文章编号: 1001－2060(2001)03－0322－03

利用双节流元件测量两相流干度

叶　强, 陈听宽, 罗毓珊
(西安交通大学 多相流国家重点实验室, 陕西 西安　710049)

摘　要: 以经典均相流和分相流模型为基础, 推导了一个理想条件下直接测量两相流干度的公式, 分析了公式的适用范围。设计了水平孔板和垂直下降文丘利管串联组合的实验装置, 并以空气和水为工质进行了实验研究。实验研究表明, 在环状流区垂直下降文丘利管的压降特性更接近于均相流模型的计算结果。这种方法在文中给定的干度范围内测量的相对误差小于±10%。

关　键　词: 气液两相流动; 质量含气率; 干度; 测量

中图分类号: TK31　　文献标识码: A

1　前言

管路内气液两相流动是能源动力和石油化工设备中常见的现象。为了对设备的安全性和生产的经济性进行在线检测, 人们对气液两相流流动相分额的测量要求也越来越高。

在各种测量方法中最常见的思路就是首先测得截面含气率 α, 然后计算出质量含气率 X(即干度)。主要包括: 光纤探针法、电导探针法、电容法、热线和 γ 射线等。这类方法的局限性主要包括两个方面, 首先在工程的实际应用中, 两相工质的组成可能十分复杂(如油井产出物), 其各项物理特性在时间和空间上都存在着严重的不均匀性。其次, 气液两相流的截面含气率 α 与容积含气率 β 并不相等, 两者之间的差异取决于气液间的滑动比 S。而滑动比也是一个未知数, 它的大小与两相流量、含气率和工质物性等许多因素有关。

另一种思路就是单相流量计的组合法。其核心思想是利用两个单相流量计的测量结果构成两个含有流量和干度的方程, 然后联立求解得到干度 X。这类方法的关键是保证两个方程不是同解方程组, 即所选用的流量计的相似性越小越好[5]。差压元件作为常见的单相流量计具有结构简单、经济可靠的优点。但差压元件之间的压降特性是非常相似的, 使这类方法具有很大的局限性。

本文在研究了流动方向和节流元件对两相流型的影响的基础上, 并通过理论分析提出了利用垂直下降文丘利管和水平段孔板的组合式干度测量方法。

2　理论模型

当气液两相流流经节流装置时, 将产生压力降, 其大小与两相流量和分相含率有关。在大量实验的基础上人们提出了各种经验和半经验公式, 主要分为两类: 即修正的均相流模型和修正的分相流模型。均相流模型假定气液间混合充分, 没有相间的滑动现象。差压流量关系可表示为:

$$\Delta P_h = (M/Y)^2 V_h \tag{1}$$

其中 ΔP_h 为均相流模型计算出的两相压降, M 为两相质量流量。V_h 为两相流均相比容, 可用下式计算:

$$V_h = XV_G + (1-X)V_L \tag{2}$$

而

$$Y = AC_F d^2 \varepsilon \tag{3}$$

上式中: A－常数项; ε－流束膨胀系数;

C_F－流量系数; d－节流元件孔径;

分相流模型是在界面切应力为零的假设下提出的, 此时的滑动比 S 仅仅是气液比容比的函数, 即:

$$S = \left(V_G/V_L\right)^{1/2} \tag{4}$$

定义用 ΔP_S 表示用分相流模型计算出的两相压降, 根据单相流体的孔板流量公式可得:

$$\sqrt{\Delta P_S/\Delta P_G} = 1 + \sqrt{\Delta P_L/\Delta P_G} \tag{5}$$

式中, ΔP_G 和为 ΔP_L 为假定气相和液相单独流过节流元件时产生的压降。进一步推导可得:

$$\Delta P_S = \left(\frac{M}{Y}\right)^2 \left(X + (1-X)\sqrt{\frac{V_L}{V_G}}\right)^2 V_G \tag{6}$$

从式(1)、(6) 可以看出, 两相压降的计算值均为流量 M 和干度 X 的函数。将式(1)、(6) 相除, 简化后可得:

$$\frac{\Delta P_h}{\Delta P_S} = \frac{X + (1-X)\dfrac{V_L}{V_G}}{\left(X + (1-X)\sqrt{\dfrac{V_L}{V_G}}\right)^2} \tag{7}$$

收稿日期: 2000－01－03; 修订日期: 2000－03－20

作者简介: 叶　强(1972－), 男, 上海青浦人, 西安交通大学博士研究生.

令 $R=\sqrt{\frac{V_L}{V_G}}=\frac{1}{S}$, 则上式还可进一步简化为:

$$\frac{\Delta P_h}{\Delta P_S}=\frac{X+(1-X)R^2}{(X+(1-X)R)^2} \tag{8}$$

因此, 当气液比容比为常数时, $\Delta P_h/\Delta P_S$ 仅为干度 X 的函数。$\Delta P_h/\Delta P_S$ 与干度 X 的关系如图 1 所示。分析式(1) 可知当干度 X 等于 $R/(1+R)$ 时, $\Delta P_h/\Delta P_S$ 取得最大值。从图 1 中可以看出, 如果将 $\Delta P_h/\Delta P_S$ 作为自变量, 干度 X 并不是 $\Delta P_h/\Delta P_S$ 的单值函数。因此, 这种方法的适用范围是已知干度 X 大于 $R/(1+R)$ 或小于 $R/(1+R)$ 的情况。

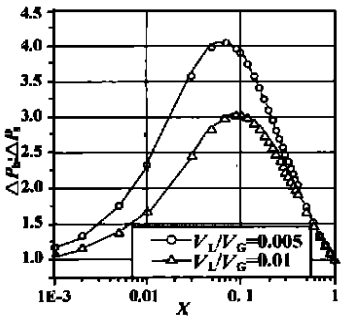
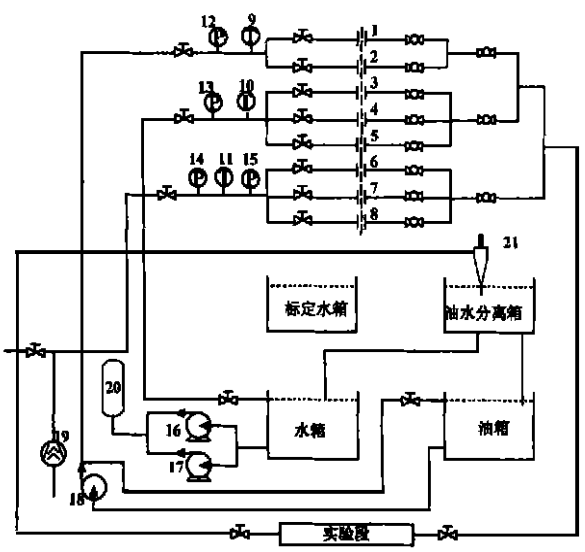


图 1　两相压降比与干度 X 的理论关系

3　实验系统

本实验是在西安交通大学多相流国家实验室的空气 / 水实验台上进行的。实验系统如图 2 所示。实验中单相流量和质量含气率的标准值是两相混合前利用单相孔板测得的。为了提高单相计量的准确性, 水路和气路分别采用了管径不同的三个孔板。



1、2— 油路孔板; 3、4、5— 水路孔板; 6、7、8— 气路孔板; 9、10、11— 热电偶; 12、13、14— 压力表; 15— 压力变送器; 16、17— 水泵; 18— 油泵; 19— 空压机; 20— 稳压罐; 21— 气液分离器

图 2　油 — 气 — 水三相流实验台

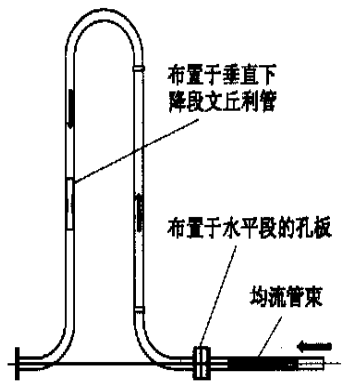


图 3　实验段示意图

实验段是用内径为 45 mm 的不锈钢制成的倒 U 型管段, 并将一个孔板和一个文丘利管串接在管路上。其中, 孔板布置在入口段的管束均流器之后的水平段, 文丘利管则布置于下降段, 如图 3 所示。

文中孔板的孔径比为 0. 486, 文丘利管的孔径比为 0. 54。实验参数范围是: 压力 $-P=0.2\sim0.7$ MPa; 折算气速 $-0.4\sim21.0$ m/s; 折算液速 $-0.08\sim0.9$ m/s; 质量含气率 $-0.003\sim0.414$; 体积含气率 $-0.309\sim0.996$。

4　实验结果与模型预测

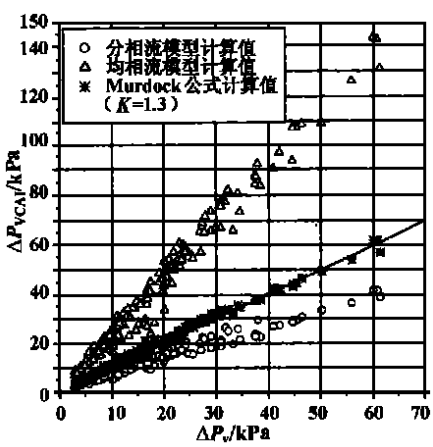


图 4　孔板差压测量值与计算值的比较

前人对于气液两相流流经节流元件的研究, 一般都是针对水平放置的孔板和文丘利管。由于汽液两相粘度的差异, 水平管中的气相流速一般要高于液相。在两相流速不是很高的前提下, 两相流流经孔板时气液间存在着明显滑动现象, 因而更趋近于分相流动。现有的大多数经验和半经验的公式也都是基于分相流模型的, 如 Chisholm 的 C 系数法[4] 和 Murdock 公式[3]。在 Murdock 公式中取 K 等于 1. 30, 所预测的结果与本次实验中孔板的压降非常吻合, 见图 4。

众所周知, 流型是研究气液两相流流动机理和压降特性的决定性因素。针对单一流型的两相流公式才更容易保证计算的准确性。而选择布置于垂直下降段的文丘利管也是出于简化流型的考虑。

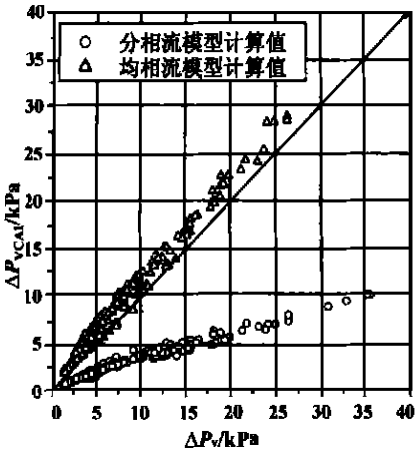


图 5 文丘利管差压测量值与计算值的比较

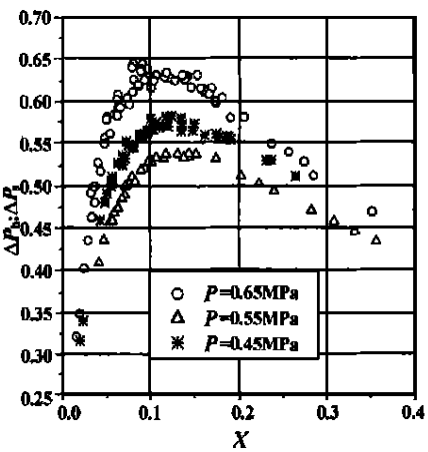


图 6 两相压降比与标准干度 X 的实验关系

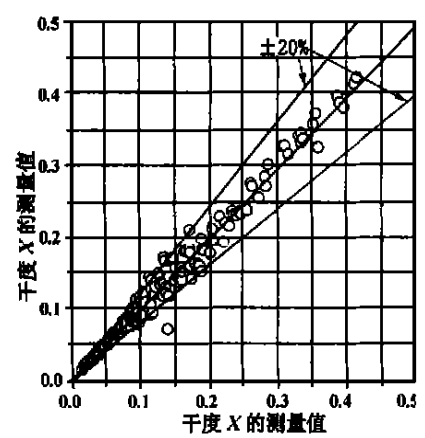


图 7 干度计算值与标准值的比较

首先垂直下降管气液两相流的流型相对简单，主要表现在当折算液速小于 0.8 m/s 时，无论气相的折算速度在什么范围内两相流都处于环状流区[1]。其次，孔板和文丘利管作为两种最为常见的节流元件在测量单相流体时具有相似的差压特性。但文丘利管对管路内气液两相流的扰动比孔板小得多[2]。这样，就可以保证在一个相当大的流量和含气率范围内两相流流经垂直下降文丘利时处于环状流区。本文的实验也验证了上述的设想。

通过对数据的整理发现，在环状流区垂直下降段文丘利管的压降特性非常接近于均相流模型的计算结果，如图 5 所示。其物理解释是：气液两相流流经垂直下降段时，在重力的作用下液相流速加快，削弱了气液两相间的滑动现象。文丘利管喉部的加速效应使两相混合加剧，更趋近于均相流动。

图 6 是 $\Delta P_h/\Delta P_S$ 的测量值与标准的干度值的关系。如果以 $R/(1+R)$ 将干度划分为两个区域，则可以利用 $\Delta P_h/\Delta P_S$ 反算出干度 X。干度的值与标准值的关系如图 7。

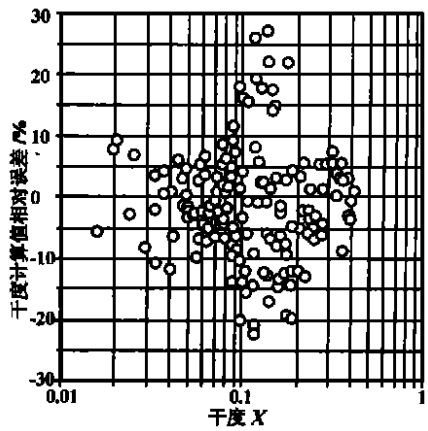


图 8 干度计算值的误差分布

在 $R/(1+R)$ 附近的区域干度对 $\Delta P_h/\Delta P_S$ 的变化非常敏感，使干度的计算误差明显增大。从图 8 中可以看出，当干度 X 处于 0.1 ~ 0.2 范围内时，误差明显增大，最大误差超过 20%。因此，保证测量精度的条件是干度 X 不能跨越 $R/(1+R)$。这与上述的理论推测也是一致的。

5 结论

（1）在给定的干度范围内，利用均相流和分相流模型组合式方法进行干度的直接测量在理论上是可行的。

（2）方法的具体实现上利用了垂直下降布置的文丘利管，但在选择文丘利管时应使喉部的折算液相流速小于 0.8 m/s，确保流动处于环状流区。

（3）气液两相管流中，垂直上升段是造成两相脉动的重要原因。如果在文丘利管前的上升段加装均流器，有望进一步提高测量的精度。

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（辉 编辑）

tomatic increase in hidden nodes has been employed to predict nonlinear time series. The proposed method allows to successfully tackle the problem of selecting local minimal hidden node number and excessive fitting in BP networks. It has been applied to predict the thermal loads of a thermal power plant. The results of prediction indicate that very satisfactory results have been achieved in forecasting the thermal loads of power plants. **Key words**: nonlinear time series, prediction, RBF (radial base function) neural network, thermal load

面向对象方法与转子故障监测诊断系统的开发=**Description of an Object-orientated Methodology and Development of a Rotor Failure Monitoring/diagnosis System** [刊, 汉] / ZHANG Heng-liang, ZHANG Qin, CHEN Ru-qing (Power Engineering Department, Wuhan University of Water Resources and Electric Power, Wuhan, China, Post Code: 430072) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —313 ~ 315

In recent years there existed some problems of poor self-stability and certain difficulties involved in the maintenance and upgrading of rotor-failure monitoring and diagnostic systems during their use in industrial fields. The proposed object-orientated method represents a good software development approach, which has been assessed as a major method for use in a software development process. The present paper gives a brief description of the method, highlighting how to use such a method to develop a rotor failure monitoring and diagnostic system. **Key words**: monitoring and diagnostic system, object-orientated methodology, rotor failure monitoring

流体流动的输出功率与功率耗散的协调优化=**Optimized Coordination of Fluid-flow Output-Power and Power Dissipation** [刊, 汉] / YAN Ning-rong (Department of Mechanical Engineering, Lujiang University, Xiamen, Fujian Province, China, Post Code: 361005) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —316 ~ 318

Ecological optimization criteria have been popularized for use in the analysis of the optimized performance of a fluid-flow work-doing unit. Some new performance parameters were derived and discussed in a meaningful way. Expounded further was the major significance of the ecological optimization criteria. The conclusions obtained may serve as new theoretical guidelines for the optimized design and selection of optimized working conditions for fluid-flow work-doing units. **Key words**: fluid-flow work-doing device, ecological optimization criteria, optimized performance

循环流化床烟气脱硫床料的质量平衡和化学成份的变化=**Mass Equilibrium of Gas Desulfurization Bed Materials in a Circulating Fluidized Bed and the Variation of Chemical Composition** [刊, 汉] / FAN Bao-guo, QI Hai-ying, YOU Chang-fu, et al (National Key Lab of Coal Clean Combustion under the Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —319 ~ 321

A theoretical analysis was conducted of the variation of bed materials mass and chemical composition in the desulfurization process in a circulating fluidized bed. It has been found that with the circulation ratio selected at 5-50 and the effectiveness of a separator attaining 83%-98% it is possible to maintain a mass equilibrium in the bed. In case a change of operating parameters gives rise to a change of mass of in-bed materials, it is possible through a quantitative change of bed materials leaving the bed to attain equilibrium very rapidly. By contrast, the dynamic state of chemical composition is unbalanced. Its transition process has been found to be dependent on bed material quantity in the bed, production rate of reaction products and the variation range of related parameters, etc. **Key words**: circulating fluidized bed, gas desulfurization, bed materials mass and chemical composition

利用双节流元件测量两相流干度=**The Measurement of Two-phase Flow Dryness by the Use of a Dual-throttle Element** [刊, 汉] / YE Qiang, CHEN Ting-kuan, LUO Yu-shan (National Key Lab of Multi-phase Flows under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —322 ~ 324

Based on a model of classical uniform-phase flow and divided-phase flow the authors have deduced a formula for the direct measurement of dual-phase flow under an ideal condition. The applicable scope of usage of the formula is analyzed. An experimental device has been designed, which incorporates a horizontal orifice plate and a vertical descending Venturi

tube connected in series. An experimental study was conducted with air and water serving as working mediums. The results of the study indicate that the pressure drop characteristics of the vertical descending Venturi tube in a ring-shaped flow zone have been found to be more approximate to the calculation results of the uniform-phase flow model. Under the proposed method the relative error of measurement within the range of dryness given in the paper is smaller than ±10%.
Key words: gas-liquid two-phase flow, mass gas-content rate, dryness, measurement

"煤气化—无烟燃烧技术"的原理及其应用＝**Basic Theory of "Gasification—Smoke-free Combustion Technology" and its Application in the Technical Modification of Boilers** [刊, 汉] / SUN Dong-hong (Harbin Institute of Technology, Harbin, China, Post Code: 150001), HAO Zhi-jing, WANG Qing (Northeast Electric Power Institute, Changchun, China, Post Code: 132012) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —325 ~ 327

An analysis is given of the present status of development of Chinese industrial boilers. On this basis briefly covered in this paper is the topic "gasification—a smoke-free combustion technology" and its application in the technical modification of industrial boilers. The implementation of that technology has opened up a new approach for the technical retrofit of industrial boilers, which can contribute not only to smoke-free and low-ash combustion but also to significant energy savings.
Key words: gasification, smoke-free combustion technology, industrial boiler, technical modification or retrofit

低 NO_x 高温空气燃烧技术＝**Low NO_x Combustion Technology of High-temperature Air** [刊, 汉] / ZHU Tong, LIU Min-fei (Thermal Energy Engineering Department, Tongji University, Shanghai, China, Post Code: 200092), RAO Wen-tao (Equipment Research Institute under the Baoshan Iron and Steel Corporation-affiliated Research Academy, Shanghai, China, Post Code: 201900) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —328 ~ 330, 321

By organically integrating traditional low NO_x combustion technology of high temperature air with a high-temperature thermal-storage type combustion system, the resulting low NO_x high-temperature air combustion technology features a high thermal efficiency, a uniform distribution of temperature within the furnace, and low NO_x emissions, etc. The present paper deals with the high-temperature air combustion technology with a focus on the analysis of basic principles of low NO_x emissions specific to the high-temperature air combustion technology. In addition, also depicted are two types of low NO_x high-temperature air combustors incorporating respectively gas recirculation and graded combustion technology. **Key words**: low NO_x, high-temperature air combustion, thermal storage type combustor, combustion technology

KA—13D 燃气轮机注水系统的应用＝**The Application of a Model KA-13D Gas Turbine Water Injection System** [刊, 汉] / LONG Xian-lin, JIA Xi-long (Desheng Electric Power Plant Co. Ltd., Shunde, Guangdong Province, China, Post Code: 528300) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —331 ~ 333

On the basis of the operating experience of a power plant over the years an analysis was conducted of the influence of water injection or no water injection on the heat resistant pad of combustor components as well as on the components of a post-cycle. The water injection has been applied to the combustor of a gas turbine operating under combined cycle power plant conditions. In this context, expounded are the merits and demerits of employing water injection or no injection into the combustor of the above-mentioned gas turbine. **Key words**: gas turbine, combustor, combined cycle power plant, heat resistant pad

200 t/h D 型锅炉设计技术特点＝**Technical Features of the Design of a 200 t/h D-shaped Boiler** [刊, 汉] / YUAN Mei-yan, LI Jing-shi (Harbin Boiler Works Company, Ltd., Harbin, China, Post Code: 150090) // Journal of Engineering for Thermal Energy & Power. —2001, 16(3). —334 ~ 335

Presented in this paper is the brief description of a 200 t/h D-shaped boiler, highlighting the structural layout of the boiler proper, the system flow path, low steel consumption, high thermal efficiency and water circulation head of the loiler.
Key words: structural design, boiler system, water circulation head of boiler