文章编号: 1001－2060(2009)01－0105－04

OWC 波能装置冲击式透平的计算流体力学分析

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摘　要: 近年来, 配有固定导流叶片的冲击式透平在 OWC 式波能发电装置的应用中受到广泛重视。利用 Fluent 软件对这种透平进行三维数值模拟, 考察了外径间隙和轮毂比对透平工作性能的影响; 研究了动叶片表面的压力分布和空气流动情况。计算结果与试验数据较为符合, 为透平的设计提供了参考值, 该数值方法可以成为深入研究波能发电装置冲击式透平的有效手段。

关　键　词: OWC; 波能发电; 冲击式透平; 计算流体力学
中图分类号: TK472; O35　　文献标识码: A

引　言

振荡水柱(Oscillating Water Column, 简称 OWC)式波能发电系统是一种气动式海洋波能转换装置, 由于它安全性好、可靠性高, 在近年来受到越来越多的重视。该装置的工作原理为: 波浪运动在气室中转换为振荡水柱的升沉运动, 进而带动气室中的空气做往复流动, 波浪能转换为空气流的动能, 气流带动电机的透平转动, 从而实现了波能发电。在 OWC 波能发电装置中, 冲击式(Impulse Turbine)透平, 相对于传统的威尔斯式(Wells Turbine)透平, 具有峰值效率高、启动性能好、适于变工况条件运行等特点, 因而得到广泛关注。

为了对比威尔斯透平和冲击式透平的工作性能。Setoguchi、梁贤光和 Thakker 等人均通过试验方法进行了研究[1~3], 其结果表明, 威尔斯透平的最高效率高于冲击式透平, 但是工作范围较小, 很快就会出现失速现象, 而冲击式则几乎不会出现失速现象。具有双向固定导流叶片(Fixed Guide Vane)的冲击式透平的最高效率与双向自调节式(Self-pitching Controlled)相比较低, 在大流量系数范围内仍有较高效率, 其工作性能介于威尔斯式透平和双向自调节导叶透平之间。随着计算流体力学和计算机的高速发展, 数值模拟技术已被广泛的应用于各种空气透平的流体力学分析及相关参数设计。Thakker 对具有导流叶片的冲击式透平进行了二维多叶片模型的数值模拟计算[4], 结果与试验数据较为吻合, 但由于二维的分析不能精确预测系统的能量损失, 因此应该采用三维模型进行分析以克服二维计算的限制。

本研究采用商业软件 Fluent, 在试验结果验证的基础上, 运用三维数值模拟技术, 考察了外径间隙 T(Tip Clearance)和轮毂比 H(Hub-to-tip Ratio)对具有固定式导流叶片的冲击式透平工作性能的影响, 并研究了透平动叶片上的压力及迹线分布情况, 以便了解透平的空气动力学性能, 可以弥补试验研究的不足。

1　装配固定导流叶片的冲击式透平

装配有固定导流叶片的冲击式透平虽然工作性能稍差于双向自调节式的冲击式透平, 但自调节式透平的结构复杂, 零部件多, 加工精度要求高, 因此固定式导流叶片是目前应用最多的。

根据前人试验结果所得出的部分透平的最佳尺寸, 给出了其设计尺寸, 如图 1 所示。其中: l_g 为导流叶片弦长; S_r 为动叶片间距; S_g 为导流叶片间距; G 为动叶片与导流叶片间距; l_r 为动叶片弦长。

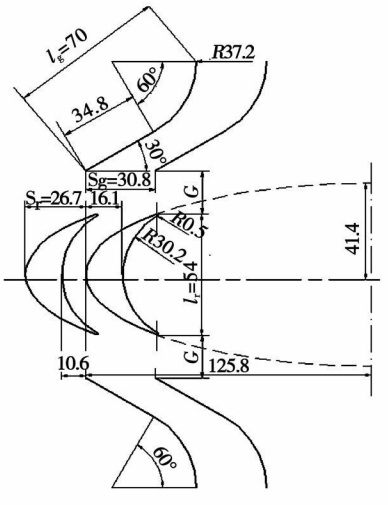

图 1　配有导流叶片冲击式透平的设计尺寸(mm)

收稿日期: 2008－02－02;　修订日期: 2008－02－19
基金项目: 国家自然科学基金资助项目(40876047)
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振荡水柱波能发电装置冲击式透平的整体工作性能参数主要有透平角速度 ω、透平输出扭矩 T、空气流量 Q，以及透平压降，即气流通过透平后的压强损失 Δp 共同决定的。透平性能可通过输入系数(Input Coefficient) C_A、扭矩系数(Torque Coefficient) C_T、透平效率(Turbine Coefficient) η 及流量系数(Flow Coefficient) ϕ 等表示，其定义为：

$$C_A = \Delta pQ / [\frac{1}{2}\rho(v_a^2 + U_R^2) bl_z v_a] \quad (1)$$

$$C_T = T / [\frac{1}{2}\rho(v_a^2 + U_R^2) bl_z r_R] \quad (2)$$

$$\phi = v_a / U_R \quad (3)$$

$$\eta = T\omega / \Delta pQ = C_T / C_A \phi \quad (4)$$

式中：v_a—轴向流速；U_R—圆周速度；b—动叶片高度；z—叶片数，r_R—中跨半径。

2 数值计算方法

三维数值模拟采用的基本控制方程为不可压缩流体的连续方程和雷诺时均的 Navier-Stokes 方程，并利用重整化群 RNG (Renormalization Group)湍流模型使方程组封闭。

采用有限体积法对控制方程进行空间离散，二阶全隐式格式进行时间离散；对控制方程中的源项和扩散项应用二阶中心格式，对控制方程中的对流项应用二阶迎风格式，速度压力耦合使用的是 SIMPLEC 算法。

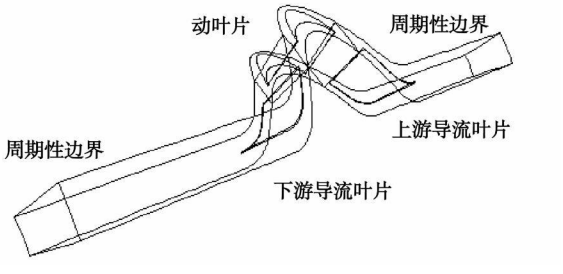

图 2 三维流动计算区域

由于透平中的流场结构具有周期性和对称性，因此计算区域选取一组动叶片和导流叶片，并分为 3 部分：动叶片区、上游导流叶片区和下游导流叶片区，如图 2 所示。其中动叶片区为转动区域，上下游导流叶片区固定不动，在计算区域边壁采用周期性边界条件。上下底面及整个动叶片(包括叶片顶端部分)均采用固壁边界条件，上游导流叶片的入口处采用速度入口条件，下游导流叶片的出口处采用压力出口条件。计算域分别向上下游延伸至 5 倍导流叶片长度处，以保证流动的充分发展，并使用多重运动参考系 MRF 模型(Multiple Reference Frame)处理动叶片的旋转问题。在壁面处采用无滑移边界条件，临近固壁的区域采用壁面函数。

如图 3 所示，计算网格采用 Cooper 型网格，利用 Gambit2.2 软件生成，整体网格数量约为(2.0 ~ 2.5) × 10^5。由于动叶片区的空气流动及叶片的受力状况将决定计算质量的好坏，因此在计算中对该区域的网格进行了加密，数量控制在 1.0× 10^5 左右，其中外径间隙区域的网格数约为 1.0× 10^4，上下游导流叶片区的网格数均为(5.0 ~ 6.0)× 10^4。

图 3 计算网格示意图

3 计算结果与讨论

计算的透平外径为 150 mm，动叶片和上下游导流叶片的个数均为 30，轮毂比为 0.7。为了验证数值模拟的计算结果，首先考察了流量系数为 $\phi = 1$ 条件下，不同径间比条件下透平的峰值效率。

图 4 给出了不同径间比(G/l_r)条件下透平峰值效率的计算和试验结果，较为吻合。由于数值模拟不能处理系统中全部的能量损失(如机械摩擦等)，因此数值计算结果在各个工况下均应比试验值稍大，这与本研究预测结果也相同，表明三维数值模拟方法能够有效的预测描述波能发电装置冲击式透平的工作性能。

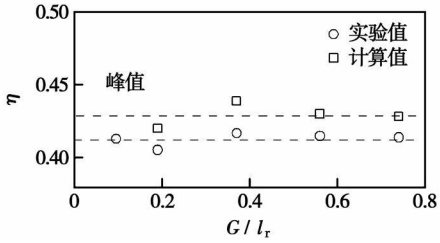

图 4 不同径间比下透平的峰值效率

计算的外径间隙分别为 0、0.5、1、3 和 5 mm，即 T = 0%、0.16%、0.34%、1.02%和 1.72%的透平形式，以考察其对冲击式透平的工作性能的影响。

图 5 给出了流量系数为 $\phi = 1$ 条件下的动叶片

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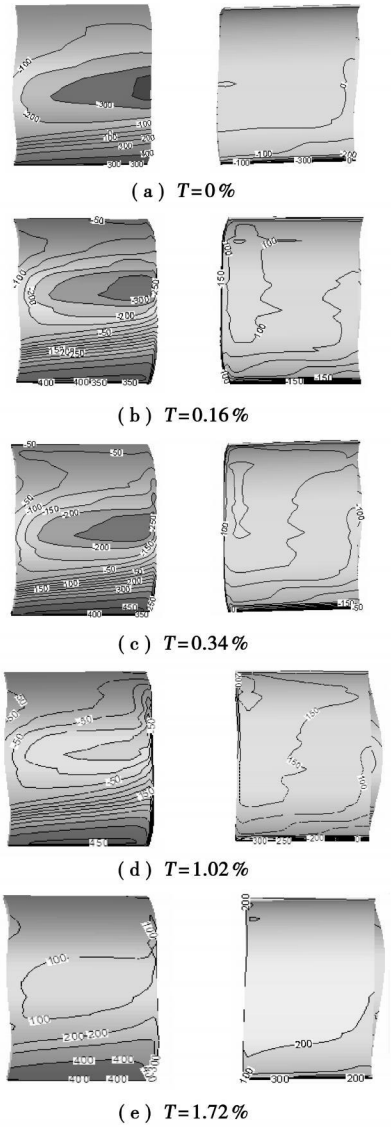
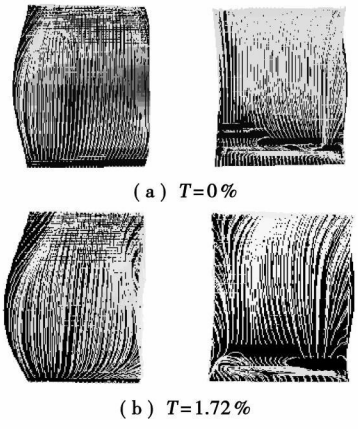
叶面的压力分布, 其中左侧为吸力面, 右侧为压力面, 气流方向为自下而上。由图中可以看出, 当外径间隙较小(即 $T\leqslant 0.34\%$)时, 在动叶片两侧的压力分布情况较为相似; 而当外径间隙达到 1.02%后, 压力分布的变化较大, 并且随着间隙的增大, 两侧的压力差会减小。



(a) T=0%　(b) T=0.16%　(c) T=0.34%　(d) T=1.02%　(e) T=1.72%

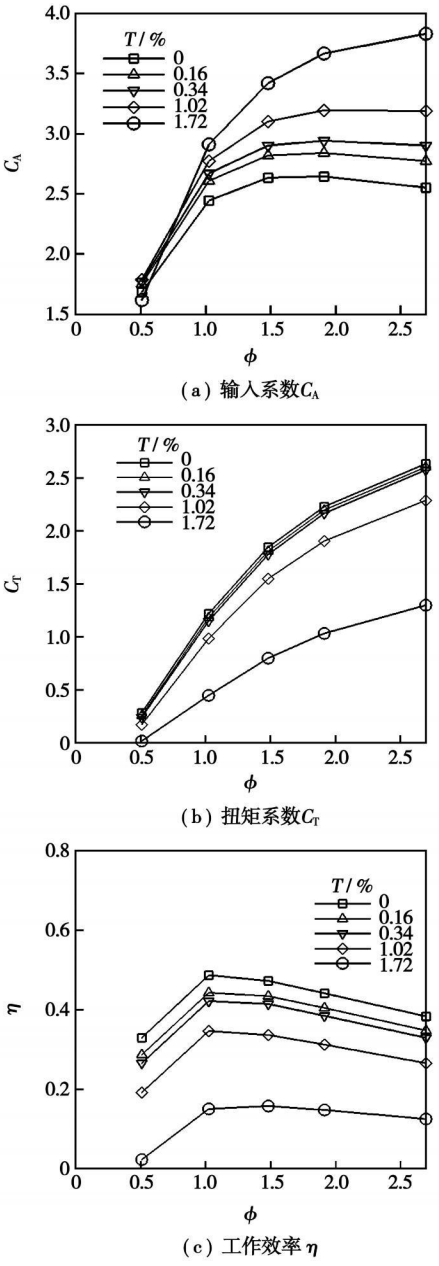
图 5　不同外径间隙下动叶片压力分布(Pa)

在上述计算条件下, 不同外径间隙下动叶片表面的迹线分布如图 6 所示, 左侧为吸力面, 右侧为压力面, 气流方向为自下而上。当 T=0%时, 在压力面的上游一侧, 由于叶片自身形状的原因, 会在边缘处产生少量的回流。当 T 增大时, 如图 6(b)所示, 在叶片压力面的顶部可以明显地看到部分气流越过顶面到达吸力面, 产生涡卷起现象。随着外径间隙的增大, 该现象会造成透平工作的能量和效率的损失。



(a) T=0%　(b) T=1.72%

图 6　不同外径间隙下动叶片表面迹线



(a) 输入系数C_A　(b) 扭矩系数C_T　(c) 工作效率η

图 7　不同外径间隙下透平的工作性能

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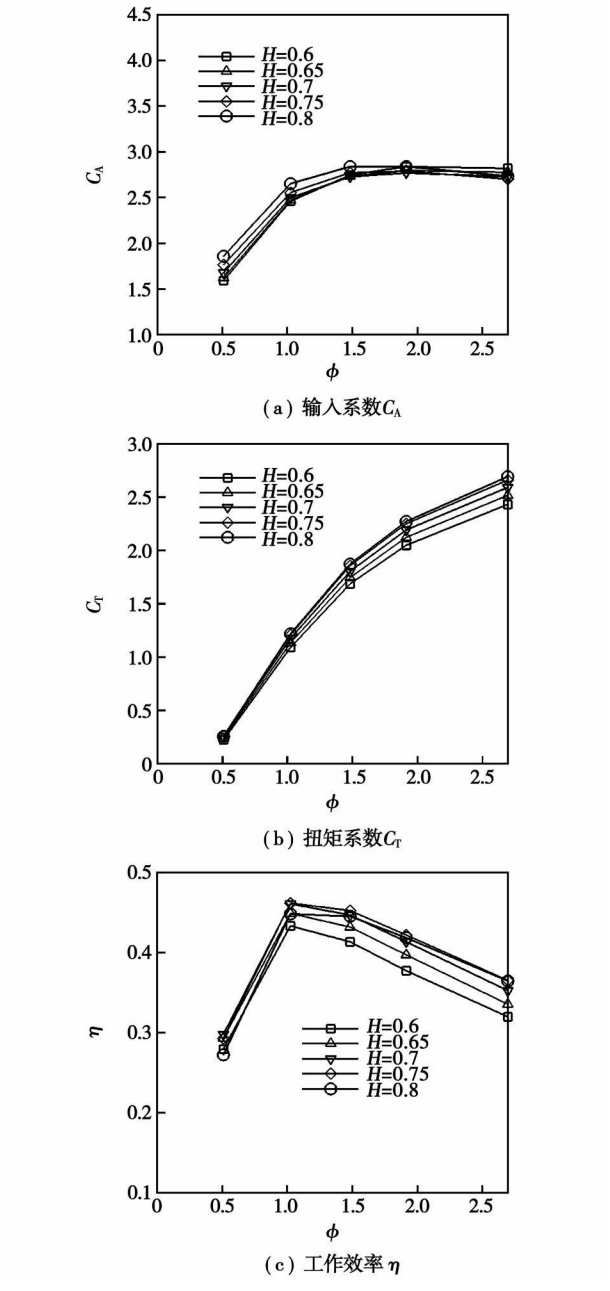
图7 给出了不同外径间隙条件下透平的工作性能。其中输入系数 C_A 除了在 $\phi=0.5$ 时之外，均会随 T 的增大而增大。当 $T\leqslant 0.34\%$ 时，扭矩系数 C_T 在各流量条件下差别不大，这与前述的动叶片表面的压力分布分析也基本一致。从总体而言，扭矩系数会随 T 的增大而减小。而透平的工作效率也会随着外径间隙的减小而增大，这与前述的能量损失的迹线图分析相一致。在实际应用中，但由于外径间隙为0或0.5 mm的透平结构复杂、制造困难，外径间隙为1 mm时较为合适。



(a) 输入系数C_A

(b) 扭矩系数C_T

(c) 工作效率η

图 8 不同轮毂比下透平的工作性能

当外径间隙确定后，考虑轮毂比对冲击式透平工作性能的影响，如图8所示。图中(a)表明轮毂比在不同的流量系数条件对输入系数的影响不大，而扭矩系数会随着轮毂比的增大而增大，如图中(b)所示，但当 $H>0.7$ 后，增幅便不明显；如图(c)所示，当流量系数大于0.5后，若要取得较高的透平工作效率，轮毂比不宜过小，考虑到透平的造价问题，则选取 $H=0.7$ 较为合适。

4 结 论

利用Fluent商业软件实现了对应用于振荡水柱式波能装置中的配有固定导流叶片的冲击式透平的三维数值模拟。

数值模拟的结果与试验数据较为符合，表明采用的计算方法是合理的。考察了外径间隙和轮毂比对于透平工作性能的影响，研究了动叶片表面的压力分布情况，发现了大外径间隙下的气流越顶及涡卷起现象。通过以上研究可知，综合考虑制造工艺、造价及透平工作效率，外径间隙宜取1 mm左右，而轮毂比则建议取为 $H=0.7$。

在此数值模拟研究的基础上，可以对冲击式透平的工作性能及空气流场的分布变化进行广泛而深入的考察，是对试验考察的有益补充，从而为更好的研究和利用冲击式透平服务于海洋波能转化利用提供更多的指导和帮助。

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利用威布尔分布模型对球磨机可靠性分析 = **Reliability Analysis of a Ball Mill by Using a Weibull Distribution Model**[刊,汉]/ ZHOU Ying-biao, FAN Du-ping (National Key Laboratory on Coal Combustion, Huazhong University of Science and Technology, Wuhan, China, Post Code: 430074), DUAN Quan-peng (Power Generation Engineering Subcompany, Central South Electric Power Design Institute, Wuhan, China, Post Code: 430071)// Journal of Engineering for Thermal Energy & Power. - 2009,24(1). - 95 ~ 99

Described were a Weibull distribution model and its merits. Fault data of B ball mill in a thermal power plant were classified and sorted out. When calculating by using a two-parameter Weibull model and three-parameter one, software Matlab and a correlative coefficient optimization method were used respectively to effect a fitting. The results calculated from the above data were compared and analyzed. The three-parameter Weibull distribution model is very similar to the two-parameter one. As the three-parameter Weibull distribution model is more compatible with actual conditions due to the location parameters being taken into account, it was used in the actual analysis of a ball mill during its status inspection and maintenance. A concrete use of reliability analysis technology is to obtain a mean time between failures (MTBF) by using the mathematical expectation formula of the three-parameter Weibull distribution. A cyclic inspection period of eqdipment condition been obtained by employing the correlation between the detection period and MTBF. Also diagnosed was the fault type based on a failure rate function. **Key words**: ball mill, reliability analysis, Weibull distribution

生物质气微型燃气轮机燃烧室的数值模拟 = **Numerical Simulation Study of a Micro Gas Turbine Combustor Burning Gasified Biomass Fuel**[刊,汉]/ ZHANG Wei, WENG Yi-wu, LIU Ai-guo (Education Ministry Key Laboratory on Power Machinery and Engineering, Shanghai Jiaotong University, Shanghai, China, Post Code: 200240)// Journal of Engineering for Thermal Energy & Power. - 2009,24(1). - 100 ~ 104

When biomass gas is used in a micro gas turbine designed for burning natural gas, the temperature field, velocity field and combustion characteristics of the relevant combustor may be influenced by a relatively low heat value and different combustible constituents of the gas. The preliminary design of a 30 kW micro gas turbine combustor was performed, and on this basis, a numerical simulation comparison of the combustor when it burns methane and the biomass gas was conducted by using software Fluent. Moreover, investigated were the influence of burning the biomass gas on the inner flow and temperature distribution in the combustor as well as the NO_x emissions, and the causes of such an influence. The foregoing will provide useful data for the future design of micro gas turbine combustors burning the biomass gas. **Key words**: biomass gas, micro gas turbine, combustor, numerical simulation

OWC 波能装置冲击式透平的计算流体力学分析 = **CFD (Computational Fluid Dynamics) Analysis of an Impulse Turbine in an OWC (Ocean Wave Converter) Wave Energy Device**[刊,汉]/ LIU Zhen, SHI Hong-da (Oceanological Engineering Department of Engineering College, Ocean University of China, Qingdao, China, Post Code: 266100), XIONG Cong-bo (National Bureau of Oceanography No. 1 Research Institute, Qingdao, China, Post Code: 266061) // Journal of Engineering for Thermal Energy & Power. - 2009,24(1). - 105 ~ 108

In recent years, impulse type turbines provided with fixed guide blades have received widespread attention when used in OWC (Ocean Wave Converter) type wave-energy power-generation plants. A three-dimensional numerical simulation has been performed of this kind of turbines by using software Fluent, and the influence of the ratio between the outer-diameter clearance and the hub on the operation performance of the turbines, investigated. In addition, the pressure distribution and air-flow conditions on the surface of rotating blades were also studied. The calculation results are in relatively good agreement with test data, thus providing a valuable reference for the turbine design. The numerical simulation method in question can become an effective means for an in-depth study of the impulse type turbines for use in wave-energy power gener-

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ation plants. **Key words**: OWC (Ocean Wave Converter), wave energy power generation, impulse type turbine, computational fluid dynamics

液幕式脱硫吸收塔中气液传质特性的实验研究 = **Experimental Study of Gas-liquid Mass Transfer Characteristics of a Liquid-curtain Type Desulfuration Absorption Tower**[刊,汉]/ LI Na, ZHOU Qu-lan, XU Tong-mo, et al (National Key Laboratory on Multiple-phase Flows in Power Engineering, Xi'an Jiaotong University, Xi'an, China, Post Code: 710049)// Journal of Engineering for Thermal Energy & Power. - 2009, 24(1). - 109 ~ 112

An experimental study has been performed of the desulfuration performance of a liquid-curtain type absorption tower, during which the influence of such parameters as flue-gas flow rate, circulating slurry quantity and pH value etc. on its desulfuration performance was studied. When the structure and operating parameters of the tower are properly chosen, the desulfuration efficiency can reach 95%. The authors have presented a method for calculating the mass transfer area of the tower and established for it a mass transfer model. It has been found that the mass transfer coefficient of the tower does not vary significantly when pH value is in a range from 5 to 10. In addition, an empirical correlation formula of the mass transfer coefficient of the tower concerning gas phase and liquid phase Reynolds Number has been obtained. **Key words**: liquid-curtain type absorption tower, desulfuration efficiency, mass transfer coefficient, equivalent mass-transfer area

喷氨格栅处烟气速度场对高效 SCR 均流与还原剂混合性能的影响 = **Influence of the Flue Gas Velocity Field at an Ammonia-injection Grid on Uniform Flows and Reducing-agent Mixing Performance of a High-efficiency SCR (Selective Catalytic Reduction) Device**[刊,汉]/ LEI Da, JIN Bao-sheng (College of Energy Source and Environment, Southeast University, Nanjing, China, Post Code: 210096)// Journal of Engineering for Thermal Energy & Power. - 2009, 24(1). - 113 ~ 119

With an ever increasing SCR (Selective Catalytic Reduction) system denitration efficiency, the flue gas velocity field at an ammonia-injection grid (AIG) becomes ever more important in SCR system uniform flow and mixing technology. With the SCR system in a high efficiency power plant serving as an object of study, analyzed was the influence of ten typical changes of the flue gas velocity field at the AIG on the uniform flow and reducing agent mixing performance in the SCR system of the power plant by using a SCR system numerical model which has been verified by a cold state model. It has been found that for the SCR system with a high denitration efficiency, any changes to the velocity field at the AIG exercise a great influence on the distribution of ammonia-nitrogen ratio at the interface of a catalyzer inlet and also a definite influence on the velocity field at the inlet interface. In a design process, the control of the inhomogeneity of the flow speed at the AIG can enhance the quality of the uniform flow and mixing in the SCR system. In a high-efficiency SCR system in which a relatively good control over the inhomogeneity of the flow speed at the AIG has been achieved, with an increase of the inhomogeneity, the nonuniformity of the ammonia-nitrogen ratio at the catalyzer inlet will increase. The velocity field at the AIG and that of the catalyzer have a similarity. **Key words**: denitration, SCR (Selective Catalytic Reduction), uniform flow and mixture performance, ammonia-injection grid, flue gas velocity field

炉排-循环床复合垃圾焚烧炉污染物生成模型 = **A Model Featuring the Formation of Pollutants in a Grate-CFB (Circulating Fluidized Bed) Compound Solid Waste Incinerator**[刊,汉]/ ZHANG Yan-guo, LI Qing-hai, CHEN Chang-he, et al (Education Ministry Key Laboratory on Thermal Science and Power Engineering, Tsinghua University, Beijing, China, Post Code: 100084)// Journal of Engineering for Thermal Energy & Power. - 2009, 24(1). - 120 ~ 126

Established was a mathematical model for the combustion in a grate-CFB (Circulating Fluidized Bed) compound solid

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