文章编号:1001－2060(2003)01－0047－03

# 新型不锈钢波纹管性能及强化传热的实验研究

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摘　要:新型不锈钢波纹管是经特殊工艺胀波凸起成型为多层波纹管,管内流动呈等直径流束型式和弧形流束型式,使流速和压力周期性的变化,冷热流体产生强烈扰动,实现了复合强化换热。文中对该波纹管进行了承压能力试验,并在水一水换热条件下,对波纹管强化换热规律进行了实验研究,分析了新型波纹管的强化传热机理,并给出该管的优化尺寸范围,为波纹管在换热器中的应用提供了理论依据。

关　键　词:新型不锈钢波纹管;实验研究;强化传热

中图分类号:TK172　　　文献标识码:A

## 1　引　言

近年来波纹管型换热器以其传热效果好,同时具有原传统的固定管板换热器结构简单、适用性强等优点,在热电系统、化工、医药、食品等行业获得了广泛的应用。这种换热器采用波纹型强化换热管代替壳管式换热器中的直管,由于波纹管的波峰与波谷之间高度为 10 mm 左右,管内流动呈等直径流束型式和弧形流束型式,导致流速和压力周期性的变化,冷热流体流动时产生强烈扰动,使流体的流动状态达到充分湍流,极大破坏了边界层和污垢层的实际厚度,因此比直管的换热系数明显提高,成为一种新型、高效能的换热器。

但目前在波纹管型换热器中采用的不锈钢波纹管,一般是由不锈钢无缝管胀制而成。一方面由于波纹管流道变化的复杂性,目前对其强化换热机理的理论研究进行得极少;另一方面这种管的最大弱点是承压低、容易发生内漏[1]。本文介绍一种新型不锈钢多层波纹管的结构,并通过传热和承压能力试验,分析了新型波纹管的传热机理,证明它能承受较高压力,具有较大传热导数,为波纹管在换热器中的应用提供了理论依据。

## 2　新型不锈钢多层波纹管的结构

选取壁厚为 $\delta=0.4\sim0.5$ mm 的特种不锈钢板材,滚压卷成外径为 $D_0=20\sim34$ mm 的几种规格圆形薄壁光管,直径相差 $\Delta d=0.8\sim1.0$ mm,将焊缝错开套装成多层薄壁圆形光管,再经特殊工艺胀波凸起成型为多层波纹管,如图 1 的两层波纹管基本结构。

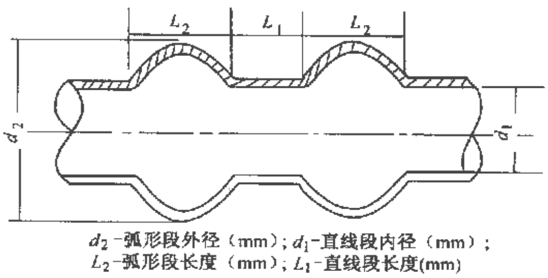


图 1　双层波纹管换热元件

## 3　试验分析

为便于比较,试验用四种类型不锈钢管,其中 1、2、4 号为波纹管,且 2 号和 4 号管有相同尺寸和波形,但 2 号双层,4 号单层,3 号为直管且与 1 号基管外径相同,尺寸详见表 1。

表 1　不锈钢管的几何尺寸

| | 1 号波纹管 | 2 号波纹管 | 3 号直管 | 4 号波纹管 |
|---|---|---|---|---|
| 波峰/mm | 44 | 32 | | 32 |
| 波距/mm | 26 | 21 | | 21 |
| 基管外径/mm | 32 | 25 | 32 | 25 |
| 壁厚/mm | 0.8 | 0.8 | 0.8 | 0.8 |
| 层数 | 双层 | 双层 | 双层 | 单层 |
| 有效管长/mm | 1 900 | 1 900 | 1 900 | 1 900 |
| 管程流道截面积/m² | 0.001 256 | 0.000 702 | 0.001 343 | 0.000 702 |
| 管程流道截面积/m² | 0.001 831 | 0.001 184 | 0.001 572 4 | 0.001 184 |

### 3.1　承压能力测试

波纹管承受外压的试验,试验装置参照文献[2],如图 2 所示。

收稿日期:2002－01－24;修订日期:2002－04－03

基金项目:黑龙江省科委基金资助项目(200A006)

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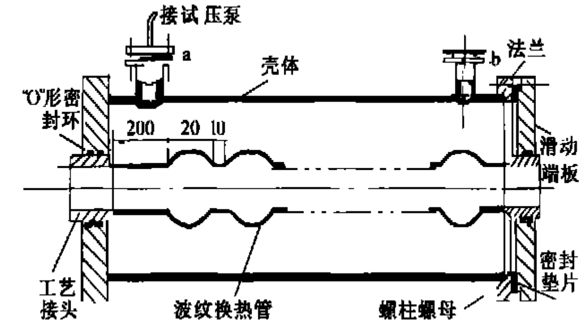


图 2　外压试验装置

为比较波纹管与直管承受外压的能力，在波纹管试件上留出直边 200 mm。试验测试了 2 号和 4 号波纹管。测试方法为：先在壳体内充满水，排净壳体内的剩余空气，当发现接口 b 出现连续水流后，用法兰盖密封好。然后打压泵起动，当压力升至 7.0 MPa 时，4 号管失效，而失效的部位在直边段。在整个直边段全部失稳，被压扁成三瓣时，而带有波的部位没发现异常，压力升到 8.0 MPa，波纹管处被压扁。继续升压至 9.5 MPa，才发现 2 号波纹管被压扁变形。

波纹换热管承受内压力的试验，主要是爆破试验以及检验管屈服时的屈服压力，仍选取 2 号和 4 号波纹管进行测试，试验结果：

4 号管：爆破压力 $P_b$ = 30.5 MPa，屈服压力 $P_S$ = 29.5 MPa。

2 号管：爆破压力 $P_b$ = 40 MPa，屈服压力 $P_S$ = 34.8 MPa。

而外径 Φ25 的同等壁厚双层不锈钢直管，其承内压试验结果：

爆破压力 $P_b$ = 23.8 MPa，屈服压力 $P_S$ = 25.4 MPa。

可见，波纹虽然是从直管发展而来，但其承受外压抗失稳能力以及承受内压抗爆破的能力均好于同厚度同材质的直管，而双层不锈钢波纹管比单层管有更强的抗外压和承内压能力。

## 3.2　传热及流动阻力的实验

实验系统如图 3 所示，整个实验装置主要包括试验段（换热器）、加热器、泵、回水箱、管路系统、电加热系统和测量系统。传热面两侧为水一水逆流运行，热流体走管程，冷流体走壳程。冷、热流体逆流运行。测试装置、测试流程、测试仪表、测试方法和计算方法等均符合《管壳式换热器》和 Q/LJ201－1998《管壳式换热器性能测试方法》标准规定的要求。

试验中水流速度的范围在 0.6～2.4 m/s 之间，这一试验范围能够满足实际应用对速度范围的要求。实验结果见图 4 和图 5，分别是各管总传热系数、压降随流速变化的测试曲线。

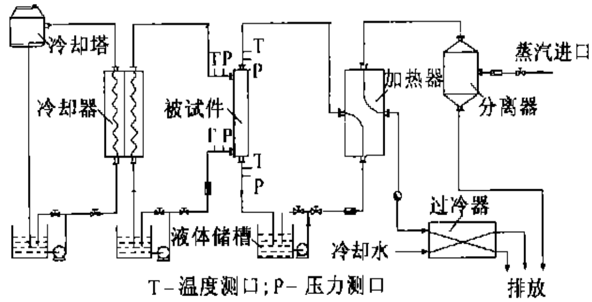


图 3　传热试验装置图

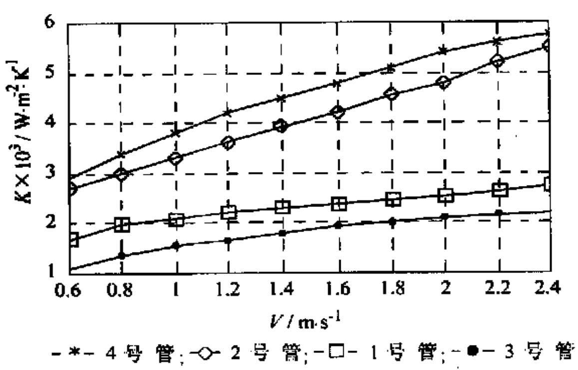


图 4　总传热系数随流速变化的测试曲线

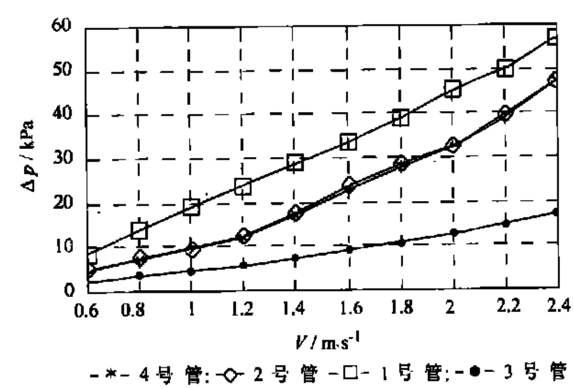


图 5　各管管内压力降随流速变化的测试曲线

试验结果分析如下：

（1）1、2、4 号波纹管总传热系数高于直管 3，但管内流动阻力比直管大，且流速越高，流动阻力越大。

（2）在三种型号的波纹管中，4 号波纹管总传热

系数最大, 2 号次之, 1 号最小, 这是由于 4 号管为单层, 导热热阻很小, 且无接触热阻。对于 1 号管, 由于 $d_2/d_1$ 过大(波峰值过高), 导致流体流动产生脱流, 降低了总传热系数, 同时流动阻力也达到最大。

可见, 虽然波纹管流动阻力比直管高, 但总传热系数可达直管的 2 倍左右。以总传热系数达最高值为目标函数, 通过试验和计算机整理, 得出双层波纹管最佳设计波峰、波距等参数的优化尺寸如下:

$$\frac{d_2}{d_1} = 1.3 \sim 1.5 \qquad \frac{L_2}{L_1} = 0.3 \sim 0.6$$

$$\frac{L_1}{d_1} = 0.35 \sim 0.55$$

## 4　结论

(1) 新型不锈钢波纹管特殊的波峰与波谷设计, 使流体沿流体方向在波峰处速度降低、静压增大; 波谷处速度增加、静压减小, 这样流体是在反复改变速度及压力梯度下进行, 产生的旋涡极大的破坏了边界层的形成。同时采用优化设计尺寸, 能使总传热系数达直管 2.5 倍。

(2) 特殊滚压工艺成形的双层波纹管, 表面曲率大、可伸缩, 产生结垢容易脱落, 这就使其同时还具有较强的防垢和自动除垢能力。

(3) 新型不锈钢波纹管采用双层设计, 虽然总传热系数略有降低, 但比单层管有更强的抗外压和承内压能力, 在实际工程中已获得了成功的应用[3]。

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(渠　源　编辑)

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颗粒两相流动的湍流强度会随粒径的减小而增加。在靠近壁面的区域, 两相流的流场湍流强度较大, 而且对粒径较小的颗粒, 其脉动速度的分布将出现脉动和随机分布的特征。

(2) 0～100 μm 颗粒的存在将会对气相流场的分布产生显著的影响。在管流的主流区域, 颗粒将会抑制气相的流动速度。而在壁面附近颗粒的存在将会影响原有的气体湍流结构, 由于尾迹区的产生和破碎, 两相流中气流的速度较单相流动增加。

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(渠　源　编辑)

水平直管道中气体—颗粒两相流实验研究= **An Experimental Study of Gas-granule Two-phase Flows in a Horizontal Straight Pipeline** [刊, 汉] / XUE Yuan, YAO Qiang, ZHANG Jin-cheng (Department of Thermal Energy Engineering, Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy & Power. — 2003, 18(1). —39 ~42, 49

The flow field of gas-granule two-phase flows was measured by using a laser technique. During a test with the help of a three-dimensional particle dynamics analyzer measurements were taken of the hourly average speed of glass micro-pearls consisting of 0 - 100 μm granules and a pulse speed distribution with the volume fraction of the granule phase being between $10^{-4}$ and $10^{-5}$. The test results indicate that even for granules with a diameter less than 100 μm their existence in the gas-phase flow field will still give rise to a change in turbulent flow field structure. It has also been observed during the test that the turbulent-flow intensity of gas-granule two-phase flows will increase with the decrease in granule diameter. Furthermore, regarding the distribution of pulsation speed the characteristics of pulsation and random distribution can be observed in the neighborhood of tube wall surfaces. **Key words**: gas-granule two-phase flow, turbulent flow, particle dynamic analyzer

加热上升管内相及相界面密度径向分布特性实验研究= **An Experimental Study on the Characteristics of Phase and Interphase-density Radial Profile in a Heated Riser Tube** [刊, 汉] / SUN Qi, YANG Rui-chang (Thermal Energy Engineering Department, Tsinghua University, Beijing, China, Post Code: 100084), ZHAO Hua (National Key Laboratory of Bubble Physics and Natural Circulation under the China National Nuclear Power Research and Design Academy, Chengdu, China, Post Code: 610041) //Journal of Engineering for Thermal Energy &Power. — 2003, 18 (1). —43 ~46

With the help of a dual-sensor optical probe measured and studied were the radial profile characteristics of both the void fraction of steam-water dual-phase flow and the interphase density in a heated riser tube. On the basis of test results the basic law of the phase and interphase density radial-profile was investigated. Through the investigation it is found that the void fraction of the two-phase flow in the heated riser tube exhibits in the radial direction a non-uniform distribution. Depending on different operating conditions, the void fraction distribution on the whole diameter may assume an approximate U-shape, saddle shape, or an approximate arc shape with a central zone located higher than a near-wall zone. The interphase density along the whole diameter features an approximate U-shaped distribution. **Key words**: two-phase flow, void fraction, interphase density, optical probe

新型不锈钢波纹管性能及强化传热的实验研究= **An Experimental Study of the Performance of Novel Stainless Steel-made Corrugated Tubes and Their Intensified Heat Transfer** [刊, 汉] / TAN Yu-fei, CHEN Jia-xin (Electromechanical College under the Harbin Institute of Technology, Harbin, China, Post Code: 150090) //Journal of Engineering for Thermal Energy &Power. — 2003, 18(1). —47 ~49

Corrugated tubes made of a new type of stainless steel are multi-layer ones fabricated by the use of a special technique involving a concave wave formation process. In-tube flows are of an equal-diameter flow cluster type and arc-shaped flow cluster type, which can introduce a periodic change of flow speed and pressure. With the production of an intensive perturbation between cold and hot fluids a compound intensified heat exchange is realized. The corrugated tubes were tested for their pressure-bearing capacity and an experimental study of intensified heat exchange law was performed under water-water heat exchange conditions. The intensified heat exchange mechanism of the corrugated tubes was analyzed and an applicable range of optimized dimensions determined for the tubes, thus providing a theoretical basis for the use of corrugated tube-based heat exchangers. **Key words**: corrugated tube made of a new type of stainless steel, experimental study, intensified heat transfer

薄层毛细多孔介质湿区干燥过程相变传热传质常压模型= **Phase-transformation Heat Transfer and Mass Transfer Constant-pressure Model for the Drying Process of a Thin-layer Capillary Porous Media Wet-region** [刊, 汉] / LU Tao, SHEN Sheng-qiang (Power Engineering Department, Dalian University of Scien e &Technology,