文章编号: 1001－2060(2001)04－0418－03

采用扩展温度振荡法测量超临界 CO_2 管内对流换热特性

张后雷[1], 宣益民[1], Wilfried Roetzel[2]

(1. 南京理工大学 动力工程学院, 江苏 南京　210094; 2. 汉堡国防大学, 德国 汉堡　22043)

摘　要: 提出了考虑小通道内流体温度变化时测量管内对流换热系数的扩展温度振荡法模型, 该法可用于测量各种光滑表面通道内流动的局部对流换热系数。实测了典型压力温度条件下 2 mm 内径不锈钢圆管内超临界 CO_2 对流换热系数。

关　键　词: 超临界 CO_2; 对流换热; 温度振荡法

中图分类号: TK124　　文献标识码: A

1　引言

近年来, CO_2 跨临界制冷系统已引起了学术界和工业界的极大关注。在空调、热泵及系统组件方面已进行了大量研究工作[1~4]。对车辆空调和一些一体化机组而言, 紧凑、重量轻的热交换器是十分必要的, 小直径换热管或微通道换热管有可能扮演重要角色[5], 并且也有利于解决系统的高压设计问题。在实际应用中一个需要深入研究的问题是 CO_2 跨临界制冷系统气体冷却器内的超临界换热过程。文献[6]曾对一般工业应用中的超临界换热做过详尽评述。文献[7]则针对 CO_2 制冷对超临界换热做了介绍。总而言之, 现有的实验数据范围有限, 相互间存在着较大的分散性, 其中适用于 CO_2 气体冷却器设计的数据仍非常缺乏, 因此有必要进行深入的实验和理论研究。

由于超临界流体可视作单相, 有多种方法可用来测量其对流换热特性。Prinzen 等[8]曾成功地运用温度振荡法测量了水在大直径管内流动的对流换热系数。这种方法假定流体温度不变, 适用于管内流体流动热容量足够大的情况。

笔者的主要工作是考虑到超临界 CO_2 在小直径圆管内流动时, 流动热容量相对较小, 取消了流体温度不变假设, 提出了扩展温度振荡法测试模型, 并实测了超临界 CO_2 在2 mm内径不锈钢圆管内的对流换热系数。为了得到更好的一维温度波, 采用电阻丝线加热代替了文献[8]中的激光点加热。

2　测试原理

测试原理如图 1 所示。测试管是一根内径 2 mm、壁厚 0.25 mm、长 500 mm 的不锈钢圆管。用电阻丝沿圆周方向缠绕在圆管外表面上, 通以周期性电流加热管外表面, 从而在管壁内产生一个温度振荡并分别沿 x 和 $-x$ 方向传播。外壁面温度场由一台红外热像仪记录。在距离加热线不同位置的温度波的相位移或振幅衰减可以通过实验测定, 其数值在稳定流动工况下和对流换热系数存在一一对应关系, 通过实验相位移或振幅衰减结果和理论计算值的配比可以确定对流换热系数的大小。当流体的流动热容量足够大时, 可假定流体温度在壁内温度振荡过程中保持不变, 这样可以得到温度振荡分析解。但在本文的测试条件下, 管径较小, 如仍采用流体温度不变假设, 在某些工况下有可能导致较大的误差甚至产生失真的结果。鉴于此, 笔者提出了考虑流体温度变化的更为一般的扩展温度振荡模型。

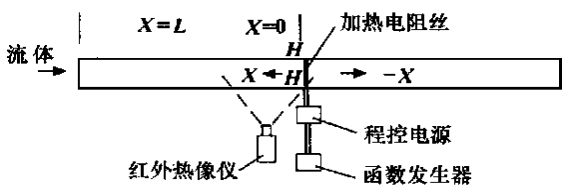

图 1　测量原理

基本假设:

流体温度变化有限, 物性为常数; 管外壁面散热忽略不计; 壁面温度仅与坐标 x 和时间 t 有关; 管壁热物性为常数; 稳定温度振荡。

固壁能量方程为

$$\frac{\partial T_w}{\partial t} = a\frac{\partial^2 T_w}{\partial x^2} + \frac{hp}{\rho_w c_{pw} A_{cw}}(T_f - T_w) \qquad (1)$$

收稿日期: 2000－05－24

作者简介: 张后雷(1971－), 男, 江苏徐州人, 南京理工大学讲师.

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流体能量方程为

$$\frac{\partial T_f}{\partial t} = -\frac{m_f}{\rho_f A_{cf}}\frac{\partial T_f}{\partial x} + \frac{hp}{\rho_f C_{pf} A_{cf}}(T_w - T_f) \quad (2)$$

初始条件为

$$T_w(0, x) = T_f(0, x) = T_0 \quad (3)$$

左边界条件为

$$q_w = (t, L) = 0 \quad (4)$$

$$q_f = (t, L) = 0 \quad (5)$$

固壁右边界条件为

$$T_w(t, 0) = T_{w,ave} + u\sin(\omega t + \Phi_0) \quad (6)$$

固壁右边界条件(6)由实验确定。式(1)~(6)中符号含义如下: a—热扩散率; A_c—截面积; C_p—定压比热; h—对流换热系数; L—研究段管长; m—质量流量; p—流体管内流动湿周; q—热流密度; t—时间; T—温度; T_0—初始温度; u—温度振荡振幅; x—位置坐标; Φ_0—初相位; ρ—密度; ω—角频率; 下标 ave, f, w—平均, 流体, 固壁。

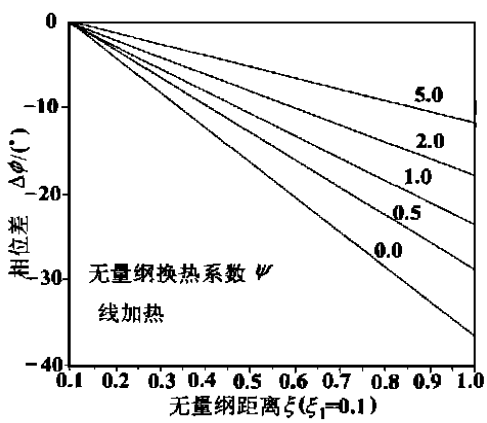
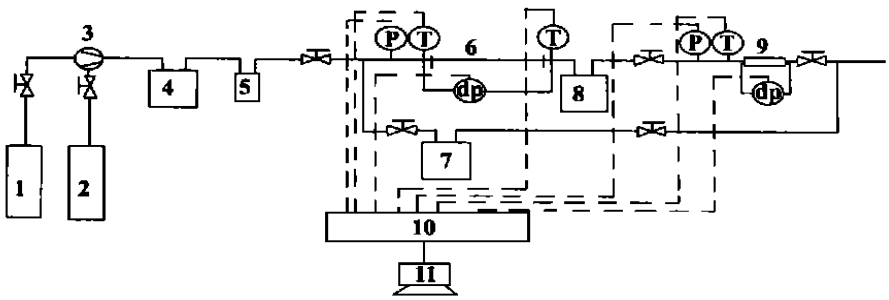


图 2　理论相位差示意图

采用有限差分法求解以上模型可得到在管壁不同位置的温度随时间的变化曲线, 进而求出相应位置温度振荡的相位和振幅, 选定一个参考位置就可以得到某位置相对于参考位置的理论相位差和振幅比。作者仅采用相位差配比来反求对流换热系数, 并仅采用加热区上游的测试数据。图2给出了相位差 $\Delta\Phi$ 与无量纲距离 ξ 和无量纲换热系数 ψ 依变关系的理论计算结果。图中 $\Delta\Phi = \Phi - \Phi_1$, Φ 为相位; $\xi = x(\omega/a)^{1/2}$; $\psi = h(\delta\rho C_p\omega)$, δ 为壁厚; 下标 1 为参考点。

3　实验装置与方法

实验装置如图 3 所示。采用开式系统, 一台气动活塞泵和一个盘管型预热器将常温下储存罐中 5 MPa 的液态 CO_2 升压升温至超临界状态, 通过调节泵的驱动压力和预热器功率, 可得到所需的压力和温度, 其范围为 7.5~12 MPa 和 35 ℃~90 ℃。考虑到泵出口流体压力波动较大, 引入了缓冲容器以消除其影响。实验测试表明, 加了缓冲容器后, 最大压力波动小于 0.8%。为了调节通过实验段的流体流量, 设置了旁路管道。后加热器和旁路加热器用于防止流体通过阀降压节流时可能出现的外壁结冰现象。实验时的流体压力由一个压力传感器和一个差压变送器来确定, 流体温度采用装在测试段进出口的两个 K 型热电偶来测量, 热电偶采用 2804A 石英温度计进行预标定。流体流量的测量在压力降至接近大气压力时进行, 同时测定流量计入口的流体压力和温度。流量计出口的流体被直接排入环境。有关流体的实验数据经 NI 数据采集卡并借助于 CVI-Lab Windows 软件送入计算机进行后续处理。



1—CO_2 瓶; 2—N_2 瓶; 3—CO_2 活塞泵; 4—前加热器; 5—缓冲容器; 6—测试管; 7—旁路加热器; 8—后加热器; 9—流量计; 10—数据采集卡; 11—计算机

图 3　实验装置示意图

测试管用直径 0.2 mm 的电阻丝加热, 并由函数发生器调制程控电源以得到所需要的加热周期和振幅。测试管外表面温度由一台液氮冷却的 Agema Thermovision 880 LW 型红外热像仪来测量。在流体流动和壁面热波均稳定后, 记录下一系列温度—时间序列热图, 采集速度为 4/25 秒/幅, 每幅热图含 140×140 个像素, 经过双丝法标定可确定每个像素相当于实际壁面面积的大小为 0.23 mm×0.23 mm。

4　结果与分析

由实验测得的热图序列可提取出每个像素的温度时间热波数据, 采用非线性回归技术可得到该温度波的相位和振幅, 即实验相位和振幅值。图 4 所

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示为流体压力 $P = 8.5$ MPa，温度 $T = 320$ K，质量流速 $G = 277.5$ kg/(m^{2}s) 时的实验相位分布。由图 4 可方便地得到任意两点的相位差数据，通过和理论结果的配比即可得到相应工况下的对流换热系数 h。

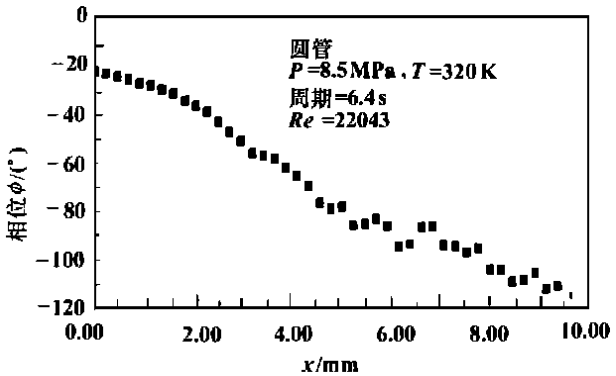

图 4 实测相位分布($G = 277.5$ kg/(m^{2}s))

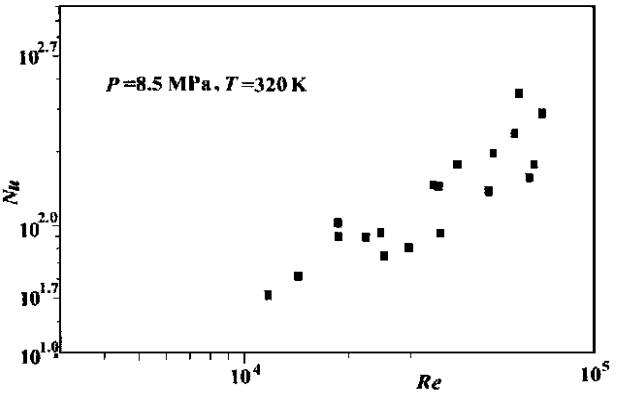

图 5 Nu 随 Re 的变化

图 5 所示是流体压力 $P = 8.5$ MPa，温度 $T = 320$ K 时的换热特性实验结果，以无量纲准则数 Nu 表示。试验 Re 数范围为 $1.1\times10^4 \sim 7.2\times10^4$。事实上，由于测试范围大部分处在流动过渡区，换热特性随 Re 数的变化存在一定的不稳定性。在近临界区域流体物性变化剧烈，其换热过程的不稳定性更强，图 5 的结果也明显反映了这一特点。为了获得适于工程设计的实用准则关系式，有必要在更宽的压力和温度范围内进行更多的实验测试。作者所采用的温度振荡法原理简单，外部加热功率小，可测量通道内流动局部对流换热特性，是一种有效的黑箱测试方法。

5 结论

(1) 本文中提出的测量流体小通道内对流换热系数的扩展温度振荡模型，可适用于不同截面尺寸光滑圆管或非圆管内局部对流换热系数的测定。

(2) 实测了超临界 CO_2 在小直径圆管内的对流换热系数，所测得的数据可供设计 CO_2 气体冷却器时参考。

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(孙显辉 编辑)

汽轮机叶片振动和温度测量

据《火力原子力发电》2000 年 3 月号报道，经长时间运行后，机组高压汽轮机调节级和低压汽轮机末 2 级的疲劳裂纹可能显著影响大修的预定计划。

为了精确估算疲劳寿命，在 1 台 220 MW 机组运行过程中测量了其高压调节级叶片的振动应力和温度以及低压级叶片的振动应力。

文章叙说了测量的方法、测量结果以及对与疲劳寿命估算有关的振动现象的考虑。

(思娟 供稿)

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空气与 O_2+CO_2 气氛下钙基脱硫剂固硫规律的实验研究＝**Calcium-based Desulfuration Agent under the Gaseous Condition of Air and O_2/CO_2**[刊, 汉] / ZHOU Ying-biao, ZHENG Ying, ZHANG Li-zhi, et al (National Key Lab of Coal Combustion under the Central China University of Science &Technology, Wuhan, China, Post Code: 430074) //Journal of Engineering for Thermal Energy Power. — 2001, 16(4). —409～411

An experimental investigation was conducted of the mechanism of SO_2 emissions and $CaCO_3$ desulfuration during the burning of Heshan bituminous coal under the gaseous condition of air and O_2/CO_2. The results of the experimental investigation indicate: 1. CaO in coal ash plays a significant role in effecting desulfuration; 2. The presence of CO_2 can markedly contribute to the desulfuration process; 3. Under the condition of a constant ratio of temperature and Ca/S it is essential to optimize the content of CO_2. These findings provide an underlying basis for the comprehensive treatment of pollutant emissions under the circulating combustion mode of O_2/CO_2. **Key words**: CO_2,, calcium-based desulfuration agent, desulfuration

激光选区烧结(SLS)成型机的粉末预热过程的实验研究＝**An Experimental Study of the Powder Preheating Process for a SLS (Selective Laser Sintering) Forming Machine** [刊, 汉] / LI Xiang-sheng, SHI Yu-sheng, WANG Zong-jun, Huang Shu-huai (Rapid Forming Technology Center of Materials College under the Central University of Science &Technology, Wuhan, China, Post Code: 430074) //Journal of Engineering for Thermal Energy &Power. — 2001, 16(4). —412～414

In the rapid forming technology of selective laser sintering (SLS) the transfer and absorption of heat energy represents a key process. The effective use and uniform distribution of heat energy constitute a major factor in ensuring the success of the SLS forming technology. The preheating of powder has been considered as one of the most important factors having a decisive influence on the forming process and forming precision. An analysis is given of the preheating process of a general preheating method in the working cavity of a forming machine. On the basis of experiments obtained was a mathematical model depicting the preheating process of a preheating temperature field. The model plays a crucial role in the design of a preheating device and the control of SLS forming process. **Key words**: selective laser sintering, thermal energy, preheating, mathematical model

汽轮机调节系统中摩擦与间隙的定位方法研究＝**A Study of the Method for Locating the Friction and Clearance in a Steam Turbine Governing System** [刊, 汉] / DAI Yi-ping, SONG Xiao-wei, DENG Ren-gang, et al (Thermal Energy Engineering Department, Xi'an Jiaotong University) //Journal of Engineering for Thermal Energy &Power. — 2001, 16(4). —415～417

The presence of friction and clearance in a steam turbine governing system can cause a limiting ring oscillation of the system. The variation of the limiting ring frequency and amplitude may serve as the characteristics of fault diagnosis. The frequency spectrum features of the limiting ring in various links will change, depending on the damping characteristics of signal transfer in the system. In view of this, by using the method of frequency spectrum analysis, the authors have attained a locating diagnosis of the friction and clearance, based on the ratio of high-order amplitude spectrum and basic wave amplitude of measurable signals. The feasibility of the above-mentioned method has been verified by a simulation test. **Key words**: steam turbine, governing system locating diagnosis, frequency spectrum analysis

采用扩展温度振荡法测量超临界 CO_2 管内对流换热特性＝**The Measurement of Convection Heat Transfer Characteristics in a Supercritical Carbon-Dioxide Gas Tube by the Use of an Extended Temperature Oscillation Method** [刊, 汉] / ZHANG Hou-lei, XUAN Yi-min (Power Engineering Department, Nanjing University of Science & Technology, Nanjing, China, Post Code: 210094), Wilfried Roetzel (University of the Federal Armed Forces at Hamburg, Germany, Post Code: 22043) //Journal of Engineering for Thermal Energy &Power. — 2001, 16(4). —418～420

Presented is an extended temperature oscillation model for the measurement of in-tube convection heat-transfer factor during the variation of fluid temperature in a small duct. The recommended method can be employed to measure the local convection heat-transfer factor of flows in various kinds of smooth-surface duct. An actual measurement was conducted of the supercritical CO_2 convection heat-transfer factor in a round stainless steel tube of 2 mm inner diameter under typical pressure and temperature conditions. **Key words**: supercritical carbon dioxide, convection heat transfer, temperature os-

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cillation method

边缘检测小波对信号奇异性的检测在汽液两相流动中的应用＝**The Use of Edge Detection of Wavelets for Signal Singularity Detection in a Gas-liquid Two-phase Flow**[刊，汉] / SHANG Zhi，GUO Yu-jun，SU Guang-hui，et al（Energy and Power Engineering Institute under the Xi' an Jiaotong University，Xi' an，China，Post Code：710049）// Journal of Engineering for Thermal Energy & Power. — 2001，16(4). —421 ~424

Currently，function（signal）singularity detection method is mainly realized through the use of wavelet transformation. As the dissociation of wavelets is characterized by a fairly good localized feature of space and frequency domain，the wavelet transformation can delineate the variation law of signals and perform the detection and analysis of various singular properties of singular points in signals. It is also possible to analyze a gas-liquid two-phase flow condition through an edge detection of wavelet transformation and detect thermodynamic data in a gas-liquid two-phase flow. The edge detection of pressure curves of a gas-liquid two-phase uniform-phase flow model shows that the edge detection of wavelets can be fully utilized to perform the edge detection of the gas-liquid two-phase flow conditions. **Key words**：wavelet transformation，edge detection，gas-liquid two-phase flow

减振算法研究及其在轴流压缩机叶片中应用＝**A Study of Vibration Damping Algorithm and Its Application on Compressor Blades**[刊，汉] / XUE Guo-xin，XIAO Li-chuan（Jiangsu Provincial Petrochemical Institute，Changzhou，Jiangsu Province，China，Post Code：213016）// Journal of Engineering for Thermal Energy & Power. — 2001，16(4). —425 ~427

The use of viscous-elastic materials has been considered as one of the effective means for coping with vibrations in major mechanical devices of power engineering units. The calculation of vibration eigenvalues，though rather complicated，is of crucial importance. In view of the possibility of a wide-range variation of damping characteristics of mechanical devices the authors have proposed a high-order perturbation model. The latter has a unified calculation scheme and can be employed to perform a reliable analysis of the eigenvalues of the relevant devices. A study of its use on compressor blades has shown that the model gives reliable results，lends itself to be easily programmed by a computer and can be readily popularized for general use. **Key words**：vibration damping，analysis of eigenvalues，perturbation method，compressor blade

汽轮机循环水系统的稳态仿真数学建模＝**Mathematical Modeling for the Simulation of the Circulating Water System of a Steam Turbine**[刊，汉] / LIU Hai-feng，SHI Xiao-ping，YAO Yu（Simulation Center under the Harbin Institute of Technology，Harbin，China，Post Code：150001）// Journal of Engineering for Thermal Energy & Power. — 2001，16(4). —428 ~430

The circulating water system of a steam turbine represents a heat exchange system of cooling water and high-temperature steam. The mathematical model based on the mechanism of the cooling water and water pressure is very complicated and not suited for a computer-based real-time simulation system. By the use of the measured data of a power plant and with the help of a hyper-curvature fitting method set up was a mathematical model for the simulation of the water temperature and water pressure of the circulating water system. The recommended model involves a relatively small computation load and features a high precision as certified by the simulation results. **Key words**：mathematical modeling，simulation，super-curvature fitting

一种电站热工流体系统故障诊断的方法＝**A Fault Diagnosis Method for the Thermodynamic Fluid System of a Power plant**[刊，汉] / YAN Shui-ping，HUANG Shu-hong，GAO Wei（Power Engineering Department，Central China University of Science & Technology，Wuhan，China，Post Code：430074 // Journal of Engineering for Thermal Energy & Power. — 2001，16(4). —431 ~433，443

Presented is a strategy of system division designed to conduct fault diagnoses for a complicated system. With the condensate system of a power plant serving as an example described are the system simulation method and its related model. Explored is a method of fault identification and diagnosis through the use of a real-time system simulation model and failure model. The recommended method can not only make a diagnosis of the common faults（for example，pipe leakage and clogging）of the system but also solve the residuals-caused difficult problems in a complicated system. This has laid the foundation for the use of autonomous type of fault diagnosis system in power plants. **Key words**：fault diagnosis，system

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