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航空煤油在微通道中传热性能的实验研究

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摘　要:此前对微通道传热性能研究所用的实验工质绝大多数属于低粘性流体,针对高粘性流体的研究很少。本研究以航空煤油和水为实验工质,在层流状态范围 Re 数为 10-100,对两种流体在微通道中的传热性能进行了实验研究。铝基微通道阵列包括163条横截面尺寸为1 mm×1 mm、长度400 mm的微通道。微通道长径比 $l/D_h=400$。实验发现,两种流体的实验结果平均 Nu 数均基本不随 Re 数变化,但小于理论预测值。煤油和水在实验微通道中的传热性能没有本质的区别。在测量误差范围内,航空煤油总体平均 Nu 数比水大10%左右,分别为2.80和2.59。

关　键　词:微通道热沉;液体冷却;传热强化;航空煤油

中图分类号:TK124　　文献标识码:A

符号说明

λ—导热系数/W·(m·K)$^{-1}$

υ—运动黏度/m^2·s^{-1}

ρ—密度/kg·m^{-3}

c_p—比定压热容/J·(kg·K)$^{-1}$

h—对流换热表面传热系数/W·m^{-2}·K^{-1}

A_w—每个微通道换热面积,包括底面和两个侧面/m^2

D_h—当量直径/m

G—微通道的总质量流量/kg·s^{-1}

N—并联通道数

Nu—努塞尔数

Re—雷诺数

T_{in}—微通道流体的入口温度/K

T_{out}—微通道流体的出口温度/K

T_m—微通道流体的平均温度/K

T_w—微通道壁面平均温度/K

u—平均流速/m·s^{-1}

l—微通道长度/m

引　言

作为一种先进的传热方式,微通道热沉(MCHS)技术有望解决工程中的各种高热流密度的传热难题。就换热工作介质而言,绝大多数的研究都选择去离子水。文献[1]最早使用水在其加工的微尺度冷却器耗散掉了790 W/cm^{2}的热功率。文献[2~3]的研究是以水作为工质,而文献[4~5]采用的是制冷剂R114和R134a,在一些对比研究中则使用了液氩做为工质[6]。

文献[7]对水和乙醇在微管中的传热试验表明,两种流体没有明显的差别,且都符合常规尺度的理论。文献[8]采用水与乙醇混合物、FC-72两种工质在微通道中的试验发现,制冷剂种类对换热性能的影响特别大。文献[9]对水、甲醇、50%水+50%甲醇、乙醇4种工质在微通道中的换热特性进行研究。文献[10]对比了水和HFE-7100流体在陶瓷微通道中的传热特性,文献[11]则研究了水和甲醇在硅基微通道中的换热性能。

以上研究中,换热介质绝大多数都属于低粘性流体,针对高粘性流体的研究很少。航空煤油是飞机自身携带的大量液体,在航空飞行器的性能优化方面具有很大的应用潜力。文献[12]以航空煤油为工质,用微通道热沉冷却电子舱的专利技术。

本研究用实验的方法,对比研究水和航空煤油在微通道中的流动和换热的特性。

1　实验系统与实验装置

1.1　实验系统

实验的整体系统如图1所示,由保温油箱、油泵、球阀、针形阀、过滤器、流量计、恒温水浴、换热段、和测量仪器等组成。航空煤油从油箱经过油泵进入两条支路,一条是经过球阀回到保温油箱的旁路,另一条是流经球阀和针形阀的主路,其中针形阀用来精细调节流量。然后在主路依次经过30 μm过滤器和流量计后进入恒温水浴,之后在换热段与等热流热源进行换热,最后流回油箱。实验系统中不需要换热的部位都用保温棉等物进行保温。

在实验中煤油管路的煤油经过恒温水浴中的盘管与管外流动的自来水换热。

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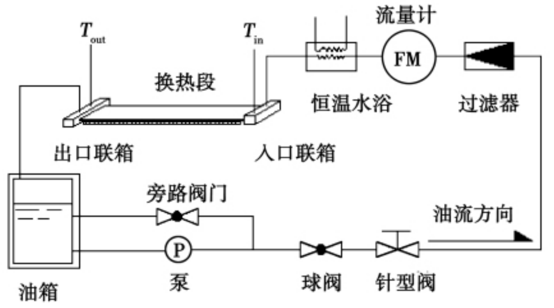

图 1　实验系统

Fig. 1 Schematic drawing of the test system

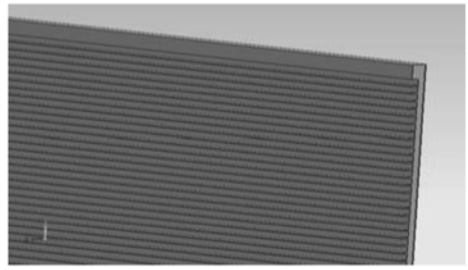

图 3　钎焊前的铝基微通道局部模型

Fig. 3 Drawing showing the aluminium-based microchannel partial model prior to the brazing

恒温水浴里通过增大自来水的流量充分带走油泵、环境、微通道传过来的热量，在微通道入口联箱内铂电阻监测温度 T_{in} 恒定 20 min 后认为实验达到稳定状态，可以用采集到的数据分析实验。根据铂电阻精度，相差在 ±0.1 ℃范围内。

1.2　实验段模型

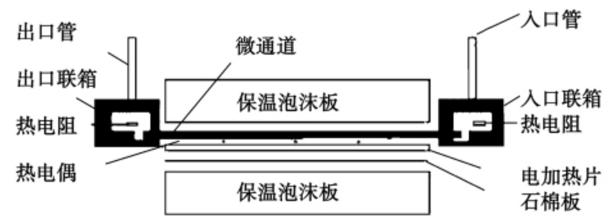

图 2　换热段示意图

Fig. 2 Schematic drawing of the heat exchange section

换热段入、出口联箱斜对角各有一个热电阻埋入孔，孔径 20 mm，深 10 mm。入、出口联箱材料均为表面光滑透明抗煤油腐蚀的塑料。在入、出口联箱中放置高精度铂电阻监测进出口温度，内含有台阶形结构的流道，以保证流体可以较为均匀的进入各个微通道。入、出口联箱尺寸相同。“管路 - 联箱 - 微通道 - 联箱 - 管路”流道结构使用商业软件 Fluent 进行流场模拟，结果显示该流道可以很好的将管路中的流体均匀分配到各个微通道。微通道换热片与联箱用 AB 胶密封连接。

组装时，在微通道实验片底面与硅橡胶电加热片上表面间涂以耐热高导热硅脂，以增加传热效率。

联箱、微通道换热片周围包括和其相连接的管路均包敷石棉板，泡沫板等绝热、耐热材料以减少热损失。

实验中，航空煤油从微尺度通道流过，电加热片则在下表面充当等热流热源，两者通过微通道换热片进行换热。

钎焊前的铝基微通道局部模型如图 3 所示。用线切割技术在一块 400 mm × 200 mm × 2 mm 的铝板上加工 163 条平行通道，微通道截面 1 mm × 1 mm，长 400 mm，肋厚 0.2 mm。两边厚度各 2.3 mm，和一块 400 mm × 200 mm × 2 mm 铝板钎焊连接，密封。此微通道截面当量直径为 1 mm，按照通常分类，产生微尺度效应的临界当量直径约为 1.2 mm，故属于微尺度范畴。微通道两侧连接入、出口联箱。

1.3　参数测量

在微通道出入口联箱中各有一个高精度铂电阻温度传感器，用来测量微通道进出口流体的平均温度，精度 ±0.08 K。微通道底面和电加热片之间贴有两排各 5 个 K 型热电偶，直径 0.5 mm，精度 ±0.7 K；采用涡轮流量传感器测量，精度 0.2%，在实验前用电子天平校验。以上流量和热电阻信号、热电偶信号接入采集卡，铂电阻传感器接入专用采集模块，用数据采集系统同时驱动并在屏幕上同步显示。检测自来水进出口温度的铂电阻只需接高精度显示仪表。

在实验中，改变入口流量，得到实验状态下不同 Re 对应的换热系数 h 和 Nu 数。

2　数据处理和误差分析

2.1　数据处理

根据热平衡关系式：

$$h(T_w - T_m) N A_w = G c_p (T_{out} - T_{in}) \tag{1}$$

式中：N—并联通道数，$N = 163$；A_w—每个微通道换热面积，包括底面和两个侧面；G—微通道的总质量流量；T_{in} 和 T_{out}—微通道流体进出口处的平均温度。

流体密度 ρ 和黏度 υ 等热物性以进出口的平均温度 $T_m = (T_{in} + T_{out})/2$ 作为参考温度。

$$T_w = \frac{1}{10}\sum_{i=1}^{10} T_i \tag{2}$$

$$Nu = \frac{hD_h}{\lambda} \tag{3}$$

则有:

$$Nu = \frac{Gc_p D_h(T_{in} - T_{out})}{N\lambda A_w(T_w - T_m)} \tag{4}$$

$$Re = \frac{uD_h}{v} = \frac{GD_h}{\rho N A_w v} \tag{5}$$

2.2 误差分析

根据误差传递得出 Re 数和 Nu 数等参数的最大误差。如表1所示。Nu 数的误差不超过9%。

表1 误差表(%)

Tab.1 Table of errors

参数		相对误差
G	油	0.8
	水	6.0
T_{in}	油	0.5
	水	0.5
T_w	油	1.9
	水	2.9
$T_w - T_m$	油	4.6
	水	10.7
T_{out}	油	0.4
	水	0.4
$T_{out} - T_{in}$	油	3.2
	水	3.2
T_m	油	0.4
	水	0.5
Re	油	0.02
	水	0.02
Nu	油	8.7
	水	20

3 结果与讨论

3.1 理论结果

实验时 Re 数在层流状态。微通道长径比 $l/D_h = 400$,在如此长径比的情况下,入口段效应对整体传热性能的影响可以忽略[9,13]。根据传热学基本理论,管内充分发展层流边界层的传热 Nu 数为常数。但本实验的热边界条件不同于常见的壁面条件,即微通道顶部壁面既不是与底部壁面相同的等热流加热,也不是一般意义上的绝热壁面[14],并未有相关的理论解析解。需要说明的是,理论上层流充分发展管流的传热 Nu 数并不随流体的热物性有任何变化。

3.2 实验结果

通过对水和航空煤油的实验数据的整理,并和上面提到的两种典型热条件(四面加热模式和三面加热、顶面绝热模式)的解析解进行对比[14],结果如图4所示。

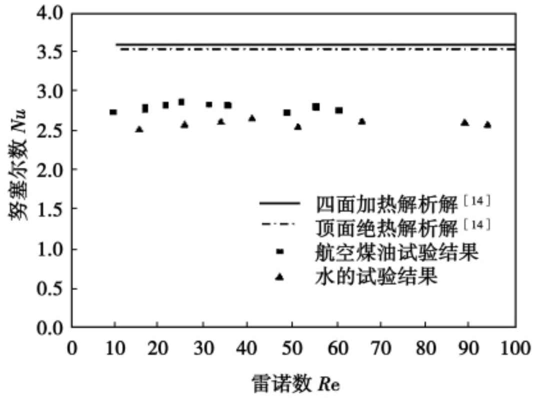

图4 Nu 数随 Re 数变化关系

Fig.4 Change of Nu with Re

根据前面的介绍,虽然实验壁面热条件下没有解析解,但从图4中可以看出,四面加热模型和顶面绝热模型的 Nu 数解析解相近。而实验条件下顶面可以通过壁面导热得到热量,传给通道中的流体,相当于比顶面绝热模型强化传热,故其 Nu 数应该略大于文献[14]的顶面绝热结果。然而水和航空煤油的试验 Nu 数均小于该分析结果约25%。是由于壁面粗糙度在 Re 数较低时使传热得到弱化[2]。因为在低 Re 数时,粗糙元的凹坑内会形成无法跟随主流流动的死区或回流区,弱化了凹坑附近的传热能力。文献[9]的试验所得4种流体在微通道中等热流加热的平均 $Nu = 2.62$,与本试验结果基本持平($Nu = 2.59$),也小于文献[14]的结果。而其试验 Re 数范围也在100以下,与本研究试验条件接近。

同时,热损失等因素也造成了一定影响。出口联箱的热损失降低了所测量温度 T_{out} 的值。从图2结构图可以看出,出口联箱的结构尺寸相对于流过微通道的流体流量比较大。联箱中的流体通过壁面和热电阻导线等持续向环境散热,而从微通道出来的温度较高的流体流入出口联箱,和其中的大量流体掺混后排出。故测得的 T_{out} 实际上感应的是出口联箱中探头周围流体的温度,要略低于实际微通道出口流体的温度。

从图 4 还可以看出，在试验中得到的水和航空煤油的 Nu 数均近似不随 Re 数变化。固定斜率为零，对两组试验的试验点使用最小二乘法进行线性拟合，如图 5 所示。

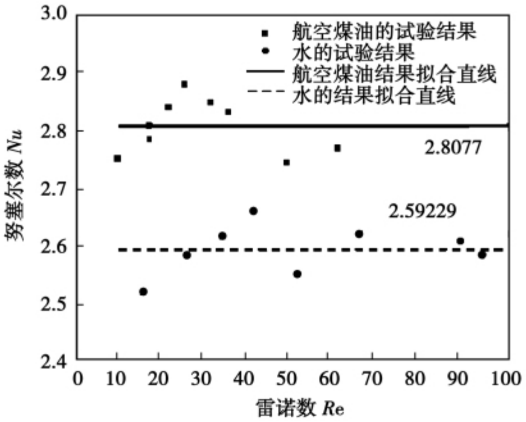

图 5 对两种流体试验结果的拟合直线

Fig. 5 Fitting curves of the test results of two kinds of fluid

航空煤油和水的拟合平均 Nu 数分别为 2.81 和 2.59，标准差 0.01。Nu 数与 Re 数的近似无关性说明在试验条件下两种流体仍然符合常规尺度充分发展管流的特征，从这个意义上说，航空煤油和水的传热特性之间并无本质区别。而前人对水在微通道中的传热特性研究的已经比较充分，可以进行借鉴。

从上图 5 还可以看出，航空煤油的所有试验点的平均 Nu 数大于水的平均结果约 10%，这是因为在实际微通道中，加工表面的粗糙度是不可避免的。在粗糙微通道中即使是层流充分发展流动，其速度矢量与温度梯度也并非处处垂直，根据场协同原理[15]，表现出传热性能与流体物性的相关性。而这种流体热物性影响的程度，尚需进一步的研究。

4 结 论

在本研究实验条件下，通过对水和煤油在微通道中传热性能的研究，得到如下结论：

（1）航空煤油和水的 Nu 数在试验条件下都基本不随 Re 数变化；

（2）两种流体的 Nu 数结果均小于理论预测值；

（3）在测量误差范围内航空煤油总体平均 Nu 数大于水的结果 10% 左右；

（4）在实验条件下，航空煤油并未表现出与水在换热性能上本质的差异。在工程上可以借鉴水的试验结果，在科学上则可以通过对粗糙度效应的研究，考察流体热物性影响传热性能的机理和程度。

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By using the commercial software ANSYS CFS, numerically calculated were the heat exchange characteristics of the cooling air inside a straight ribbed rectangular channel and compared were the calculation results with the test data obtained by Han. Furthermore, the influence of Reynolds and the angle of ribs on Nusselt number was also analyzed. It has been found that the average Nusselt number obtained from the numerical calculation assumes an identical variation tendency to the test values. The calculation results, however, were bigger than the test values. Due to the flow disturbance role played by the ribs, two vortexes will be produced in the zone between any two ribs, enhancing the heat exchange between the cooling air and the solid wall surfaces. With an increase of Reynolds and Nusselt number, the average friction resistance coefficient will also increase. When the angle of ribs falls in a range from 45 to 60 degrees, the intensified convection heat exchange effectiveness in the cooling channel is assessed as the best.
Key words: blade cooling, rectangular channel, flow and heat exchange

以水为工质的 EHD 强化管内对流换热实验研究 = Experimental Study of the Electrohydrodynamically (EHD)-intensified Convection Heat Exchange Inside a Tube With Water Serving as the Working Medium **[刊,汉]** YANG Xia, ZHANG Jie, WU Yan-yang, ZHANG Tao (College of Electromechanical Engineering, Wuhan Engineering University, Wuhan, China, Post Code: 430073) // Journal of Engineering for Thermal Energy & Power. - 2011, 26(5). - 547 ~ 550

With water serving as the working medium, experimentally studied was the EHD (electrohydrodynamics) intensification mechanism controlling the convection heat exchange inside water jacket heat exchanger tubes. During the test, a direct current type high voltage electrode was mounted at the center of the water jacket heat exchanger tubes and the voltage of the electrode was within a range from DC 0 ~ 40 kV. A total of five groups of combined intensification test were performed at different flow rates and voltages respectively. The test results show that under the condition of different flow rates inside the tubes, the electric field all played intensification role to various extents on the heat conduction process inside the tubes. When the flow rate is 0.1 m^3/h, the intensification coefficient of the electric field θ attains its maximal value, being up to 1.224. When the flow rate is 1.0 m^3/h, the above-mentioned coefficient θ attains its minimal value, verifying that the electric field plays an intensification role on the convection heat conduction process with water serving as the working medium. It has also been found, however, that the intensification effectiveness achieved by the electric field enjoys a specific feature, which is susceptible to any change of the flow rate and at an identical flow rate, there exists an optimum intensification voltage value. It is not true that the higher the voltage value the better the intensification effectiveness. **Key words:** electrohydrodynamics (EHD), convection heat exchange, intensified heat transfer, electric field

航空煤油在微通道中传热性能的实验研究 = Experimental Study of the Heat Transfer Performance of Aviation Kerosene in Microchannels **[刊,汉]** CHEN Hai-gang, HUANG Yong, MIAO Hui (Key Laboratory on Aero-engine Aerodynamics and Thermodynamics, College of Energy Source and Power Engineering, Beijing University of Aeronautics and Astronautics, Beijing, China, Post Code: 100191) // Journal of Engineering for Thermal Energy

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The majority of working media used in tests by the predecessors to study the heat transfer performance of microchannels pertain to fluids with a low viscosity and very few pertains to fluids with a high viscosity. With aviation kerosene and water serving as the working medium respectively in the test and Reynolds number in the laminar flow state ranging from 10 to 100，the heat transfer performance of two fluids in microchannels was experimentally studied. The aluminium-base microchannel array included 163 microchannels with their section sizes being 1 mm × 1 mm and the length being 400 mm. The length/diameter ratio l/D_h = 400. Under the condition of such a length/diameter ratio，the influence of the inlet section on the overall heat transfer performance can be neglected. It has been found from the test results during the test that the average Nusselt numbers of two fluids are all basically not varied with a change of Re，however，smaller than the theoretical predictive values. From such a sense，the heat transfer performances of kerosene and water have no substantial difference. In addition，within the measurement error range，the overall average Nusselt number of aviation kerosene is about 10% higher than that of water and their average Nusselt numbers are 2.80 and 2.59 respectively. **Key words:** microchannel heat sink，liquid cooling，heat transfer intensification，aviation kerosene

散堆拉西环蓄热室热工特性的数值模拟 = Numerical Simulation of the Thermotechnical Characteristics of a Randomly Packed Rasching Ring Heat Accumulating Chamber **[刊，汉]** LIU Ying-hui，ZHANG Zhi (College of Architectural Engingering Anhui Institute of Technology，Ma'anshan，China，Post Code: 243002) //Journal of Engineering for Thermal Energy & Power. －2011，26(5). －555～560

In the light of the problems present in commonly used heat accumulative bodies，presented was a technical imagination for heat accumulative elements destined for heat accumulative chambers. Through establishing a mathematical model，a simulation study was performed of the thermotechnical characteristics of a randomly packed Rasching ring heat accumulative chamber. The research results show that at different times，the temperature distribution of the heat accumulative body and gas roughly assumes the shape of a logrithm curve. With a decrease of the direction diversion duration and the flow speed of the gas and an increase of the length of the heat accumulative chamber，the temperature efficiency and thermal one will gradually rise. The average temperature of air at the outlet depends on the lowest temperature of the air at the outlet while that of the flue gas depends on its highest temperature at the outlet. To attain a relatively high waste heat recovery rate，a relatively high air temperature at the outlet and a relatively low flue gas temperature at the outlet will be necessarily guaranteed. **Key words:** heat accumulative technology，Rasching ring，thermotechnical characteristics，temperature，efficiency

锅炉管内腐蚀结垢过程的实验研究 = Experimental Study of the Corrosion and Fouling Process In Boiler Tubes **[刊，汉]** PEI Wei，WANG Shu-zhong，TONG Zhen-xia (National Key Laboratory on Multi-phase Flows in Power Engineering，Xi'an Jiaotong University，Xi'an，China，Post Code: 710049) // Journal of Engineering for