

低温低雷诺数氮气对流换热特性实验

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摘要 为了充分利用低温流体的冷量, 需要设计高效率换热器, 翅片式换热器因其具有换热比面积大、换热效率高、流体流动均匀等优点而被广泛采用. 本文研究的用于低温液氮容器冷量回收的换热器为内翅式狭缝结构, 流体介质为冷氮气, 温度为90~200 K, 气体流速为0.03~0.60 m/s, 雷诺数范围为0~100, 属于低温低雷诺数的流动状态. 本文介绍了低雷诺数冷氮气在内翅式狭缝换热器中的流动换热特性试验研究结果, 得到换热器内流体流动换热规律, 可指导进行高效低温容器的设计.

关键词 低温, 低雷诺数, 流动换热系数, 氮气

低温液体受热蒸发后, 形成冷气体, 具有一定显冷(即显热)的冷气体直接排放到室温环境会造成很大的冷量损失和浪费, 尤其对于具有较大显冷的4.2 K的冷氮气, 这种冷能不加以利用还可能会使得低温液体的储存时间大大缩短, 系统工作效率降低, 甚至液氮根本到达不了所要求的被冷却表面上. 为此, 低温技术人员一般会在冷气体的排放管道外壁焊接或机械连接换热器, 用于回收冷气体的显热^[1]. 如将换热器与包围低温储槽的冷屏连接, 可以屏蔽外界进入低温液体的辐射热; 将换热器与低温储槽的固体支撑连接则可阻挡室温至低温液体的传导热量; 将低温测量引线与换热器连接后也可以减少引线至低温液体的导热. 本实验室提出在冷气体排放管道的内部安装换热器的思路, 设计出一种狭缝内翅式换热器, 使得冷量回收效率大大增加, 在此基础上研制出高效低温液体储存容器.

目前这种冷量回收换热器设计过程缺少低温气体低流速下的对流换热系数数据. 由于温度会影响

流体的物性^[2], 进而影响流体的换热特性, 因此当常规流体的换热关联式应用到低温流体时, 往往会带来误差, 不仅如此, 低温流体还会产生震荡, 这种震荡对低温流体的换热也会产生影响^[3]. 尽管国内外研究人员对狭缝通道的流动换热进行了不少研究^[4~8], 但对于低温低雷诺数下换热器流动换热的研究较少. 因此, 为了进一步提高换热器效率, 为换热器的优化设计提供依据, 本文针对狭缝内翅式换热器在低温低雷诺数下的对流换热特性进行了实验研究.

1 实验原理与方法

冷气体流经换热器的换热模型如图1所示, 假设冷气体为稳定流动, 期间没有压力和体积变化, 则冷气体经过换热器后吸收的热量等于冷气体焓值的增加, 即:

$$h \times A \times (T_s - T_{\text{fluid}}) = C_p \times Q_m \times (T_{\text{out}} - T_{\text{in}}) = \Phi, \quad (1)$$

由上式可得到冷气体的对流换热系数为

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Li X L, Hong G T, Wang G P. The experimental research on heat transfer coefficients of low temperature and low Reynolds number nitrogen gas (in Chinese). Chin Sci Bull, 2017, 62: 335-342, doi: 10.1360/N972016-00074

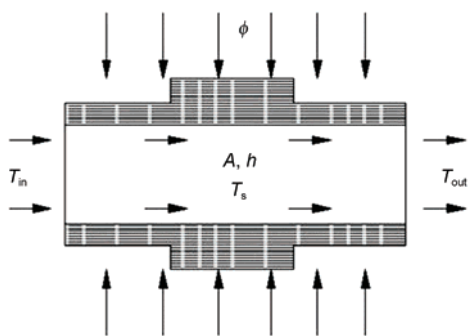


图1 冷气体流经换热器的换热模型

Figure 1 The heat transfer model of cold gas flows through the heat exchanger

$$h = \frac{C_p \times Q_m \times T_{out} - T_{in}}{A \times (T_s - T_{fluid})}, \quad (2)$$

式中, h 为换热器对流换热系数, A 为换热器与流体的换热面积, T_s 为换热器表面温度, T_{fluid} 为流经换热器的流体平均温度, C_p 为流经换热器的流体等压比热容, Q_m 为流经换热器的流体质量流量, T_{out} 为换热器出口流体温度, T_{in} 为换热器入口流体温度, Φ 为换热器向流体传递的热量。

由式(2)可知, 只要实验测量得到冷气体的进出口温度、换热器温度、流体流量, 就可计算得到冷气体的换热系数 h 和努赛尔数 Nu 。改变流体的温度和流速就可以得到不同温度和雷诺数下的换热系数实验数值。将这些试验数据进行拟合, 就可以得到该条件下的对流换热通用关系式。

冷气体流经换热器时的阻力模型如图2所示, 局部水头损失和沿程水头损失分别由式(3)和(4)计算^[9]。

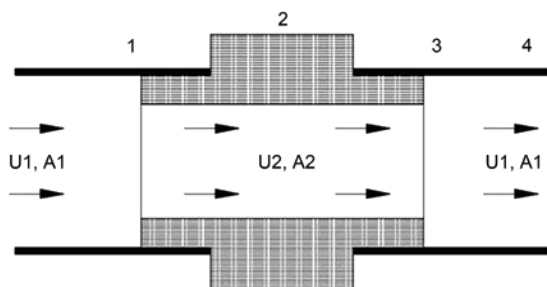


图2 冷气体流经换热器的阻力模型。1, 突缩阻力; 2, 换热器沿程阻力; 3, 突扩阻力; 4, 管道沿程阻力

Figure 2 Resistance model of cold gas flows through the heat exchanger. 1, Sudden shrinkage resistance; 2, frictional drag of heat exchanger; 3, the sudden enlargement resistance; 4, frictional drag of pipe

$$h_t = \delta \times \frac{u^2}{2g}, \quad (3)$$

$$h_m = \lambda \times \frac{l}{d} \times \frac{u^2}{2g}, \quad (4)$$

式中, l 为管长, d 为管径, u 为断面平均流速, g 为重力加速度, λ 为沿程阻力系数, δ 为局部阻力系数。

实验中利用氮气出口处测得的流量值, 得到经过换热器的冷气体流速, 再通过上述阻力公式计算得到冷气体流经换热器的流动阻力损失。

2 实验系统

2.1 实验系统组成

为了获得冷气体的低温低流速状态, 以便对换热器的低温低流速换热性能进行测试, 专门设计了一套以200 mL容积的微型液氮低温容器为主体的换热器实验系统。如图3所示, 换热器实验系统由液氮低温容器主体、安装在排气管路上的用于测量换热器内氮气流量的流量计(1)、连接温度计的测温仪(4)、连接加热丝和加热膜的加热电源(13)、真空泵(2)、真空计(14)、液氮罐(15)等组成。

2.2 液氮容器主体

液氮容器主体包括200 mL的液氮槽(9)、换热器(12)、安装在液氮槽底部的加热膜(10)、换热器上的

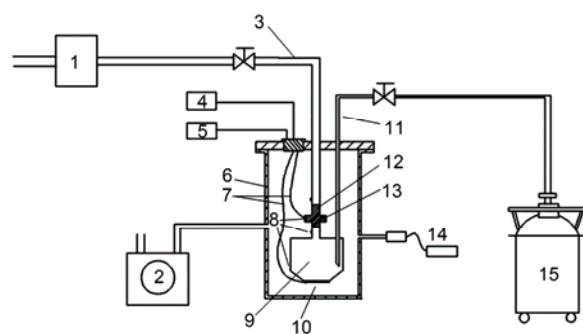


图3 换热器实验系统组成简图。1, 流量计; 2, 真空泵; 3, 排气管; 4, 温度测控仪; 5, 外接加热电源; 6, 真空罐体; 7, 连接导线; 8, 温度计; 9, 液氮槽; 10, 液氮槽加热膜; 11, 输液管; 12, 换热器; 13, 换热器加热丝; 14, 真空计; 15, 液氮罐

Figure 3 The system diagram of heat exchanger experiment. 1, Flow meter; 2, vacuum pump; 3, vent pipe; 4, temperature measurement and control instrument; 5, external heating power; 6, vacuum vessel; 7, connecting wire; 8, temperature sensor; 9, liquid nitrogen tank; 10, liquid nitrogen tank heating film; 11, liquid inlet pipe; 12, heat exchanger; 13, heat exchanger heating wire; 14, vacuum gauge; 15, nitrogen container

加热丝(13)、测温温度计(8)、输液管(11)、真空罐体(6)和排气管(3)等。其中加热膜(10)用于调节液氮槽内液氮的蒸发量,从而控制流过换热器的冷氮气流量;加热丝(13)则用于调节换热器的温度,并模拟不同的换热器加热量。用于测量换热器前后冷氮气温度的传感器为直径 $\phi 1.27$ mm的微球状二极管温度传感器,换热器和液氮槽表面温度的测量传感器为贴片式二极管温度传感器,两种温度计的测温范围为1.4~500 K,测量精度 ± 10 mK。

2.3 换热器

图4为换热器的外形图,换热器内侧加工了50个沿周向均匀分布的长条狭缝,狭缝宽度0.4 mm,长度4.5 mm,换热器高度37 mm,材料为紫铜,中心孔由聚四氟乙烯实心圆柱体堵住。换热器安装在液氮槽的上部,位于排气管道上。冷氮气从换热器下部进入,沿轴向流动,从换热器上部流出。

2.4 温度测量

为减少气体管路中温度传感器对流体流动的影响,温度计选用体积较小的直径 $\phi 1.27$ mm球状二极管温度计。温度传感器引脚从与排气管路焊接于一体、沿气体流动方向倾斜安装的铜管内引出,由低温胶封装,确保系统真空度。封装时需确保温度传感器探头处于被测流体内,封装方式及封装之后温度计安装位置如图5所示。其余测温点温度传感器通过低温胶将传感器探头黏附于固体表面的测温点处,为消除温度传感器内引线以及连接导线电阻对测温造

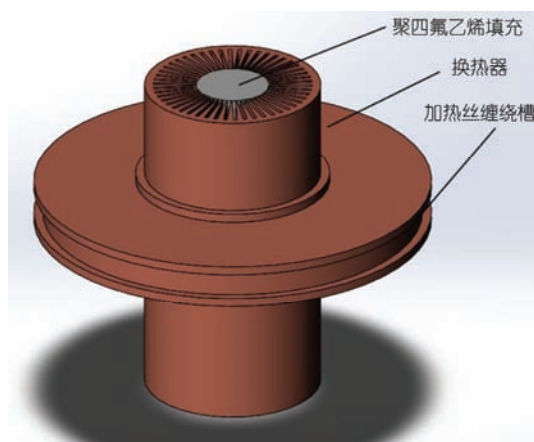


图4 (网络版彩色)换热器结构

Figure 4 (Color online) The structure of heat exchanger

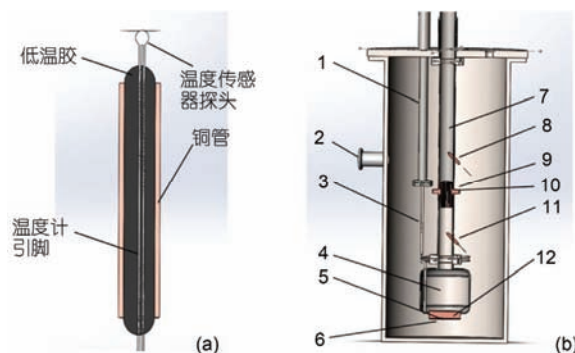


图5 (网络版彩色)流体管路内温度计封装(a)及安置位置(b). 1, 进液直管; 2, 真空接头; 3, 进液螺旋管; 4, 液氮槽; 5, 换热器加热膜; 6, 加热膜压板; 7, 气体排出管; 8, 换热器出口温度计; 9, 换热器; 10, 换热器加热丝; 11, 换热器入口温度计; 12, 铜座

Figure 5 (Color online) The package and installment of the thermal sensor in the pipe. 1, Inlet liquid pipe; 2, vacuum connector; 3, inlet liquid spiral pipe; 4, liquid nitrogen tank; 5, liquid nitrogen tank heating film; 6, heating film pressing plate; 7, vent pipe; 8, thermal sensor placed in the outlet of heat exchanger; 9, heat exchanger; 10, heat exchanger heating wire; 11, thermal sensor installed in the inlet of heat exchanger; 12, copper base

成的影响,所有温度传感器采用四线制连接。所有温度信号由Lakeshore 218温度测控仪实时测量记录,测控仪使用已标定的温度传感器曲线。

2.5 加热器

换热器加热丝缠绕于换热器外圆柱面的槽内,液氮槽加热膜通过压板压紧在与液氮槽焊接于一体的铜座底面。加热丝和加热膜均使用直流电源输入功率加热,直流电源输出电压精度0.001 V,电流精度0.001 A,考虑到加热丝与加热膜电阻在低温下变化不大,其加热功率由式 $\phi = I^2 R$ 计算得到。

2.6 真空与流量测量

真空计安装于真空罐体外部的真空管道上,测量试验主体所处环境真空度。流量计安置于冷氮气排出口,同时为验证流量计示数,采用排水法测量冷氮气出口体积流量,进行比较,两者的结果相近。

3 实验工况及测试结果

试验时,首先开启真空泵通过真空接头对真空罐抽真空,待真空度达到 1×10^{-2} Pa时,通过进液直管和进液螺旋管向液氮槽内充注液氮。液氮槽内充注液氮之后,蒸发出来的冷氮气进入气体排出管,依次流经换热器入口温度计、换热器、换热器出口温度计。

液氮充注过程通过温度测控仪对各测温点温度进行实时监测. 液氮槽内注满液氮后停止液氮供给, 在气体排出管出口接入流量计, 实时监测出口冷氮气流量.

实验针对不同流速、不同换热器加热量的换热器换热性能进行了测试. 两种实验工况如下.

实验工况1: 控制换热器加热丝的加热量不变, 通过调节液氮槽加热膜的加热量改变储液槽内液氮的蒸发速率来改变冷氮气经过换热器的流速, 以研究相同换热量下不同气体流速对换热器换热性能的影响.

实验工况2: 控制液氮槽加热膜的加热量不变, 通过调节换热器加热丝的加热量控制流经换热器的热流, 以研究相同气体流速条件下, 不同换热量(即不同换热器温度)对换热器换热性能的影响.

上述两种实验工况的具体实验参数设置如表1所示.

图6为实验工况1的实验测试结果, 换热器加热丝的加热量维持0.3 W不变, 调节液氮槽加热膜的加热量依次为0.9, 1.2, 1.5, 1.8, 2.1 W, 测得的换热器温度和换热器前后的冷氮气温度、冷氮气流量的变化曲线如图4所示, 由于加热膜在0.9和1.2 W时系统温度未达到平衡, 所以只选取后3组数据(表2).

图7为实验工况2的实验测试结果, 液氮槽加热膜的加热量维持在2.1 W不变, 换热器加热丝的加热量依次为0.3, 0.5, 0.7 W时的换热器温度、换热器前后冷氮气的温度、冷氮气流量的试验曲线如图7所示, 相应的试验数据如表3.

针对两种实验工况, 在进行完上述两组实验操作后, 为得到较大范围换热器入口流体流速和温度的实验测试结果, 在上述两组实验基础上, 通过控制换热器加热丝和液氮槽加热膜功率继续实验, 加热膜加热功率控制在0.3~23.3 W; 加热丝功率控制在0.3~1.5 W. 最终得到换热器入口流速范围0.03~

0.60 m/s, 换热器入口流体温度范围90~200 K. 具体实验工况参数如表4所示.

当液氮槽加热膜和换热器加热丝均不加热时, 以流量计稳定后的流量示数可以计算得到系统的总漏热量为1.56 W, 经计算, 气体流速为0.045 m/s, 代入流动阻力计算式(3)和(4)中可以得到气体流经换热

表 1 实验工况参数设置

Table 1 The parameter settings of experimental condition

实验工况1		实验工况2	
换热器加热丝 加热量 (W)	液氮槽加热膜 加热量 (W)	换热器加热丝 加热量 (W)	液氮槽加热膜 加热量 (W)
0.3	0.9	0.4	2.1
0.3	1.2	0.5	2.1
0.3	1.5	0.7	2.1
0.3	1.8	—	—
0.3	2.1	—	—

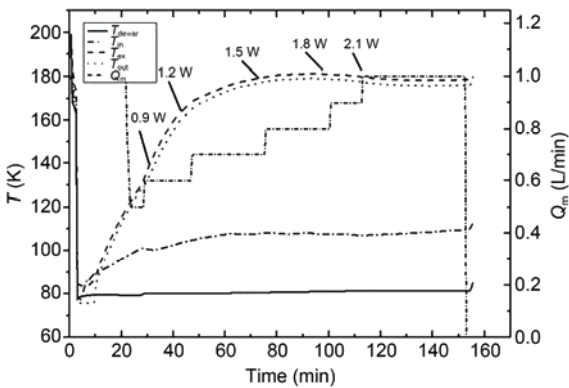


图 6 不同液氮槽加热量的试验曲线(换热器加热量为 0.3 W时). T_{dewar} : 铜座温度; T_{in} : 换热器入口流体温度; T_{ex} : 换热器温度; T_{out} : 换热器出口流体温度; Q_{m} : 出口流体体积流量

Figure 6 The test curve of different liquid nitrogen tank heat (heat of heat exchanger keeps 0.3 W). T_{dewar} : the copper basement temperature; T_{in} : the heat exchanger inlet temperature; T_{ex} : the heat exchanger temperature; T_{out} : the heat exchanger outlet temperature; Q_{m} : the outlet volume flow rate

表 2 不同液氮槽加热量的试验数据(换热器加热量为 0.3 W时)

Table 2 The test data of different liquid nitrogen tank heat (heat of heat exchanger keeps 0.3 W)

加热膜加热量	Q_{m} (LPM)	T_{out} (K)	T_{ex} (K)	T_{in} (K)	T_{dewar} (K)
$\phi_{\text{膜}}=1.5 \text{ W}$	0.822	178.90	181.08	107.97	79.23
$\phi_{\text{膜}}=1.8 \text{ W}$	0.887	178.81	181.03	107.52	79.12
$\phi_{\text{膜}}=2.1 \text{ W}$	0.955	176.28	178.72	107.47	79.31

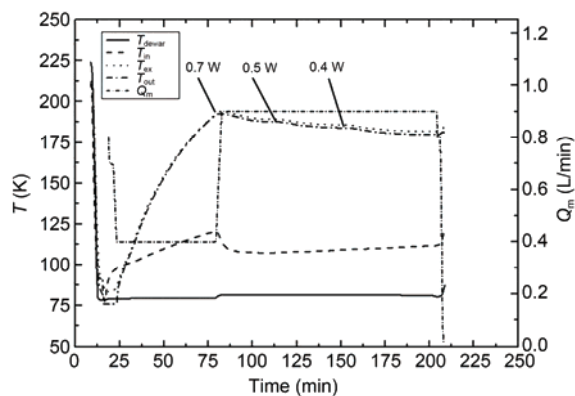


图7 不同换热器加热量的试验曲线(液氮槽加热量为 2.1 W 时)
Figure 7 The test curve of different heat exchanger heat (liquid nitrogen tank heat keeps 2.1 W)

表3 不同换热器加热量的试验数据(液氮槽加热量为 2.1 W 时)
Table 3 The test data of different heat exchanger heat (liquid nitrogen tank heat keeps 2.1 W)

加热膜加热量	Q_m (LPM)	T_{out} (K)	T_{ex} (K)	T_{in} (K)	T_{dewar} (K)
$\phi_{丝}=0.7$ W	0.900	187.57	189.57	111.14	81.00
$\phi_{丝}=0.5$ W	0.892	183.80	185.63	109.12	81.11
$\phi_{丝}=0.4$ W	0.871	179.76	181.70	107.42	81.32

器时的阻力为 271.29 Pa. 由此可以看出, 试验过程换热器流道内的流动阻力较小, 相对于排出管外的大气压(101325 Pa)可以忽略.

4 对流换热特性分析与关系式拟合

将上述实验得到的换热器温度、换热器前后冷氮

表4 其余实验工况具体参数设置

Table 4 The parameter settings of the rest experiment condition

实验工况1		实验工况2	
换热器加热丝 加热量 (W)	液氮槽加热膜 加热量 (W)	换热器加热丝 加热量 (W)	液氮槽加热膜 加热量 (W)
0	0.5	1.2	5
	1.0	0.6	
	1.5	0.1	
0.1	10	—	—
	12.6	—	—
	15.3	—	—
	18	—	—
	20.6	—	—
	23.3	—	—

气的温度、冷氮气流量值代入式(2)计算得到相应的冷氮气在换热器内的对流换热系数. 图8(a)为换热器入口冷氮气温度及换热器加热丝加热量不变的情况下, 换热器对流换热系数随流速之间的变化关系, 此时的对流换热系数与流速近似为线性正比关系, 流速越大, 换热系数也越大. 图8(b)为换热器入口氮气温度及流速不变的情况下, 冷氮气对流换热系数与换热器温度的关系, 此时的对流换热系数与换热器温度也成正比关系, 换热器温度越大, 换热系数也越大.

上述实验数据结合换热器通道的几何尺寸由式(5)计算氮气的努塞尔数 Nu 、雷诺数 Re 和普朗特数 Pr , 计算结果如表5所示. 计算过程考虑了氮气的密度、运动黏度、比热容、热导率随温度的变化因素.

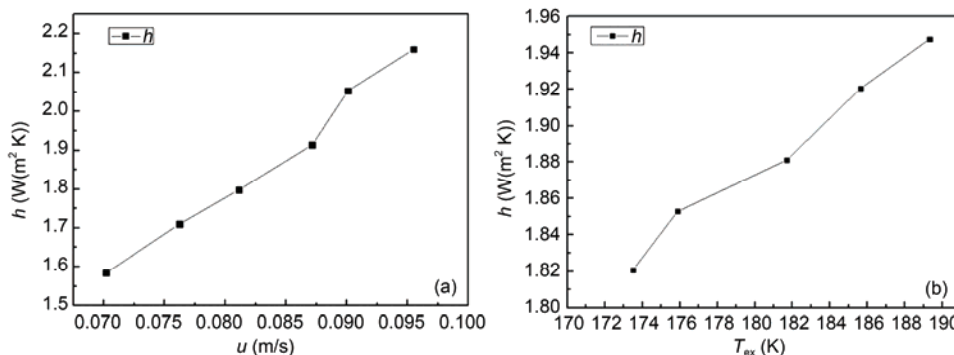


图8 对流换热系数与气体流速和换热器温度的关系. (a) 对流换热系数与气体流速的关系, 此时换热器入口冷氮气温度为 105 K, 换热器温度为 150~180 K; (b) 对流换热系数与换热器温度的关系, 此时换热器入口冷氮气温度为 115 K, 流速为 0.09 m/s

Figure 8 The relation of heat transfer coefficient and gas velocity, heat exchanger temperature. (a) The relationship between heat transfer coefficient and gas velocity with inlet nitrogen gas temperature 105 K and heat exchanger temperature between 150–180 K; (b) the relationship between heat transfer coefficient and heat exchanger temperature with inlet nitrogen gas temperature 115 K and velocity 0.09 m/s

表5 努塞尔数 Nu 、雷诺数 Re 和普朗特数 Pr

Table 5 The calculation of Nusselt numbers, Reynolds numbers and Prandtl number

	换热器加热丝 加热量(W)	液氮槽加热膜 加热量(W)	换热器前 N_2 温度(K)	换热器后 N_2 温度(K)	换热器 温度(K)	N_2 流量 (LPM)	Nu	Re	Pr
工况1	0	0.5	109.72	151.97	153.97	0.38	0.04	5.84	0.73
		1	107.47	147.95	149.95	0.48	0.05	7.41	0.73
		1.5	106.74	142.65	142.65	0.58	0.06	8.92	0.73
	0.1	10	92.33	99.72	100.58	2.82	0.31	43.37	0.73
		12.6	91.25	97.83	99.02	3.56	0.41	54.75	0.73
		15.3	90.47	95.55	97.54	4.21	0.46	64.75	0.73
		18	89.31	94.74	96.24	4.89	0.55	75.21	0.73
		20.6	89.64	92.56	93.18	5.47	0.61	84.13	0.73
		23.3	89.58	91.67	92.02	6.25	0.75	96.13	0.73
	0.3	1.5	107.97	178.9	181.08	0.82	0.09	12.64	0.73
		1.8	107.52	178.8	181.03	0.88	0.09	13.64	0.73
		2.1	107.47	176.28	178.82	0.95	0.10	14.69	0.73
工况2	0.7		111.14	187.57	189.57	0.90	0.10	13.84	0.73
	0.5	2.1	109.12	183.8	185.63	0.89	0.09	13.72	0.73
	0.4		107.42	179.76	181.70	0.87	0.09	13.40	0.73
	1.2		98.39	123.97	125.56	1.79	0.18	27.53	0.73
	0.6	5.0	96.25	113.79	114.81	1.76	0.18	27.07	0.73
	0.1		95.40	106.42	100.58	1.82	0.18	27.99	0.73

$$Nu = \frac{h \times D_h}{\lambda}, Re = \frac{\rho \times u \times D_h}{\eta}, Pr = \frac{\eta \times C_p}{\lambda}, \quad (5)$$

式中, h 为对流换热系数, $W/(m^2 \cdot K)$, D_h 为当量直径, 由式 $D_h=4 \times (A/L)$ 定义, 其中, A 为截面积, L 为湿周; λ 为热导率, $W/(m \cdot K)$; ρ 为密度, kg/m^3 ; u 为气体流动速度, m/s ; η 为气体黏度, $Pa \cdot s$; C_p 为比热容, $J/(kg \cdot K)$; 由于氮气普朗特数变化不大, 所以计算时取0.73.

由表5的努塞尔数 Nu 、雷诺数 Re 和普朗特数 Pr 数值进行对流换热关系式 $Nu=f(Re, Pr)$ 的拟合, 得到拟合公式如下:

$$Nu = 0.0060 \times Re^{1.0239} \times Pr^{-0.3367}, Re \in (0, 100). \quad (6)$$

图9为计算得到的努塞尔数 Nu 点和通过拟合公式得到的努塞尔数 $Nu(\text{fit})$ 曲线, 拟合式的相关系数为

$$R^2 = \frac{\sum_{i=1}^n y_i^2}{\sum_{i=1}^n y_i^2 - \sum_{i=1}^n (y_i - Y_i)^2} = 0.98,$$

式中 y_i 为实验值, Y_i 为拟合计算值. 由此可见, 拟合公式与实验数据的符合度很高.

5 实验误差分析

实验误差主要来自温度测量以及气体流量的测

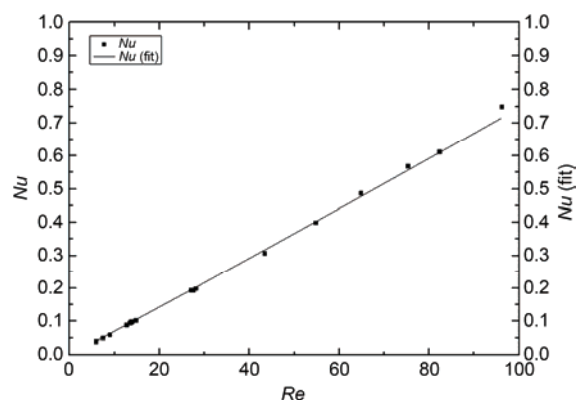


图9 试验数据与拟合数据的比较

Figure 9 The comparison of test data and fitting data

量. 实验中采用的球状二极管温度计和贴片式二极管温度计测温精度均为 $\pm 0.25\%$. 为了减少温度计的插入对氮气流体的影响, 将温度计沿氮气流体方向倾斜布置, 同时采用直径为 $\phi 1.27 \text{ mm}$ 的微球状二极管温度传感器的标定精度为 $\pm 1\%$. 所有的温度采集信号均由Lakeshore218数据采集系统采集, 并传输到与之相连的计算机进行实时监视和记录, Lakeshore218测量精度为 $\pm 0.01\%$. 温度测量总误差约为 $\pm 1\%$. 气体

流量通过在氮气排出管安放质量流量计测得,选用的ALICAT低压损微小流量计,量程为0~10 LPM,其标称读数精度为 $\pm 0.86\%R$,测量精度为0.2%FS.

由式(2)可以得到对流换热系数的最大相对误差计算公式为^[11]

$$\begin{aligned}\frac{\Delta h}{h} &= \frac{\Delta Q_m}{Q_m} + \frac{\Delta(T_{out} - T_{in})}{T_{out} - T_{in}} - \frac{\Delta(T_s - T_{fluid})}{T_s - T_{fluid}} \\ &= \frac{\Delta Q_m}{Q_m} + \frac{\frac{\Delta T_{out}}{T_{out}} T_{out} - \frac{\Delta T_{in}}{T_{in}} T_{in}}{T_{out} - T_{in}} - \frac{\frac{\Delta T_s}{T_s} T_s - \frac{\Delta T_{fluid}}{T_{fluid}} T_{fluid}}{T_s - T_{fluid}} \\ &\approx \frac{\Delta Q_m}{Q_m} + 2 \frac{\Delta T}{T},\end{aligned}\quad (7)$$

上式假设了4只温度计的相对误差相同,并考虑了其

绝对值的叠加.将上述温度和流量的测量误差代入式(7)就可计算得到对流换热系数的相对误差值为 $\pm 3.46\%$.同理,由式(5)可知, Nu , Re 的实验相对误差分别为对流换热系数 h 和氮气流量 Q_m 的线性传递,分别是 $\pm 4.86\%$, $\pm 2.86\%$.

6 小结

本文针对90~200 K的冷氮气在内翅式狭缝换热器内低雷诺数状态下的流动换热特性进行了实验研究,得到了不同换热器温度 and 不同流量的换热系数数据,并由此得到冷氮气与换热器之间的换热特性拟合关系式,可用于冷氮气在90~200 K温区低雷诺数流动换热器的设计.

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Summary for “低温低雷诺数氮气对流换热特性实验”

The experimental research on heat transfer coefficients of low temperature and low Reynolds number nitrogen gas

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The aim of this experimental research is to study the performance of heat transfer and pressure drop in the internally finned heat exchanger with low-velocity nitrogen gas flow at low temperature, which is often used in low temperature liquid vessel to reduce cool loss.

In this experiment, a special structure had been designed to get the fitting test data. A 200 mL liquid nitrogen tank was installed at the bottom of the system, which provided low velocity and low temperature nitrogen gas. The heat exchanger was installed in the outlet pipe of nitrogen gas. There were heating film installed at the bottom of liquid nitrogen tank and heating wire installed on the surface of the heat exchanger to get the different inlet nitrogen gas velocity, temperature and different heat exchanger temperature. Both the liquid nitrogen tank and heat exchanger were placed in a vacuum vessel. In this way, the heat exchanger cannot perform convection with the air but can only convective heat with the nitrogen gas.

The nitrogen gas temperature was measured by diode thermal sensor with using special package and installment in order to get the accurate temperature. A flow meter was installed at the end of the nitrogen gas outlet pipe to measure the gas flow rate in the heat exchanger. With the temperature and the flow rate been measured, the heat transfer coefficients

can be obtained as $h = \frac{C_p \times Q_m \times T_{out} - T_{in}}{A \times (T_s - T_{fluid})}$, where h is heat transfer coefficients, A is heat exchanger area, T_s is heat

exchanger temperature, T_{fluid} is average fluid temperature in the heat exchanger, C_p is fluid isobaric specific heat, Q_m is fluid mass flow rate, T_{in} is inlet fluid temperature and T_{out} is outlet fluid temperature. Also, the pressure drop can be

obtained as $h_f = \delta \times \frac{u^2}{2g}$, $h_m = \lambda \times \frac{l}{d} \times \frac{u^2}{2g}$, where l is pipe length, d is pipe diameter, u is average velocity, g is

gravitational acceleration, λ is on-way resistance coefficient and δ is local resistance coefficient.

In this paper, the heat exchanger was studied with nitrogen gas temperature in the range of 90 to 200 K, velocity 0.03 to 0.60 m/s. The Reynolds number is small, ranging from 0 to 100. The pressure drop was calculated about several hundred Pascal, which is very small compared with the nitrogen outlet pressure (101325 Pa). So the analysis focuses most on the property of heat transfer coefficients. From the test data, the relationship between heat transfer coefficient value and gas velocity shows linearly direct ratio when inlet nitrogen gas temperature was 105 K and heat exchanger temperature was between 150 to 180 K; The relationship between heat transfer coefficient value and heat exchanger temperature also shows linearly direct ratio when inlet nitrogen gas temperature was 115 K and velocity was 0.09 m/s. The Nusselt numbers, Reynolds numbers and Prandtl number were calculated and a dimensionless correlation can be obtained as $Nu = 0.0060 \times Re^{1.0239} \times Pr^{-0.3367}$, $Re \in (0, 100)$. The experimental error had been taken into account. Using the error transfer formula, the relative experimental error of Nusselt numbers and Reynolds numbers number were $\pm 4.86\%$ and $\pm 2.86\%$.

This experiment studies the performance of heat transfer and pressure drop in the internally finned heat exchanger with nitrogen gas temperature 90 to 200 K and velocity 0.03 to 0.60 m/s. The heat transfer coefficients of different nitrogen gas temperature and different flow rate had been obtained to form a dimensionless correlation. And this dimensionless correlation can be used for designing heat exchanger especially when nitrogen gas temperature between 90 and 200 K with low Reynolds number.

low-temperature, low-Reynolds number, heat transfer coefficients, nitrogen gas

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