第 21 卷第 2 期
2006 年 3 月
热　能　动　力　工　程
JOURNAL OF ENGINEERING FOR THERMAL ENERGY AND POWER
Vol. 21, No. 2
Mar., 2006

文章编号: 1001－2060(2006)02－0175－04

燃煤可吸入颗粒物声波团聚效果的实验研究和数值分析

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摘　要: 通过对平面驻波声场的理论分析, 设计并建立了燃煤可吸入颗粒物声波团聚清除特性的实验台。研究了燃煤可吸入颗粒物在高强度声波场作用下, 不同声波强度和声场停留时间对于声波团聚前后颗粒粒径分布变化的影响。在实验的基础上, 进行了数值计算, 将数值解和实验解进行了比较, 两者吻合得较好, 并通过数值算法对颗粒初始浓度和声波频率影响进行了预测。实验和数值结果表明: 对于可吸入颗粒物, 提高声波强度、延长声场停留时间、增加初始颗粒浓度均有利于颗粒的团聚。发现频率增加有利于小颗粒的团聚, 但是对整体清除效果则存在一个最佳频率。

关　键　词: 燃煤可吸入颗粒物; 声波团聚; 数值预测

中图分类号: X513　　　文献标识码: A

1　引　言

我国是燃煤大国, 每年燃煤产生的一次和二次颗粒物数量巨大。排放到空气中的颗粒物不仅降低了大气的能见度, 影响环境和气候, 而且危害人体健康, 使致病率和死亡率上升。可吸入颗粒物(< 10 μm)是目前我国城市大气环境的主要污染物, 尤其是空气动力学直径小于 2.5 μm 的颗粒物($PM_{2.5}$)在我国的许多大中城市超标十分严重, 并且具有上升趋势。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, 目前主要是研究其对环境和人体危害程度, 但最关键的问题是还没有控制可吸入颗粒物排放的有效方法。现有的除尘技术如静电除尘器, 旋风除尘器, 袋式除尘器和湿式除尘器, 对 0.1～5 μm 颗粒的清除效率都很低。因此, 要从源头上控制可吸入颗粒物的排放, 必须寻找新的控制方法。高强声波团聚技术是一种有效的可吸入颗粒清除方法, 它利用高强度声场来使气溶胶中微米和亚微米颗粒产生相对振动, 增加它们的碰撞几率, 一旦颗粒发生了碰撞, 它们便容易产生粘附而形成较大一级的团聚物[1～4], 在很短的时间范围内, 颗粒的分布密度函数(PDF)将发生从小尺寸向大尺寸范围的演变, 平均粒径变大, 细颗粒的数目变少, 结果便很容易地通过旋风分离器、静电除尘器等常规的颗粒清除设备将相对较大的颗粒从气体中清除掉。

2　高强声波团聚实验台

可吸入颗粒物高强声波团聚效果实验台主要由声源系统、声波团聚室、流化床气溶胶颗粒发生器和 ELPI 实时颗粒分布测量系统 4 个部分组成, 如图 1 示。

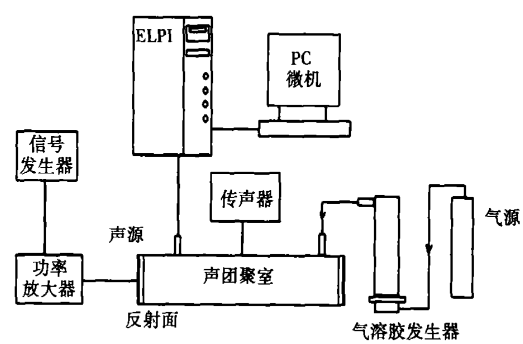

图 1　声波团聚效果实验台示意图

实验时, 由信号发生器产生一定频率的正弦信号, 经功率放大器放大, 驱动声源产生高强声波, 声波团聚室的另一端为可调节刚性反射面, 调节它可在团聚室内产生驻波声场, 通过传声放大器测量驻波场实际声压值。实验采用的颗粒为电厂第四电场的飞灰颗粒, 其中值直径 D_{50} 约为 3 μm, 利用气溶胶发生器产生所需浓度的细颗粒并引入团聚室, 通过 ELPI 实时测量和记录团聚前后颗粒分布。

收稿日期: 2005－07－27;　修订日期: 2005－12－08
基金项目: 国家重点基础研究发展计划基金资助项目(2002CB211600)
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2.1　声源系统及其频率特性

由于声波团聚对声源,特别是声源的声压级要求比较高,因此采用了 KTD－250 型警报扬声器为声源。由于电扬声器在输入电压值相同的情况下,不同频率其输出的声强是不同的,因此在实验前首先对扬声器的频率特性(实际上是扬声器和管子组成的系统的频率特性)进行了标定,结果如图 2 所示。其输出功率为 250 W,阻抗 8 Ω,频率范围 180～7 000 Hz,经实际测试其工作在 1 000～3 000 Hz 工作时,管内 1 m 处声压级可以达到 160 dB。

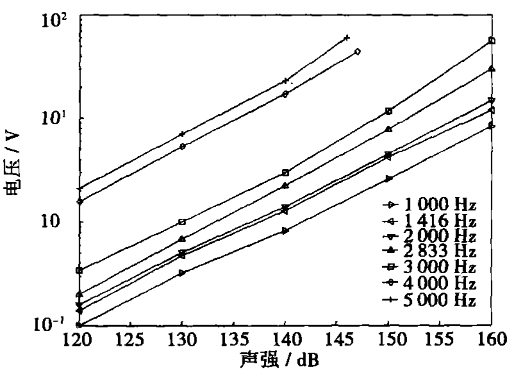

图 2　声源系统的声强和电压特性

2.2　团聚室声波衰减程度测量

声音传播是会产生衰减的[5~6]。实验前,我们对声波团聚室的衰减程度进行了测试。图 3 是对声压沿着管长衰减情况实际测量的结果。声波频率为 2 826 Hz 和 1 413 Hz,衰减< 0.8 dB,管端和声源处声压比> 0.994,从测试结果可知,实验时声波的管内衰减很小,可以不予考虑。

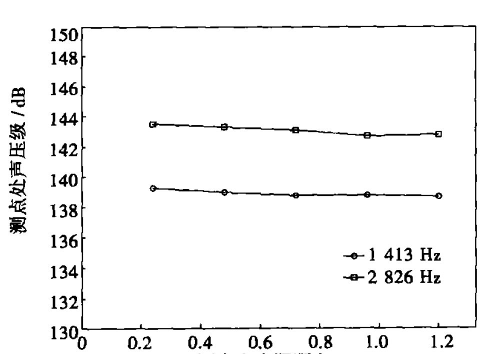

图 3　声压级沿管长的分布

2.3　声波团聚室

为便于观测和操作方便,声波团聚室主体设计为一个有机玻璃制成的长方体,观测室壁的厚度为 8 mm,内部空腔横截面的尺寸为 20 mm× 20 mm,长度为 1 420 mm,沿着管长在壁面上等间隔开了 5 个孔,作为团聚室内声压测量和改变颗粒停留时间之用。团聚室一端与声源连接,另一端布置可移动刚性反射面,通过调节声源和反射面的距离 L,当满足 $L = n\dfrac{\lambda}{2}$ 时(λ 为声波波长),在管内形成驻波声场。

2.4　颗粒粒径分布测量

实验利用电称低压冲击器(ELPI)来实时测量和记录颗粒粒径的分布。根据颗粒的空气动力学直径大小,冲击器内部从上至下共被分为了 13 级。最上面为第 13 级,其切割直径为 9.84 μm,最下面为第 1 级,其切割直径为 0.027 6 μm,见表 1。冲击器各级彼此绝缘,每级都有独立的静电计用于测量收集在上面颗粒的总电荷,通过收集到的电荷量,ELPI 可以通过相应的函数计算出收集在各级颗粒的数目、表面积、体积和质量,从而得到整个测量范围内颗粒的尺寸分布和总数。

表 1　ELPI 的各级切割直径、压力和停留时间

级	D_{50}/μm	压力/kPa	停留时间/ s
1	0.027 6	10.00	0.017
2	0.054 8	21.94	0.029 9
3	0.093 6	38.78	0.053
4	0.155	69.00	0.069 3
5	0.260	89.28	0.075 7
6	0.379	97.12	0.077 6
7	0.608	99.62	0.078 2
8	0.941	100.49	0.1
9	1.59	101.00	0.1
10	2.37	101.18	0.11
11	3.97	101.24	0.12
12	6.64	101.30	0.14
13	9.84	101.32	0.0

3　声波团聚实验结果和分析

3.1　声强的影响

图 4 是改变声强大小对同一初始分布声波团聚前后各级飞灰颗粒清除比例的影响。实验时的频率为 1 413 Hz,团聚时间为 5 s,采用的声强大小分别为 150 dB、155dB 和 160 dB。从图中可以看出,随着声强的增加,第 1～11 级的清除比例都在增加,第 12 级的颗粒不降反升,这是由于小颗粒团聚长大引起的,还可以看出在该工况下声波对较大(第 7 级以

上)颗粒的清除效果要比较小颗粒的好, 这是由于选取的声波频率比较低, 有利于较大颗粒的团聚。根据实验数据, 在 150 dB、155 dB 和 160 dB 下对总颗粒的清除效率分别为 10.2%、18.2% 和 34.8%, 因此高强声场有利于可吸入颗粒物的团聚。

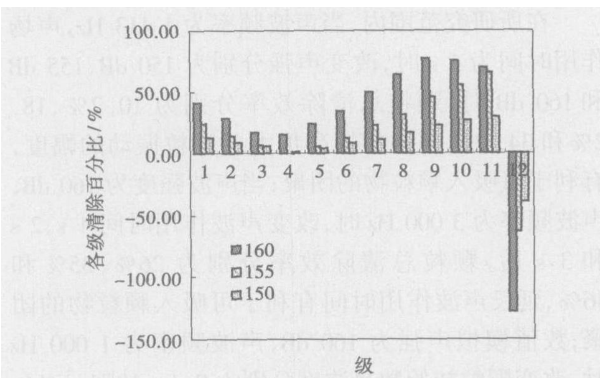

图 4　不同声强下各级颗粒清除百分比

3.2　声波作用时间的影响

图 5 是改变声波作用时间对飞灰颗粒清除的情况。实验时声波强度为 160 dB, 声波频率为 3 000 Hz, 声波作用时间选取 1 s、2 s 和 3 s。

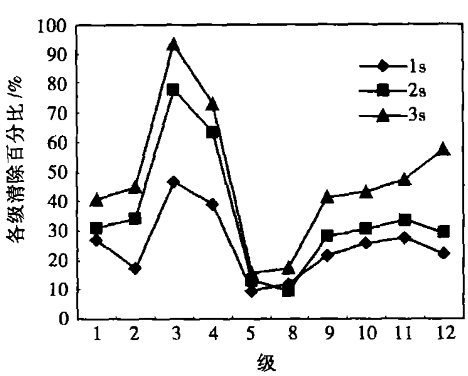

图 5　不同时间各级颗粒清除百分比

从图中可以看出随着声波作用时间的增加, 颗粒的清除效果也增加; 还可以看出在实验工况下, 声波对较小粒径段的颗粒的清除要优于较大粒径段的颗粒, 这是由于声波频率增加更加有利于小颗粒的清除。根据实验数据, 声波作用 1 s、2 s 和 3 s 时, 对所有颗粒的清除效率分别为 26%、35% 和 46%, 延长声波作用时间增加了可吸入颗粒物的团聚清除效果。

4　声波团聚数值模拟和预测

4.1　数值模拟

在实验的基础上, 利用区域算法对颗粒动力学方程进行求解[7~10], 得到声波团聚后颗粒粒径分布的情况, 结果如图 6 所示。

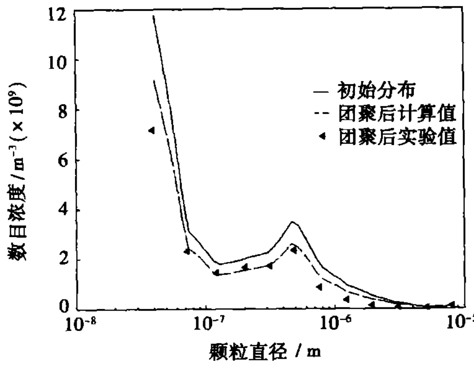

图 6　飞灰颗粒声波团聚数值模拟

模拟的参数和实验相同, 声场强度为 160 dB, 声波频率为 1 413 Hz, 声波作用的时间为 5 s 中, 从图中可以看出数值模拟的结果和实验结果吻合较好, 数值解反映了声波对颗粒团聚分布的影响。

4.2　数值预测

在上述数值计算的基础上, 利用计算模型研究了颗粒浓度和声波频率对飞灰颗粒声波团聚效果的影响。图 7 是不同颗粒起始浓度对团聚效果的影

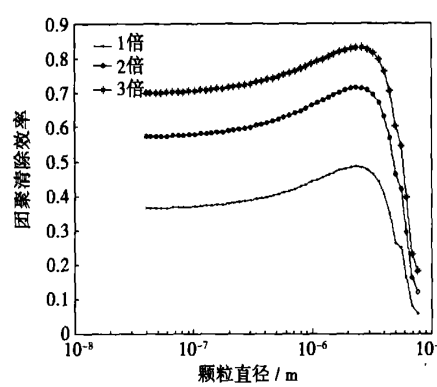

图 7　颗粒起始浓度对团聚效果的影响

响, 计算时声波强度 160 dB, 团聚时间 5 s, 声波频率 1 000 Hz。初始数目浓度为 $7.1\times 10^{10}/m^3$, 图中从下到上分别是 1 倍、2 倍和 3 倍初始浓度的团聚效果, 可以看出随着颗粒浓度的增加, 颗粒的清除效果也增加。这是因为浓度的增加, 使得单位体积内颗粒之间碰撞的几率增大, 因此对团聚有利。在 1 倍、2 倍和 3 倍初始浓度时, 颗粒整体清除效率分别为 37.4%、58.3% 和 70.1%, 虽然浓度的增加有利于颗粒的清除, 但是清除效率增长速度是逐渐减慢的, 对于特定的团聚条件, 当浓度到达一定数值时, 浓度对

清除的贡献已经不大,这时就不能通过增加浓度来提高颗粒清除效率,这时需考虑浓度和其它参数的配合问题。图 8 是不同声波频率对团聚效果的影响,计算时声波强度为 160 dB,团聚时间为 5 s,声波频率选取了 1 k、2 k、3 k 和 10 kHz,初始数目浓度为 $7.1\times 10^{10}/m^3$。可以看出最佳团聚的颗粒位置随着声波频率的增加向小粒径方向移动,声波频率的增加更加有利于小颗粒的清除。在 1 k、2 k、3 k 和 10 kHz 频率下,最佳团聚的粒径分别为 2.35 μm、1.7 μm、1.5 μm 和 0.8μm。对本计算工况,在一定范围内声波频率的增加有利于颗粒整体清除效果,如图 9 所示,图中 f 为声波频率,根据数值计算的结果,频率为 1 k、2 k、3 k 和 10 kHz 时颗粒总的清除效率为 37.4%、41.9 %、43.7%和 47%。但是通过进一步的计算发现,总颗粒清除的效果并不是随频率单调上升的,当声波超过某个频率时,声波团聚清除效果反而开始下降。因此对于特定的颗粒分布和声学参数存在一个最佳的团聚声波频率。

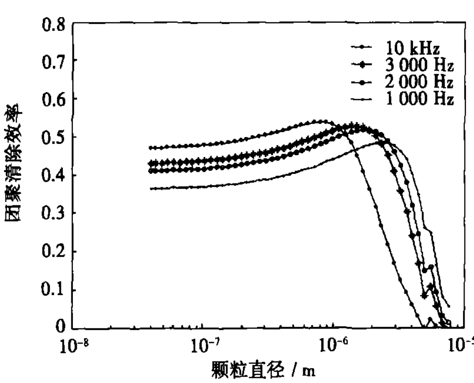

图 8　声波频率对团聚效果的影响

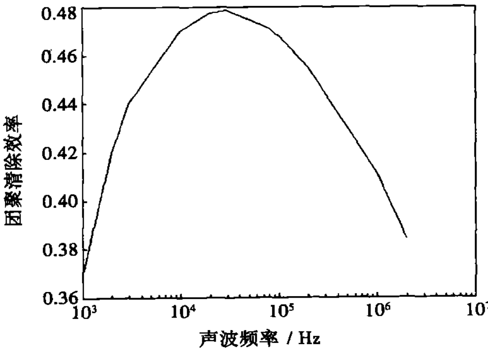

图 9　声波频率和团聚清除效果关系

5　结　论

利用高强驻波声场对燃煤可吸入颗粒物清除规律进行了研究,通过实验和数值模拟分析发现颗粒物团聚效果受到的影响因素很多,比如颗粒初始分布、声强、声场作用时间、频率、浓度等。

在所研究范围内,当声波频率为 1 413 Hz,声场作用时间为 5 s 时,改变声强分别为 150 dB、155 dB 和 160 dB 时,颗粒总清除效率分别为 10.2%、18.2%和 34.8%,声强的提高加大了颗粒振动的幅度,有利于可吸入颗粒物的团聚;当声波强度为 160 dB,声波频率为 3 000 Hz 时,改变声波作用时间 1 s、2 s 和 3 s 后,颗粒总清除效率分别为 26%、35%和 46%,延长声波作用时间有利于可吸入颗粒物的团聚;数值模拟声强为 160 dB,声波频率为 1 000 Hz 时,改变颗粒初始数目浓度分别为 $7.1\times 10^{10}/m^3$, $14.2\times 10^{10}/m^3$ 和 $21.3\times 10^{10}/m^3$ 时,颗粒总清除效率分别为 37.4%、58.3%和 70.1%,增加颗粒浓度后,从而增加了颗粒碰撞的几率,有利于可吸入颗粒的团聚。声波频率的增加在一定范围内对小颗粒和总体清除效率均有利,当频率由 1 k 增加到 10 kHz 时,清除率由 37.4%增加到 47%,但是当频率过高时,清除率反而会下降,所以频率的作用不是单调性的。对于给定的实验工况,存在一个最佳的团聚频率值,本文中最佳团聚频率为 30 kHz。

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(丹　编辑)

单平面主动平衡技术消除弯曲转子振动故障的研究＝**A Study of the Elimination of Vibration Faults Occurring in a Bended Rotor through the Use of a Single-plane Active Balancing Technology**[刊，汉]/LIU Jin-nan，HE Li-dong，SHEN Wei，et al（Diagnosis amd Self-healing Engineering Research Center under the Beijing University of Chemical Engineering，Beijing，China，Post Code：100029）//Journal of Engineering for Thermal Energy & Power．—2006，21(2)．—165～168

A rotor affected with bending is one of the major fault sources leading to an increase in vibration level of a rotor. The causes of the bending occurring on various kinds of rotor are first analyzed. Then, it is proposed to use single-plane active balancing techniques to eliminate the vibration fault of a bended rotor. Moreover, the feasibility of the proposed method is verified by tests. The results of the tests indicate that by using a single-plane active balancing device it is possible to reduce the vibration peak value of the bended rotor at a location of the first-order critical speed from 550 μm to below 100 μm, a reduction higher than 80%. From this example it can be seen that the technique under discussion can very effectively control the vibration caused by the bending of a rotor, demonstrating its high value in engineering practice. **Key words**: bended rotor, active balancing, single plane, vibration fault

环形扩压叶栅弯叶片对流场性能的影响＝**The Impact of Bowed Blades of an Annular Diffuser Cascade on Flow Field Performance**[刊，汉]/ZHANG Yong-jun，FENG Guo-tai，SU Jie-xian，et al（College of Energy Science & Engineering under the Harbin Institute of Technology，Harbin，China，Post Code：150001）//Journal of Engineering for Thermal Energy & Power．—2006，21(2)．—169～174

After a contrast study of the different phenomena displayed at the suction-side corner zone and at the lower end-wall flow field by the straight-blade cascades and bowed blade ones it has been found that the bowed blades exercise a relatively great influence on the separation flow structure at the corner zone. The bowed blades can also significantly lower the dimensions of horseshoe vortex and weaken the transverse secondary-flow near the end-wall zone. With the location and intensity of three-dimensional flow-oriented vortices (passage vortex and concentrated shed vortex) in different cascades and in sections along the flow direction serving as an object of investigation a detailed analysis was conducted of the variation of vortex location and intensity prior to and after the adoption of the bowed blades. The results of the analysis indicate that the location of two kinds of vortex is subject to a relatively great influence of the bowed blades. The variation of the intensity of the passage vortex along the flow direction due to the influence of bowed blades is comparatively evident while the influence of the bowed blades on the intensity of concentrated shed vortex is very small. Mach number of an incident flow, the turning angle of a blade profile and solidity exercise in a certain range a regular influence on the function of the bowed blades. At a Mach number of 0.7 the bowed blades with an optimal curved angle will lower losses by 7%. When the Mach number is 0.2, the above-mentioned blades can reduce the losses by only 4%. **Key words**: low speed, compressor, bowed blade, separated flow, passage vortex, concentrated shed vortex

燃煤可吸入颗粒物声波团聚效果的实验研究和数值分析＝**Experimental Study and Numerical Analysis of the Acoustic Agglomeration Effectiveness of Inhalable Particles of Burned Coal**[刊，汉]/YAO Gang，ZHAO Bing，SHEN Xiang-lin（Education Ministry Key Laboratory of Clean Coal Power Generation under the Southeastern University，Nanjing，China，Post Code：210096）//Journal of Engineering for Thermal Energy & Power．—2006，21(2)．—175～178

Through a theoretical analysis of a plane standing-wave sonic field a test rig on acoustic agglomeration and removal characteristics of burned coal inhalable particles has been designed and set up. Under the condition of the inhalable particles of burned coal being subject to the action of a high intensity sonic field studied was the impact of different acoustic intensity and particle retention time in sonic field on the change of particle diameter distribution prior to and after the acoustic agglomeration. On the basis of experiments a numerical calculation was conducted. A comparison of the results of numerical calculation with those of experiments revealed a relatively good agreement. Moreover, by way of a numerical algorithm a forecast was performed of the influence of particle initial concentration and acoustic frequency. The results of experiments and numerical calculation indicate that as for the inhalable particles an increase in acoustic intensity, a lengthening of retention time in sonic fields and an enhancement in initial particle concentration is, without exception, favorable to particle agglomeration. It has been found that an increase in frequency can contribute to the agglomeration of small particles. However, there exists an optimum frequency for attaining integral removal effectiveness. **Key words**: inhalable particle of burned coal, acoustic agglomeration, numerical forecast

混煤煤灰软化温度的实验研究与预测＝**Experimental Research and Forecast of the Softening Temperature of Blended Coal Ash**[刊, 汉] / WU Chang-hong, MA Xiao-qian (College of Electric Power under the South China University of Science & Technology, Guangzhou, China, Post Code: 510640) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(2). —179 ~182

Samples of blended coal ash were taken from the boiler of a power plant 700MW unit. Their softening temperature was measured by a pyramid method on an intelligent ash-melting point measuring device. Experimental results indicate that the softening temperature of blended coal ash and blend/mixture ratio assume a nonlinear relationship. Through the use of a radial-based function neural network (RBFNN) an intelligent forecasting model for the blended-coal softening temperature was set up under MATLAB environment. To verify the forecast effectiveness of the model, with 8 blended coal ash samples under test serving as samples to be examined a forecast of their softening temperature was conducted using the above-mentioned RBFNN-based model. The results of the forecast indicate that the forecast results of the RBFNN model agree well with those of experiments. The maximum relative error between the above two results is 3.79% with the average relative error being 1.56%. The effectiveness of the forecast has been found to be by far superior to that of a linear forecast model. **Key words**: blended coal, softening temperature, forecast, radial-based function neural network, nonlinear

结构及运行参数对内混喷嘴压力的影响研究＝**Experimental Study of the Influence of Structural and Operating Parameters on the Pressure of an Internal-mixing Nozzle**[刊, 汉] / MA Qi-liang, BI Zheng-yi (College of Power Engineering under the Shanghai University of Science & Technology, Shanghai, China, Post Code: 200093) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(2). —183 ~185

In the design calculations of a media-atomization nozzle of internal mixing type it is common practice to regard the ratio between the pressure in a mixing chamber and the inlet pressure of atomization media as approximately a critical pressure ratio. Such an approximation will give rise to a relatively great difference with respect to the results of experiments. The results of an experimental study indicate that the pressure in the mixing chamber of the internal mixing type nozzle is not equal to the product of atomization-media inlet pressure and the critical pressure ratio, but has been closely related to the