垂直布置倒 U型管内汽液两相流稳态特性及脉动特性研究

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〔摘要〕 本试验以 Freon- 113为工质 ,从试验和理论两方面研究了垂直布置倒 U型管内汽液两相流的稳态、脉动曲线。试验范围如下: 出口压力 p_e= 0. 2~ 0. 4 M Pa,系统加热功率 Q= 6. 4~ 10. 4 kW,质量流速 m= 3~ 24 kg /min. 理论研究采用一维均相模型 ,用差分法求解守恒方程组 ,得到稳态的流量—— 差压特性曲线 ,同时还采用数值计算方法模拟了压力降型脉动曲线。

关键词　倒 U型管　两相流　不稳定性　脉动

分类号　TK17

凡是存在汽液两相流的工业换热器都不希望发生汽液两相流体的脉动现象,因为持续的脉动流动会造成传热恶化. 疲劳损坏等严重后果. 倒 U型管在实际生产中是一种常见的换热元件,目前在这方面的研究还不多,因此本文针对倒 U型管中的压力降型脉动进行了研究 ,计算机模拟 ,以便进行理论预测.

本试验系统是一个封闭的强制循环系统 ,由不锈钢管连接而成 ,管外包有保温材料 ,系统示意图见图 1

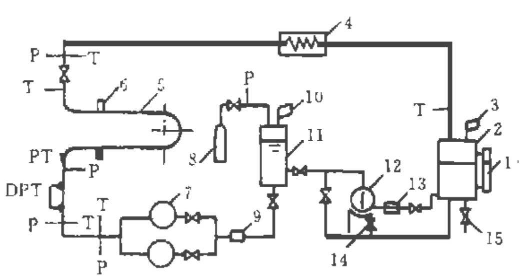

图 1 氟利昂— 113试验系统图

1. 玻璃液位计　2. 主液罐　3, 10. 安全阀　4. 冷凝器　5. 试验段　6. 电极　7. 双重孔板　8. 氮气瓶　9, 13. 过滤器　11. 稳压罐　12. 屏蔽泵　14. 屏蔽泵冷却水　15. 排污阀　DPT. 差压传感器　PT. 压力传感器　P. 压力表　T. 热电偶

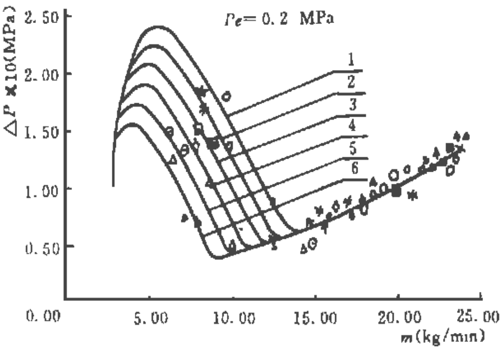

图 2 稳态的流量—— 差压特性曲线 ($\Delta p = p_2 - p_e$)

图 2表示在不同的加热功率下系统的稳态特性曲线 ,其中实线为理论计算得到. 从稳态曲线可以看出 ,随流量减小 ,系统差压随之减小 ,这一段属单相区 ;当减小到某一值后 ,随流量的进一步减小 ,系统

收稿日期: 1996- 03- 19

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差压反而增大,这是因为出现了汽相,使系统阻力增大之故;随流量的再进一步减小,差压又开始减小。在试验所做的每一种工况下都能得到这样的流量——差压特性曲线,其规律是随热负荷的减小或随压力的升高,负斜率区域向小流量方向移动且区域缩小。

在稳态的流量——差压特性曲线的负斜率区段上,观察到压力降型脉动。在本试验范围内,压力降型脉动的周期为 5~ 15 s,流量与压力脉动反相,系统压力增大脉动周期略有增大。压力降型脉动发生后,若再减小流量,则有可能观察到密度波形脉动。此刻一个最显著的变化就是压力,流量脉动的振幅、周期都减小,如图 3(b)所示。

下面从理论方面对稳态特性进行研究。整个系统的简化模型如图 4 工质在流经 3~ 4段时被电加热而沸腾。描述系统的方程组可写成如下形式:

$$\frac{\partial(\mathrm{d}u)}{\partial z} = 0 \tag{1}$$

$$\frac{\partial h}{\partial z} = \frac{q'}{m} \tag{2}$$

$$\frac{\partial p}{\partial z} + \frac{\partial(\mathrm{d}u)}{\partial z} + 2\cdot\frac{f}{d}\cdot \mathrm{d}u^2 + \mathrm{d}g\cos\theta = 0 \tag{3}$$

式中: q' —— 单位管长上的热负荷

状态方程　$$\mu = \begin{cases} \mu(T) & x < 0 \\ \mu(P) & 0 \leqslant x < 1 \end{cases} \tag{4}$$

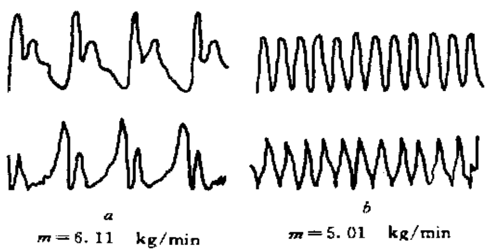

图 3　$P_s = 0.4$ MPa, $Q = 8.8$ kW 流量、压力脉动曲线

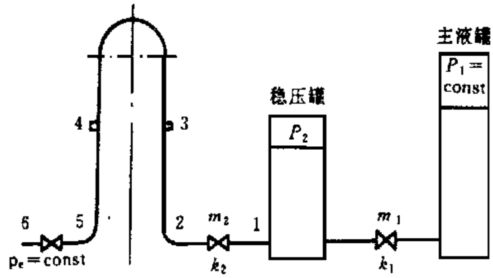

图 4　实验系统简化模型

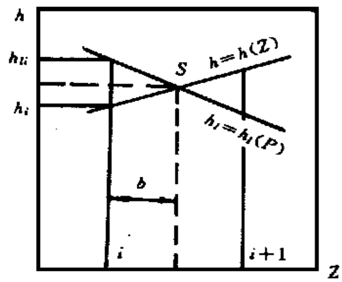

图 5　始沸点确定

式中,_—— 任意一种物性参数

x—— 干度

边界条件: T_{in}= 常数; P_e= 常数,如图 5,始沸点 b可确定如下:

$$b = \frac{h_{li} - h_i}{\frac{\mathrm{d}h}{\mathrm{d}z} - \frac{\mathrm{d}h_l}{\mathrm{d}z}} \tag{5}$$

系统的控制方程组采用分段有限差分求解,即认为系统是由图 4所示的五个区段组成,分段求解。流体参数均采用平均值。守恒方程组写成如下形式:

$$\mathrm{d}_i u_i = \mathrm{d}_{i-1}\cdot u_{i-1} \tag{6}$$

$$h_i = h_{i-1} + \frac{q'\cdot\Delta z_i}{m_i} \tag{7}$$

$$p_i = p_{i-1} - \left[2\cdot\frac{f_i}{d}\cdot\frac{\mathrm{d}_i^2 u_i^2}{\overline{\mathrm{d}}_i} + \frac{\mathrm{d}_i^2 u_i^2}{\Delta z_i}\left(\frac{1}{\mathrm{d}_i} - \frac{1}{\mathrm{d}_{i-1}}\right)\right]$$
$$\times \Delta z - \overline{\mathrm{d}}_i g\cos\theta\cdot\Delta z_i \tag{8}$$

图 2中的实线即是求解方程 (6)~ (8)所得,可以看出,试验数据和理论计算的结果符合良好。

稳态问题的解可以作为随时间变化量的初始条件。压力降型脉动的一个模拟方法即是给稳压罐的压力一个小扰动。试验中发现压力降型脉动的周期远大于流体粒子流过加热段的时间,所以有理由认为加热段中的流动是准稳态流动。

同样,我们给出整个系统随时间变化的控制方程组:

$$p_1 - p_2 = \left(k_1 m_1^2 + p_L\frac{L_1}{A_1}\frac{\mathrm{d}m_1}{\mathrm{d}t}\right)\cdot\frac{1}{\mathrm{d}_L} \tag{9}$$

$$p_2 - p_e = (p_2 - p_e)_0 + \frac{L_2}{A_2}\frac{\mathrm{d}m_2}{\mathrm{d}t} \tag{10}$$

$$m_1 - m_2 = -(p_L - p_g)\cdot\frac{\mathrm{d}v_g}{\mathrm{d}t} \tag{11}$$

$$\frac{\mathrm{d}v_{N2}}{\mathrm{d}t} = -\frac{(p_{N2}v_{N2})_0}{p_{N2}^2}\cdot\frac{\mathrm{d}p_2}{\mathrm{d}t} \tag{12}$$

$$Q - Q_f = c_w \cdot m_w \cdot \frac{dT_w}{dt} \quad (13)$$

$$Q_f = T \cdot A_h \cdot (T_w - T_f) \quad (14)$$

通过改变式(9)中的 k_1 值来实现系统的扰动,

令 $k_1(t) = k_0[1 + a(1 - e^{-bt})]$ (15)

式中,k_0—— 常数,与阀门初始开度有关

a—— 阀门开度幅度变化系数

b—— 阀门开度速度变化系数

边界条件: p_1= 常数, T_{in}= 常数, p_e= 常数, Q_0= 常数

初始条件: $m_1 = m_2$, $Q = Q_0$

采用有限差分法求解非线性方程组,稳态解由前面得出。考虑到计算方法的稳定性,时间步长取为:

$$\Delta t^j = \frac{\Delta z_{min}}{(u_i^{j-1})_{max}}$$

式中,u_{max}—— 流体在试验段的最大流速

图 6给出理论计算的压力和流量的脉动曲线,与图 3比较,除振幅有一定差异外,其余均符合良好。

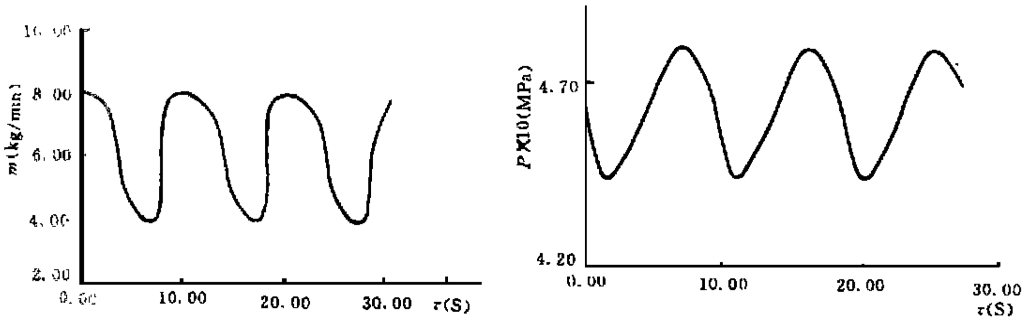

图 6 计算机模拟进口压力和流量的脉动曲线

Pe= 0.4 MPa　Q= 8.8 kW　m= 6.11 kg/min

根据上述理论分析,结论为:

(1)压力降型脉动发生在流量—— 差压特性曲线的负斜率区段上,压力与流量脉动反相。

(2)热负荷增加,系统稳定性下降;系统压力升高,稳定性上升。

(3)系统压力增大,脉动周期略有增大。压力降型脉动发生后,若继续减小流量,压力降型脉动会转变成密度波形脉动,此刻最明显的变化就是压力、流量脉动的振幅和周期均减小。

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符　号

p	密度, kg/m^3	下标:
u	流体速度, m/s	e 试验段出口
h	流体焓值, kJ/kg	f 流体
A	管子流通截面积, m^2	g 汽相
p	压力, Pa	l 液相
Q	加热功率, kW	w 管壁
f	阻力系数	N_2: 氮气
m	质量流速, kg/s	o 稳态值:
θ	加热段与竖直方向夹角	in 试验段进口
d	管内径, m	
v	体积, m^3	
T	温度, K	
T	传热系数, kW/(m^2° K)	

大型电站锅炉炉内温度场的数值试验研究= **An Experimental Study of the Temperature Field Inside a Large - sized Utility Boiler Furnace by CAT** [刊,中]/Chen Xiaodong, Dong Peng, Cheng Congshu, Qin Yukun (Harbin Institute of Technology) //Journal of Engineering for Thermal Energy & Power. - 1997, 12(5). - 321～ 323

Through the use of a computer aided test method a fundamental research is conducted of the characteristics of the temperature field in a large-sized utility boiler furnace. On the basis of a three-dimensional numerical simulation of the working medium radiation heat transfer in the furnace obtained is a pertinent in-furnace temperature field distribution law. The numerical test results in most cases are in relatively good agreement with those of the on-site tests. **Key words**: boiler, temperature field, computer aided test

垂直布置倒 U型管内气液两相流稳态特性及脉动特性研究= **A Study of the Steam/Liquid Dual-phase Flow Steady-State and Pulsation Characteristics in a Vertically Placed and Inverted-U Shaped Pipe** [刊,中]/Wu Yining, Lin Zonghu (Xi'an Jiaotong University) //Journal of Engineering for Thermal Energy & Power. - 1997, 12(5). - 324～ 326

With Freon- 113 serving as a working medium the steady-state and pulsation curves of steam/liquid dual-phase flow in a vertically placed inverted-U shaped tube is studied from both the experimental and theoretical aspects. The test range can be given as follows: outlet pressure Pe= 0.2- 0.4 MPa, system heating power output Q= 6.4- 10.4 kW, mass flow speed m= 3- 24 kg/m. For the theroetical study adopted is a one-dimensional uniform-phase model with a difference method used for solving a group of conservation equations. Obtained are the steady-state flow ratedifferential pressure characteristics curves. Moreover, a numerical calculation method has been used to simulate pressure-drop type pulsation curves. **Key words**: dual-phase flow, unstability, pulsation

螺旋槽管凝结换热器的研究与应用= **The Study and Application of Condensation Heat Exchangers Consisting of Spirally Corrugated Tubes** [刊,中]/Wu Huiying, Shuai Zhiming (Southeastern University) //Journal of Engineering for Thermal Energy & Power. - 1997, 12(5). - 327～ 329

An experimental study is made of a condensation heat exchanger with spirally corrugated tubes. Dimensionless correlations are obtained separately for phase transformation-related convective heat transfer in spirally corrugated tubes, tube-outside condensation heat transfer criteria and tube-inside flow resistance. On the basis of the test results the spirally corrugated tubes have been successfully used in power station condensation heat exchangers. **Key words**: spirally corrugated tube, condensation heat exchanger, intensified heat transfer

含湿多孔介质内热量迁移的研究= **A Study of Heat Migration in Unsaturated Porous Media** [刊,中]/Jin Feng, Shi Mingheng, Yu Weiping (Southeastern University) //Journal of Engineering for Thermal Energy & Power. - 1997, 12(5). - 330～ 331

An analysis is given of the mechanism of heat migration under the coupled action of heat and moisture in unsaturated porous media. A mathematical model for calculating the heat migration in porous media is proposed. Also discussed is the effect of different boundary conditions on the temperature distribution in porous media. **Key words**: heat transfer, porous media, coupled action, heat/moisture migration

煤燃烧特征点变化规律的研究= **A study of the Variation Law of Coal-combustion Characteristic Points** [刊,中]/Zhu Qunyi, Zhao Guangbo, et al (Harbin Institute of Technology) //Journal of Engineering of Thermal Energy & Power. - 1997, 12(5). - 332～ 334

An experimental study is performed of the combustion characteristics of thirteen kinds of coals by using a