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电场和螺旋线圈复合强化管内强制对流的实验

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摘　要: 对管内油的层流流动换热采用内插螺旋线圈和外加高压电场两种强化技术进行了复合强化换热实验研究。实验结果发现, 内插螺旋线圈强化管可以强化层流对流换热大约一倍左右; 同时采用高压电场强化换热技术后, 换热强化率可以再提高 4 倍左右; 油温、流速对换热强化率没有显著影响, 换热强化特性基本取决于外加高压电场。

关　键　词: 对流换热; 复合换热强化; 电流体力学

中图分类号: TK124　　　文献标识码: A

1　引　言

电场强化换热以非常小的能耗取得相当好的强化效果, 有其应用前景。这一领域的研究就是所谓的电流体力学(Electro－Hydro－dynamics, 简称 EHD)。20 世纪 70 年代以来, 国内外研究者在该领域进行了大量的基础性研究工作[1～7]。管内油的层流对流换热在工业中比较常见, 如燃油锅炉中油的预热及输油管路中油的加热、油的换热系数和水, 氟里昂类流体相比非常低。传统的油的对流传热强化方法是采用各种强化管技术, 如肋管、轧槽管、内插螺旋线圈和内插纽带管等。这些强化技术一般只能强化换热系数 1～2 倍, 而且大大增加了摩擦阻力, 综合效应并不理想。作者曾对光滑管内油的层流对流换热采用外加高压电场技术进行了强化换热研究[7], 发现在低热负荷条件下, 高压电场具有很好的强化换热特性, 但在高热负荷条件下, 强化效果显著下降。另一方面, 在一般的光滑传热管中内插螺旋线圈, 可以在阻力增加不大的情况下, 传热得到较大的提高; 同时具有拆装方便、工艺简单的优点。在本研究中, 被动式的强化管技术和主动式的外加高压电场技术被同时采用。对内插螺旋线圈的强化管内油的对流换热再进行外加高压电场强化, 研究复合强化技术对管内层流强制对流的综合强化效应, 探讨一些基本换热规律。

电场对绝缘性流体强制对流的主要作用力是库仑力。由于库仑力与速度场、温度场以及它们的梯度场有关, 因此强制对流换热与工质种类, 流动条件及加热条件等因素有十分复杂的关系。

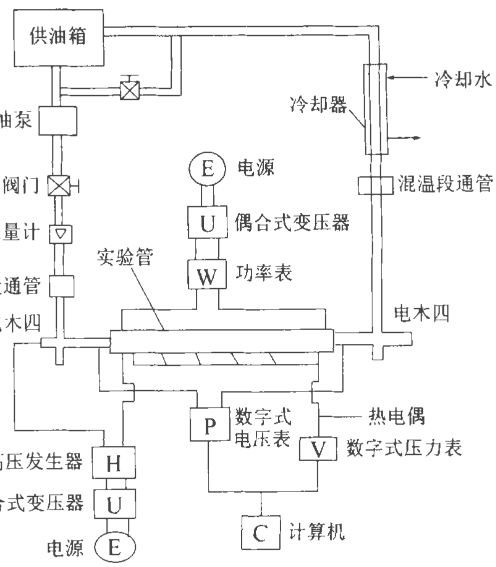

图 1　实验系统图

2　实验装置

图 1 给出了实验系统图。实验装置和文献[7]实验相同, 工质循环通过油泵进行。通过调节油泵功率和管路阀门调整油的流量, 油从供油箱流出, 经过流量计进入水平引管, 然后进入实验段, 最后经引管流出, 经冷却器冷却后由油泵送回供油箱。实验段长 1 m, 实验管为内径 20 mm 的紫铜光滑管, 管外壁上等间距焊有 6 根直径 1 mm 的铠装式热电偶, 管内壁平均温度由 6 根热电偶测量值取平均后通过一维导热方程推算得到。实验管外绕电阻丝, 电阻丝和实验管间绕有云母片用于绝缘, 电阻丝外裹上石棉丝绝热材料。实验采用电加热, 加热功率由变压

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器调节，由功率表测出，壁面热负荷由加热电功率和传热面积推算出，在实验段前后的引管内装有铠装式热电偶和数字式压力计用来测量进出口油温和静压差，所有的热电偶输出电势通过一台数字式电压表接入智能终端。

外加高压直流电场由一台高压变压器和直流高压整流器获得，直流电压的负极直接接在实验管上，同时接地；正极接在通过管内轴线的一根直径1mm不锈钢丝上，这样在管内形成径向高压电场。实验范围是：油流速 0.05～0.25 m/s，进口油温 20～52 ℃，雷诺数 30～500，本文以 15 号机油为实验工质。

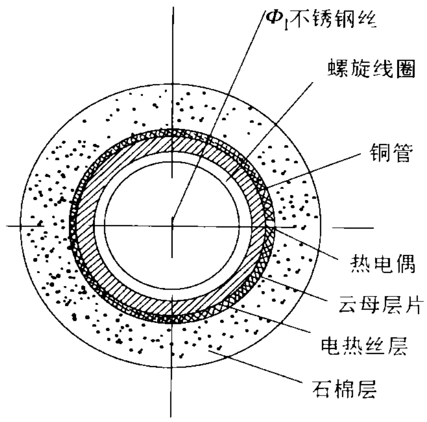

图 2　传热管的截面示意图

图2给出了传热管的截面示意图。本实验中采用了 3 种螺旋线圈，尺寸分别为线径 1.5 mm，节距 5 mm（A 型）；线径 1 mm，节距 5 mm（B 型）；线径 1.5 mm，节距 10 mm（C 型）。在零电场条件下的实验表明A 型螺旋线圈有最好的强化换热作用，因此在高压电场实验中，只使用A 型线圈。

实验测量误差已在文献[7]中进行了分析，温差的最大相对误差 8%，热负荷的最大相对误差 5%，流量测定相对误差小于 5%。

3　实验结果

图3给出了一例光滑管内高压电场强化对流换热的实验结果。u_0 是油流速，T_{in} 是油的实验管入口温度，横坐标为壁面热负荷，纵坐标是平均换热系数（$h = q/(\bar{t}_w - \bar{t}_f)$，$\bar{t}_w$ 和 $\bar{t}_f$ 是平均壁温和平均油温，q 是壁面热负荷），外加高电压为参变量。从图中可以看到外加高电压对对流换热有明显强化作用。在低热负荷区域，换热系数可以增大 8 倍，但随着热负荷增加，强化作用逐渐降低。在高热负荷区域，换热系数大约增加 1 倍多一点，高压电场的强化换热效果是由于带电分子的运动引起的。在高电场作用下，一部分分子被极化，在库仑力作用下，从负极（管中心）流向正极（壁面），冲击扰乱流体壁面边界层，从而强化换热，同时分子的径向运动引起管内二次流也能强化换热。随着热负荷增加，分子的热运动（从高温壁面指向管中心）增加，这一热运动部分抵消了带电分子的冲击扰乱作用。

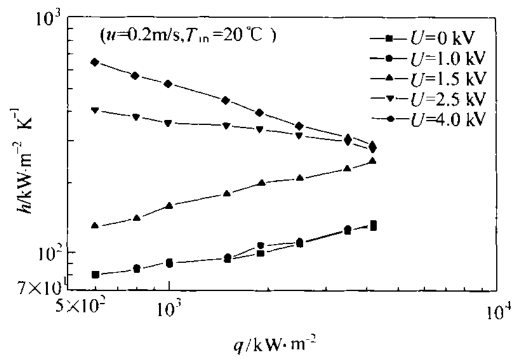

图 3　光滑管内高压电场强化对流换热的实验结果

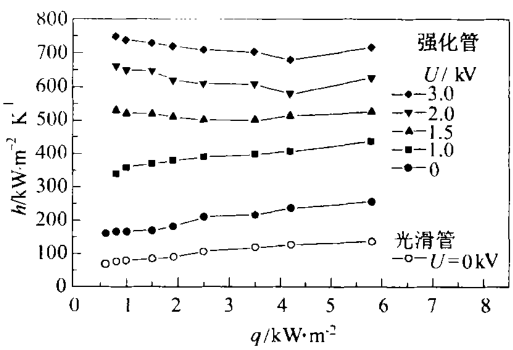

图 4　螺旋线圈强化管内高压电场强化对流换热的实验结果

图 4给出了 A 型螺旋线圈强化管内高压电场强化对流换热的实验结果．流动条件和油温与图 3 相同（$u_0 = 0.2$ m/s，$T_{in} = 20$ ℃）。在内插螺旋线圈后，换热系数提高了 1 ～ 1.5 倍左右；在施加高压电场后，换热系数有了一个更加显著的增加，与零电场时强化管的换热系数相比，在整个实验热负荷区域内，换热系数增加了3.5 ～ 5倍左右；与光滑管零电场时的换热系数相比，换热系数增加了7 ～ 9 倍左右。显

然在低热负荷区域, 复合强化效应不是很显著。但在高热负荷区域, 复合强化效应十分明显。采用强化管后, 基本上弥补了光滑管时强化率随热负荷增加而下降的不利之处。

实验结果证明了对于一般强化管, 使用高压电场技术仍然可以大幅度强化换热。

对于光滑管高压电场强化换热, 管摩擦系数最大只增加约一倍[7]。对于内插螺旋线圈强化管, 在零电场时, 摩擦系数大约增加了 1.5 ~ 2 倍, 其增加率略大于换热强化率。在施加高压电场后, 摩擦系数几乎没有变化。这可能是由于螺旋线圈引起的摩擦系数增加率要远远大于高压电场引起的摩擦系数增加率。在复合强化作用下, 摩擦力的增加基本只与螺旋线圈有关, 这使得复合换热强化的综合效率十分显著。

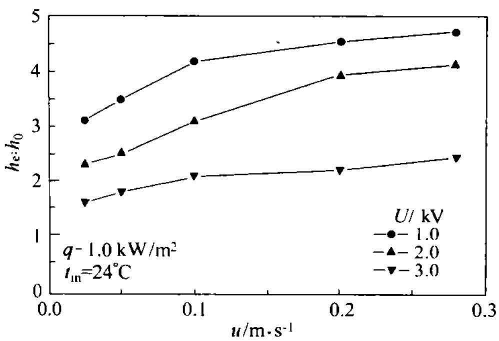

图 5　流速对换热强化率的影响

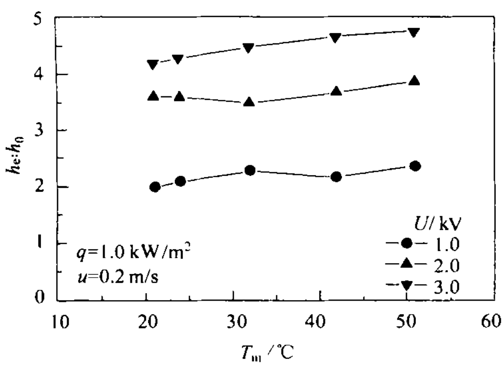

图 6　入口油温对换热强化率的影响

图5给出了流速对换热强化率的影响曲线。本文中的换热系数强化率 h_e/h_0 被定义为施加电场时的换热系数与零电场时的换热系数之比。图中可以看出随着流速增加换热强化率有比较缓慢的增加, 但流速的影响并不明显。这可能是由于随流速的增加, 雷诺数也增加, 在高雷诺数条件下, 流体更容易被扰乱。

图 6 给出了入口油温对换热强化率的影响曲线。与图 5 相似, 油温对换热强化率的影响很小。基本上换热强化率随着油温增加而十分缓慢的增加, 当入口油温增加时, 油的粘度降低, 同样使得雷诺数有所增加。因此, 油温的影响与流速的影响在定性上是相同的。

综上所述: 对螺旋线圈强化管内油的强制对流再使用高压电场强化换热是十分有效的复合强化手段, 在管摩擦系数基本不变化的情况下, 换热系数可以强化 4 ~ 5 倍。

4　结论

(1) 单纯采用内插螺旋线圈强化管, 油的强制对流换热系数可以增加 1 ~ 1.5 倍, 同时摩擦系数的增加率略大于换热强化率。

(2) 对螺旋线圈强化管, 同时使用外加高压电场可以达到显著的复合强化换热效果。在摩擦系数基本不变的条件下, 强化管的换热系数可以再增加 4 ~ 5 倍, 同时, 热负荷的影响明显减弱。

(3) 流速和油温对换热强化率的影响很小, 换热强化特性基本取决于外加高压电场。

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(辉　编辑)

grinding capacity for these coals has been identified by an analysis the authors point out the practical service limitations of the raw coal grindability index measured in a laboratory. In addition, investigated are the coal quality factors to be considered during the revision of these grindability indexes. The relevant findings can serve as reference data during a more in-depth study by design and operation management personnel of coal pulverizers. **Key words**: grindability index, maximum grinding capacity, test, revision

链式能量系统热经济孤立化的新方法与证明＝**Thermo-economic Isolation of Chain Type Energy Systems and Its Convergence Proof** [刊,汉] / LI Shi-wu, SU Mo-ming (Department of Aeronautical Power and Thermal Engineering, Northwestern Polytechnical University, Xi'an, China, Post Code: 710072) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). —465～468

Based on the ideology of thermo-economic isolation the author has proposed a new method for the optimized thermo-economic isolation of a chain type energy system and provided a proof for the convergence of the method. The effectiveness of the method has been verified for a nonlinear chain type energy system. This enables the thermo-economic isolation acquire a practical usage value for a decision-making during the design and optimized operation of chain type energy systems, providing a solid basis for the application of the thermo-economic isolation in thermal energy and power engineering systems as well as in other energy systems. **Key words**: energy system, chain type system, thermo-economic isolation

湿法烟气脱硫系统中的低温腐蚀及烟气再热问题＝**Low-temperature Corrosion and Flue-gas Reheat Problems in a Wet-method Flue Gas Desufurization System** [刊,汉] / WANG Hong-tao, WU Shao-hua, SAI Jun-cong, et al (Thermal Energy Engineering Department, Harbin Institute of Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). —469～471

Described are the low-temperature corrosion problems quite prevalent in the flue-gas desulfurization system of a coal-fired power plant. In conjunction with specific cases a brief analysis is performed of some types of flue gas reheat system and their ensuing secondary corrosion problems. **Key words**: wet-method flue gas desulfurization, flue gas reheat, low-temperature corrosion

火焰筒耐热搪瓷漆熔烧工艺实验研究＝**Experimental Research of a Fusing Technique Involving the Coating of Heat-resistant Ceramic Lacquer on a Gas Turbine Flame Tube** [刊,汉] / DONG Bin, ZHANG Yong-quan (Harbin No.703 Research Institute, Harbin, China, Post Code: 150036) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). —472～474

The inner and external surfaces of a gas turbine flame tube have been coated with a foreign-made heat-resistant ceramic lacquer. With a view to mastering in the shortest possible time the fusing technique of heat-resistant ceramic lacquer, contrast tests were conducted on test pieces with regard to the main procedures of fusing technique by applying that technique for the coating of the flame tube. These tests have brought forth the following conclusions. The size of spray sand particles and the change in the viscosity of the coating material have a relatively small influence on the fusing quality while the fusing temperature and time duration exert a fairly large influence on that quality. By putting parts into the fusing furnace at a relatively high stipulated furnace temperature and taking them out after a relatively short time it is possible to obtain a satisfactory coated surface quality and service performance. **Key words**: gas turbine, flame tube, ceramic lacquer, fusing

电场和螺旋线圈复合强化管内强制对流的实验＝**An Experiment on Forced Convection in a Combined-intensi-**

fication Heat-transfer Tube Incorporating an Electric Field and Spiral Coils [刊, 汉] / LIU Zhen-hua, YI Jie (Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). —475 ~477

An experimental study of combined-intensification heat transfer was conducted by using two intensification techniques to the laminar flow heat transfer of in-tube oil, namely, the installation of internally inserted spiral coils and an externally added high-voltage electric field. The result of the experiment indicates that the intensification tube with the use of internally inserted spiral coils can lead to an enhancement of convection heat transfer of the laminar flow by about 100%. The use of intensified heat exchange with the help of a high-voltage electric field in addition to the above approach can further enhance the heat exchange intensification rate by about four times. Oil temperature and its flow speed do not exert any significant influence on the heat exchange intensification rate. The heat exchange intensification rate basically depends on the externally applied high-voltage electric field. **Key words**: convection heat transfer, combined intensification of heat exchange, electro-hydrodynamics

梯形剖面圆形肋片管温度场的研究＝**A Study of the Temperature Field of Annular Finned Tubes with a Trapezoidal Cross-section** [刊, 汉] / LU Guo-dong, ZHOU Qiang-tai (Power Engineering Department, Southeastern University, Nanjing, China, Post Code: 210096), CHENG Lin, TIAN Mao-cheng (School of Energy & Power Engineering under the Shandong University, Jinan, China, Post Code: 250061) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). —478 ~480

A new method is proposed for calculating the temperature distribution along the fin height (i.e., along the fin-root to fin-end direction) of an annular finned tube with a trapezoidal cross-section. Measurement results indicate that the proposed calculation method features a fairly high precision. Meanwhile, a non-uniform distribution of temperature was identified along the fin-width direction (namely, along the fin thickness direction), which is of major reference value for the structure optimization of annular fins. **Key words**: finned tube, temperature field, heat transfer characteristics, structure optimization

高温鼓泡流化床的流化行为＝**Fluidization Behavior of a High-temperature Bubbling Fluidized Bed** [刊, 汉] / GUO Qing-jie, LU Jun-fu, WANG Xin, et al (Department of Thermal Engineering, Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). —481 ~484

With the bed temperature ranging from 20 - 1000 ℃ and coal ash of four kinds of particle diameter serving as experimental materials the variation relationship of the following parameters is investigated under various apparent gas speeds. The parameters include: the minimum fluidization speed, bed average voidage, pressure fluctuation standard deviation and main frequencies. The minimum fluidization speed will decrease with a rise in bed temperature. Under the same bed temperature the average voidage will increase with a rise in apparent gas speed. Under different temperatures the pressure fluctuation deviation will experience an increase with an increase in fluidization number. Under the same fluidization number the influence exerted by a change in bed temperature on pressure fluctuation standard deviation of B particles is insignificant, while for particles of D category the pressure fluctuation standard deviation will decrease with a rise in bed temperature. An increase in fluidization number will lead to a decrease in the main frequency of pressure fluctuations. **Key words**: fluidized bed, high temperature, minimum fluidization speed, pressure fluctuation deviation

一维管道汽液两相流动的小波数值瞬态计算＝**Transient Calculation by a Wavelet Numerical Method for a One-dimensional Piping of Vapor-liquid Two-phase Flows** [刊, 汉] / SHANG Zhi, YANG Rui-chang (Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy & Power. — 2002, 17