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紧凑高效型水平管束降膜蒸发换热器的实验研究

刘振华, 张　彤
(上海交通大学 机械与动力工程学院, 上海　200030)

摘　要: 在大气压条件下使用单列和 3 列叉排光滑管和滚压强化换热管紧凑管束进行了水降膜蒸发换热实验, 确认了滚压管在中, 低热负荷范围内能够增强换热系数 3～4 倍, 有很好的沸腾强化换热性能。管间距及液膜溅射损失对蒸发换热特性影响很小。同时也考察了单列和 3 列管束换热特性间的差异。实验发现这种差异在低雷诺数区域时更加明显。

关　键　词: 强化换热; 蒸发; 沸腾; 降膜; 紧凑型换热器
中图分类号: TK124　　文献标识码: A

1　前　言

海水淡化蒸发器, 太阳能或余热吸收式制冷机, 以及各种工业设备中的蒸发换热器目前大多使用水平管束降膜式对流蒸发方式, 对此类降膜式对流蒸发换热器已有很多理论和实验研究[1~8]。目前传热管基本使用光滑管或低肋管, 低肋管作为目前蒸发换热器的主要强化手段, 在低膜雷诺数时换热强化效果较好, 但在大膜雷诺数时强化效果则不显著[6~7], 如将传热管与液膜间的换热形态由强制对流蒸发变为沸腾蒸发, 不仅单管的换热系数大幅度提高, 而且不必考虑流速影响, 管间距可以极为紧凑。

在蒸发器实际运行的中、低热负荷范围内, 光滑管或低肋管表面都是不会发生沸腾现象, 必须采用特殊的沸腾强化管。对海水这样含高杂质的工质, 因为烧结管, 特殊翼片管等商业化强化管的微通道结构很容易被堵塞, 这些强化管并不适用。而机械滚压管具有加工简单, 耗材少的优点, 而且表面不易被杂质污染。本文使用光滑管和滚压管两种管束进行了降膜蒸发换热实验, 确认了滚压管在中、低热负荷范围内具有很好的沸腾强化换热性能, 为紧凑高效型管束降膜式蒸发换热器提供了可行方案。

以往的管束降膜蒸发实验几乎都使用单列管排。由于降膜的溅射损失, 下部管子的实际降膜流量在不断减少。而在实际装置中, 都是多列管排, 从一根管子上溅射的液体会溅射到相邻管排下方的管子上。每根管子上接受的液流量不会变化, 但是管子上液膜流动形态变得十分复杂, 这种流动形态的不同可能会对传热产生较大影响。本文使用单列和 3 列两种管束进行了实验, 考察了两种管束换热特性间的差异。

2　实验装置

实验装置如图 1 所示, 高位供液箱内有加热器将工质加热到接近饱和温度。工质流过流量调节阀和浮子式流量计后, 由辅助加热器加热达到饱和温度, 进入供液器。工质从供液器底部的一排喷孔(孔径 1 mm, 孔距 2 mm)中流出, 在下面的传热管束上形成液流。所有实验中供液器距传热管顶部距离固定在 5.0 mm。产生的蒸汽由冷凝器冷凝。使用后的饱和液体排入排液箱后再送回供液箱。传热管束和供液器排列如图 2 所示。共三竖列, 每列 6 根管, 中间一列为测量管。在进行单列降膜换热实验时, 两侧两列管子拆除。传热管是外径 18 mm, 内径 12 mm, 总长 150 mm 的紫铜管, 内插处直径 12 mm 的电热棒, 铜管端面圆周上开 4 个直径 1.1 mm 的小孔, 深度到水平加热管的中央位置。孔内插入直径 1.0 mm 的铠装式热电

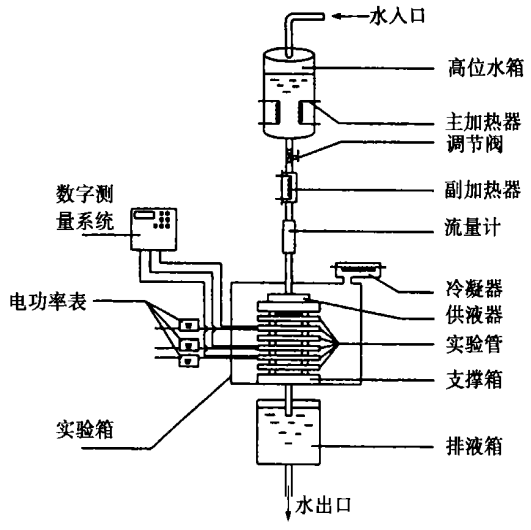

图 1　实验系统图

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作者简介: 刘振华(1956－), 男, 江苏无锡人, 上海交通大学教授, 博导.

偶。铜管, 电热棒和热电偶间添满焊锡。热负荷由加热功率换算得出, 表面温度由热负荷与铜管内4 根热电偶平均温度根据一维稳态圆柱导热方程计算。所有的热电偶连接到一台数字采集系统上。

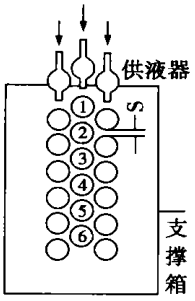

图2　管束排列示意图

图 3 显示了单列管束中每根管子上面实际液流量的测量方法以及各管上部液流量的符号定义。测量在不加热条件下进行, 每次将要测量位置的加热管去掉, 换上一根相同外径的半圆薄不锈钢管, 不锈钢管接一个量液器, 在一定间隔时间测量接受的总流量, 由此换算出实际降膜流量。供液器出口流量直接由流量计测量。

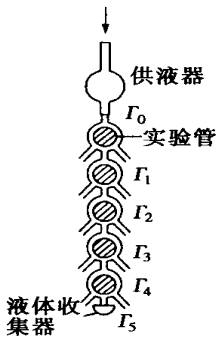

图3　单列管束内各管实际液流量测量方法示意图

滚压管用外径 18 mm 的紫铜管加工而成, 以加工前的表面为基准面。图 4 给出了滚压管的外形照片。

实验在大气压下进行, 实验工质是纯水。根据数值计算传热管两端散热损失不影响管中央部位温度测精度。热电偶校正误差不超过 0.2 K。热负荷测量误差(仪器误差, 传热面积误差, 两端散热损失)最大不超过 4%。壁面过热度是壁温减理论饱和温度。壁面过热度测量误差最大不超过 8%。

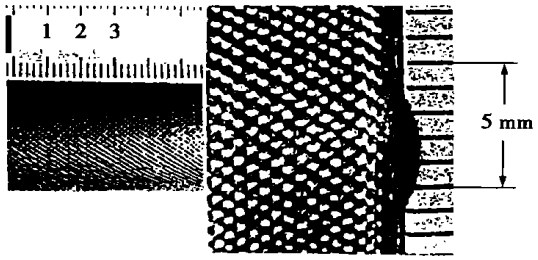

图4　滚压管外型

3　实验结果

3.1　光滑管束实验

图5 显示了在不加热时单列管束中各管实际液膜流量测量结果。当供液器出口雷诺数 $Re(0)$大约在500以下时, 第二根管上部的实际膜流量基本等于供液器出口雷诺数, 即没有液膜溅射损失。当供液器出口雷诺数超过 500 后, 出现溅射损失, 溅射损失随着雷诺数增加而增加, 而最下部管子的实际液膜量随着雷数增加而迅速降低, 当供液器出口雷诺数在2 000时, 最下部管子(第6 根管)上的实际雷诺数只有 820, 下降了一半多。

图6 是单列管束换热实验结果, 纵坐标是各管平均努谢尔特数$\overline{Nu}$。横坐标是供液器出口雷诺数 $Re(0)$。因为在对流蒸发区域换热系数与壁面热流密度无关, 实验时壁面

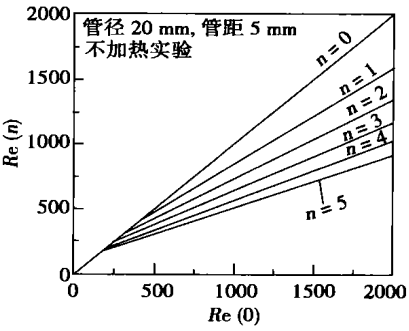

图5　单列光滑管束内各管实际液流量分布

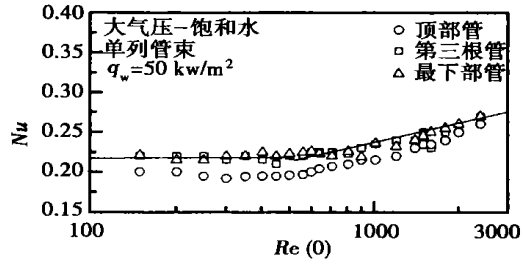

图6　单列光滑管束内各管换热特性

热流密度 q_w 固定在5×10^4 W/m^2。壁面热过度大约4 ~ 5 K。图中实线是直径 20 mm 单管时的湍流流动模型数值计算结果[8], 用下面模拟公式表示:

$$\overline{Nu} = 0.21 \qquad 200 \leq Re \leq 500 \qquad (1)$$

$$\overline{Nu} = 0.073 Re^{0.17} \qquad 500 \leq Re \leq 2500 \qquad (2)$$

式中: $\overline{Nu} = q_w lc/((T_w - T_S)\lambda)$, λ: 导热系数, T_W 和 T_S 分别是壁温和水饱和温度, $lc = (v^2/g)^{1/3}$; $Re = 4\Gamma/\mu$, μ: 水粘性系数, Γ: 管半侧的单位管长液膜质量流量。由图 5 和图 6 可见; 虽然下部各管的实际膜雷诺数逐次下降, 但是下部各管的$\overline{Nu}$ 反要比顶部管高出一些, 最大提高 10%。管子的位置对$\overline{Nu}$ 没有明显影响。这是由于在实验范围内, 理论上 Re 对$\overline{Nu}$ 的影响就很弱, 而随着液膜逐管降落, 扰动效果不断强化, $\overline{Nu}$ 反而略有增加。

图7 是3 列管束换热实验时, 中间一列管束的测量结果. 3 列管束实验时, 由于两侧管束上的液膜溅

射到中间管束上，中间一列管束中各管上的液膜流量不再变化，但液膜受到的扰动更加强烈，因此，管束下部各管子的$\overline{Nu}$比顶管要大 10% ~ 30%。当 *Re* 小于 500 时，液膜呈柱状流下、溅射、扰动效果明显，因此下部管的$\overline{Nu}$增加幅度更大。比较图 7 和图 6 可知：在低 *Re* 区域，多列管束的$\overline{Nu}$要远大于单列管束$\overline{Nu}$，用一个单列管束实验结果代表多列管束蒸发器是不合适的。而随着 *Re* 增加，单列管束$\overline{Nu}$和多列单束$\overline{Nu}$逐渐接近。

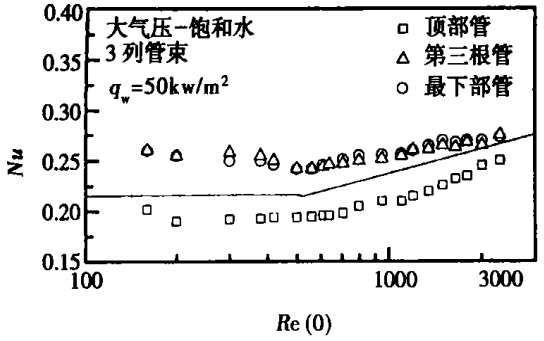

图 7 3 列光滑管束内各管换热特性

3.2 滚压管束实验

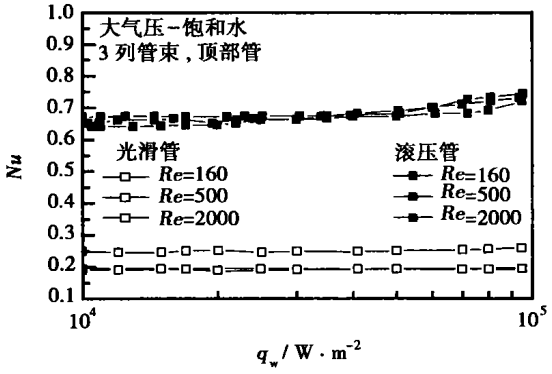

图 8 3 列滚压管束内顶管换热特性

图 8 显示 3 列滚压管束中顶部管的换热实验结果，纵坐标是顶部努谢尔特数。由于各管子的换热特性几乎完全相同，因此不再图示各管子的换热特性比较。由于在中低热流密度区域已经出现了局部沸腾现象，壁面热流密度 q_w 成为支配参数，因此将壁 q_w 作为横坐标。供液器出口雷诺数作为参变量。实验观察中发现：在整个低热负荷区域传热面上都产生了很多微小气泡。随着热负荷增加，气泡数量也渐增加，其直径很小，大量集中在管底部液膜较厚区域。由于产生了这种局部沸腾，因而其换热系数要大大高于光滑管的换热系数，平均达到 3 倍。与一般的沸腾曲线不同，此时的$\overline{Nu}$ ~ q_w 曲线依然近似一条水平曲线，表现出对流换热特征。这说明此时的换热支配依然是对流，气泡的产生和运动强烈扰乱了液膜流，尤其是传热面近旁的边界层，因而大幅度强化了换热，可以认为这一区域是对流和沸腾的混合区域。由于出现沸腾传热、管间距、液膜流量和液膜扰动等因素成为二次影响因子，因此单管实验$\overline{Nu}$可以代表整个管束。

4 结 论

（1）对光滑管管束，在单列管束实验时，各管的实际液膜流量逐管下降，而各管的换热特性基本不变，下部各管$\overline{Nu}$比顶管$\overline{Nu}$略高一些。

（2）对光滑管管束，在多列管束实验时，各管的实际液膜液量保持不变，但管间溅射强化了换热。在低 *Re* 区域，下面各管的$\overline{Nu}$比顶管$\overline{Nu}$要高许多，最大可增加 30%。在中高 *Re* 区域，下面各管的$\overline{Nu}$比顶管$\overline{Nu}$略高一些。

（3）滚压管束具有非常好的换热强化作用。尤其在中低热负荷范围就可以产生局部沸腾，$\overline{Nu}$可以提高 3 倍。由于出现沸腾传热，*Re* 管间距，液膜溅射，液膜扰动等因素都成为二次影响因子，对$\overline{Nu}$几乎无影响。各管子的换热系数基本相同。

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injector has been found to be correlated to the back pressure of the pneumatic conveying system. **Key words**: pneumatic conveying, gas nozzle, transport characteristics, gas-solid injector

排气管偏置对 CFB 锅炉旋风分离器性能的影响＝**The Impact of an Offset Mounted Exhaust Pipe on the Cyclone Separator Performance in a Circular Fluidized Boiler** [刊, 汉] / PENG Lei, LI Jun (College of Energy and Power Engineering under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049), WANG Guo-hong (Design Department, Dongfang Boiler Group Co. Ltd., Zigong, China, Post Code: 643001) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). —153 ~ 156

Through cold-state modeling tests a study was conducted of the influence of an offset mounted exhaust pipe on the performance of a cyclone separator installed on a circular fluidized bed boiler. The results of the tests indicate that the offset mounted exhaust pipe has markedly enhanced the efficiency of the cyclone separator along with a reduction of its total resistance. In view of this the adoption of a suitably offset exhaust pipe can be considered as one of the major methods for improving the performance of the cyclone separator. **Key words**: offset mounted exhaust pipe, separation efficiency, separator resistance, cyclone separator, circular fluidized bed boiler

四墙切圆布置燃烧器炉内实际切圆大小的试验研究＝**Experimental Research on the Actual Diameter of a Tangential Circle in a Tangential-fired Boiler Furnace** [刊, 汉] / TAN Hou-zhang, YU ZHAN-ying, XU Tong-mo, HUI Shi-en (School of Energy and Power Engineering under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). —157 ~ 159, 166

On a 1 MW test rig measurements were taken of the actual tangential circle diameter of a tangential-fired furnace respectively under cold-state and hot-state test conditions. The hot-state test results indicate that in case of firing Yibin anthracite the tangential circle diameter at a primary air section under a hot state test condition is three times that of the supposed diameter. When Shenmu bituminous coal was fired the tangential circle diameter of the primary air section under a hot-state test condition is 7.7 times that of the supposed diameter. The analysis of the test data allows one to predict that under cold-state test conditions the tangential circle diameter along the furnace height assumes a linear increase, and under hot-state test conditions the same diameter undergoes a wave-like increase. **Key words**: pulverized coal combustion, tangential-fired furnace, experimental research

紧凑高效型水平管束降膜蒸发换热器的实验研究＝**Experimental Study of a Falling-film Evaporative Heat Exchanger Composed of Compact and High-efficiency Horizontal Tube Banks** [刊, 汉] / LIU Zhen-hua, ZHANG Tong (College of Mechanical and Power Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). —160 ~ 162

Under atmospheric conditions a water falling-film evaporative heat-exchange test was performed of compact tube banks composed of single-row and three-row staggered smooth tubes and roll-pressed intensified heat-exchange ones. It has been confirmed that under intermediate and low thermal loads the heat exchange factor of the roll-pressed tubes can be enhanced 3-4 times, thus exhibiting excellent intensified boiling heat-exchange performance. Tube pitch and losses due to liquid-film splatter have a very small influence on evaporative heat exchange characteristics. Also investigated is the difference in heat exchange characteristics of the single row and three-row tube banks. Tests have shown that such difference is more marked in a low Reynolds number zone. **Key words**: intensified heat exchange, evaporation, boiling, falling

film, compact heat exchanger

一种多孔介质蒸发冷却中冷器性能的初步研究＝**A Preliminary Study of the Performance of a Porous-medium Evaporative Cooling-based Intercooler** [刊, 汉] / ZHANG Zhen-yi, ZHANG Yan, SUN Yu-feng (College of Power and Nuclear Energy Engineering under the Harbin Engineering University, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). —163 ~ 166

The theory and construction of an evaporation-cooled intercooler is briefly described. By way of wind tunnel tests the resistance and temperature-reduction characteristics of various packings were verified, resulting in the selection of proper packing media. It is shown that the evaporation-cooled intercooler is simple in theory and can be installed at the inlet of a diesel and gas turbine and employed on a ICR (intercooled recuperative) marine gas turbine. It is feasible to use the intercooler under discussion to replace an originally installed intercooler. **Key words**: evaporative cooling, intercooler, packing

基于复合进化算法和Navier—Stokes方程求解技术的透平叶栅气动优化设计＝**Optimized Aerodynamic Design of Turbine Cascades Based on Composite Evolutionary Algorithms and Navier-Stokes Equation Solution Techniques** [刊, 汉] / LI Jun, REN Bin, FENG Zhen-ping (College of Energy & Power Engineering and Institute of Turbomachinery under the Xi' an Jiaotong University, Xi' an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). —167 ~ 170

The optimized aerodynamic design of turbine cascades is presented, which has been based on composite evolutionary algorithms and Navier-Stokes equation solution techniques. By combining evolutionary algorithms with a Simplex method the resulting composite evolutionary algorithms can enhance the search efficiency of evolutionary hereditary algorithms through a reform of the worst individuals in a population by using the Simplex method. The design objective of turbine cascade aerodynamic optimization is to minimize the total pressure loss. The coordinates of the control points of Bezier curves for the cascade profile parametrization serve as the optimized design variables. Reynolds-averaged Navier-Stokes equation solution techniques were used to calculate the total pressure loss. Baldwin-Lomax algebraic turbulent model is used as a turbulent model. The optimized design has reduced the total pressure loss of the cascades by 20%. The design results demonstrate that the optimization techniques used by the authors for the turbine-cascade aerodynamic design proved to be an effective approach. **Key words**: composite hereditary algorithm, turbine cascade, optimization, design

一种多股流换热器综合性能优化设计方法＝**Comprehensive-performance Optimization Design Method for Multi-stream Heat Exchangers** [刊, 汉] / ZHAO Yong-qin, CUI Guo-min, LU Hong-bo, LI Mei-ling (Research Institute of Thermal Engineering under the Shanghai University of Science and Technology, Shanghai, China, Post Code: 200093) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). —171 ~ 174

On the basis of a comprehensive consideration of such factors as volume, weight and resistance, etc a flow-channel layout and an optimized design were carried out for a multi-stream heat exchanger. Moreover, a dimensionless analytical method is applied to define a synthesis (syn) factor and synthesis line, etc in order to evaluate the comprehensive performance of the heat exchanger. A detailed analysis is performed of the process of fin-structure comprehensive optimization by making use of the synthesis factor. A comparison of the analysis results with design ones indicates that the method under discussion is suitable for the comprehensive-performance optimization design of the multi-stream heat exchangers. **Key words**: