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大速差射流燃烧室内三维湍流气固两相流的实验研究*

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摘 要

本文用二维激光多普勒测速仪和探针取样法对大速差射流燃烧室中冷态三维湍流气固两相流动进行了实验研究，测量了气相速度、颗粒速度、颗粒质量流分布及两相各自的湍流特性，探讨了高速射流作用下两相流场的主要物理特征及其对火焰的稳定和强化燃烧的作用。

大速差同向射流对稳定及强化两相燃烧效果十分显著，已经得到广泛应用，但其机理还有待系统研究。文献〔1〕用热球探针测量了大速差射流预燃室内冷态气相流场，文献〔2〕则数值模拟三维气相流场，文献〔3〕数值模拟了二维气固两相流动和燃烧。本文用取样探针和二维激光多普勒测速仪测气固两相速度分布，湍流度分布及颗粒质量流率分布，研究三维大速差气固两相湍流流动与混合的规律，探讨大速差射流对稳焰和强化燃烧的作用机理。

一、实验装置及测量方法

实验装置如图1所示。实验段由有机玻璃制成，其几何形状及结构见图2，长度为$L=400mm$，直径为$D=100mm$；主气流进口直径为$d=24mm$，进口速度$u_0=15m/s$，雷诺数$R_e=23000$；高速射流小孔孔径为$d_J=1mm$，孔心距$D_J=67mm$，射流速度$u_J=265m/s$，射流流量与主气流量之比$Q_J/Q_0=6.1\%$；供入的颗粒为氧化铝粉末，其材料密度$\rho_s=2900kg/m^3$，平均粒径为$d_p=60\mu m$，供粉量$Q_p=0.001kg/s$，进口粉气质量比$Q_p/Q_0=0.12$。颗粒用SKQ-4C型电磁振荡式供粉器从远上游供入主气流中，并经过1.5m长的预混段，使其与主气流充分混合。测量纯气相及颗粒速度及湍流度场分别采用DISA公司二维双色激光测速仪，信号处理器为计数式。在本文工况下，流场中存在大面积平均速度低而湍流度高的区域，给计数式测量带来一定困难。实验中，严格选择带通滤波器的滤波频带，以得到清晰的高信噪比的多普勒波形，使一般信噪比不低于5：控制数据

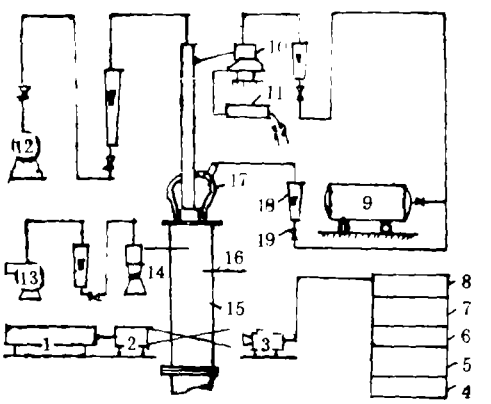


图1 实验设备

(1.激光器，2.发射光路系统，3.接收系统，4.散热设备，5.计算机，6.频移调制，7.计数器，8.滤波器，9.压气机，10.供粉器，11.供粉器电源，12.鼓风机，13.吸尘器，14.取样探针，15.试验段，16.双向探针，17.射流分流管路，18.浮子流量计，19.阀门)

* 本文于1988年5月收到。

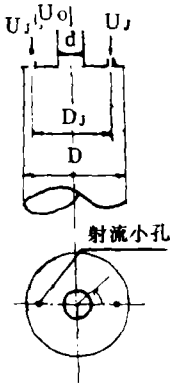


图2 流动示意图

采集宽度(即采样数)，使采样频率大于湍流脉动频率，同时还使采样数不小于满足统计误差要求所需要的数值；适当设置频移量，低速区及逆流区中一般置为与平均速度对应的中心频率的1～2倍左右，高速正流区中置为零。测量时采用：初设频移量→测量→修正频移量→再测量，直到两次测量之值小于给定误差。本文采用探针取样法测量颗粒质量流。取样探针外径5mm，管口内径3mm。为了探讨在强逆流的复杂三维流动中探针取样扰动对测量的影响，曾在一些典型装置及测量位置处用不同的抽气量进行了取样对比实验，并用逆向抽气取样的办法进行了检验，结果发现取样扰动、取样速度均对惯性较大颗粒的质量流分布影响不大。

二、实验结果及讨论

图3是气相回流区位置的测量结果。LDV和双向探针绘出的回流区形状大致相同，但起始和结束位置有差别，其原因可能是在这些位置附近流速低脉动大，因此零速度位置的两种测量均可能存在较大误差。数值计算结果与实验定性上相符，但定量上存在明显差别。图4给出了颗粒质量流分布(图中$G=\rho_p U_p$)，其峰值位于轴线处，表明有大量的粉进入气相中心回流区中，与无大速差射流的简单突扩相比，颗粒混合大大地强化了。在$x/D=2.2$处，颗粒质量流分布已相当均匀，表明其质量弥散很快，到此已接近混合均匀。颗粒与纯气相速度分布(图5)的差别较为显著，最主要的是气相存在大片逆流，而颗粒由于惯性则基本保持前向流区。同时，由于中心回流区的作用，颗粒动量的湍流混合也很强烈，到燃烧室下游，其速度

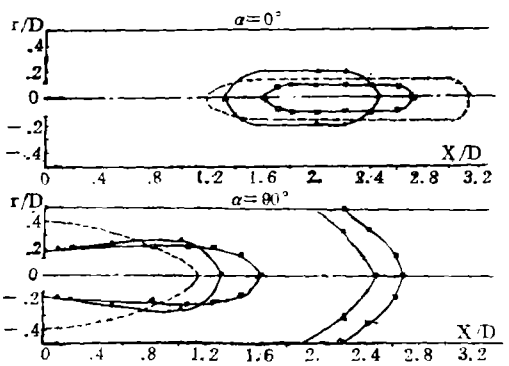


图3 气相回流区测量结果
(△-LDV，□-双向探针，…数值计算)

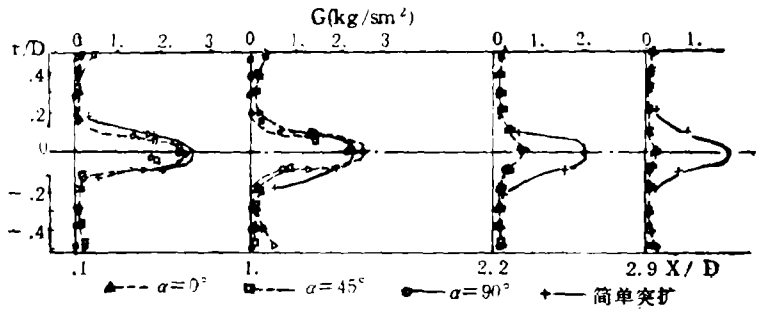


图4 颗粒质量流分布(△—$\alpha=0$，□—$\alpha=45°$，○—$\alpha=90°$，+—简单突扩)

分布也已均匀。从图6可以看出，纯气相湍流度在$\alpha=0°$平面有四个峰值，射流小孔附近的峰值要比进口台阶附近的大很多(图6)。在中心回流区附近颗粒湍流度略高于纯气相湍流度。这表明，颗粒的运动、混合及其湍流特性都与其发展经历有关，颗粒湍流也不仅仅是简

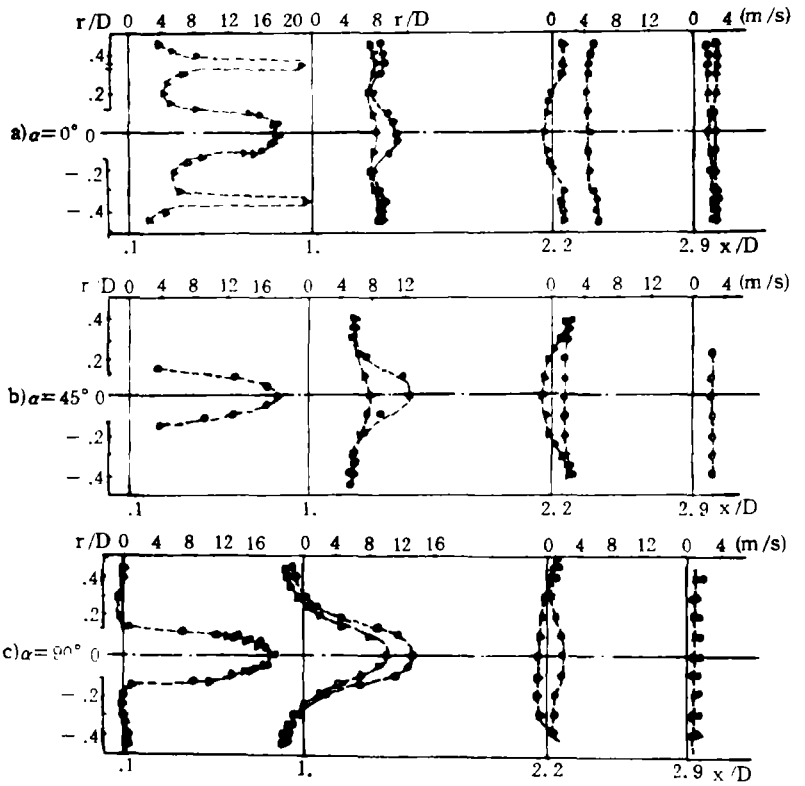
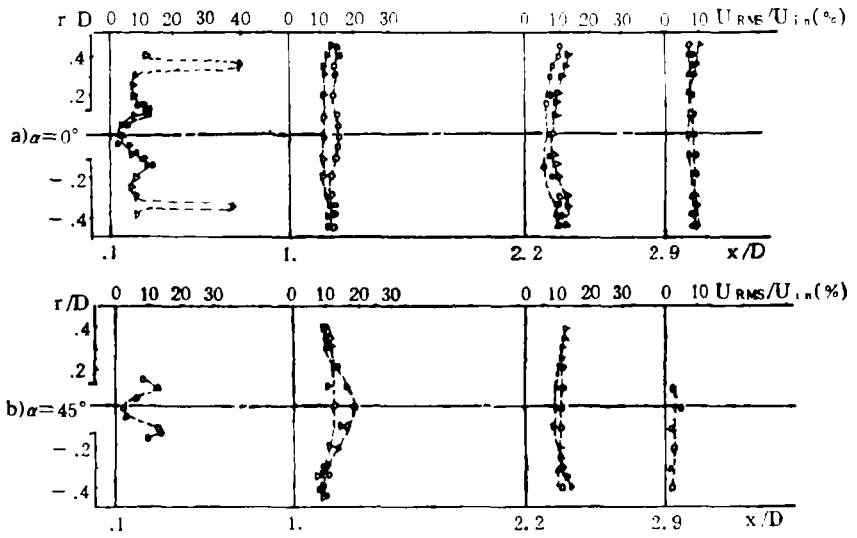


图 5　气相和颗粒平均速度分布（△—气相，○—颗粒）



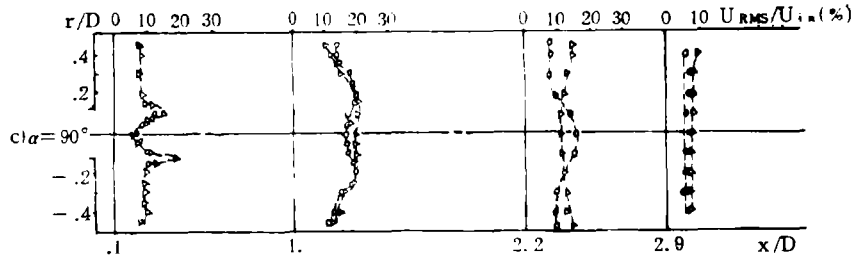


图 6 气相、颗粒脉动速度均方根值分布（△—气相，○—颗粒）

单地跟随当地气相湍流，目前颗粒湍流的局部追随理论不能反映颗粒湍流运动的物理实质。

大速差射流突扩燃烧室的两相流动特性对燃烧十分有利。燃烧室上游颗粒质量集中于轴线附近，很少进到旁边的冷气流里，而是冲入高温的中心回流区中，显然有利于火焰稳定。颗粒进入中心回流区后，一边受到高温燃气的加热，参加燃烧，一边很快散布开，与回流区外的空气掺混均匀，这对提高燃尽率也是很有利的。

三、结 论

1. 用二维激光多普勒测速仪及探针取样的联合测量方法研究复杂的三维气固两相流动是可行的。

2. 气相回流区大小、形状的探针和LDV测量结果定性一致，但定量上有差别。

3. 颗粒质量流峰值位于轴线处，颗粒与纯气相平均速度存在较大差别，气相有大面积回流区，但颗粒在燃烧室绝大部分区域没有逆流。

4. 颗粒的运动、混合及其湍流特性都与发展经历有关，受其自身上游影响较大，目前颗粒湍流运动的局部追随理论不能反映这一特点，应予改进。

5. 高速射流的存在大大改善了燃烧室内颗粒混合特性和燃烧特性，对火焰稳定和强化燃烧都十分有利。

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A STUDY ON GH169 CRACK PROPAGATION UNDER CREEP-FATIGUE INTERACTION

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As a new technique of crack detection at high temperatures, Reversing DC Electric Potential Method is used to study the crack propagation behaviours of aero-engine turbine disk material GH169 under creep-fatigue interaction at 650 C and at different hold-times. The fracture surfaces has examined with a scanning electron microscope. The experimental results indicate that the life prediction model by hyperbolic sine function is superior to the life prediction model by Paris formulation in correlativity with experimental data and predictability at the crack initiation propagation. Moreover, the former model is more convinient in application. It has been found that the crack propagation ratio obtained in the case of gradually increasing loading is smaller than that resulted from one-time loading.

EXPERIMENTAL RESEARCH ON 3D TURBULENT GAS-PARTICLE FLOWS IN A COMBUSTOR OF CO-FLOW JET WITH LARGE VELOCITY DIFFERENCE

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The time-averaged and root-mean-square fluctuation velocities of gas and particle phases and particle mass flux distributions have been measured by a 2-dimensional laser Doppler velocimeter combined with a sampling probe in a combustor of co-flow jets with large velocity difference. The results show large velocity slip between gas and particle phases. The gas-phase flow has astrong reverse flow in the near-axial region, while particles keep their forward motion almost everywhere, even in the strongly reverse flow region. The particle mass flux distributions measured have their maximum values in the near-axial reverse flow region. Presence of high-velocity jets remarkably enhances particle mixing. All these facts reveal the mechanism of flame stabilization and combustion intensification in the combustor of co-flow jets with large velocity difference. The four peaks of gas turbulence intensity observed in experiments demonstrate that the turbulence is caused by large velocity gradient resulted from sudden expansion and high velocity jets. Particle

turbulence intensity has the similar behaviour as gas one, but the former is not always smaller than the latter. This means that the classical Hinze-Tchen's theory of particle following gas motion must be reexamined.

A STUDY ON EXIT RADIAL TEMPERATURE PROFILE OF 2D EXPERIMENTAL COMBUSTOR

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Jing Rushan (Beijing University of Aeronautics and Astronautics)

The exit radial temperature profiles formed by four configurations of dilution hole design have been studied experimentally on a two-dimensional experimental combustor. According to the results the effect of different configurations of dilution hole design on combustor exit radial temperature profile shows certain regularity. A semi-empirical and semi-analytical model has been developed for predicting the exit temperature profile of gas turbine combustor. The model can predict the effect of change in dilution zone design or combustion operating conditions on the variation of combustor exit radial temperature profile based on exit temperatures meassured before change. The comparison of the predictions with the measurements shows excellent agreement. The model provides a quantitative design tool for adjustment of temperature profile of gas turbine combustor.

ANALYSIS AND CALCULATION OF VAPOR PUMP CHARACTERISTICS

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A calculation method of hydraulic losses in a vapor pump is proposed with reference to calculation method for high-speed centrifugal pumps. The pressure distribution in the collectors is determined by means of segmentation of flow together with pipe line, therefrom the radial force, pressure head and vapor core variation are found. Some numerical examples are also persented. The method can be applied either to estimation of the characteristics of a new pump in its preliminary design or to approximate evaluation of existing pumps.