

γ射线法测量亚临界汽-水两相流截面含气率的实验研究

胡日查¹, 刘春龙¹, 毕勤成², 吕海财²

(1. 中国科学院长春光学精密机械与物理研究所, 吉林 长春 130033;
2. 西安交通大学 动力工程多相流国家重点实验室, 陕西 西安 710049)

摘要: 采用单束、窄束伽马射线测量了亚临界垂直上升管内汽-水两相截面含气率。管内工况设定在 17-21 MPa, 质量流速在 600-1 000 kg/(m²·s), 温度在 25-400 °C 范围内。通过分析探讨了伽马射线测量亚临界汽液两相流截面含气率的可行性, 并进一步分析了工质质量流量、压力、温度对伽马射线测量的影响。分析得出, 质量流量及压力对伽马射线测量亚临界汽液两相流截面含气率几乎没有影响, 而大区间温度变化对于测量影响较显著。通过实验测量值与经典理论公式的对比发现, 实验测量值与 Smith 公式吻合最好。

关键词: 截面含气率; 伽马射线; 气液两相流; 亚临界

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引言

为更好地适应电网调峰需求, 超(超)临界压力火电机组多采用变压运行方式。变压运行方式下, 主蒸汽压力随着负荷的变化而变化, 水冷壁管内工质压力要经常性地超临界到亚临界的广泛压力范围内变化^[1]。在临界压力区, 水的物性在相变点(或拟临界点)附近随温度的变化特别剧烈, 这使得管内临界压力区水的传热机制较为复杂, 出现传热恶化的可能性加大, 准确测量此时的截面含气率对研究传热恶化显得至关重要^[2]。

而目前测量截面含气率方法主要有快关阀门法、射线法、电学法、光导探针法、压差法和层析成像法^[3-4]。快关阀门法对阀门的性能和同步性要求较高, 需要同时关闭两个阀门, 不能在高温高压亚临界下应用。电学法和光学法干扰流场, 高温下探测元件精度低^[5]。层析成像法测量出的截面含气率值精度较高, 但操作较复杂, 气液两相接触界面的信号

处理存在难点^[6]。射线测量法是利用射线在穿过不同密度介质时衰减程度不同来测量, 不会破坏管道中的流场和温度场的自然分布, 适用于高温高压亚临界条件下测量^[7-8]。

目前虽然国内外诸多学者采用伽马射线测量截面含气率, 但测量工质基本集中在低压冷态气水、油水两相流。涉及到高温、高压尤其是亚临界甚至超临界流体的测量, 则研究较少。只有赵于等在此方面做过一些工作^[8]。本研究采用伽马射线法对亚临界气液两相流截面含气率进行研究, 并分析了温度、质量流量和压力等因素对测量的影响。通过实验值与经典理论公式值对比, 为射线法在亚临界下测量汽-水的截面含气率提供依据。

1 伽马射线测量原理

伽马射线的单能放射源可以看成各相同性点源, 强度 S (光子/s) 则有:

$$I_0 = \frac{S}{4\pi R_{st}^2} e^{-\mu_r R_{st}} \quad (1)$$

式中: μ_r — 空气对伽马射线的线性衰减系数, R_{st} — 射线源与物体的距离, m。

将管内流动的汽-水两相简化为汽和水完全分层的模型, 并对公式进行推导得^[9]:

$$\alpha = \frac{\ln(N/N_1)}{\ln(N_g/N_1)} \quad (2)$$

式中: α — 管内截面含气率; N — 射线穿过结构层、汽水两相后的计数(1/s); N_1 — 管内充满饱和水时出射射线的计数(1/s); N_g — 管内全为高压蒸汽时出射射线的计数(1/s)。

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作者简介: 胡日查(1986-), 男, 内蒙古通辽人, 中国科学院长春光学精密机械与物理研究所研究实习员。

为实现该测量原理,提高测量精度,演化出以下 4 种形式的伽马射线测量截面含气率的方法^[10]。图 1(a) 为一次测量法,测量结果易受空泡分布的影响。图 1(b) 为扫描测量法,能克服空泡分布不均的影响,精度较高但要求被测介质的流动状态保持较长时间的稳定。图 1(c) 为改进型一次测量法,通过设计特殊准直孔形状达到消除空泡分布影响。图 1(d) 为多束测量法,可同时测量平均截面含气率,减少空泡分布的影响。本研究采用一次测量法,该测量法较为简单,且其测量精度符合工程测量精度。

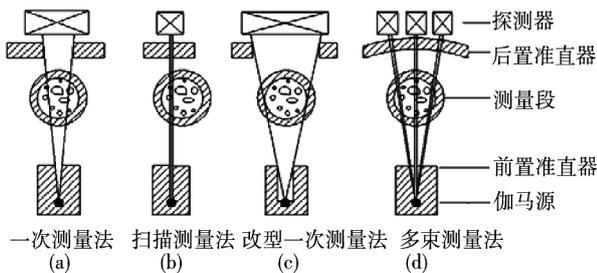


图 1 伽马射线法测截面含气率多种方法比较
Fig. 1 Comparison of the different methods by using gamma densitometer in measuring void fraction

实验段圆管材料为 1Cr18Ni9Ti, 尺寸为 $\Phi 25 \times 2.5$ mm。其中伽马射线测量系统如图 3 所示,实验使用 Cs-137 放射源,活度为 1.628×10^8 Bq。准直器的直径为 $\Phi 5 \times 10$ mm,闪烁晶体采用碘化钠 (NaI)。计数器每次采集时间步长为 2 s,每组数据共采集 90 次。为避免工作状态变化及其他未知因素的干扰,每测一种气液两相工况时本底计数率均对全液相及全汽相进行重新标定。整个伽马射线测量系统在常温常压下空气 - 水两相流动实验台中运行稳定^[11]。

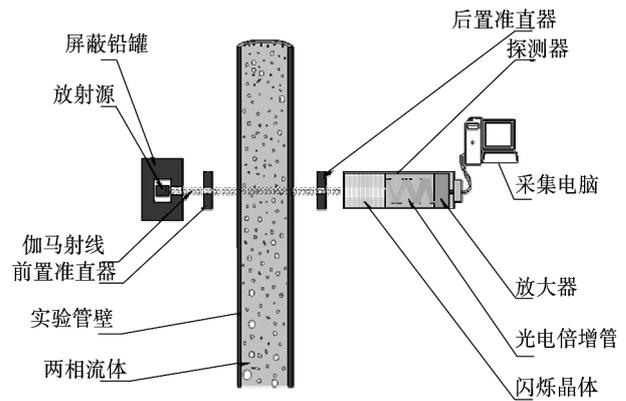


图 3 γ 射线测量装置原理图
Fig. 3 The schematic diagram of gamma densitometer measuring device

2 实验系统

本实验是在西安交通大学高温高压实验台上进行。实验系统如图 2 所示,实验台最高压力可达 40 MPa,最高流量为 4.5 t/h,加热功率可达 1 MW。

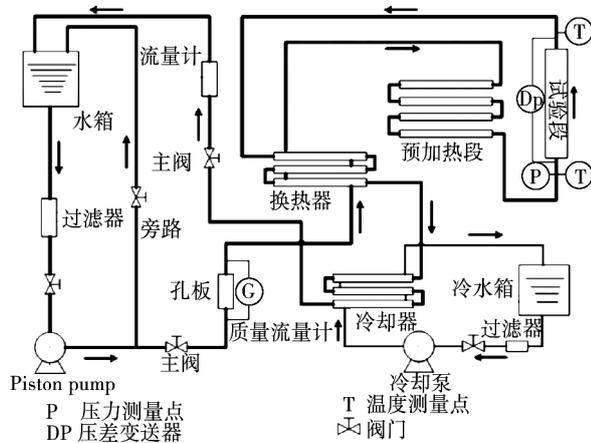


图 2 高温高压汽 - 水两相流实验系统
Fig. 2 The high temperature and pressure steam-water two-phase flow system

3 实验结果与分析

3.1 质量流量、压力对计数率的影响

20 $^{\circ}\text{C}$ 时不同压力下计数率随质量流量的变化如图 4 所示,说明在温度为 20 $^{\circ}\text{C}$ 时探测器测得 γ 射线穿过全液相垂直上升管的计数率。在同一压力条件下,工质质量流量的变化对计数率几乎没有影响。在相同质量流量,不同压力条件下,计数率存在微小波动。图 5 显示了在无外界条件变化时,计数率概率性波动。通过比较图 4、图 5 得出,质量流量和压力变化基本不影响射线衰减。计数率的波动主要由放射源本身辐射粒子的概率性波动引起的。

3.2 流体工质温度对计数率影响

图 6 展示了工质在质量流速为 $1\ 000\ \text{kg}/(\text{m}^2 \cdot \text{s})$ 压力在 17、19、21 MPa 条件下,探测器测得计数率随工质温度变化的趋势。从图 6 中可以看出随着工质温度增加计数率先有微小减小过程,之后逐渐

增大。图 7 反映了在饱和温度以下工质温度越高，管内工质密度呈现减小的趋势。

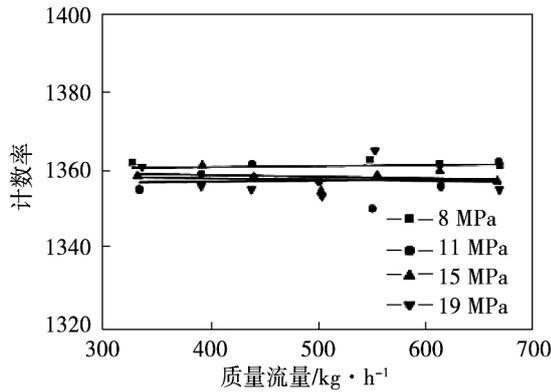


图 4 20 °C 时不同压力下计数率随质量流量的变化

Fig. 4 The change of count rate varying by mass flow at various pressures

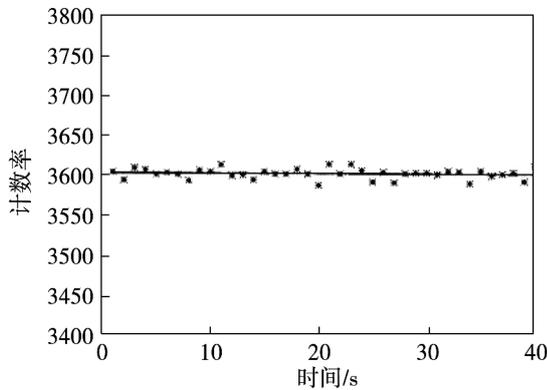


图 5 外界条件无变化时计数率概率性波动
Fig. 5 Probabilistic fluctuation of count rate with unchanged external conditions

比较图 6 和图 7 可得，在过冷度大于 100 °C 温度对计数率影响有微小减小过程，随着过冷度进一步减少，温度对计数率影响将呈现指数上升趋势。在饱和温度以下温度对伽马射线影响可分为 3 个阶段：(1) 递减阶段：分子热运动主导阶段，密度减弱的趋势较小。微观热运动作用强于宏观粒子数减少作用。(2) 平衡阶段：分子热运动与密度减弱平衡阶段。微观热运动与宏观粒子数增加相持平。(3) 指数递增阶段：密度减弱主导阶段，热运动作用较小。宏观粒子数减少远大于微观热运动程度。

3.3 本底计数率基准的选取

图 8 显示了在不同压力下计数率随着工质温度

变化(饱和温度前后)的趋势。在饱和温度以下，管内工质未产生蒸汽，大区间温度变化对伽马射线衰减较为明显。到达饱和温度后，管内工质流体密度基本不变，工质汽化为蒸汽，导致计数率增加。在选取液态本底计数率时，不可选取常温下的全液相计数率作为基准，而应取密度基本不变的饱和状态下的计数率作为基准，可以剔除饱和温度以前工质密度由于温度变化对射线衰减的影响。在 400 °C 附近计数率变化曲线已经趋于平缓，管内两相流中液相几乎蒸发完毕，气相几乎占全部份额，此时的计数率作为纯气相的标定计数率。

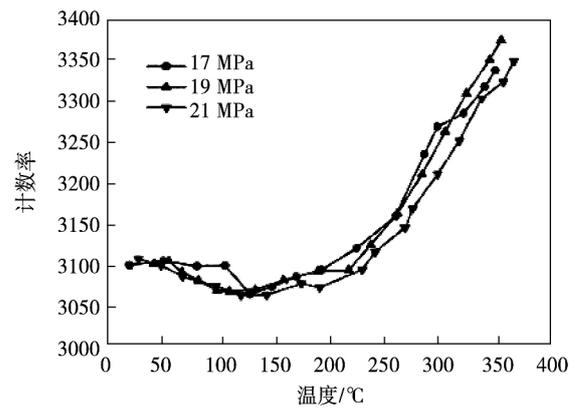


图 6 计数率随温度变化趋势

Fig. 6 The trend of count rate varying by temperatures

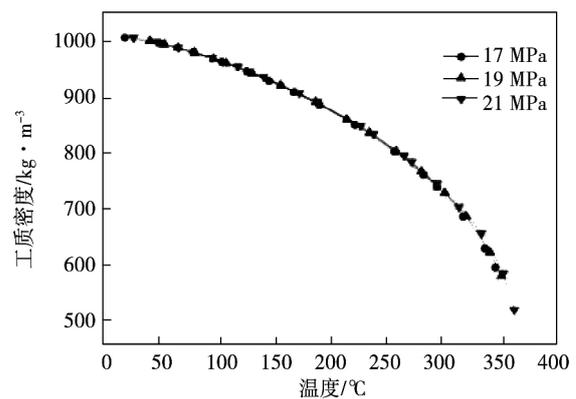


图 7 管内单相水密度随温度变化

Fig. 7 The graph of water density varying by temperatures in single-phase tube

3.4 实验结果与经验公式对比

Armand - Massena 在内径为 56 mm 的圆形管，以气 - 水混合物为工质进行实验，其实验压力 P 达 9.0 MPa，质量流速为 $2\ 000\ \text{kg}/(\text{m}^2 \cdot \text{s})$ ，根据实验

数据得到截面含气率计算式为^[12]:

$$\alpha = \frac{(0.833 + 0.167x)}{\frac{1 - x \rho_g}{x \rho_l} + 1} \quad (3)$$

式中: α —截面含气率; x —干度; ρ_g —气相密度, kg/m^3 ; ρ_l —液相密度 kg/m^3 。

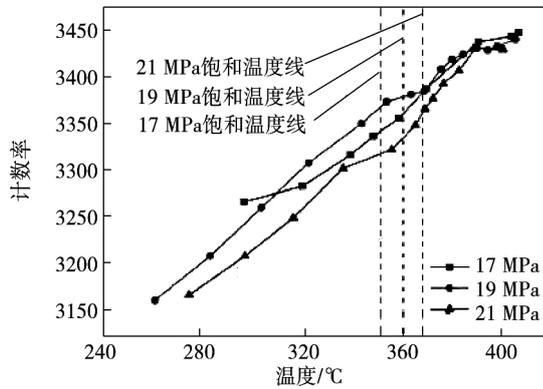


图 8 饱和温度前后计数率随工质温度变化

Fig. 8 Counting rate changing with working fluid temperature before and after saturation temperature

Bankoff 基于变密度模型, 推导了管子截面上的平均截面含气率^[13], 即:

$$\alpha = \frac{K}{1 + \left(1 - \frac{1}{x}\right) \frac{\rho_g}{\rho_l}} \quad (4)$$

式中:

$$K = \frac{2(m + n + mn)(m + n + 2mn)}{(n + 1)(2n + 1)(m + 1)(2m + 1)} \quad (5)$$

Bankoff 比例常数, m 和 n 值可通过图表查询^[13]。

Smith 提出均相单相并流的流动模型, 其实验压力 $P = 0.1 - 10.8 \text{ MPa}$, 质量流速 $650 - 2500 \text{ kg}/(\text{m}^2 \cdot \text{s})$, 管子内径 $6 - 38 \text{ mm}$ ^[14]。其截面含气率计算式为:

$$\alpha = \left\{ \frac{1 + \frac{\rho_g}{\rho_l} \left(\frac{1}{x} - 1\right) e + \left(\frac{\rho_g}{\rho_l}\right)^{1/2} \left(\frac{1}{x} - 1\right)}{(1 - e) \times \left[\frac{1 + \left(\frac{1}{x} - 1\right) e \frac{\rho_g}{\rho_l}}{1 + \left(\frac{1}{x} - 1\right) e} \right]^{1/2}} \right\}^{-1} \quad (6)$$

式中: e —均匀混合物中液相质量和总的液相质量之比。

图 9、图 10 和图 11 分别比较了 Armand - Mas-

sena 计算式、Bankoff 计算式及 Smith 计算式计算值与 γ 射线法测量值。从图 9 可知, 当截面含气率数值小于 0.3 时 Armand - Massena 计算式与射线法测量值误差较大, 当截面含气率大于 0.3, 误差相对减小, 最大误差在 $\pm 20\%$ 以内。Armand - Massena 模型将管内流体视为均相流, 实际管内流体随着气相的增加, 在近壁面处形成一层水膜, 气液两相基本处于分离状态。

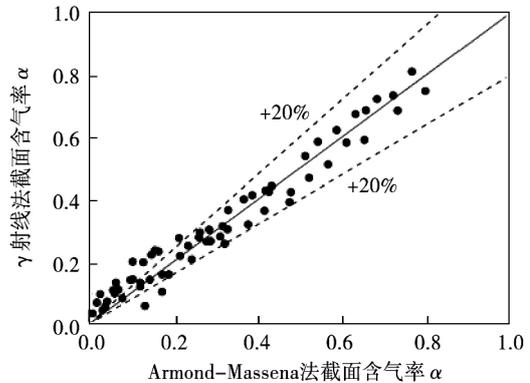


图 9 γ 射线法值与 Armand - Massena 公式比较

Fig. 9 The gamma densitometer compared with Armand - Massena formula

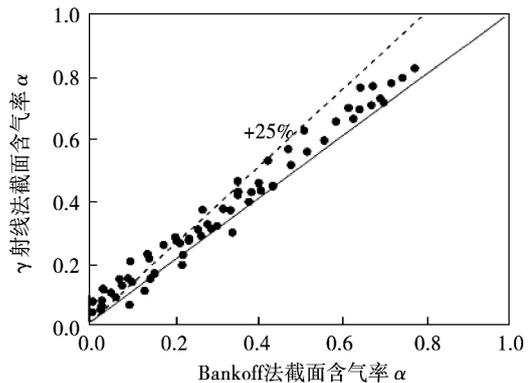


图 10 γ 射线法值与 Bankoff 公式计算值比较

Fig. 10 The gamma densitometer compared with Bankoff calculated values

从图 10 中可以看出, 采用 Bankoff 计算式计算得到截面含气率数值普遍小于射线法测量得到截面含气率。截面含气率数值在 $0 - 0.35$ 时误差较大, 在 0.35 后误差逐渐减小, 最大误差在 25% 内。Bankoff 模型假设气泡悬于液体中, 两相流速沿截面呈指数分布。在弹状流及环状流中, 气泡中的气相在径向基本保持速度不变, 导致分布参数 $K = 0.6$ 不

能与实际流型吻合^[13]。图 11 说明,在截面含气率为 0~0.2 时计算误差比较大。当截面含气率在 0.2 后 Smith 计算式计算得到截面含气率和射线法测量值最大误差在 ±20% 以内。Smith 模型假设近管壁处为单相水膜,管子中间流动为均相汽-水混合物,认为汽水两相的动压头相等。不管是泡状流还是环状流,在弦截面上均表现为近壁面处为水膜,管中心为均相流体。射线法测量弦截面上的气液份额比,这与 Smith 模型基本吻合。通过比较也发现,Smith 计算法与 γ 射线法截面含气率值吻合范围最广,Armand-Massena 计算法为次,Bankoff 计算法普遍比实验测量值小,且误差较大。截面含气率在 0-0.25 范围内,流型大致为泡状流,气泡直径较小,横截面上气泡分布不均匀性较大,射线穿过时,受分布不均匀影响较大^[15]。截面含气率继续增大时,管内流型从泡状流向弹状流过渡,气相逐渐在管中心处聚集。在伽马射线路径上,气泡直径较大,其分布不均匀较小,弦截面含气率与真实截面含气率较为吻合。

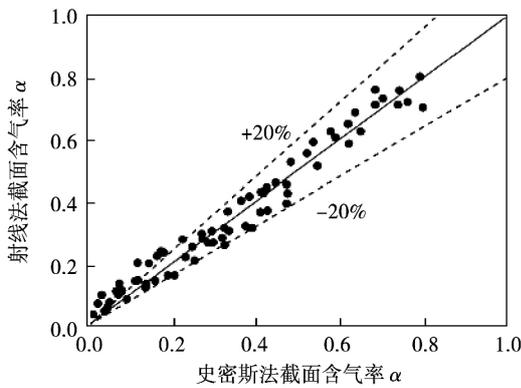


图 11 γ 射线法测量值与史密斯法公式计算值比较

Fig. 11 The gamma densitometer compared with Smith calculated values

4 结 论

探讨了伽马射线法测量亚临界汽-水两相截面含气率的影响因素,并与经验公式进行对比,分析了该方法在亚临界条件下的使用的误差,得到以下结论:

(1) 通过将伽马射线法测量截面含气率数值与

传统理论公式对比,实验测量值与 Smith 公式吻合最好,Armand-Massena 公式次之,而偏大于 Bankoff 公式,测量结果与理论值偏差较小,为 γ 射线测量亚临界流体有一定的借鉴意义。

(2) 影响亚临界下伽马射线测量汽水两相截面含气率因数较多,通过测量得出流体工质压力及质量流速对测量的影响可忽略不计;流体工质温度对测量影响较大,计数率随温度先有微小减小过程,而后基本不变,最后呈指数变化规律。这对提高测量精度有着指导性作用。

(3) 对于亚临界流体,其汽相本底计数率不能选取常温常压全气相工况计数率,而应选取饱和蒸汽对应的计数率。工质温度达到一定程度,计数率曲线的平缓区域,为水蒸气的本地计数率。饱和液相计数率选取在饱和温度附近的计数率,可以消除温度对测量精度的扰动。

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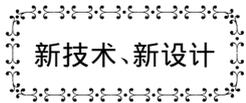
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(陈 滨 编辑)



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沙特集成的太阳能联合循环电站

据《Diesel & Gas Turbine Worldwide》2015年6月刊报道,SEC(沙特电力公司)选择GE作为第一个太阳能光场和燃气轮机联合循环电站项目的合作伙伴,并首次采用冷凝液作为燃气轮机燃料。

绿色杜巴集成的太阳能联合循环电站将建造在沙特阿拉伯沿红海海岸的西北部,并具备每年供应大约600 000个沙特阿拉伯家庭所需电力的能力。

该项目设计成联合循环电站发电达550 MW,太阳能光场将提供另外发电功率为50 MW的蒸汽。

GE将供货联合循环电站工程的全套设备,包括1台7F.05和1台7F.03燃气轮机、1台汽轮机、3台发电机、2台余热锅炉、冷凝器、Mark VIe分布式控制系统和长期服务协议。

沙特电力公司将单独提供其余设备、太阳能光场、土木工程、安装、验收运行和试验。

(吉桂明 摘译)

ment of supercritical water was established and a numerical simulation study was made of the heat exchange and phase-change process of materials in both tube and shell side by making use of the software CFX (computational fluid dynamics analytic software). The IAPWS IF97 database was successfully used to numerically simulate the physical property and state of the supercritical water and the phase-change process of the material in the tube side from its subcritical state to supercritical one was expounded. By making use of the available test results, the model in question was verified. The simulation results show that the pressure drop and heat transfer coefficient in the shell side will increase with an increase in the flow rate in the shell side. The growth rate of the temperature at the outlet of the shell side will first become big and then small. To increase the interval of the baffles in the heat exchanger from 117 mm 150 mm will be not conspicuous in enhancing the heat transfer effectiveness, however, the flow resistance in the shell side will increase greatly. At a pressure of 23 MPa, under the operating condition of the temperature changing from 400 °C to 600 °C, the influence of the radiative heat transfer in the heat exchanger is relatively big. When a numerical simulation is made, the amount of heat transferred in the form of radiation cannot be ignored. The actual structure of the heat exchange will be finalized by comprehensively considering the influence of the heat transferred and coal particle deposition. The above-mentioned numerical simulation results can offer a certain theoretical significance and practical value in engineering projects in the design and study of the heat exchangers for use in supercritical water coal gasification process. **Key words:** shell and tube type heat exchanger, numerical simulation, supercritical water, coal gasification

γ 射线法测量亚临界汽-水两相流截面含气率的实验研究 = Experimental Study of the γ-ray Method for Measuring the Gas Content in a Cross Section with a Subcritical Steam-water Two-phase Flow [刊, 汉] HU Ri-cha, LUO Zhi-chao (Changchun Optic Precision Machinery and Physics Research Institute, Changchun, China, Post Code: 130033), BI Qin-cheng, LU Hai-cai (National Key Laboratory on Multi-phase Flow in Power Engineering, Xi'an Jiaotong University, Beijing, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. -2015, 30(6). -842-847

By adopting a single narrow beam γ-ray method, the void fraction in a section featuring a subcritical steam-water two-phase flow in a vertical riser was measured. The operating conditions in the riser were given as follows: the pressure ranged from 17 MPa to 21 MPa, the mass flow speed of the working medium was in a range from 600 kg/

($\text{m}^2 \cdot \text{s}$) to $1\,000\text{ kg}/(\text{m}^2 \cdot \text{s})$ and the temperature fell in a range from $25\text{ }^\circ\text{C}$ to $400\text{ }^\circ\text{C}$. Through an analysis the feasibility to measure the void fraction in a section of a subcritical steam-liquid two-phase flow by adopting the γ -ray method was investigated and the influence of the mass flow rate, pressure and temperature of the working medium on the measurement results by using the γ -ray method was also analyzed. It has been found that the mass flow rate and pressure of the working medium will have almost no influence on the measurement of the void fraction in a section of a subcritical steam-liquid two-phase flow by adopting the gamma-ray method while a change in the temperature by a great margin will exercise a relatively marked influence on the measurement. A comparison of the test and measurement values with those calculated by using the classic theoretical formula shows that the test and measurement values are in very good agreement with those calculated by using the Smith formula. **Key words:** sectional void fraction, γ -ray, gas-liquid two-phase flow, subcritical

基于专家 PID 的燃气机转速控制试验 = **Experiment of the Rotating Speed Control Over a Gas Engine Based on an Expert PID (Proportional Integral and Differential) Control Method** [刊, 汉] WANG Ming-tao (College of Energy Source and Power Engineering, Ludong University, Yantai, China, Post Code: 264025) ZHANG Bai-hao (College of Mechanical Engineering, Tianjin University, Tianjin, China, Post Code: 300072) // Journal of Engineering for Thermal Energy & Power. - 2015, 30(6). - 848 - 852

According to the historic data and experience from experts, designed was a rotating speed controller for gas engines based on the expert PID control method and experimentally studied were the rotating speed control of a gas engine when it was suddenly added with a load, variable speed control and anti-interference performance of the gas engine. It has been found that no rotating speed reduction and flame failure occurs to the gas engine when it is suddenly added with a load and the time required for attaining a new steady operating condition is less than 10 seconds. No overshoots of the rotating speed emerge during the variable speed control process and the time required for attaining a new steady operating condition is less than 20 seconds. The expert PID controller exhibits its good dynamic response characteristics and for the fluctuation arisen from changes of the superheating degree of the gas engine, the expert controller also displays its relatively good anti-interference performance. **Key words:** gas engine-driven heat pump, rotating speed control, expert PID (proportional, integral and differential), suddenly-added load, variable capacity, anti-interference performance