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自转清洗扭带管对流传热强化机理的实验研究

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摘　要: 具有传热强化功能的自转螺旋扭带清洗防垢技术发展较快。应用激光测速仪 LDV(Laser Doppler Velocimeter)实验研究自转清洗扭带管内流体的湍流特性。结果表明: 在自转扭带的带动下, 管内流体的流动结构发生了反常态的变化, 在近管壁环形区域内流体的轴向分速度明显比管中心区域的高, 轴向湍流度比无自转扭带时大; 切向分速度随半径的增大而增大, 并且存在很大的径向湍流度。这些结果初步说明了自转螺旋扭带管对流传热强化的机理是: 管内由扭带带动形成的强制旋流和轴向平行流叠加而形成的螺旋流动, 以及近管壁环形区域内流速的增大, 不仅加强了边界层流体的扰动以及边界层流体与主流流体的混合, 并且使边界层厚度减薄, 从而才使管内的对流传热得以强化。本文试验研究的结果为自转螺旋扭带管内对流传热强化机理的深入理论研究提供实验基础。

关　键　词: 自转螺旋扭带; 激光测速 LDV; 湍流特性; 强化传热机理; 实验研究

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1　引　言

换热器在石油、化工、冶金、动力、制冷等工业部门有着广泛的应用。在现代石油化工企业中, 换热器的投资要占全部设备投资的 30%～40%[1]。因此, 换热器的高效率运转对企业的经济效益非常重要。近 20 年, 国内外学者就换热器污垢的自动清洗及其传热强化进行了大量的研究, 不少成果已在工业上应用。

其中, 插入传热管内的扭带技术, 由于其具有自动清洗污垢和强化传热的双重功能, 且方法简便有效, 不仅适合新投运设备的强化传热和抑制污垢沉积, 而且易于对在役旧设备进行技术改造, 因而应用广泛[2～8]。特别是自转螺旋塑料扭带技术, 由于特殊塑料材料的研制和成型技术的成功, 解决了金属螺旋扭带对传热管壁的磨损问题, 市场前景更加广阔[9～10]。其工作原理如图 1 所示: 在每根换热管的流体进口端安装一根塑料扭带, 利用传热介质自身流过扭带所传递的动量矩使扭带旋转, 不断地刮扫和撞击管内壁, 从而达到清洗管内污垢、抑制污垢沉积和强化对流传热的目的。

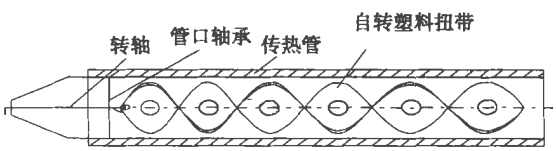

图 1　自转塑料扭带的工作原理图

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5　结　语

本文作者仅对柴油机进口加湿技术的理论和试验进行了初步的探讨, 理论计算和试验结果基本一致, 为增压柴油机进口加湿的研究提供了依据, 同时这项技术对增压柴油机在恶劣环境下恢复功率、提高工作可靠性方面也有着积极的意义。

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(渠　源　编辑)

尽管具有传热强化功能自转螺旋扭带清洗防垢技术发展较快, 但是, 国内外至今未见有关螺旋扭带传热强化机理深入研究的文献。为此, 本文应用激光测速仪 LDV (Laser Doppler Velocimeter), 通过对装有自转扭带圆管内流体湍流特性的实验研究, 对其强化传热机理进行初步探索研究, 以便为旋转螺旋扭带的传热强化理论研究的深入提供实验基础。

2　实验装置与方法

实验装置如图 2 所示。激光测速测试的有机玻璃管为 Φ38× 2.5, L = 1 000 mm。扭带材质为 PVC, 扭带宽度 B = 24 mm, 扭带厚度 t = 2 mm, 扭带的螺距 H = 120 mm, 带长 L = 600 mm。为了降低圆管壁面折射率对激光测试的影响, 在外面安装了一个方形水匣, 如图 2A － A 剖面图所示。

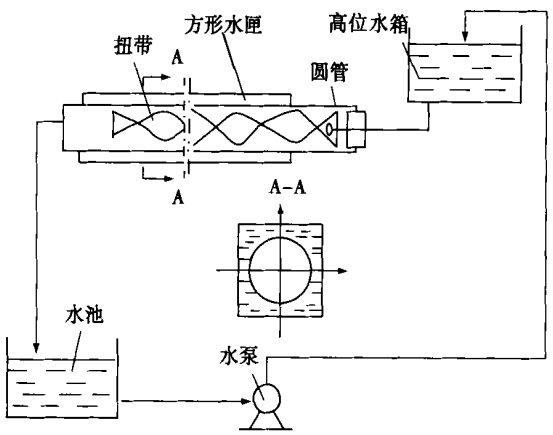

图 2　循环水单管试验装置简图

SCD － 1 型频移激光多普勒测速仪用来测量自转塑料螺旋扭带管内流体的轴向速度、切向速度和湍流度。该系统包括一台 20 mW 的 He－Ne 激光器、频移入射光单元、偏振分离接受光单元和多普勒信号处理器及计算机数据采集系统等, 激光测速仪的布置如图 3 所示。为了便于测量空间的流速分布, 整个仪器的光学系统安装在一台有四个自由度的光学导轨和坐标架上, 通过导轨的移动可以沿测量截面改变测速点的位置。由于激光测速仪是利用流体中示踪粒子散射光的多普勒频移频率来获取速度信息的, 流场中如果有不透光物, 则会阻碍速度信号的获得, 所以为测得旋转螺旋扭带管内的流场的分布, 测量截面选在紧靠扭带尾部的位置, 流体由于惯性, 尾部截面的流场基本能反映扭带管内扭带段的流场。为了避免扭带尾部厚度产生的尾流对流场测试的影响, 扭带尾部逐渐减薄, 尾端厚度近零, 并且打磨得非常光滑。

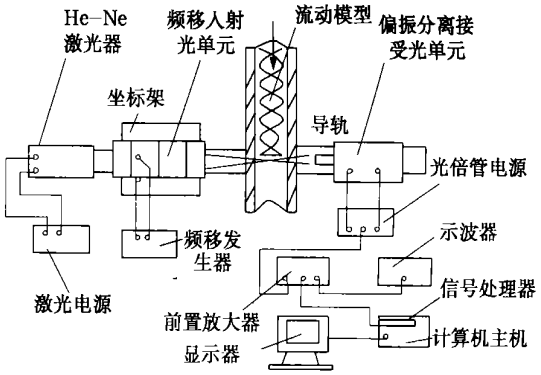

图 3　激光测速仪 LDV 系统布置简图

3　实验结果及其分析

实验中测量了旋转螺旋扭带管横截面的流速分布, 测得的轴向平均速度 $\overline{V}_x$、周向平均速度 $\overline{V}_y$、轴向湍流度 $\sqrt{\Sigma(V_i-\overline{V}_x)^2/N}/\overline{V}_x$ 和径向湍流度 $\sqrt{\Sigma(V_i-\overline{V}_y)^2/N}/\overline{V}_y$ 的分布图如图 4 ~ 图 7 所示, 其中, V_i 为每次采样的速度, N 为采样的个数, 流体的雷诺数 Re = 2.7× 10^4。

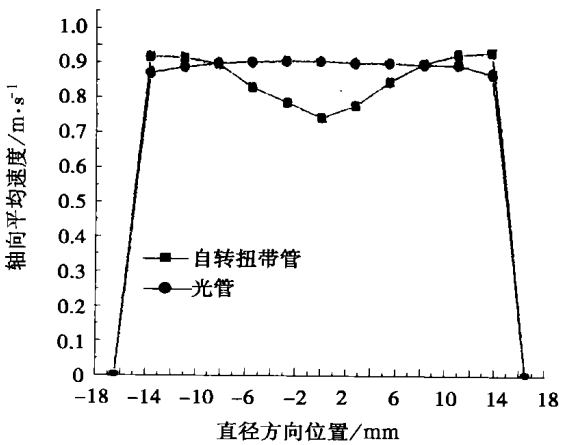

图 4　轴向平均速度的分布

由图 4 可看出: 圆管中没有插扭带时, 测得的管流轴向平均速度的分布与经典的管道边界层粘性流动模型一致, 近管壁区域由于流体粘性的影响, 其流速小于管中心区域。而当圆管中插入螺旋扭带时, 流体的流动结构发生反常态的改变, 管中心区域流

体的轴向流速比常态的低一些，并且愈靠近中心线的流速愈低，中心线处的流速反而最低；在半直径处不变；近管壁环行区域的流速明显增大。这种变化是由于管中心区域存在扭带使流体的轴向流动必须做螺旋线流动，阻力显著增大。按其阻力最小原理，更多的流体必然流向阻力较小的区域，引起近管壁环行区域的流速增大，中心区域的流速减少；由于中心线处流体必须要克服扭带表面的粘性摩擦力，出现流速最低现象。

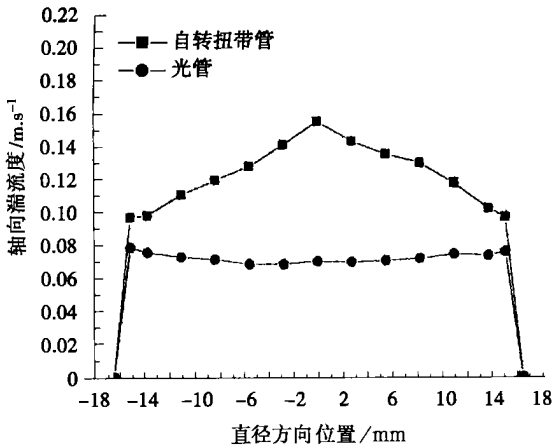

图 5 轴向湍流度的分布

从图 5 可看出：当管中没有扭带时，流体在圆管横截面上的轴向湍流度基本上是一样的；而当管中有旋转扭带时，流体的轴向湍流度明显比没有扭带时的高，且中心区域流体的轴向湍流度比近管壁区域的轴向湍流度要大。这是由于扭带旋转，流体也随着扭带做旋转运动的结果。

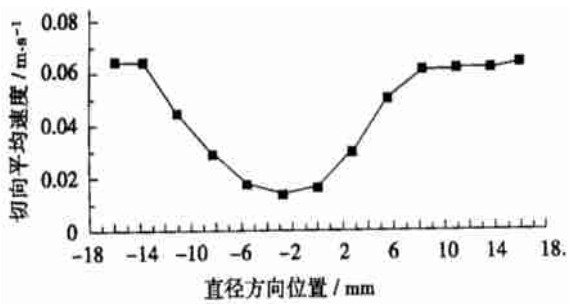

图 6 切向平均速度的分布

由图 6 管流的周向速度曲线可知：旋转扭带的确使管中的流体产生了旋转运动，旋转运动的周向速度随半径的增大而增大。但是，经多次试验发现流体旋转的中心与管中心线不重合，在管中心线下方的 2.75 mm 处，这是由于扭带的密度大于循环水引起的偏心自转所致。最大的周向速度只有 0.065 m/s，比轴向速度低一个数量级。结合扭带宽度 24 mm 可以算出流体的旋转速度为 51.75 r/min，与用光电转速仪测得的扭带实际转速基本一致。这说明流体确实是随着扭带一起做旋转运动的。

用激光测速仪在测普通光管中流体的周向速度时，在同样的采样周期和采样点数目(500 个)的情况下，偶尔会采集到流体的周向速度，有正有负，且数量级比有扭带时的周向速度小，这说明光管中流体的运动有杂乱无章的周向质点运动，但没有象扭带管中的流体一样存在明显的切向旋转运动，由于测试过程中偶尔能采到信号，所以激光测速仪数据处理软件无法求得光管中流体的周向速度和周向湍流度的平均值，不能给出非零值的对比曲线。

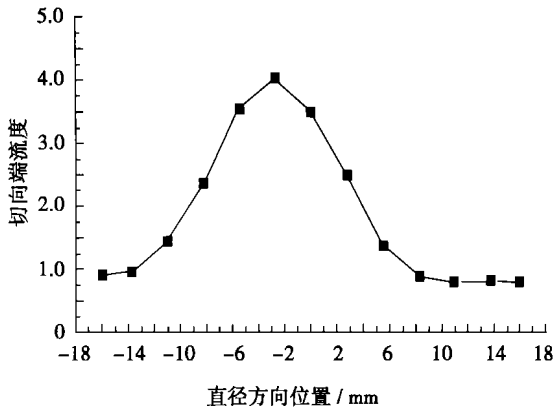

图 7 切向湍流度的分布

由图 7 的切向湍流度曲线可知，虽然切向速度不及轴向速度的 1/10，但切向的湍流度却很大，反过来比轴向的湍流度高一个数量级。这是由于流体随着扭带作旋转运动，速度的周向脉动频率很快。旋转中心的切向湍流度最大，其原因可能由于旋转中心线处的周向速度反方向，粘性摩擦力引发出二次涡流所致。

4 传热强化机理分析

传热管内对流传热过程的热阻主要在热边界层。图 4 轴向速度曲线显示，扭带管中近管壁环区域内流体流速的增大，将加快管壁区域边界层流体

的流动, 使边界层的厚度减薄, 有利于管内的传热热阻减小, 从而使管内的传热得到强化。但是, 轴向速度提高的幅度平均只有 5%, 图 5 的轴向的湍流度增加也不大, 平均也只有 5%左右。因此, 不是传热强化的主要机理。

但是, 图 7 旋转扭带管中管壁邻区流体的周向湍流度比无扭带时增大值为 1.0, 达到轴向的湍流度增加值的 10 倍以上, 因此是管内的对流传热强化的主要原因。

5　结　论

通过激光测速仪 LDV 对自转扭带管内流体湍流特性的实验研究分析, 初步结果表明自转扭带管内对流传热强化的机理为:

(1)自转扭带管内近管壁的环行区域内流体的流速增大, 将使边界层的厚度减薄, 有利于扭带管内的对流传热过程的强化。但轴向速度及其湍流度增加不大, 不是自转扭带传热强化的主要机理。

(2)自转扭带使管内流体随之一起旋转, 虽然周向速度的绝对值小, 但是产生的切向湍流度的绝对值却高达轴向湍流度的 10 倍, 是使管内的换热过程得以强化的主要原因。这一结果将为管内自转扭带强化传热理论的深入研究奠定基础。

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(渠　源　编辑)

新技术

船舶蒸汽锅炉内燃料悬浮液的应用

据《Судостроение (造船)》2002 年 2 月号报道, 燃料悬浮液作为船用锅炉的燃料是可以减少传统燃料消耗的方法之一。

基于以便宜类型燃料部分代替昂贵类型燃料并同时保证可以控制蒸汽锅炉内的炉膛过程, 可解决在于选择(或建造新的)燃料悬浮液制备装置、分析该装置与蒸汽锅炉炉膛的相容性、实时评定和预测使用非计算类型燃料对蒸汽锅炉部件可靠性的影响的问题。

燃料悬浮液由液体(可燃的或不可燃的)弥散介质组成, 在该介质中均匀分布着固体燃料粒子—弥散相。利用重油、柴油作为可燃的弥散介质, 还可利用水作为不可燃的弥散介质。固体燃料是从褐煤、焦炭、油页岩、泥煤、木材废料以及具有相当高燃烧热量的工业和生活废物中获取。

应用燃料悬浮液作为蒸汽锅炉燃料的重要前提是始终能得到补充的非传统类型燃料——工业和生活废料以及含石油的水。

水燃料悬浮液(BTC)燃烧产物烟气分析结果表明, 明显减少了 CO 排放(减少到三分之一), 以及在 BTC 中水含量不大于 15%时使 NO_x 排放减少 20% ~25%。

(吉桂明　供稿)

Post Code: 150036), GAO Pu-zhen (Harbin Engineering University, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2003, 18(6). — 597 ~ 599

By using software ANSYS a three-dimensional model was set up for the turbine cylinder and rotor of a marine steam turbine. The thermal expansion during a cold-state startup was calculated and analyzed. Presented are the time-dependent thermal expansion displacement curves and relative thermal expansion curves of the turbine cylinder and rotor at the gland seal of a rear shaft end, and also at other locations. The calculation results may be used for the research of steam turbine dynamic characteristics and the design of startup procedures. **Key words**: marine steam turbine, thermal expansion, cold-state startup

湿压缩压气机特性的研究= **Research on the Characteristics of a Wet Compression Compressor** [刊, 汉] / LI Shu-ying (School of Electronic Engineering under the Harbin Institute of Technology, Harbin, China, Post Code: 150001), ZHU Jian-hong, LU Wei (College of Power & Nuclear Engineering under the Harbin Engineering University, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2003, 18(6). — 600 ~ 604

Compressor compression work can be decreased by the injection of water into a compressor. The change of working medium properties after the water injection will lead to a change in compressor characteristics. To identify the compressor characteristics following the water injection, a simulation of such characteristics was conducted by using an approximate analogous theory in order to ascertain the effect of the water injection on the compressor pressure ratio and flow rate, etc. As a result, the wet compression compressor characteristics were identified through the above-mentioned approximate modeling. The above work can provide a solid basis for the applied research of wet compression technology in gas turbines, turbocharged diesels and turbocharged gasoline engines. **Key words**: wet compression, compressor, characteristics, simulation

N6135 柴油机进口加湿技术中压气机的性能研究= **An Investigation of the Impact on Compressor Performance of Water Injection at a Diesel Inlet** [刊, 汉] / ZHANG Zheng-yi, ZHENG Qun, ZHANG Wei (College of Power & Nuclear Engineering under the Harbin Engineering University, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2003, 18(6). — 605 ~ 607

A theoretical calculation and an experimental study were performed concerning the water injection at the inlet of a turbocharged diesel. On this basis the authors have developed a method for studying the evaporation/compression process in a compressor and preliminarily verified the theory that the above-mentioned water injection can lead to a reduction of compressor outlet temperature and also compression work. The foregoing provides a solid basis for the reliable operation of turbocharged diesel engine under poor environmental conditions. **Key words**: diesel engine, water injection, compressor

自转清洗扭带管对流传热强化机理的实验研究= **Experimental Investigation of the Mechanism of Intensified Convective Heat Transfer in a Tube with Self-rotating Twisted Tapes for Cleaning Purposes** [刊, 汉] / ZHANG Lin, XUAN Yi-min (College of Power Engineering under the Nanjing University of Science & Technology, Nanjing, China, Post Code: 210094), YU Xiu-min, PENG De-qi (Research Institute of Mechanical Cleaning under the Zhuzhou Engineering College, Zhuzhou, China, Post Code: 412008) // Journal of Engineering for Thermal Energy & Power. — 2003, 18(6). — 608 ~ 611

Fouling prevention technology involving the use of self-rotating spiral-twisted cleaning tapes featuring an intensified heat transfer function has seen a relatively rapid development these days. The authors have with the help of a Laser Doppler velocimeter performed an experimental investigation of the fluid turbulent characteristics in a tube with self-rotating cleaning twisted tapes. The results of the investigation indicate that under the driving force of the self-rotating twisted tapes the fluid flow structure in the tube undergoes an abnormal change. The axial velocity component in the ring-shaped zone near a tube wall is markedly higher than that in the tube central zone with the axial turbulence being greater than in the case

when no self-rotating twisted tapes are used. The tangential velocity component increases with an increase in radius. Meanwhile, there exists a very great radial turbulence. These results explain in a preliminary way the following mechanism of intensified convection heat transfer brought about by the tube with self-rotating spiral twisted tapes. A spiral flow is formed by an overlap of a twisted tape-caused forced rotation flow and an axial parallel flow. The increase in flow speed at the ring-shaped zone near the tube wall not only enhances the perturbation of a boundary layer fluid and the mixing of boundary layer fluid with a main flow fluid, but also leads to a thinning of the boundary layer thickness. This results in an intensified convection heat transfer. The findings of the present experimental study may serve as an experimental basis for the in-depth theoretical study of intensified convection heat transfer mechanism in a tube with self-rotating spiral-twisted tapes. **Key words**: self-rotating spiral-twisted tape, laser Doppler velocimetry, turbulence characteristics, intensified heat transfer, mechanism study, experimental study

导流片结构对物流分配性能影响的实验研究＝**Experimental Study of the Impact of Deflector Plate Configuration on the Performance of Material Flow Distribution** [刊, 汉] / ZHANG Zhe, LI Yan-zhong, XU Qing (College of Energy & Power Engineering under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2003, 18(6). — 612 ~ 614, 638

Through a study of the material flow distribution in a plate-fin heat exchanger it was found that an irrational deflector-plate configuration would lead to a very non-uniform material-flow distribution in the heat exchanger and also a different degree of non-uniformity of the flow distribution in the transverse and longitudinal directions. The authors have, for the first time, come up with an innovative deflector-plate construction, which incorporates a liquid replenishment cavity. The construction parameters of the above-mentioned plate are defined. The results of experimental studies indicate that the use of this innovative plate can effectively solve the problem of non-uniform distribution of internal material flow in the heat exchanger. Moreover, it is found that under the present experimental conditions the deflector plate with a construction parameter of 0.2 offers the optimum flow-guide performance. Through experimental investigations a relation has been identified, which exists between the material flow non-uniformity characteristics of different deflector-plate configurations and a fluid Reynolds number. **Key words**: plate-fin heat exchanger, material flow distribution, deflector plate

垂直放置的高温热管翅起动与运行过程的实验研究＝**Experimental Research of the Startup and Operating Process of a Vertically Placed High-temperature Heat-pipe Fin** [刊, 汉] / ZHAO Wei-lin (College of Materials Science under the Jinan University, Jinan, China, Post Code: 250022), ZHUANG Jun, ZHANG Hong (College of Machinery and Power Engineering under the Nanjing Polytechnic University, Nanjing, China, Post Code: 210046) // Journal of Engineering for Thermal Energy & Power. — 2003, 18(6). — 615 ~ 617

After an experimental study of the startup and operating process of a vertically installed high-temperature heat-pipe fin the temperature distribution curves during the said process were determined for the pipe fin. It was found that with the high-temperature heat-pipe fin being placed vertically the temperature at the bottom of an evaporation section would rise very quickly with time. The temperature at the upper portion of the evaporation section and at a condensation section lagged behind the temperature at the bottom of the evaporation section. The temperature at the evaporation section outlet coincides with that at the middle portion of the condensation section. Concerning the temperature at the end of the condensation section there appeared a phenomenon of temperature pulsation during operation. If the high-temperature heat-pipe fin is placed horizontally for a certain period of time and then tested in its vertical position, the temperature pulsation phenomenon at the condensation section end of the heat-pipe fin will disappear and there emerges instead a good isothermal condition at the condensation section. A further analysis has revealed that the startup and operation of the heat-pipe fin at a higher power rating will yield a higher temperature than that at a lower power rating. During a steady operation a weakening of the temperature pulsation phenomenon at the end portion of the condensation section can be observed. **Key words**: heat pipe, high-temperature heat-pipe fin, startup process, operation process, temperature pulsation