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大流量标准Y型喷嘴内部流动特性的数值模拟

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摘 要:采用计算流体动力学方法对大流量标准Y型喷嘴内部的流动特性进行了数值模拟,通过计算获得了喷嘴内部的流动特性,并研究了气耗率变化对喷嘴出口流动状态的影响。结果表明:当气耗率较小时,喷嘴出口表现出环状流特征;当气耗率较大时,出现类雾状流特征;进一步增大气耗率对气液掺混效果改善作用有限。数值计算获得的流量数据与试验结果吻合较好,液流量相对误差小于5%,气流量相对误差小于10%。

关 键 词:标准Y型喷嘴;气耗率;流动特性;两相流;数值模拟
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引 言

标准Y型喷嘴又称中间混合式喷嘴,由油孔、气孔和混合孔组成,具有燃油供给量大、调节比大、雾化质量好、雾化耗气量低和雾化锥角不变等优点[1],在各种工业窑炉和燃油电站锅炉上被广泛使用[1-3]。对于燃油燃烧器而言,喷嘴雾化质量的好坏是影响燃烧质量高低的关键因素。随着工业技术的发展,锅炉设备参数不断提高,燃油喷嘴逐步向高压力、大流量、小粒径方向发展。目前已有不少学者开展了标准Y型喷嘴的冷态雾化特性的试验研究[3-11],但是标准Y型喷嘴结构紧凑,通过试验方法获得混合孔内流动参数的难度较大。在Y型喷嘴早期开发过程中,文献[3]通过试验观察到喷嘴混合孔内的气液两相流为典型的环状流。以此为基础,文献[7]通过数值模拟方法,在不考虑气体压缩性的条件下研究了低压小流量Y型喷嘴混合段的流场结构。对于高压、大流量的标准Y型喷嘴,气体的压缩性不容忽略,混合孔内的气液掺混和两相流动过程更加复杂。

本研究采用计算流体动力学方法对大流量标准Y型喷嘴内部的流动特性进行数值模拟,获得了较准确的流量数据,分析了喷嘴内部的流动状态和气液掺混效果,并与实验结果进行了对比,为进一步提高标准Y型喷嘴的性能提供了依据。

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1 计算模型

大流量标准Y型喷嘴模型如图1所示。模拟介质为压缩空气和水,并假设压缩空气为理想气体。湍流模型采用RNG$k-\varepsilon$模型,气相和液相入口设置为压力入口边界条件,并与试验条件保持一致。

图1 网格模型
Fig. 1 Grid model

由于高压大流量喷嘴内部流动过程复杂,采用欧拉模型模拟喷嘴内部气液两相流动,其质量和动量控制方程为:

$$\frac{\partial}{\partial t}(\alpha_q\rho_q)+\nabla\cdot(\alpha_q\rho_q\vec{v}_q)=\sum_{p=1}^{n}(\dot{m}_{pq}-\dot{m}_{qp})$$

$$\frac{\partial}{\partial t}(\alpha_q\rho_q\vec{v}_q)+\nabla\cdot(\alpha_q\rho_q\vec{v}_q\vec{v}_q)=-\alpha_q\nabla p+\nabla\cdot\bar{\bar{\tau}}_q+\alpha_q\rho_q\vec{g}+\sum_{p=1}^{n}(\vec{R}_{pq}+\dot{m}_{pq}\vec{v}_{pq}-\dot{m}_{qp}\vec{v}_{qp})+\vec{F}_q+\vec{F}_{\mathrm{lift},q}+\vec{F}_{\mathrm{vm},q}$$

式中: $\vec{v}_q$ —相 q 速度，m/s; $\dot{m}_{pq}$ —相间质量流量，kg/s; $\bar{\bar{\tau}}_q$ —相 q 应力－应变张量，Pa; $\vec{F}_q$ —外部体积力，N; $\vec{F}_{lift,q}$ —升力，N; $\vec{F}_{vm,q}$ —有效质量力，N; $\vec{R}_{pq}$ —相间相互作用力，N; p —相所受压力，Pa; $\vec{v}_{qp}$ —相交界面分离速度，m/s。

2　模拟结果分析

2.1　流量特性

以水和压缩空气作为试验介质进行标准 Y 型喷嘴流量特性试验，其试验系统如图 2 所示。系统主要包括喷嘴试验件及工装、气液供应管路、气储箱、水储箱、压力测量装置、流量测量装置、气液路阀门，防返雾装置及高速动态摄影系统。通过试验，可以得到标准 Y 型喷嘴流量、压力、雾化锥角、粒径等流动和雾化特性。

喷嘴在不同工况下的流量试验值与计算值对比如表 1 所示，从表 1 可以看出，数值计算结果与试验值吻合良好，液流量计算值的相对误差普遍小于 5%，气流量计算值的相对误差基本在 10% 以内。数值计算可以较准确地预测高压大流量标准 Y 型喷嘴的流量特性。

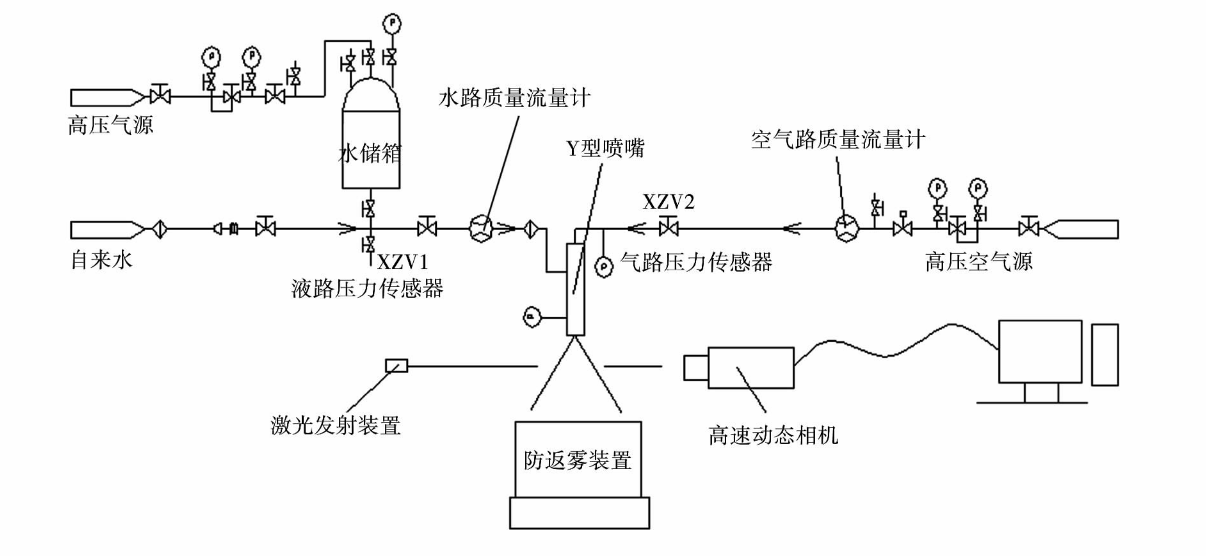


图 2　喷嘴水试试验系统图

Fig. 2 Diagram of a nozzle hydraulic test system

表 1　流量的试验值与计算值比较

Tab. 1 Comparison between the experimental values and calculation ones of the flow rate

工况	水压 /MPa	气压 /MPa	液流量/g·s⁻¹ 试验值	液流量 计算值	液流量 相对误差	气流量/g·s⁻¹ 试验值	气流量 计算值	气流量 相对误差
1	0.27	0.29	32.7	33.7	3.0%	5.0	5.5	10.0%
2	0.24	0.21	39.3	37.4	-4.8%	2.8	2.6	-7.1%
3	0.50	0.50	51.0	51.9	1.7%	8.4	9.1	8.3%
4	0.63	0.46	81.0	78.5	-3.1%	5.5	5.2	-5.4%
5	1.14	1.08	88.4	88.7	0.3%	17.3	20.0	15.6%
6	0.87	0.64	95.8	93.1	-2.8%	8.0	8.0	0
7	1.42	1.07	120.3	119.2	-0.9%	15.3	15.3	0

2.2　喷嘴内部的流场分布

喷嘴在大流量条件下的内部流动状态如图 3 所示，喷嘴气相入口压力 1.07 MPa，液相入口压力 1.42 MPa，供应压力与工况 7 保持一致。从图 3(a) 可以看出，喷嘴内部气液混合点的压力变化比较剧烈。在油孔出口上游，液流刚性较强，从气孔喷出的高速气流与液流撞击之后形成局部高压; 在油孔出口下游，气流受到液束的阻滞作用导致其局部压力较低。如图 3(b) 所示，气液的激烈撞击增强了两相掺混效果，在混合孔下游，液相体积分数迅速降低，液流没有直接撞击混合孔壁面。如图 3(c) 所示，在混合孔出口位置，壁面附近看不到明显的液膜存在，液流中空气体积分数超过 60%，在液流和壁面之间存在一个空气体积分数较高的“气垫”。喷嘴混合

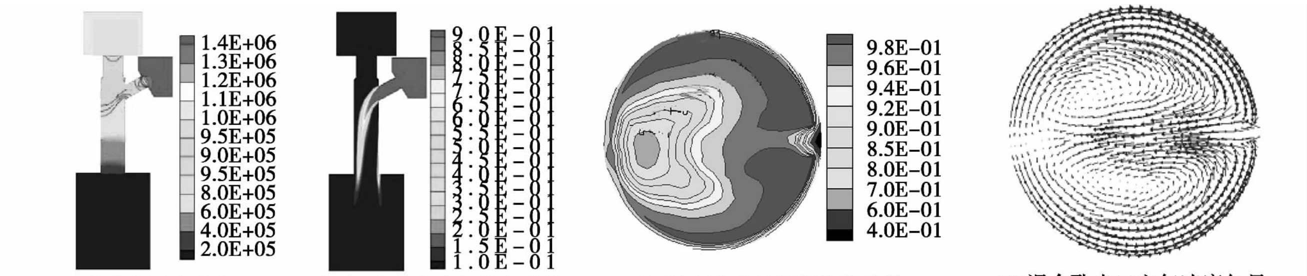
孔出口截面上空气速度矢量的分布情况如图 3(d) 所示，在液流后方存在两个明显的对称涡。在混合孔出口附近，气相和液相主要通过气流卷吸作用进行掺混，且气流卷吸的液滴在油孔下方的壁面附近聚集形成一小股液束，如图 3(b) 和图 3(c) 所示。

仿真计算结果表明，大流量标准 Y 型喷嘴混合孔内壁没有明显的环状液膜，喷嘴出口位置呈现类雾状流特征。在混合孔入口，由于气相较强的可压缩性，气、液相在混合点强烈撞击使该点压力变化剧烈；受液流的扰动，气相在混合孔出口截面附近形成两股对称性回流。

2.3 气耗率对流动特性的影响

计算时保持油孔流量不变，通过改变气孔流量获得不同气耗率下的流动特性。

图 4 所示为气相和液相入口压力随气耗率的变化趋势。随着气耗率增加，气流量增大，气相入口压力相应提高，导致混合点压力升高，在液流量保持不变的情况下，液相入口压力随之增大。



(a) 喷嘴内压力分布 (：Pa) （b）喷嘴内液相体积分数 (c) 混合孔出口气相体积分数 (d) 混合孔出口空气速度矢量

图 3 喷嘴内部的流场分布云图

Fig. 3 Atlas showing the distribution of the flow field inside the nozzle

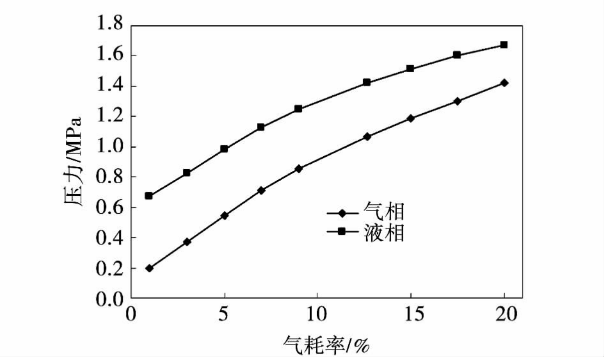


图 4 喷嘴入口压力随气耗率的变化

Fig. 4 Changes of the pressure at the inlet of the nozzle with the air consumption rate

图 5 所示为喷嘴混合孔出口位置流体速度随气耗率的变化趋势。从图 5 中可以看出，在混合孔出口，当气耗率较低时，气液相流速低，两相速度差较小；随着气耗率增大，气、液相的出口流速增大，两相的速度差也随之增加；当气耗率增大到一定程度之后，随着气耗率增大，气液相速度变化趋于平缓，两相的速度差趋于稳定。

在喷嘴出口位置，不同气耗率对应的空气体积分数分布如图 6 所示。从图 6 中可以看出，当气耗率较低时，气流量小，气体流速低，液流进入混合孔后撞击壁面形成液膜，受雾化空气的卷吸作用，液流在喷嘴出口位置形成均匀的环状液膜；随着气耗率增加，气流量增大，气体流速升高，液膜厚度减薄；当气耗率增大到一定程度之后，液膜几乎消失，在混合孔内形成一股气液掺混的类雾状流动；随着气耗率的进一步增大，雾状液束与壁面之间的“气垫”增厚，其气液掺混区域无明显变化，气耗率的增加对气液掺混效果的改善作用不再明显。

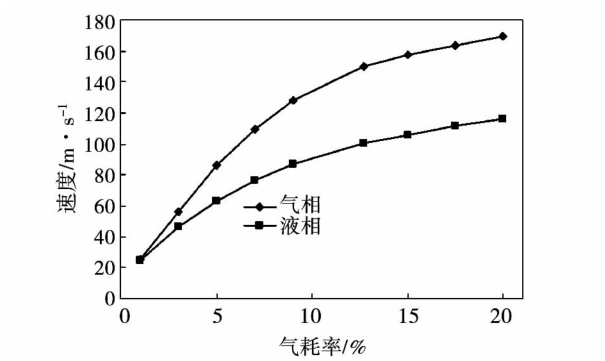


图 5 喷嘴出口速度随气耗率的变化

Fig. 5 Changes of the velocity at the outlet of the nozzle with the air consumption rate

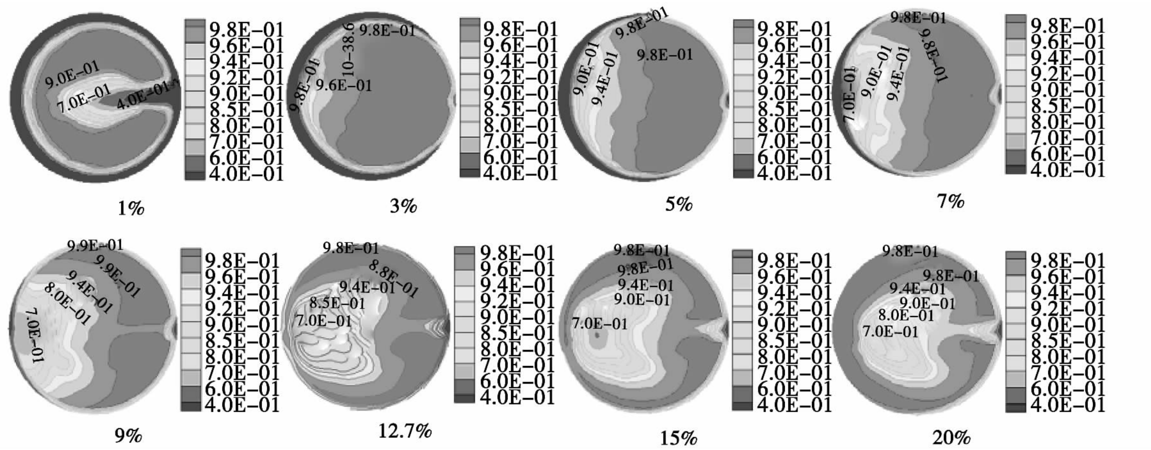


图 6　不同气耗率下的空气体积分数分布

Fig. 6 Distribution of the air volumetric fraction at various air consumption rates

分析喷嘴出口位置的空气体积分数发现，由于标准 Y 型喷嘴结构不对称，喷嘴出口位置的最大质量通量分布偏离喷孔中心位置，这与流量试验观测到的现象吻合，也与文献[6]的试验结果一致。

3 结　论

通过对大流量 Y 型喷嘴内部流动特性的数值仿真研究，获得了喷嘴内部的流动特性，得出结论：

(1) 模拟计算的流量数据和试验结果吻合良好，液流量相对误差小于 5%，气流量相对误差在 10% 以内。

(2) 模拟获得了大流量标准 Y 型喷嘴内的流动特征。在混合孔入口，气、液相混合点压力变化剧烈；受液流的扰动，气相在喷嘴出口截面附近形成两股对称性回流。

(3) 气耗率对喷嘴内部流动状态影响较大。当气耗率较小时，喷嘴出口表现出环状流特征；当气耗率较大时，环状液膜消失，喷嘴表现出雾状流特征。喷嘴出口形成类雾状流之后，气耗率进一步增大对气液掺混效果的改善作用不明显。

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heating value coal gases are all 660 ℃. The flame is stable and cannot be blown off. However, the prototype burner can only burn the low heating value coal gases with their heating values being greater than 16.31 MJ/Nm^3 and the preheating temperature being 660 ℃. Furthermore, the flame is unstable and serious flame-out phenomena occur at the root of the flame. **Key Words:** burner, high temperature low heating value coal gas, preheating temperature, flame characteristics

水力旋流器分离石膏浆液的试验研究 = Experimental Study of a Hydrocyclone in Separating Gypsum Slurry［刊，汉］ ZHANG Xian-chen, WANG Hai-quan, LU Xiao-feng (National Key Laboratory on Low Grade Energy Source Utilization Technology and Systems, Chongqing University, Chongqing, China, Post Code: 400030), ZHENG Xian-guo (Hangzhou Yunzhong Electric Power Science and Technology Co. Ltd., Hangzhou, China, Post Code: 310000) //Journal of Engineering for Thermal Energy & Power. -2014, 29(6). -682-687

In the light of such problems as the underflow concentration being excessively low in engineering applications of gypsum hydrocyclones and the classification precision being poor, from the angle of optimizing the flow division ratio, separation efficiency, underflow concentration and classification precision, explored were the methods for enhancing the separation performance of a gypsum hydrocyclone. Through an experimental study, the law governing the influence of the structural parameters, operation parameters and physical parameters of the hydrocyclone on its separation performance was identified. It has been found that under the precondition of guaranteeing the underflow concentration being not lower than 50%, when the concentration at the inlet is 16%, the underflow tube diameter at which optimum separation performance can be obtained is 23 mm and at such a time, the flow division ratio is not less than 0.16 and the classification precision is the highest. **Key Words:** hydrocyclone, gypsum slurry, classification precision, separation performance

大流量标准 Y 型喷嘴内部流动特性的数值模拟 = Numerical Simulation of the Flow Characteristics Inside a Large Flow Rate Y Type Nozzle［刊，汉］ CHEN Peng-fei, FEI Jun, LI Long-fei, YANG Wei-dong (Xi'an Spaceflight Power Research Institute, Xi'an, China, Post Code: 710100) //Journal of Engineering for Thermal Energy & Power. -2014, 29(6). -688-692

By using the methods proposed in the CFD, numerically simulated were the flow characteristics inside a large flow rate standard Y type nozzle, emulated and calculated were the flow characteristics inside the nozzle and studied was the influence of the change in the air consumption rate on the flow state at the outlet of the nozzle. The calculation results show that when the air consumption rate is relatively small, the flow at the outlet of the nozzle displays the annular flow characteristics. When the air consumption rate is relatively big, the flow at the outlet of the nozzle exhibits the quasi-dispersed flow characteristics. The role of further increasing the air consumption rate played in improving the gas-liquid dilution-mixing effectiveness is limited. The data of the flow rate obtained during the numerical calculation is in relatively good agreement with the test data. The relative error of the liquid flow rate is less than 5% and that of the gas flow rate is less than 10%. **Key Words:** standard Y type nozzle, air consumption rate, flow characteristics, two-phase flow, numerical simulation

浮点型涡流发生器 $CaSO_4$ 析晶污垢沉积的模拟研究 = Simulation Study of the $CaSO_4$ Crystallization Foul Deposition in a Floating Point Type Vortex Generator [刊,汉] ZHANG Yi-long, LIU Zuo-dong (College of Energy Source, Power and Mechanical Engineering, North China University of Electric Power, Beijing, China, Post Code: 102206), XU Zhi-ming (College of Energy Source and Power Engineering, Northeast University of Electric Power, Jilin, China, Post Code: 132012) //Journal of Engineering for Thermal Energy & Power. -2014, 29(6). -693-697

By using the model for crystallization fouls, numerically simulated was the deposition of foul in a rectangular channel equipped with a floating point type vortex generator. It has been found that the amount of foul deposited in a unit area will decrease with an increase of the floating point dimensions and increase with an increase of the spacing between the floating points arranged. However, when the radius of the floating point is definite and the spacing between the floating points is less than two times of the diameter of the floating point, to decrease the spacing cannot decrease the amount of foul deposited. A comparison of the simulation results with the relevant test results verifies that the model adopted is correct. **Key Words:** vortex generator, crystallized foul, CaSO4, numerical simulation

超临界直流锅炉变工况实时运行中间点温度控制研究 = Study of the Real Time Operation Intermediate Point Temperature Control of a Supercritical Once-through Boiler Under the Off-design Operating Conditions [刊,汉] YUAN Shu-juan, MA Li-xin, DAI Shu-guang (College of Photoelectric Information and Computer Engineering, Shanghai University of Science and Technology, Shanghai, China, Post Code: 200093), YUAN Shu-juan (College of Electrical Engineering, Shanghai College of Electric Power, Shanghai, China, Post Code: 200092) //Journal of Engineering for Thermal Energy & Power. -2014, 29(6). -698-702

To set up a dynamic load response system for power generation equipment items is regarded as an effective method for enhancing the power source control efficiency. The output power of a thermal power generation unit depends on the feedwater and fuel quantity fed into its boilers. With a supercritical once through boiler serving as the object of study, the authors analyzed the relationship of the feedwater and fuel quantity with the intermediate point temperature of the boilers and on this basis, established a nonlinear discrete model for intermediate temperatures and de-