水平管内乙烷饱和流动冷凝传热实验

庄晓如^{1,2}, 公茂琼^{1*}, 邹鑫¹, 陈高飞¹, 吴剑峰¹

1. 中国科学院理化技术研究所, 中国科学院低温工程学重点实验室, 北京 100190;

2. 中国科学院大学, 北京 100049

* 联系人, E-mail: gongmq@mail.ipc.ac.cn

2016-01-25 收稿, 2016-03-04 修回, 2016-03-08 接受, 2016-06-01 网络版发表

国家自然科学基金(51506210)资助

摘要 开展了乙烷在内径为4 mm的水平管内饱和流动冷凝传热特性的实验研究. 实验测量的压力范围为1.01~2.56 MPa, 质量流率范围为100~257 kg/(m² s), 干度范围为0~0.8. 分析了质量流率、干度和饱和压力对饱和流动冷凝传热系数的影响, 结果表明在较高质量流率和干度下, 传热系数随着质量流率和干度的增大而增大, 随着饱和压力的增大而减小; 在低干度和质量流率下, 干度、质量流率和饱和压力对传热系数的影响均较小. 另外, 还将实验数据与9种常用的饱和流动冷凝传热关联式进行对比, 发现Chato和Wang等人的模型关联式对实验数据预测较好, 平均偏差均在35%以内.

关键词 流动冷凝, 乙烷, 传热系数, 传热关联式, 水平管

随着人们对环保问题的重视, 传统的氟利昂制冷剂由于破坏臭氧层及引起温室效应而被禁止或限制使用, 寻找高效且对环境友好的新型制冷剂已成为制冷行业的重要任务. 乙烷属于碳氢化合物(HCs), 也是天然气的重要成分, 具有极佳的环境友好性, 作为制冷剂已在多元混合工质节流制冷系统中得到了广泛应用, 且可替代R13, R503应用于复叠制冷系统中^[1]. 因此, 研究其流动传热特性具有重要的理论意义和实用价值.

近年来, 关于HCs的流动冷凝传热特性研究已有大量的报道. Lee和Son^[2]研究了丙烷和异丁烷在管内径分别为10.07, 7.73, 6.54和5.8 mm的水平圆形光管内流动冷凝的传热及摩擦压降特性, 实验结果表明传热系数和摩擦压降会随着管内径的减小而增大. Del Col等人^[3]对丙烷在质量流率为100~800 kg/(m² s)和管内径为0.96 mm的微管道内流动冷凝传热及摩擦压降特性进行了研究, 发现传热系数和摩擦压降会

随着质量流率和干度的增大而增大. Murphy^[4]开展了丙烷在饱和压力分别为47和74°C及管内径为1.93 mm的垂直管内流动冷凝传热及摩擦压降特性的研究, 结果表明随着饱和压力的增大传热系数会出现轻微的减小, 并根据实验数据提出了半经验的传热及压降预测模型. Darzi等人^[5]研究了异丁烷在管内高度分别为6.7, 5.2和3.1 mm的扁形管道以及管内径为8.7 mm的圆形管道内流动冷凝的传热及摩擦压降特性, 发现扁形管道的换热优于圆形管道, 且随着扁形管道管内高度的减小传热系数增大, 但摩擦压降也会随着管内高度的减小而增大, 并在Shah^[6]关联式的基础上提出了适用于扁形管道的传热预测模型. Macdonald和Garimella^[7,8]对丙烷在管内径分别为7.75和14.45 mm的水平圆管内流动冷凝传热及摩擦压降特性进行了研究, 得到随着管内径的增大传热系数是存在轻微的增大, 该结论与Lee和Son的结论相反, 并提出了新的传热和压降预测模型.

引用格式: 庄晓如, 公茂琼, 邹鑫, 等. 水平管内乙烷饱和流动冷凝传热实验. 科学通报, 2017, 62: 320~327

Zhuang X R, Gong M Q, Zou X, et al. Experimental investigation on flow condensation heat transfer of ethane in a horizontal tube (in Chinese). Chin Sci Bull, 2017, 62: 320~327, doi: 10.1360/N972016-00104

虽然目前已有大量关于HCs流动冷凝传热特性的研究,但对于乙烷的相关研究还极为缺乏.为了了解乙烷饱和流动冷凝的换热规律,本文研究了其在水平管内的饱和流动冷凝传热特性,分析了质量流量、干度和饱和压力对传热系数的影响,并将实验数据与9种饱和流动冷凝传热关联式进行对比,找出预测效果较好的关联式.

1 实验装置及测量方法

1.1 实验系统

实验装置如图1所示,测试工质在换热器中被冷却成过冷液体,通过一个可调速的磁力循环泵驱动经加热段进入传热测试段,其质量流量由一台科氏力质量流量计测得,加热段用于控制进入测试段工质的入口干度.在测试段内,工质通过导热铜板将热量输送至制冷系统的制冷剂进行冷凝放热.测试段两端进出口分别设置了观察管用于观察流型的变化,并通过高速摄像仪进行记录.

传热测试段具体结构及实物图如图2所示,测试段为一块尺寸100 mm×20 mm×200 mm的紫铜板.铜板上下端分别打通圆形流道作为测试工质流经的实验测试管段(直径4 mm)和制冷剂流过的吸热段(直径7 mm).通过在铜板上打孔(直径1.8 mm)并按规律布置12支PT100温度计形成测温阵列,获取铜板的二维温度场,再根据绝热条件下的傅里叶导热定律推算出铜板上测试工质壁面的热流密度及壁面温度,从

而获得测试段流动冷凝的传热系数.测试段进出口安装有压力和压差传感器,分别用于测量测试段进出口的绝对压力及压降值.测试段后还设置了绝热压降实验段用于测量流体的摩擦压降.

1.2 测量方法

流动冷凝传热系数可由下式计算得到:

$$h = \frac{q}{T_{\text{sat}} - T_w}, \quad (1)$$

式中, T_{sat} 为工质饱和温度, K, 其值通过测量测试段进出口压力,并取两者平均值查找Refprop V8.0确定; q 为热流密度, W/m^2 ; T_w 为铜板测试工质端管内壁面温度, K.

假设铜板为二维导热,通过12支PT100温度计测量其相应的温度值,并利用Derrick和Grossman提出的回归模型计算整块铜板的温度场,模型方程具体如下所示:

$$T(r, \theta) = A_0 + \sum_{n=1}^{\infty} r^n [A_n \cos(n\theta) + B_n \sin(n\theta)]. \quad (2)$$

Kedzierski^[9]提到,回归模型所含参数量应小于测量数据点的一半,否则模型容易出现错误.因此,对于本文12个温度测点,取模型参数个数为5个,并将式(2)转换成直角坐标系,取 $n=2$ 得铜板的二维温度分布模型方程如下:

$$T = A_1 + A_2x + A_3y + A_4(x^2 - y^2) + 2A_5xy, \quad (3)$$

式中, x, y 分别为温度计布置的横纵坐标值, m; A_1, A_2 ,

图1 (网络版彩色)流动冷凝实验系统流程图

Figure 1 (Color online) Schematic view of the experimental apparatus

图2 (网络版彩色)传热测试段示意图。(a) 结构图; (b) 实物图
Figure 2 (Color online) Schematic view of the heat transfer test section. (a) Structure diagram; (b) photograph

A_3 , A_4 和 A_5 为模型所求参数。则测试工质壁面的热流密度 q 和壁面温度 T_w 可分别由下式求得:

$$q = - \frac{\int_0^{x_L} k \frac{\partial T}{\partial y} dx}{x_L} \bigg|_{y=0, x_L=0.1} = -k(A_3 + A_5 x_L) \bigg|_{x_L=0.1}, \quad (4)$$

$$T_w = \frac{\int_0^{x_L} T dx}{x_L} \bigg|_{y=0, x_L=0.1} = A_1 + \frac{A_2}{2} x_L + \frac{A_4}{3} x_L^2 \bigg|_{x_L=0.1}, \quad (5)$$

式中, k 为铜板的导热系数, $W/(m \cdot K)$; x_L 为铜板长度, m 。

1.3 不确定度分析

实验中各测量装置的型号、测量范围和测量不确定度如表1所示。根据文献[10]中的计算方法, 传热系数不确定度可由下式计算得到:

$$\frac{u(h)}{h} = \sqrt{\left[\frac{u(q)}{q} \right]^2 + \left[\frac{u(T_w)}{T_w - T_{sat}} \right]^2 + \left[\frac{u(T_{sat})}{T_w - T_{sat}} \right]^2}, \quad (6)$$

式中, $u(T_{sat})$ 为工质饱和温度不确定度, K , 本实验工

质饱和温度是通过测量测试段进出口压力, 并取两者平均值查找Refprop V8.0确定, 根据压力测量及Refprop数据库的不确定度合成得到在实验工况下其最大值为 0.03 K ; $u(q)$ 为热流密度不确定度, W/m^2 ; $u(T_w)$ 为壁面温度不确定度, K 。根据文献[11]中的计算方法, 热流密度和壁面温度的不确定度主要与温度计本身测量不确定度和12支温度计的排布有关。本实验所使用的温度计测量不确定度为 $\pm 0.1 \text{ K}$, 长度测量的不确定度为 $\pm 0.02 \text{ mm}$, 计算可得在实验工况下 $u(q)$ 最大值为 452.03 W/m^2 , $u(T_w)$ 最大值为 0.09 K 。取置信区间为95%, 得到流动冷凝传热系数的最大扩展不确定度为3.33%。

1.4 实验装置验证

为了验证实验系统的准确性和可靠性, 对丙烷分别进行了单相流动传热系数和饱和流动冷凝传热系数的实验, 并与相关文献上的实验数据进行了对比。如图3所示, 将丙烷的单相流动传热系数实验数据与Dittus-Boelter(1930)方程的计算值进行比较, 得到其平均偏差在12%以内, 表明了本实验系统数据测量的准确性。图4所示的是丙烷饱和流动冷凝传热系数的测量结果, 与文献[2,12]中的实验数据进行比较得到其具有相似的变化趋势。实验结果与文献数据间的差异主要与管内径、质量流率和饱和压力等实验参数的不同造成的, 但这些参数对饱和流动冷凝传热系数的影响近似相同, 这种一致性证明了本实验系统数据测量的可靠性。

2 实验结果分析及关联式对比

2.1 实验结果

本文对乙烷在饱和压力范围为 $1.01 \sim 2.56 \text{ MPa}$,

表1 测量参数的不确定度

Table 1 Measurement instruments and their uncertainties

参数	仪器	测量范围	测量不确定度
温度	PT100温度计	80~373 K	$\pm 0.1 \text{ K}$
压力	Mensor 6000压力传感器	0~3 MPa	0.02%
压差	GE UNIK 5000压差传感器	0~100 kPa	0.04%
质量流量	EMERSON高准科里奥利流量计ELITE系列	0~108 kg/h	0.1%
直流电压	Keithley 2700数据采集器	0~300 V	0.005%
电流	ZW1659T电流表	0.03~15 A	0.2%
长度	游标卡尺	0~300 mm	$\pm 0.02 \text{ mm}$

图3 丙烷单相流动传热系数实验数据
Figure 3 Single-phase heat transfer results for propane

质量流率范围为100~257 kg/(m² s), 干度范围为0~0.8, 管内径为4 mm的水平管内饱和流动冷凝传热特性进行了实验研究, 分析了质量流率、干度和饱和压力对传热系数的影响。

如图5所示, 饱和压力分别大约为1, 1.5, 2和2.5 MPa时, 不同质量流率下乙烷饱和流动冷凝传热系数随干度的变化。可以看到, 传热系数随着质量流率和干度的增大而增大。对于较高质量流率, 传热系数

图4 (网络版彩色)丙烷饱和流动冷凝传热系数实验数据与文献数据的对比

Figure 4 (Color online) Comparison of condensation heat transfer coefficients for propane with other literature results

随干度增大的趋势较为明显。这是因为在高质量流率和干度下, 乙烷大多处于环状流, 对于该流型, 传热主要通过对流换热实现, 而对流换热主要受流速的影响, 质量流率越大, 流速越大, 所以传热系数也越大。另外, 干度增大会使得液膜厚度减小, 且气相流速会增大, 增强了液膜的湍流度, 导致传热系数增大。而在低干度和质量流率下, 干度和质量流率对传

图5 (网络版彩色)乙烷流动冷凝传热系数在不同质量流率下随干度的变化。(a) $p \approx 1$ MPa; (b) $p \approx 1.5$ MPa; (c) $p \approx 2$ MPa; (d) $p \approx 2.5$ MPa
Figure 5 (Color online) The change of condensation heat transfer coefficient with vapor quality for several mass fluxes. (a) $p \approx 1$ MPa; (b) $p \approx 1.5$ MPa; (c) $p \approx 2$ MPa; (d) $p \approx 2.5$ MPa

热系数的影响均较小. 这是因为在低干度和质量流率下, 乙烷流型大多为非环状流, 对于该流型, 管底部一般形成较厚的液层, 而传热热阻主要与该液层的厚度有关, 因此减弱了干度和质量流率对传热系数的影响. 饱和压力大约为2.5 MPa时(图5(d)), 对于低干度下质量流率大约为200和250 kg/(m² s)的传热系数明显比100和150 kg/(m² s)的大, 主要是因为前者的热流密度大于后者, 增强换热, 使得传热系数增大.

如图6(a)所示, 对于质量流率大约为100 kg/(m² s), 传热系数几乎不随饱和压力的增大而变化, 其值均较小. 这是因为在这个质量流率下, 乙烷流型大多为非环状流, 该流型下的传热主要是通过液相导热实现, 使得传热系数很小, 且低质量流率导致两相流速较低, 减弱了饱和压力对传热系数的影响. 对于较高质量流率(图6(b)和(c)), 传热系数则随饱和压力的增大而减小. 这是因为乙烷气相密度随饱和压力的增大而增大, 使得在一定质量流率下气相流速减小而液膜厚度增大, 而气相速度减小还会导致液膜湍流度减弱, 最终使得传热系数减小.

2.2 实验数据与文献关联式比较

本文选取了9种常用的计算饱和流动冷凝传热系

数的关联式与乙烷的实验结果进行对比. 其中, θ 为实验结果与关联式预测结果的绝对平均偏差在30%以内的数据量占总实验数据量的比例, 而绝对平均偏差(MARD)的表达式如下:

$$\text{MARD} = \frac{1}{n} \sum_{i=1}^n \left| \frac{h_{\text{cal}} - h_{\text{exp}}}{h_{\text{exp}}} \right| \times 100. \quad (7)$$

对比结果如表2及图7所示, Chato模型和Wang等人模型对本实验的预测结果较好, 绝对平均偏差均在35%以内, 而其他关联式偏差均较大, 且大多是预测值大于实验值. 由图7(a)可得, Chato模型和Wang等人模型对低传热系数的实验数据预测明显优于高传热系数, 分析认为这主要是因为本实验乙烷流型大多处于非环状流, 而Chato模型和Wang等人模型是基于非环状流提出的, 其余模型则大多基于环状流提出, 因此对实验结果的预测较差, 且预测值大多偏大. 另外, 现有的模型大多基于常温工质提出, 对于乙烷这种低温工质的预测存在一定的偏差.

3 总结

本文实验研究了乙烷在水平管内的饱和流动冷凝传热特性, 分析了质量流率、干度和饱和压力对传

图6 (网络版彩色)乙烷流动冷凝传热系数在不同饱和压力下随干度的变化. (a) $G \approx 100$ kg/(m² s); (b) $G \approx 150$ kg/(m² s); (c) $G \approx 200$ kg/(m² s)

Figure 6 (Color online) The change of condensation heat transfer coefficient with vapor quality for several saturation pressures. (a) $G \approx 100$ kg/(m² s); (b) $G \approx 150$ kg/(m² s); (c) $G \approx 200$ kg/(m² s)

表 2 乙烷饱和流动冷凝传热系数实验数据与关联式计算结果的对比偏差

Table 2 Deviations between calculated and experimental heat transfer results for ethane

关联式模型	MARD(%)	θ (%)
Wang等人模型(2002) ^[13]	31.01	54.13
Chato模型(1962) ^[14]	33.97	46.33
Koyama等人模型(2003) ^[15]	57.67	29.82
Shah模型(2009) ^[6]	78.18	21.10
Huang等人模型(2010) ^[16]	84.31	11.01
Cavallini等人模型(2006) ^[17]	108.76	1.38
Rosson和Myers模型(1965) ^[18]	115.73	15.60
Dobson和Chato模型(1998) ^[19]	119.01	8.72
Haraguchi等人模型(1994) ^[20]	168.09	0.46

热系数的影响,并选取了9种常用的计算饱和流动冷凝传热系数的关联式与实验结果进行对比,得到以下结论:

(1) 传热系数随着质量流率和干度的增大而增大.对于较高质量流率,传热系数随干度增大的趋势较为明显.而在低干度和质量流率下,干度和质量流率对传热系数的影响均较小.

(2) 对于较低质量流率,传热系数几乎不随饱和压力的增大而变化,其值均较小.对于较高质量流率,传热系数则随饱和压力的增大而减小.

(3) Chato(1962)和Wang等人(2002)的模型关联式对实验数据的预测较好,平均偏差均在35%以内.

图 7 (网络版彩色)乙烷流动冷凝传热系数实验值与关联式计算值的对比

Figure 7 (Color online) Comparison between the experimental condensation heat transfer coefficients and the calculated data for ethane

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Summary for “水平管内乙烷饱和流动冷凝传热实验”

Experimental investigation on flow condensation heat transfer of ethane in a horizontal tube

ZHUANG XiaoRu^{1,2}, GONG MaoQiong^{1*}, ZOU Xin¹, CHEN GaoFei¹ & WU JianFeng¹

¹ Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China;

² University of Chinese Academy of Sciences, Beijing 100049, China

* Corresponding author, E-mail: gongmq@mail.ipc.ac.cn

In recent years, due to the environmental problems of traditional chlorinated refrigerants, it has become an urgent task to search for suitable substitutes. Hydrocarbons, with zero ozone depleting potential, low global warming potential and high thermodynamic performance, are good alternative refrigerants in refrigerators and heat pump systems. In addition, hydrocarbons also the important parts of the natural gas. As one kind of hydrocarbons, ethane and its mixtures have been widely applied in the mixed refrigerant throttling refrigeration systems and recommended to be used in the cascade refrigeration systems to replace R13 and R503. As the heat transfer characteristics of ethane play important parts in the design of the heat exchangers in refrigeration cycles, the heat transfer coefficients during condensation should be well examined and analyzed. Although there are massive experimental studies of heat transfer on flow condensation of hydrocarbons in horizontal tubes, the published experimental investigations for ethane are rare. Therefore, it's desirable to conduct an experimental investigation on condensation heat transfer of ethane in a horizontal tube and find suitable correlations. In this paper, condensation heat transfer of ethane was studied experimentally in a horizontal tube with inner diameter of 4 mm. The heat transfer test section was a copper plate (100 mm× 20 mm× 200 mm) embedded twelve four-wire PT100 platinum resistance thermometers. Using the assumption of two-dimensional heat conduction for the copper plate, both the wall temperature and heat flux could be obtained. The tests were carried out at saturation pressures from 1.01 MPa to 2.56 MPa for mass fluxes from 100 kg/(m² s) to 257 kg/(m² s) and vapor qualities from 0 to 0.8. The uncertainties for the heat transfer coefficient with a 95% confidence interval were less than 3.33% under the employed operation conditions. The effects of mass flux, vapor quality and saturation pressure on condensation heat transfer coefficient were examined and analyzed. Some conclusions can be drawn that (1) in relative high mass fluxes and vapor qualities, the condensation heat transfer coefficients increased with the increasing mass flux and vapor quality while decreased with the increasing saturation pressure; (2) in relative low mass fluxes and vapor qualities, the vapor quality, mass flux and saturation pressure had a little influence on condensation heat transfer coefficients. In addition, the experimental data were compared with nine well-known correlations of condensation heat transfer coefficient. The comparison results showed that Chato (1962) correlation and Wang et al. (2002) correlation relatively agreed well with the experimental data with the mean absolute relative deviations less than 35%. The other correlations showed larger predicted results than the experimental data with the mean absolute relative deviations more than 55%. And the Chato correlation and Wang et al. correlation were both in good agreement with the relative low heat transfer coefficients rather than the relative high heat transfer coefficients.

flow condensation, ethane, heat transfer coefficient, correlation, horizontal tube

doi: 10.1360/N972016-00104