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气体横掠单管强制对流换热的大涡模拟

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摘　要: 应用大涡模拟与二阶全展开 ETG 有限元离散格式相结合的方法对气体横掠单管强制对流换热进行了数值模拟, 分别计算了气体横掠圆管和方管时的温度场, 得到了管壁平均换热系数, 数值结果与实验关联式符合较好。同时还表明大涡模拟方法善于捕捉温度场以及流场涡系的时间演化过程, 非常适合于具有大尺度涡的绕流运动温度场的分析。

关　键　词: 横掠单管; 强制对流; 大涡模拟

中图分类号: TK124　　　文献标识码: A

1　引　言

近年来, 在计算流体力学领域内, 湍流的大涡模拟(LES)技术引起了广泛关注。在分辨大尺度涡系及跟踪其随时间演化过程方面, LES 具有显著优点, 因此被列入了湍流的高级数值模拟范筹[1~2]。LES 的基础是由 Richardson 所提出的湍流旋涡的级联衰变理论, 这一理论也为其它不同类型的湍流学说所接受[2]。LES 的与众不同之处在于: 认为在级联衰变过程中所形成的大尺度涡基本上是确定的, 其随机性质相当微弱; 而小尺度涡则基本上是随机的, 是构成随机脉动的源泉。基于这种设想, LES 通过空间滤波滤去小尺度涡, 并通过模化的亚格子应力来反映小尺度涡对大涡的平均影响以及湍动能的平衡, 从而把 Navier－Stokes 方程转化为能够比较准确地描述大尺度涡系非定常演化的确定型控制方程。由以上分析可见, LES 特别适用于流场中存在若干个组织得很好的大尺度涡, 而且这些大尺度涡对全局的动力状态起决定性作用。在工程实践中这类问题相当普遍, 例如各种类型的绕流运动, 内流中的局部障碍(弯头、三通及其它几何形状复杂的构件)处的流动等等。在这些流动中, 大尺度涡系不仅存在, 而且对于动量及热质交换起主要作用。LES 的优点及其广泛应用前景, 特别是在热能动力方面的应用前景, 是其获得不断发展的根本原因。与计算流体力学相比, 在计算传热、传质以及动力机械的流致振动等方面, LES 的研究工作还相当薄弱, 特别是在选择恰当计算格式与之配合以取得较高精度和运算效率方面, 存在大量问题有待探索。本文拟以具有丰富实验结果的气体横掠单管(圆管及方管)的强制对流换热为研究对象, 将 LES 与笔者等发展的二阶全展开 ETG 有限元方法[3~5]相结合进行数值模拟, 并与已有的实验结果对比, 分析这种模拟方法用于工程实际问题的可行性及优越性。

2　控制方程及数值方法

2.1　基本方程

大涡模拟的基本思想是运用空间滤波的方法将流动变量划分为大尺度量和小尺度量两部分。大尺度量可通过数值求解运动方程直接计算出来; 小尺度运动对大尺度运动的影响将在运动方程中表现为类似于雷诺应力的应力项, 称之为亚格子应力, 通过建立亚格子应力模型来对其进行模化。

大涡模拟中常用的滤波器主要有富式截断滤波器、盒式滤波器和高斯滤波器三种, 本文采用盒式滤波器进行空间滤波, 将任一瞬时的物理量 f 划分为两部分

$$f=\bar{f}+f' \tag{1}$$

其中: $\bar{f}$ 为大尺度部分; f' 为小尺度部分, 称为亚格子分量。大尺度部分用如下加权积分形式来表示

$$\bar{f}=\int_{\Omega} G(x-x',\Delta)f(x')\mathrm{d}\Omega \tag{2}$$

式中: Ω—— 计算域;

$G(x-x',\Delta)$—— 空间滤波因子, 取决于相对

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位置矢量 $x-x'$ 和网格尺寸 Δ。

盒式滤波器的滤波因子为

$$G(x-x')=\begin{cases}\prod_i \dfrac{1}{\Delta_i} & |x_i-x'_i|\leqslant \dfrac{\Delta_i}{2}\\ 0 & |x_i-x'_i|\geq \dfrac{\Delta_i}{2}\end{cases} \tag{3}$$

当不考虑热膨胀以及粘性耗散转化的热量时，对N－S方程组进行空间滤波，得到了大涡模拟的无因次基本方程

$$\frac{\partial \overline{u}_i}{\partial x_i}=0 \tag{4}$$

$$\frac{\partial \overline{u}_i}{\partial t}+\frac{\partial(\overline{u}_i\overline{u}_j)}{\partial x_j}=-\frac{\partial \overline{p}}{\partial x_i}+\frac{1}{Re}\frac{\partial^2 \overline{u}_i}{\partial x_j\partial x_j}-\frac{\partial \tau_{ij}}{\partial x_j} \tag{5}$$

$$\frac{\partial \overline{\theta}}{\partial t}+\frac{\partial(\overline{u}_j\overline{\theta})}{\partial x_j}=\frac{1}{Pr\cdot Re}\frac{\partial^2 \overline{\theta}}{\partial x_j\partial x_j}-\frac{\partial h_j}{\partial x_j} \tag{6}$$

其中：$\overline{\ \ }$ 代表经过空间滤波的变量；u_i 为速度；p 为压力；θ 为温度；Re 为雷诺数；Pr 为普朗特数；$\tau_{ij}=\overline{u_iu_j}-\overline{u}_i\overline{u}_j$ 为亚格子应力；$h_j=\overline{u_j\theta}-\overline{u}_j\overline{\theta}$ 为亚格子热流项，以上各量均进行了无因次化。

本文采用 Smagorinsky 涡粘模型[6] 来模化亚格子应力，在 Smagorinsky 涡粘模型中亚格子应力张量中的偏量部分为

$$\tau_{ij}=-2v_t\overline{S}_{ij} \tag{7}$$

式中：v_t 为涡粘系数，$\overline{S}_{ij}$ 为经过滤波后的速度变形张量

$$\overline{S}_{ij}=\frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j}+\frac{\partial \overline{u}_j}{\partial x_i}\right) \tag{8}$$

涡粘系数 v_t 的定义为

$$v_t=(C\Delta)^2|\overline{S}| \tag{9}$$

其中：C 为 Smagorinsky 常数，取决于滤波尺度 Δ，通常取值为 0.1－0.23；Δ 为滤波尺度，通常与网格间距有关；$|\overline{S}|=\sqrt{2\overline{S}_{ij}\overline{S}_{ij}}$。

亚格子热流项为

$$h_j=-\alpha_t\frac{\partial \overline{\theta}}{\partial x_j} \tag{10}$$

式中：$\alpha_t=\dfrac{v_t}{Pr_t}$，$Pr_t$ 通常取为 0.25－0.5。

2.2　数值方法

采用笔者等所发展的二阶全展开 ETG 有限元方法对方程进行离散，通过对 N－S 方程中的时变项进行 Taylor 展开，从而把时间导数用空间导数来代替，其作用相当于引入了人工粘性。采用二阶全展开 ETG 方法处理方程后整理得

$$\left(1-\frac{1}{2}\Delta t\frac{1}{Re}\frac{\partial^2}{\partial x_i\partial x_i}\right)\frac{(u^{n+1}-u^n)}{\Delta t}=\left(1-\frac{1}{2}\Delta t u_j^n\frac{\partial}{\partial x}\right)\left(-u_j^n\frac{\partial u_i^n}{\partial x_j}-\frac{\partial p^n}{\partial x_i}+\frac{1}{Re}\frac{\partial^2 u_i^n}{\partial x_j\partial x_j}\right)+\frac{1}{2}\Delta t\left(u_k^n\frac{\partial u_j^n}{\partial x_k}+\frac{\partial p^n}{\partial x_j}-\frac{1}{Re}\frac{\partial^2 u_j^n}{\partial x_k\partial x_k}\right)\frac{\partial u_i^n}{\partial x_j}-\frac{1}{2}\left(\frac{\partial p^n}{\partial x_i}-\frac{\partial p^{n-1}}{\partial x_i}\right)+o(\Delta t^2) \tag{11}$$

采用标准 Galerkin 方法，有限元积分表达式可化为

$$\int_{\Omega_e}\left(1-\frac{1}{2}\Delta t\frac{1}{Re}\frac{\partial^2}{\partial x_i\partial x_i}\right)\frac{(u^{n+1}-u^n)}{\Delta t}N_I\mathrm{d}\Omega=\int_{\Omega_e}\left(1-\frac{1}{2}\Delta t u_j^n\frac{\partial}{\partial x_j}\right)\left(-u_j^n\frac{\partial u_i^n}{\partial x_j}-\frac{\partial p^n}{\partial x_i}+\frac{1}{Re}\frac{\partial^2 u_i^n}{\partial x_j\partial x_j}\right)\times N_I\mathrm{d}\Omega+\int_{\Omega_e}\frac{1}{2}\Delta t\left(u_k^n\frac{\partial u_j^n}{\partial x_k}+\frac{\partial p^n}{\partial x_j}-\frac{1}{Re}\frac{\partial^2 u_j^n}{\partial x_k\partial x_k}\right)\frac{\partial u_i^n}{\partial x_j}\times N_I\mathrm{d}\Omega-\int_{\Omega_e}\frac{1}{2}\left(\frac{\partial p^n}{\partial x_i}-\frac{\partial p^{n-1}}{\partial x_i}\right)N_I\mathrm{d}\Omega \tag{12}$$

将

$$u=N_Ju_J^n \tag{13}$$

代入上式有

$$A_{IJ}u_J^{n+1}=(B_{IJ}u_J^u+C_{IJ}u_J^n+P_{IJ}+F_I)\Delta t+A_{IJ}u_J^n \tag{14}$$

其中：

$$A_{IJ}=\int_{\Omega_e}N_IN_J\mathrm{d}\Omega+\int_{\Omega_e}\frac{1}{2}\frac{1}{Re}\Delta t\frac{\partial N_I}{\partial x_i}\frac{\partial N_J}{\partial x_i}\mathrm{d}\Omega \tag{15}$$

$$B_{IJ}=\int_{\Omega_e}\left(-N_Iu_j\frac{\partial N_J}{\partial x_j}-\frac{1}{Re}\frac{\partial N_I}{\partial x_i}\frac{\partial N_J}{\partial x_i}\right)\mathrm{d}\Omega-\int_{\Omega_e}\frac{1}{2}\Delta t u_ju_j\frac{\partial N_I}{\partial x_j}\frac{\partial N_J}{\partial x_j}\mathrm{d}\Omega \tag{16}$$

$$C_{IJ}=\int_{\Omega_e}\frac{1}{2}\Delta tN_I\left(\left(u_k\frac{\partial u_j}{\partial x_k}+\frac{\partial p}{\partial x_j}-\frac{1}{Re}\frac{\partial^2 u_j}{\partial x_k\partial x_k}\right)\right)\frac{\partial N_J}{\partial x_j}\mathrm{d}\Omega \tag{17}$$

$$P_{IJ}=\int_{\Omega_e}\left(-\frac{1}{2}\left(\frac{\partial p^n}{\partial x_i}-\frac{\partial p^{n-1}}{\partial x_i}\right)\right)N_I\mathrm{d}\Omega \tag{18}$$

$$F_I=\int_{\Omega_e}\left(N_I+\frac{1}{2}\Delta tu_j\frac{\partial N_I}{\partial x_j}\right)\left(-\frac{\partial p}{\partial x_i}\right)\mathrm{d}\Omega \tag{19}$$

以上完成了单元的分析，在计算域内将所有单

元的有限元方程进行迭加,从而构成总体的有限元方程

$$Au^{n+1} = (Bu^n + Cu^n + P + F)\Delta t + Au^n \quad (20)$$

上式这种离散格式隐含了流线迎风的耗散作用,具有较高的精度和稳定性,可以有效地应用于高雷诺数流动问题的求解。本文采用SIMPLE算法求解 $N-S$ 方程,压力修正的 Poisson 方程形式为

$$\frac{\partial^2 \delta p^{n+1}}{\partial x_i \partial x_i} = \frac{1}{\Delta t}\frac{\partial u_i^*}{\partial x_i} \quad (21)$$

对离散方程采用迭代法进行求解,速度修正量必须满足下式

$$\delta u_i^{n+1} = -\Delta t \frac{\partial \delta p^{n+1}}{\partial x_i} \quad (22)$$

如果速度的近似值使式(21)右端项为零,说明速度满足连续性方程,压力修正量为零得到收敛解,否则继续修正。

2.3　气体横掠单管强制对流换热的数值模拟

气体横掠单管的计算模型如图1所示,图中圆管的直径为D,若为方管时则定义其边长为D。计算采用的雷诺数为10 000,普朗特数为0.687,无量纲时间步长为0.001。计算的边界条件为:

(1) 入口:给定无量纲速度 $u=1$, $v=0$,给定无量纲温度 $\theta=0$;

(2) 出口:给定无量纲压力 $p=0$,速度和温度采用Neumann条件,即 $\frac{\partial u}{\partial x}=0$, $\frac{\partial v}{\partial x}=0$, $\frac{\partial \theta}{\partial x}=0$;

(3) 固壁:速度采用无滑移边界条件,即 $u=0$, $v=0$,给定无量纲温度 $\theta=1$;

(4) 上下侧边界:$\frac{\partial u}{\partial y}=0$, $v=0$, $\frac{\partial \theta}{\partial y}=0$。

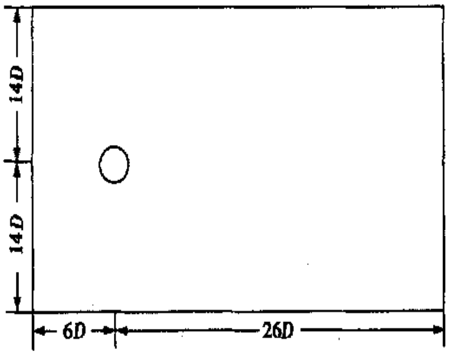
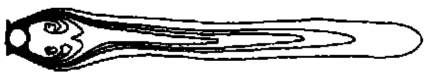


图1　气体横掠单管的计算模型

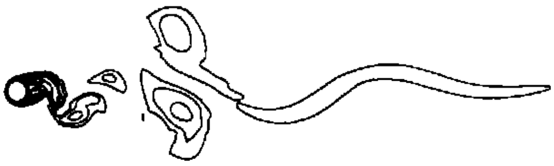
3　结果分析



(a) $t=20$ 时刻等温线图

(b) $t=25$ 时刻等温线图

(c) $t=30$ 时刻等温线图



(d) $t=35$ 时刻等温线图

图2　气体横掠圆管不同时刻的等温线图

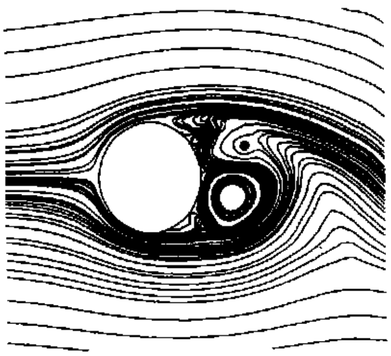
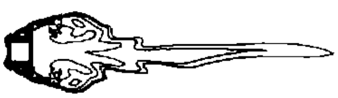


图3　气体横掠圆管某一时刻的流线图

气体横掠圆管时不同时刻的等温线图和某一时刻的流线图分别如图2和图3所示,气体横掠方管时不同时刻的等温线图如图4所示,从图中我们可以看出采用二阶全展开ETG有限元离散格式与大涡模拟相结合的方法,可以很好地捕捉到涡系发展的时程,清晰地看到旋涡的发生、发展及脱落过程。

迄今为止,得到人们公认和广泛采用的气体横掠圆管和方管的实验关联式是由希尔帕特[7]和雅各布[8]得到的,分别如式(23)和式(24)所示。



(a) t=25 时刻等温线图

(b) t=30 时刻等温线图

(c) t=35 时刻等温线图

(d) t=40 时刻等温线图

图4 气体横掠方管不同时刻的等温线图

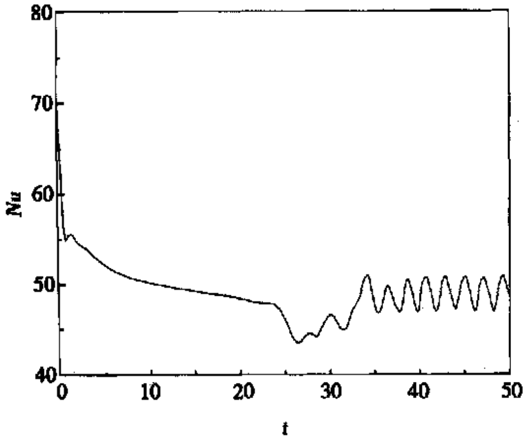


图5 圆管管壁平均换热系数时程曲线

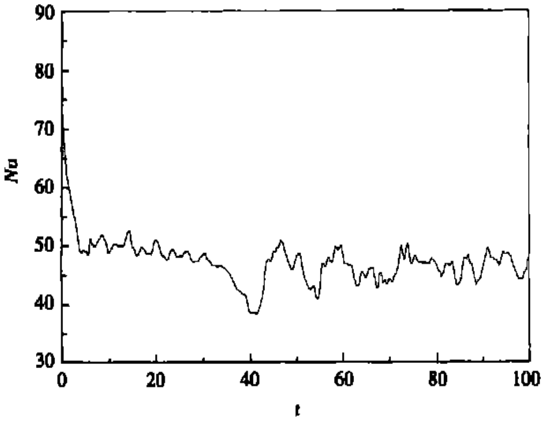


图6 方管管壁平均换热系数时程曲线

$$Nu = 0.193\ Re^{0.618} Pr^{1/3} \tag{23}$$

$$Nu = 0.102\ Re^{0.675} Pr^{1/3} \tag{24}$$

气体横掠圆管和方管时的平均换热系数随时间的变化曲线分别如图5和图6所示。数值计算得到的壁面平均换热系数与由实验关联式计算所得的平均换热系数的对比如表1所示，从中可以看出本文所得到的结果与实验关联式符合较好。

表1 数值结果与实验关联式结果的对比

	Nu 准则的数值结果	实验关联式的计算结果
圆管	48.73	50.49
方管	46.25	45

4 结 论

（1）采用大涡模拟与二阶全展开 ETG 有限元离散格式相结合的方法对气体横掠圆管和方管的强制对流换热进行了数值模拟，Nu 准则的数值结果与实验关联式(23)和式(24)的计算结果符合较好。

（2）采用大涡模拟方法捕捉到了温度场以及流场涡系的时间演化过程，提供了丰富的温度场和流场信息，可用于计算各种参数（包括热应力等）的动态过程，为进一步改善热质交换提供了重要依据。随着大涡模拟技术的不断完善及数值计算经验的积累，大涡模拟方法一定会在热能动力领域发挥越来越大的作用。

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Electric propulsion represents a main propulsion mode for future ships. After a brief description of the status quo and future prospects of electric propulsion units the authors have proposed an approach for the research and introduction of integrated all-electric propulsion systems on board naval vessels. In connection with a university-installed test rig for combined diesel and gas turbine power plants a combined power plant is assumed as an electric propulsion prime-mover module and a series of problems are explored and investigated, such as power distribution, single and parallel operation, etc. **Key words:** combined power plant, electric propulsion

水蒸气对液体燃料高温分解碳黑形成影响的研究 = **An Investigation of the Influence of Water Vapor Injection on Soot Formation During Liquid Fuel Pyrolysis** [刊,汉] / HU Sheng-teng, FU Wei-biao (Department of Engineering Mechanics, Tsinghua University, Beijing, China, Post Code: 100084), XING Gui-ju (Anshan Iron &Steel Institute, Anshan, China, Post Code: 114002) //Journal of Engineering for Thermal Energy &Power. — 2003, 18 (3). —252~255

The influence of water vapor injection on soot formation during liquid fuel pyrolysis is investigated. By directly measuring the mass of soot deposited on a solid wall surface it was found that water vapor can suppress the formation of soot particles. Some characteristics concerning the deposition of soot on a solid wall surface were ascertained. Meanwhile, by using software "Fluent" the soot particle concentration field was simulated under two kinds of experimental operating conditions, making it possible to confirm the relevant experimental conclusions. Finally, a calculation formula is given. When suitable parameters to be determined are selected, the results of calculation agree quite well with those of tests. **Key words:** soot, pyrolysis

小型燃气轮机热电联供系统的性能计算和分析 = **Performance Calculation and Analysis of a Small Gas Turbine-based Cogeneration System** [刊,汉] / WU Jian-qiang, LIU Bao-xing, GUAN Xin (Institute of Power Engineering under the Shanghai University of Science &Technology, Shanghai, China, Post Code: 200093) //Journal of Engineering for Thermal Energy &Power. - 2003, 18 (3). —256~258

On the basis of the first and second law of thermodynamics as well as stoichiometric combustion proposed is a method for calculating and analyzing the performance parameters of a small gas turbine-based cogeneration system. The method under discussion mainly involves such aspects as power plant cycle efficiency, fuel utilization rate and second law efficiency, etc. with emphasis on identifying the impact on plant performance of some major parameters, such as compressor pressure ratio, turbine inlet temperature, steam process pressure and pinch-point temperature difference, etc. A case study was conducted of a 200kW gas turbine, which provided a practical and feasible method as well as reference data for the rational design of small gas turbine-based cogeneration systems. **Key words:** small-sized gas turbine, cogeneration, performance calculation, stoichiometry

气体横掠单管强制对流换热的大涡模拟 = **Large Eddy Simulation of Forced Convection Heat Exchange by Gases Sweeping Across a Single Tube** [刊,汉] / WEI Ying—jie, HE Zhong—yi (College of Municipal and Environmental Engineering under the Harbin Institute of Technology, Harbin, China, Post Code: 150090) //Journal of Engineering for Thermal Energy &Power. — 2003, 18 (3). —259~262

By using a method of large eddy simulation combined with a second-order full-developed ETG finite element discrete scheme a numerical simulation was performed of the forced convection heat exchange by gases sweeping across a single tube. The temperature fields in the case of a circular tube and a square tube being swept by gases were calculated separately. As a result, an average heat-exchange factor for tube walls was obtained. Numerical results agree relatively well with those of experimental correlation. Meanwhile，this also shows that the large eddy simulation method is especially effective in capturing temperature fields and the time evolution process of flow field eddy series and very suitable for the analysis of temperature fields involving the flow movement of large eddies. **Key words**：gas sweeping across a single tube，forced convection，large eddy simulation

基于遗传算法的汽轮机 DEH 控制系统的参数优化研究 = **A Study on the Parameter Optimization of a Digital Electro-hydraulic（DEH）Control System for a Genetic Algorithm-based Steam Turbine** [刊，汉] / DAI Yi-ping，LIU Zhao（Turbomachinery Research Institute under the Xi' an Jiaotong University，Xi' an，China，Post Code：710049），LIU Jiong（Dongfang Steam Turbine Works，Deyang Sichuan Province，China，Post Code：618000）//Journal of Engineering for Thermal Energy &Power. — 2003，18（3）. —263～266

After an explanation of the basic theory of genetic algorithm the latter is used for the parameter optimization of the PID（proportional-integral-differential）governor of a steam turbine DEH（digital electro-hydraulic）control system. The dynamic characteristics of the system after parameter optimization are compared with those of a system，which has undergone an adjustment by a conventional method. The results of comparison indicate that the improved genetic algorithm offers the merit of high convergence speed and the acquisition of global optimization. After being optimized the control system will enjoy better dynamic response characteristics. The genetic algorithm can be advantageously employed for the parameter optimization of the governor of a steam turbine DEH control system. **Key words**：genetic algorithm，parameter optimization，steam turbine，digital electro-hydraulic control system

再热汽轮机性能试验系统修正方法研究 = **Investigation of a Method for Correcting the Performance Test System of a Reheat Steam Turbine** [刊，汉] / ZHANG Cai-wen，HUANG Hai-zhou（Steam Turbine Department，Hubei Provincial Electric Power Testing Institute，Wuhan，China，Post Code：430077）//Journal of Engineering for Thermal Energy &Power. — 2003，18（3）. —267～269

An in-depth investigation was conducted of two kinds of revision calculation for the performance test system of a reheat steam turbine on the basis of "ASME PTC6-1996 Steam Turbine Performance Test Rules and Regulations". The process for realizing two kinds of calculation method is presented with their difference being analyzed. Moreover，through a calculation example the effect of these two calculation methods on the results of calculation is investigated，on the basis of which a revision calculation method is recommended. **Key words**：steam turbine，performance test，calculation

不同进风结构下煤粉燃烧器冷态流场实验研究 = **An Experimental Study of the Cold-state Flow Field of a Pulverized-coal Burner under Different Air-entry Versions** [刊，汉] / JIANG Li-qiao，CHEN En-jian，YAN Chang-feng（Guangzhou Energy Source Research Institute under the China Academy of Sciences，Guangzhou，China，Post Code：510070）//Journal of Engineering for Thermal Energy &Power. — 2003，18（3）. —269～271

An experimental study was conducted of the cold-state flow field characteristics of a pulverized-coal burner under two different air-entry versions，namely，air tangential entry and end-face air prewhirl entry. Test results indicate that the end-face prewhirl entry of air can lead to a considerably enhanced symmetry and uniformity of axial-speed distribution of the burner flow field. Furthermore，from the perspective of flow field distribution the integration of primary and secondary air into one stream of end-face prewhirl flow entry will be more contributive to the rational distribution of flow field than in the case of single axial entry of primary air. **Key words**：swirl flow，blade，five-hole probe

注蒸汽对涡轮增压器的影响 = **The Influence of Steam Injection on a Turbocharger** [刊，汉] / LU Ben，WEN Xue-you（Harbin No. 703 Research Institute，Harbin，China，Post Code：150036），XIA Jun-sheng（Hebei Jiteng Paper