文章编号: 1001－2060(2006)03－0267－03

# 可吸入颗粒粒径声学夹带法测量的实验研究

姚　刚, 赵　兵, 杨林军, 沈湘林
(东南大学 洁净煤燃烧教育部重点实验室, 江苏 南京 210096)

摘　要: 1 μm 左右的单颗粒粒径测量目前仍然是一技术难题。文中提出了一种新的利用声波夹带测量微米级和亚微米级单颗粒粒径的方法。该法充分利用了单个颗粒在驻波声场压力节点位置水平振动和重力自由沉降二维力场的动力学特性, 经分析推导出细颗粒粒径和驻波声场中颗粒振动之间的关系。实验测量结合了先进的显微高速摄像技术, 成功地拍摄到单个微米级颗粒的运动轨迹, 经过对图像的分析, 获得所需的参数, 经求解直接得到单颗粒的粒径和滑移系数, 避免了计算过程中的滑移经验假设。实验和计算结果表明: 本实验平台可进行微米级和亚微米级单颗粒粒径的测量以及动力学特性的观测和记录; 声波夹带法具有可靠的理论基础, 作为一种新的微米级单颗粒粒径测量法是可行的。

关　键　词: 微米; 声波夹带; 显微拍摄; 粒径测量
中图分类号: X513　　　文献标识码: A

## 1　引　言

可吸入颗粒物(空气动力学直径小于 10 μm)是目前我国城市大气环境的首要污染物, 尤其是空气动力学直径小于 2.5 μm 的颗粒物(PM2.5), 这些细颗粒物主要来源于燃煤电厂的粉尘排放和城市中的机动车尾气排放, 其数目浓度高, 颗粒粒径小, 富集了大量的重金属和有机化合物, 不能在人体体内降解, 因此毒性很大, 对环境造成很大的危害。目前我国许多大中城市可吸入颗粒物超标十分严重, 并且具有上升趋势[1～2]。国外已经开展了细颗粒排放控制问题的研究, 而我国在可吸入颗粒物产生机理和污染控制方面的研究才刚刚起步, 认识还很不充分, 主要工作是其环境和人体危害程度的研究[3～4], 目前还没有能够找到控制其排放的有效办法。颗粒的粒径对于其物理化学性质具有重要的影响。如燃料颗粒大小及其分布直接影响到燃烧效率、火焰稳定性及排放污染程度; 空气中不同大小的颗粒对有害物的吸附性存在差异, 因而对呼吸系统和人体的危害也不同; 水泥、染料等行业, 颗粒的大小直接影响其使用质量和效果。因此对颗粒物进行精确测量, 测定其直径及直径分布, 有着重要的现实意义。

但是, 目前对于 1 μm 左右单个细颗粒粒径的测定, 一直是困扰颗粒测量界的技术难题, 利用已有的测量手段, 如: 沉降法、光全散射法、光角散射法、夫朗禾费衍射法、动态光子相关技术和库尔特原理为指导设计的仪器, 对这一尺寸段单颗粒的测量都遇到了困难。如在利用沉降法和离心法等常规方法时, 测量粗颗粒时误差较小, 但是研究微米级细颗粒时, 因为颗粒处于滑移区, 须采用经验性的颗粒滑移修正, 影响了测量精度; 各种冲击器可得到颗粒的分布, 但是不能够测量单个颗粒的直径; 而利用光学散射法测量时, 拍摄图像中微米级细颗粒光学衍射像的影响很难消除, 还需要知道颗粒的相对折射率, 其对粒径测量结果的影响评估困难, 且利用这种方法的测量仪器得到的是颗粒平均粒径; 质谱分析中的飞行时间颗粒尺寸测量法虽可测量单颗粒粒径, 但测量空间必须有很高的真空度, 条件苛刻, 技术难度很大; 目前这一尺寸段的测量通常采用电子显微镜图像法测量才能获得精确可靠的测量结果, 但由于电子显微镜图像处理系统成本较高, 且需要事先采样工作, 另外需要大量的显微照片才能评价测量结果, 工作量很大, 不易于实际推广, 必须寻找新的测量方法。

本文提出了一种通过声学夹带法测量超细颗粒单颗粒粒径的新方法, 根据声学理论设计了测量装置并进行了实验。该方法可测量亚微米级到微米级超细颗粒(0.1～10 μm)的单个颗粒空气动力学直径和滑移修正系数。

## 2　测量原理

单颗粒粒径测量主要利用驻波场中颗粒的声波夹带法, 即处于驻波声场中的细颗粒会在所处位置随着气体的振动而振动, 但是颗粒振动幅值是由当地声场和颗粒组成的系统特性决定, 即颗粒气体振幅比是一个多变量函数, 它和颗粒大小、密度、声场

收稿日期: 2005－07－27;　修订日期: 2006－02－27
基金项目: 国家重点基础研究发展计划基金资助项目(2002CB211600)
作者简介: 姚　刚(1976－), 男, 江苏扬州人, 东南大学博士研究生.

频率和声强等都有关。由于声波颗粒作用的复杂性,因此有必要对空气驻波声场特性和处于驻波场中细颗粒的受力情况做一个简要说明。

2.1 空气驻波场中压力、速度的分布

根据声学原理,一维驻波场的压力和速度分布表达式为[5]:

$$p = p_A \cos \omega t \cos kx \quad (1)$$

$$u = (p_A/\rho_0 c)\sin \omega t \sin kx \quad (2)$$

式中:$p_A$—声压幅值;$\omega$—角频率;$\rho_0$—空气密度;$c$—声速;$k$—波数。

驻波场内的小颗粒受到的辐射压力的大小为[6~7]:

$$F_r = \frac{4}{3}\pi k a^3 \overline{E} \sin 2kx \left(\frac{2.5-\delta}{2+\delta}\right) \quad (3)$$

对于空气中的硬质小颗粒,由于 $\delta \ll 1$,式(3)可简化为:

$$F_r = (5/3\lambda)\pi^2 \rho_0 a^3 U_0^2 \sin(4\pi x/\lambda) \quad (4)$$

式(3)、式(4)中:$a$—颗粒半径;$\overline{E}$—平均声能量密度;$U_0$—速度有效值;$\delta = \rho_0/\rho_p$,其中 $\rho_p$ 是颗粒密度。

根据式(1)、式(2),图 1 给出了当声源和反射面相距两个波长时形成的驻波场中速度、压力的分布。在驻波场中,$x = (2n-1)\lambda/4$ 处,声压振幅为零,为声压波节点,而在该位置,速度幅值最大。根据式(4),在该位置细颗粒受到的辐射压力幅值也为零。因此驻波场中速度波腹点刚好是声压和细颗粒辐射压力波节点,下面的实验方法正是利用了驻波场中的这一重要特性。

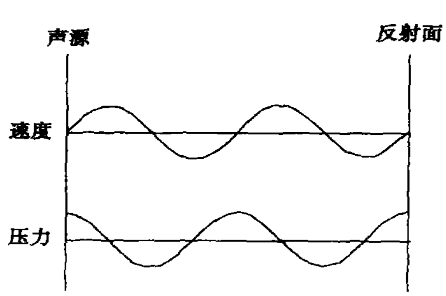


图 1 空气驻波场中速度、压力分布示意图

2.2 细颗粒在力场中的受力及运动

被测颗粒在声波和重力场中受到的力有:粘性力、重力、浮力、声场辐射力。根据式(3),如果颗粒处于驻波场的压力波节位置,颗粒受到的声场辐射力为零。另外由于 $\delta$ 很小,与重力相比颗粒浮力可以忽略。水平方向只会受到粘性力作用,结果使得颗粒被声场夹带;竖直方向由于粘性力和重力共同作用,二者达到平衡后,颗粒将以恒定速沉降。

根据受力分析,水平方向上由于粘性作用,在声波场中颗粒会随着声波振动在其平衡位置振动,即颗粒会受到声波的夹带运动。根据文献[8~9],如果满足粒径远小于声波长 $ka \ll 1$、颗粒密度远大于空气密度 $\delta \ll 1$、颗粒粒径远小于声波振动边界层厚度 $\sqrt{\omega a^2/2v_0} \ll 1$ 这 3 个条件,那么颗粒振动的位移幅值 $X_p$ 和空气质点振动的位移幅值 $X_0$ 的比值可以表示为:

$$\frac{X_p}{X_0} = \frac{1}{\sqrt{1+(\rho_p \pi d_p^2 f/9\mu C)^2}} \quad (5)$$

式中:$\mu$—空气动力粘度;$d_p$—颗粒直径;$C$—肯宁汉滑移修正系数,为一经验系数。

竖直方向上,由于重力的作用,颗粒将发生自由沉降运动,沉降速度方程为:

$$V_t = \frac{\rho_g d_{pg}^2}{18\mu} C \quad (6)$$

式中:$V_t$—颗粒的终极沉降速度,联立式(5)、式(6)得到颗粒粒径的表达式为:

$$d_p = \left(\frac{162 V_t \mu^2 \sqrt{(X_0/X_p)^2 - 1}}{\rho_p^2 \pi f g}\right)^{\frac{1}{4}} \quad (7)$$

式(7)表明颗粒的粒径是终极沉降速度,空气粘度,颗粒和空气振动幅值,颗粒密度和声波频率的函数。其中当颗粒密度、声波频率已知时,只要知道了 $X_0$、$X_p$ 和 $V_t$ 就可以计算得到颗粒的空气动力学直径。

## 3 实验装置和方法

根据上节所述原理,本实验用显微摄像系统拍摄和记录颗粒在水平驻波声场中压力波节处的夹带和沉降轨迹,依据声场的参数和图像处理颗粒轨迹来确定颗粒粒径。实验装置如图 2 所示。

图 2 中 9 为声波场颗粒运动观察室。信号发生器 1 产生的一定频率的正弦信号,经功率放大器 2 放大,驱动平面扬声器 3 产生声波,观察室的另一端为可调节刚性反射面 7,调节 7 在观察室内形成平面驻波声场。将显微镜头 11 调节到声压节点处,利用激光光源 10 产生观测所需要的合适照射光强度,利用声传声放大器 5 测量驻波场声压的有效值。实验时,开启气溶胶发生器 8 产生一定浓度和大小细颗粒并引入观测室,经过一段时间后关闭观察室进出口开关 6 和 4。由于粒径很小,故很快进入稳定的沉降过程(对于 10 μm 颗粒,达到稳定下降时间只需约 0.7 ms)。在观测室中,颗粒受到的力有:粘性

力、重力、浮力和声场辐射力。因为显微镜拍摄位置处于驻波场的压力波节位置, 所以该处颗粒的受到声场辐射力为零; 又 $\delta \ll 1$, 颗粒浮力也可以忽略。那么水平方向的粘性力作用的结果颗粒受到声场的夹带; 竖直方向粘性力和重力处于平衡后使得颗粒于均匀的速度沉降。颗粒在力场中的运动轨迹通过显微镜和 CCD 高速摄像机 12 进行实时显微记录, 对拍摄图象做进一步分析。

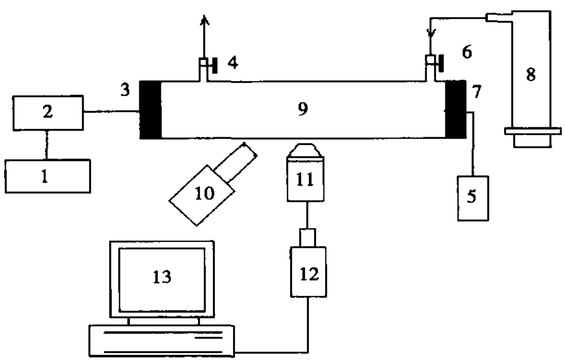


图 2　颗粒粒径测量实验装置简图

实验中, 被测颗粒由气流带入声场。对于颗粒的加入也可以采取在压力波节点处设置加料装置, 直接从观测室上方加入被测颗粒的方式。

需要说明的是, 从测量精度方面考虑, 应满足声场沿着管轴做水平振动, 无其它方向的振动, 即管子里产生的应该是一维平面声波。但是当声波被约束在管子中传播时, 声波并不总是沿着管轴方向一维传播, 管子的形状、尺寸和声源等因素必须满足一定条件方可。根据声学基础关于矩形声波导管的理论[5], 当满足 $f < f_c = c_0/2l_{max}$ ($l_{max}$是矩形管口最大边的尺寸), 在管子内就只会产生无横向振动的一维平面声波。$f_c$ 称为管子的截止频率。本文实验矩形管口最大边长为 0.02 m, 计算该管的截至频率 $f_c$ = 8 500 Hz, 实验时只要保证声源的频率低于 8 500 Hz, 就可以满足管内一维平面声传播的要求。

## 4　实例结果分析和颗粒粒径计算

图 3 是利用显微高速摄像拍摄的飞灰颗粒在声波场中同时产生水平振动和竖直下降的轨迹。实验时使用的飞灰平均直径为 3 μm, 高速摄像的拍摄速率为 60 Fps, 声场强度为 124 dB, 声波频率为 3 000 Hz。

根据声学关系, 计算得到空气质点的振幅 $X_g$ 为 4.20 μm[5], 对图 3 图像分析得到颗粒的夹带振幅 $X_p$ 为 2.47 μm。下降距离 12.4 μm, 下降所经历的时间 1/60 s, 下降速度 742.5 μm/s。根据以上参数, 求解式(5)、式(6), 得到颗粒的直径 $d_p$ 为 3.24 μm, 其滑移修正系数 $C$ 为 1.02。如果只是根据重力沉降公式, 计算得到颗粒的沉降直径为 $d_g = 3.17$ μm, 其滑移修正系数 1.05。另外通过计算得到: $ka = 8.98e^{-5} \ll 1$, $\delta = 5.2e^{-4} \ll 1$, $\sqrt{\omega a^2/2v_0} = 0.036 \ll 1$, 满足夹带公式成立的条件, 可使用式(7)进行单颗粒粒径计算。

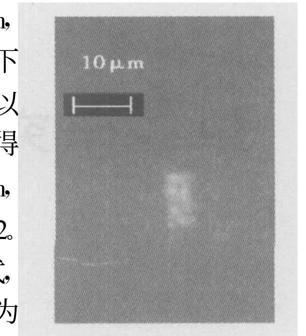


图 3　二维力场中颗粒显微运动轨迹

## 5　结　论

(1) 本实验系统可以微观观测和记录微米、亚微米颗粒的运动轨迹, 为研究其动力学特性提供了较好的平台;

(2) 利用声波场对颗粒的夹带作用, 建立颗粒的粒径和颗粒的振动之间的函数关系, 联合颗粒的自由沉降公式, 通过显微拍摄技术获得测量参数, 求解二元方程组, 可求得亚微米和微米级单颗粒的粒径并同时求出颗粒的滑移系数, 如综合多次测量的统计结果也可以得到所测颗粒的尺寸分布;

(3) 粒径测量方法上, 由于采用二维力场通过颗粒运动轨迹来确定颗粒动力学直径的方法, 避免了单纯利用沉降法时, 要考虑滑移修正系数为经验公式时的不足, 也避免了光学测粒径法中衍射误差分析的影响, 因此是一种新的粒径测量法。

参考文献:

[1]　朱广一. 大气可吸入颗粒物研究进展[J]. 环境保护科学, 2002, **28**(5): 3－5.
[2]　邵龙义. 都市大气环境中可吸入颗粒物的研究[J]. 环境保护, 2000, **1**: 24－29.
[3]　杨铁戬. 细颗粒物对呼吸系统的毒性作用[J]. 毒理学杂志, 2005, **19**(2): 146－148.
[4]　李　红. 可吸入颗粒物对人体健康危害的研究进展[J]. 环境与健康杂志, 2002, **19**(1): 85－87.
[5]　杜功焕, 声学基础[M]. (第二版). 南京: 南京大学出版社, 2001.
[6]　富克斯. 气溶胶力学[M]. 北京: 科学出版社, 1960.
[7]　ROSENBERG. Physical principles of ultrasonic technology v. 2[M]. New York: Plenum, 1973.
[8]　TEMKIN S. Elements of acoustics[M]. New York: John Wiley, 1981.
[9]　张国权. 气溶胶力学基础[M]. 北京: 中国环境科学出版社, 1987.

(渠　源　编辑)

lege of Technology, Harbin, China, Post Code: 150040)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —259 ~263

A full three-dimensional non-steady numerical simulation method was employed to solve the parameters of the flow field of a small-sized fan under the condition of a square-wave type total-pressure distortion at the inlet single-distortion zone. The effect of the total-pressure distortion on the parameters of the flow field of the fan has been analyzed in detail. Moreover, from the standpoint of amplitude and frequency analysis discussed are the phenomena of attenuation of total-pressure distortion via the fan and the interference between stator blades and moving ones. The calculation and analysis results indicate that the method under discussion can clearly depict the distribution of flow field parameters along the circumferential direction. The total-pressure distortion at the inlet along the circumferential direction may cause a redistribution of the inlet parameters, resulting in a marked circumferential lateral-flow at the boundary of high and low pressure areas and triggering a total-temperature distortion, which took place simultaneously with an attenuation via the fan. In addition, when the distortion degree at the inlet is identical, with an increasing distortion angle, the distortion disturbance and the interference between stator blades and moving ones will undergo a marked intensification. **Key words**: non-steady numerical simulation, fan, total-pressure distortion

花瓣稳燃器流场的数值模拟与特性分析=**Numerical Simulation and Characteristic Analysis of the Flow Fields in a Petal-shaped Combustion Stabilizer**[刊,汉] /ZHAO Ling-ling, ZHOU Qiang-tai, ZHAO Chang-sui (Power Engineering Department, Southeast University, Nanjing, China, Post Code: 210096)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —264 ~266, 274

A calculation model of three-dimensional (360°) curvilinear coordinates and complex curved-surface geometry has been set up to conduct the numerical simulation of the flow-field of a petal-shaped combustion stabilizer along with a theoretical analysis of the flow field characteristics and mixing-dilution ones of the stabilizer. The operating principle of the latter's combustion stabilization has been studied. The specific design of the petal-shaped combustion stabilizers has made it possible to lengthen the thermal mixing boundary between "air"-"pulverized-coal"- "gas-flow" and flue gas return-flow. Apart from a central return-flow zone, a radial return-flow zone has been formed behind each petal to fuse with the central return-flow zone. By introducing a convection mixing of pulverized-coal gas flow with high-temperature flue gas flow, the heat-mass exchange strength of both flows was enhanced, and the circulation time of the pulverized-coal in the return zone prolonged, thus providing a stable heat source for the ignition and burning of pulverized-coal particles. This will be conducive to the ignition and burning-off of the pulverized-coal, especially for low-volatile coal and in case of operation at a low load. The research results of the authors can provide a theoretical basis for the optimized design of petal-shaped combustion stabilizers. **Key words**: petal-shaped combustion stabilizer, numerical simulation, stable combustion, flow field characteristics

可吸入颗粒粒径声学夹带法测量的实验研究=**Experimental Study of the Measurement of Inhalable Particle Diameter by the Use of an Acoustic Entrainment Method**[刊,汉] /YAO Gang, ZHAO Bing, YANG Lin-jun, et al (Education Ministry Key Laboratory of Coal Clean Combustion under the Southeast University, Nanjing, Jiangsu, China, Post Code: 210096)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —267 ~269

To date, the measurement of a single particle with a diameter of about 1 μm is still a technically intractable problem. A new approach is proposed for the measurement of micron grade and sub-micron grade single particle size by the use of acoustic wave entrainment. This approach makes full use of the dynamic characteristics of the two-dimensional force field composed of the horizontal vibration and gravity-free sedimentation of a single particle at the pressure node location in a standing-wave acoustic field. Through an analysis the relationship between a fine particle size and the particle vibration in the standing-wave acoustic field has been derived. By combining experimental measurements with an advanced microscopic high-speed photography technique, the movement trajectory of a single micron-grade particle has been successfully photographed. Through an analysis of the pictures the required parameters were obtained. By way of seeking a solution the diameter and slippage factor of a single particle were obtained, avoiding a slippage assumption based on experience in the calculation process. The experimental and calculation results show that the present experimental platform can be used to measure micron and sub-micron grade single particle size as well as to observe and record dynamic characteristics. The acoustic entrainment method, being supported by a reliable theoretical basis, can serve as a new and feasible method for the measurement of micron-grade single particle size. **Key words**: micron, acoustic wave entrainment, microscopic photography, particle size measurement

数值研究扩散式旋风分离器流场与颗粒分离特性＝**Numerical Study of the Flow Field and Particle Separation Characteristics for a Diffusion Type Cyclone Separator**[刊, 汉] /TAN Xiao-jun, CHEN Li-hua, LI Hong-jian, et al (Mechanical and Energy Engineering College under the Zhejiang University, Hangzhou, Zhejiang, China, Post Code: 310027)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —270～274

With respect to a diffusion type cyclone separator in a gas/solid separation device, a RNG $k-\varepsilon$ turbulent-flow model and discrete-phase random trajectory model were adopted respectively to perform a numerical simulation of its inner flow field and particle separation behavior. The trajectory of particles with different diameters at a constant flow speed was calculated and the impact of various inlet concentrations and flow speeds on the separation efficiency as well as the effect of a reflector screen on separation efficiency and particle residence time were discussed. The calculation results indicate that the separator as a whole assumes a double-layer flow structure and features a relatively good symmetry. In general, the radial speed is lower than the axial and tangential speed with an extremely low flow speed within the reflector screen. There exists a short-circuit flow at the inlet of exhaust pipes. This kind of separators provides a low separation efficiency for small particles with a diameter less than 4 $\mu$m. The flow speed has a relatively high impact on separation efficiency. The reflector screen can make small particles stagnate in the separator for a longer time, thus enhancing their chances of being separated out. **Key words**: diffusion type cyclone separator, two-phase flow, particle separation, numerical simulation

液柱冲击塔雾化特性的试验研究＝**Experimental Study of the Atomization Characteristics of a Liquid-column Impingement Tower**[刊, 汉] /WANG Jun, GAO Xiang, GUO Rui-tang, et al (State Key Laboratory on the Clean Utilization of Energy Resources under the Zhejiang University, Hangzhou, Zhejiang, China, Post Code: 310027)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —275～278, 282

The atomization effectiveness of a liquid column in a liquid-column impingement tower has a direct influence on the desulfurization efficiency of a whole system. The main influencing factors include: the type of damper plates, liquid inlet flow rate, gas velocity and the clearance between the nozzles and damper plates. On a simulation test rig of a small-sized liquid-column impingement tower, by using particle image velocimetry (PIV) measuring technology, measurements were taken of the gas-liquid two-phase flow field formed by the liquid column atomization inside a simulation test tower. The test results show that the above-mentioned structural factors and operational parameters have a significant effect on the size of liquid droplets in the atomization flow field and their kinematic speed. Moreover, it was found that the liquid droplet size in the flow field complies with Rosin-Rammler distribution law. **Key words**: PIV (Particle Image Velocimetry) technology, liquid-column impingement tower, particle size distribution

高热流密度下 R113 核态沸腾中汽化核心密度的识别＝**Identification of Densities at the Nucleation Sites in a**