算可变更为式(6)。

$$\alpha=\left[\frac{T_{sat}-T_8}{Q}-\frac{\ln(d_{wo}/d_{wi})}{2\pi kL}\right]^{-1}A_{wi}^{-1} \tag{6}$$

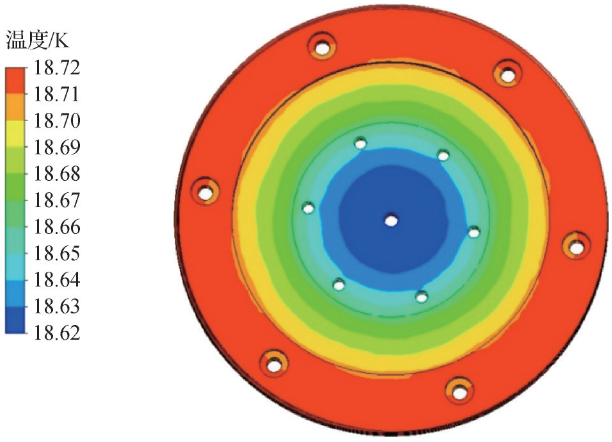


图9 温度云图

Fig.9 Temperature contour

本实验中干度采用基于焓值的推断方法进行计算,因为所测温度为壁温,所以当测试冷凝器进、出口位置温度与对应饱和压力下的饱和温度差小于0.2 K时认为氢处于两相状态,并根据换热量计算进、出口焓值,进而由式(8)求得干度;若温差过大,则分别取干度为1或0。最终以进、出口干度的算术平均值作为平均干度x_{av}。

$$Q/\dot{m}=h_3-h_4 \tag{7}$$

$$x_{3(4)}=\frac{h_{3(4)}-h_f}{h_g-h_f} \tag{8}$$

式中:$\dot{m}$为质量流量,kg/s;x为干度;h为比焓,kJ/kg;下标3、4分别表示测试冷凝器进、出口,下标g、f分别表示饱和氢气、饱和液氢。

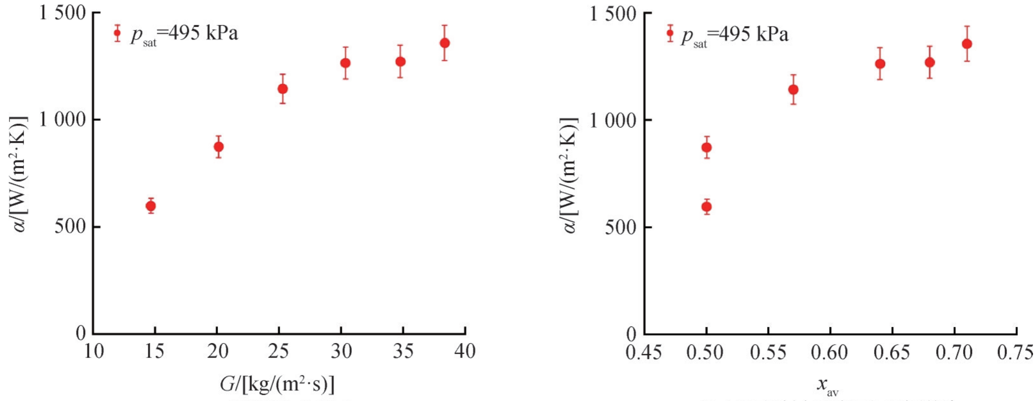
3 实验结果及分析

3.1 质量流率影响

图10所示为质量流率对氢气冷凝传热系数的影响。在饱和压力为495 kPa时,冷凝传热系数随质量流率的变化如图10(a)所示。由图10(a)可知,冷凝传热系数随质量流率的增大而增大,低质量流率下的冷凝传热系数增长速率较大,而在高质量流率下增长趋于缓和。质量流率的增大一方面提高了气液两相的流速,从而增强了对流传热;另一方面导致干度上升,气相比例增大,进而提高空隙率与气相速度,使管壁液膜进一步变薄,从而降低传热热阻(图10(b))。

3.2 饱和压力影响

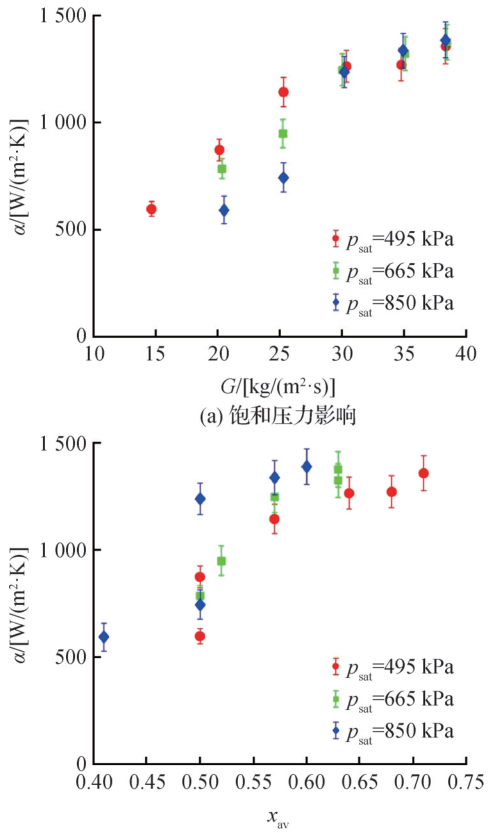
图11所示为饱和压力对氢气冷凝传热系数的影响。冷凝传热系数随饱和压力的变化如图11(a)所示,在低质量流率下,氢气冷凝传热系数随着饱和压力的增大而减小,这是因为饱和压力增大会导致氢气相密度增大和液相密度减小,从而在相同质量流率下气相表观速度下降、液膜厚度增加,导致液膜波动与湍流减弱,氢的导热系数也随着饱和压力的升高而降低。冷凝传热系数随干度的变化如图11(b)所示。饱和压力变化会引起干度改变,从而影响冷凝传热系数。随着饱和压力的增大,相同的质量流率下干度更低,进而导致更厚的液膜。而上述因素均会增加热阻,因此冷凝传热系数随饱和压力的升高而降低;但是在高质量流率下,传热过程几乎完全受气液两相湍流控制,压力对冷凝传热系数的影响减弱,因此在高质量流率3种饱和压力下的冷凝传热



(a) 质量流率影响
(b) 不同质量流率下干度影响

图 10 质量流率对氢气冷凝传热系数的影响

Fig.10 Influence of mass flow rate on the heat transfer coefficient of hydrogen condensation



(a) 饱和压力影响
(b) 不同饱和压力下干度影响

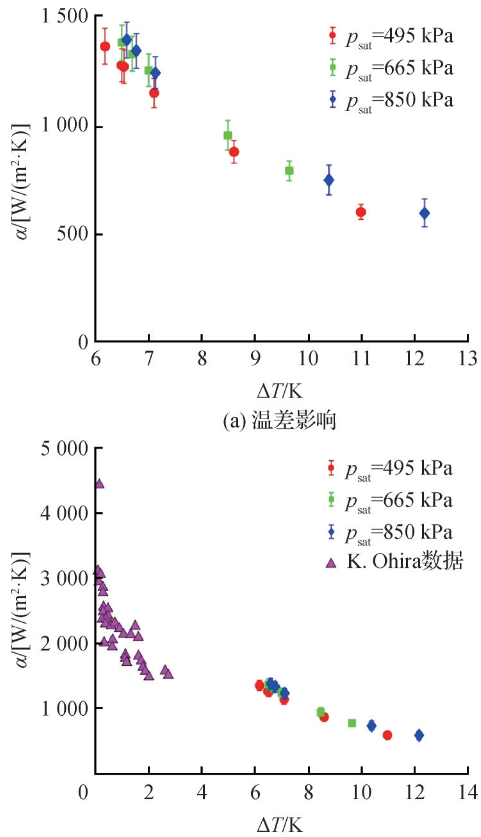
图 11 饱和压力对氢气冷凝传热系数的影响

Fig.11 Experimental results of the hydrogen flow condensation heat transfer coefficient

系数趋于一致。

3.3 温差影响

图 12 所示为温差对氢气流动冷凝传热系数的影响。在相同饱和压力下，饱和温度保持不变，质量流率增大会导致壁温上升，从而引起温差减小。由图 12(a)可知，冷凝传热系数随着温差的增大而减小，这是因为温差增大会导致冷凝液更易积聚从而导致液膜变厚，它还会导致液相温度降低进而引起液相黏度升高和气液密度比增大，前者会增大液膜流动阻力，后者会影响流动稳定性和界面形态，上述物性效应与液膜厚度增加的几何效应叠加，共同导致冷凝传热系数随温差的增大而下降。图 12(b)所示为本



(a) 温差影响
(b) 对比K. Ohira数据[12]

图 12 温差对氢气流动冷凝传热系数的影响

Fig.12 Influence of temperature difference on the condensation heat transfer coefficient of hydrogen flow

实验结果与K. Ohira等[12]数据的对比，两者在趋势上具有较好的一致性，即冷凝传热系数均随温差的增大而减小，该对比验证了实验结果的可靠性。

4 结论

本研究针对氢气在螺旋管内流动冷凝传热过程,基于低温实验平台,研究了质量流率、饱和压力和温差对冷凝传热性能的影响,得到结论如下:

1)在饱和压力一定的条件下,冷凝传热系数随质量流率的增加而显著上升,低质量流率区间内增长幅度更大,高质量流率下增长趋缓。其原因在于气液两相流速的提升增强了对流传热,同时使液膜变薄,降低了传热热阻。

2)低质量流率条件下,饱和压力升高会显著降低冷凝传热系数,主要由于液膜增厚、液相导热系数下降及液膜波动减弱等因素共同作用;而在高质量流率下,传热过程受湍流主导,压力影响减弱,不同饱和压力下的冷凝传热系数趋于一致。

3)冷凝传热系数随着温差的增大而减小,这是因为温差增大会导致液膜加厚,还会导致液相温度降低进而引起液相黏度上升以及气液密度比增加,从而增大热阻,该效应在低质量流率下尤为明显。

4)相同质量流率条件下,高饱和压力会导致氢气凝固(101 kPa下氢的凝固点为13.96 K,且凝固点会随着饱和压力的增大而增大)。此外,冷凝传热系数随着饱和压力的升高而减小。推荐在低于临界压力、正压范围内选择较低的饱和压力下的高质量流率进行实验,以此满足提升小型氢液化装置产量需求。

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通信作者简介

陶轩，男，副教授，浙大城市学院低温中心，19558304577，E-mail：taox@hzcu.edu.cn。研究方向：低温沸腾和冷凝传热。

About the corresponding author

Tao Xuan, male, associate professor, Cryogenic Center, Hangzhou City University, 86-19558304577, E-mail: taox@hzcu.edu.cn. Research fields: cryogenic boiling and condensation heat transfer.