

方形截面弯管二次流数值模拟

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摘 要:应用湍流大涡模拟方法对含有和不含导流叶片的方形截面 90°弯道的二次流动进行了数值模拟, 同时给出了 Taylor—Galerkin 有限元离散格式。管道加装叶片后, 形成了两对二次流, 其强度较低且沿程变化不大, 改善了流动状态。

关 键 词:湍流; 大涡模拟; 流场; 有限元法; 弯道流; 导流叶片

中图分类号: TB115 文献标识码: A

1 引 言

在热能动力工程中大量存在着弯曲形状的流动通道, 其内部流动特性不同于一般的长直管道。由于曲率的影响, 弯道内会出现垂直于主流的二次流^[1~2], 并形成尺度很大的横向旋涡加。横向涡的大小、位置以及发生的频率会造成出口速度偏转以及流场压力畸变, 详细了解流场信息就有可能通过调整区段的几何形状或其它参数来控制二次流, 使之达到较好的工作状态。近年来, 计算机技术的飞速发展以及湍流数值模拟理论不断改进, 通过数值仿真逐步代替物理实验来提供场信息

开始有了希望。其中的湍流大涡模拟^[2~3] (Large Eddy Simulation, LES) 方法是建立在湍流统计和旋涡的级联衰变理论基础上的一种较新的数值预测方法, 它克服了湍流模式理论的时均处理和普适性方面存在的缺陷。目前, 高密度时空网格的 LES 已被列入湍流

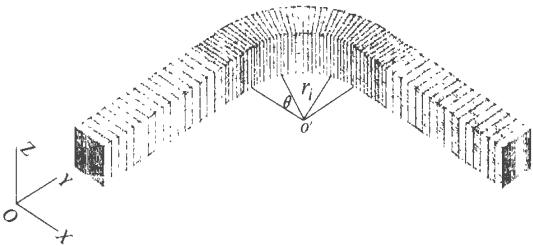
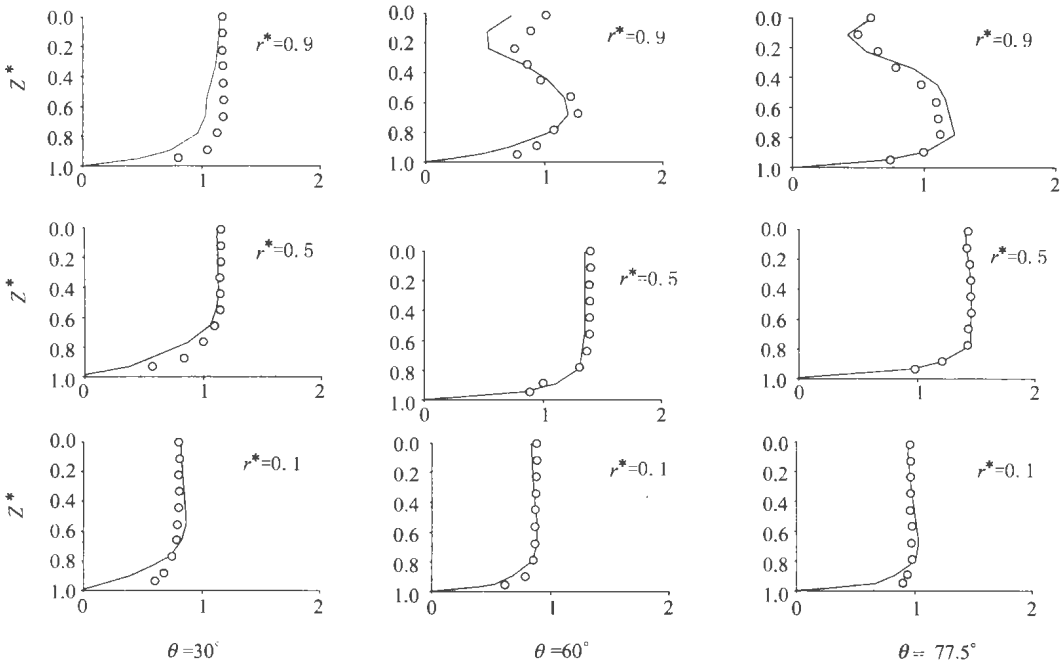


图 1 计算域与网格划分



— 本文数值模拟结果; ○ 实验结果^[1]

图 2 典型截面处的总流平均速度

高级数值模拟范畴^[4]。本文拟以方形截面 90° 弯道为例, 采用 LES 方法, 对设置和不设置导流叶片两种情况下二次流状态的变化进行仿真研究, 作为进一步控制流动状态的工作基础。笔者对 90° 方形截面弯管内流动所进行的研究结果^[3]表明, 基于 Taylor—Galerkin 有限元法的湍流大涡模拟具有较高的稳定性及精度, 特别适合于边界形状复杂, 存在各向异性大尺度涡的内流情况。

2 大涡模拟基本方程

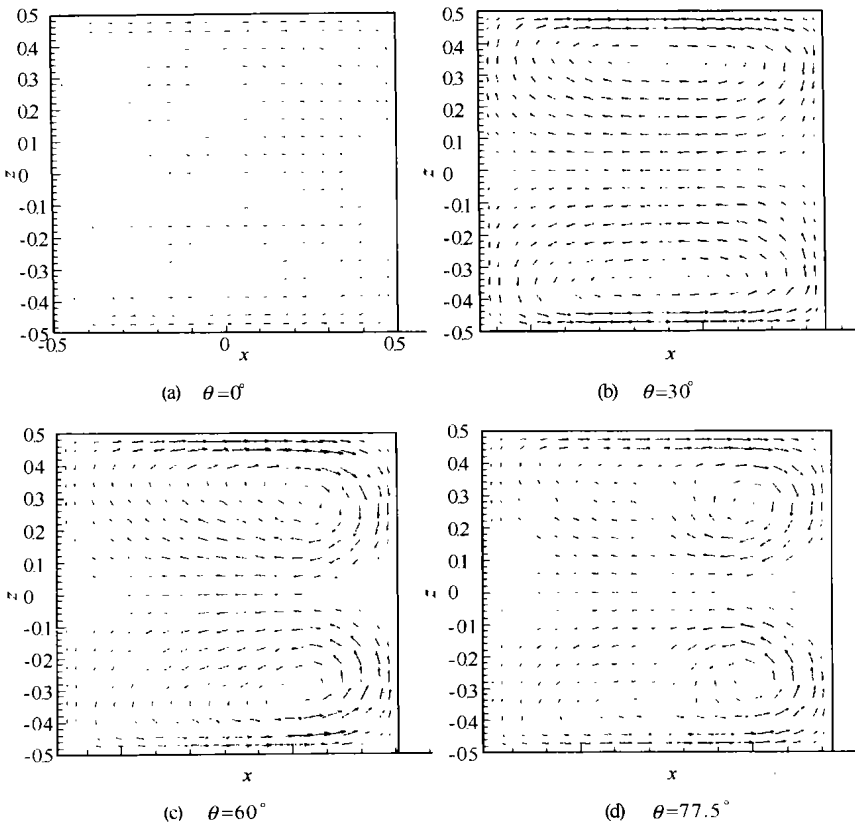


图 3 典型截面处的平均速度矢量图(无导流叶片)

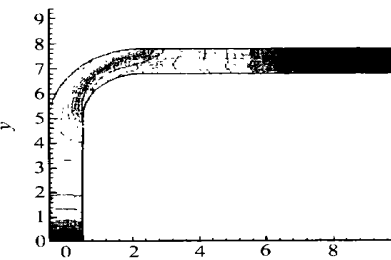


图 4 X—Z 平面的流线
(无导流叶片)

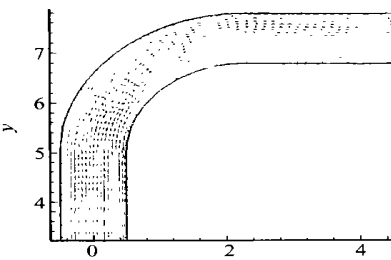


图 5 X—Z 平面的压力等
值线(无导线叶片)

经过 Gauss 滤波后的连续方程和运动方程为

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j - \frac{\Delta^2}{12} \nabla u_i \nabla u_j) = - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} [\nu (\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i})] + \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

式中的上标“—”表示大尺度分量; $\bar{u}_i$ 为速度; $\bar{p}$ 为压强; ν 为运动粘性系数; τ_{ij} 为亚格子剪切应力。

本文采用涡粘 SGS 模式, Deardorff 假设

$$\tau_{ij} = \mu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \tag{3}$$

其中 μ_t 为亚格子涡粘性系数, Smagorinsky 假设

$$\mu_t = (c \Delta)^2 \left[\frac{\partial \bar{u}_i}{\partial x_j} (\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}) \right]^{\frac{1}{2}} \tag{4}$$

式中 c 为无量纲常数, 本文取 $c = 0.12$; $\Delta = (\Delta x_1^2 + \Delta x_2^2 + \Delta x_3^2)^{\frac{1}{2}}$ 。

有限元法是计算流体力学的一个有力工具, 能很好地适应复杂的几何形状和边界条件。本文采用具有三阶部分展开的 Taylor—Galerkin 有限元法进行离散计算。对 N—S 方程组采用压力校正法求解, 对离散方程组采用迭代法求解。

3 算例与结果分析

针对文献[1] 的实验, 取 $Re = 40\,000$, 进行对比性计算, 计算域如图 1 所示。笛卡尔坐标系的原点 O 位于管道入口截面的中心。在弯道部分另设一柱坐标系, 其坐标原点为 O_1 , θ 为极角, 并令 90° 弯道的主流入口截面处 $\theta = 0^\circ$, 出口截面处 $\theta = 90^\circ$ 。方管边长 $D = 40\text{ mm}$; 90° 弯道内侧回转半径为 $r_i = 1.8 D$; 外侧回转半径为 $r_0 = r_i + D$; 弯道前后直段长分别为 $5D$ 。

图 2 给出沿总流方向在 $\theta = 30^\circ$ 、 $\theta = 60^\circ$ 和 $\theta = 77.5^\circ$ 三个有代表性的截面处的数值模拟结果与实验结果^[4]。图中 $Z^* = Z/Z_{V2}$ 为展向无因次坐标 (其中 $Z_{V2} = D/2$); $r^* = (r - r_0)/(r_i - r_0)$ 。整体而言, 两者吻合良好, 说明本文的数值模拟具有较高的稳定性及精度。

图 3 给出垂直总流方向在 $\theta = 0^\circ$ 、 $\theta = 30^\circ$ 、 $\theta = 60^\circ$ 和 $\theta = 77.5^\circ$ 四个典型截面上的面内流动速度矢量图。图 4 和图 5 给出 $Y = 0$ 处的平面, 即 $X-Z$ 平面的流线和压力等值线图。

从图 4 和图 5 可以清楚看出二次涡的产生与发展。流体流经弯道时, 贴附壁面形成两个涡流区, 内侧的涡流区是由于流体的惯性使边界层脱离内壁造成的; 外侧的涡流区是由于流体与管壁冲击引起的。由于这两个涡流区的存在, 使得这个区域的通流面积减小, 管道中心处的流体速度要比管壁附近速度大, 引起流体旋转, 导致流动局部阻力增加。

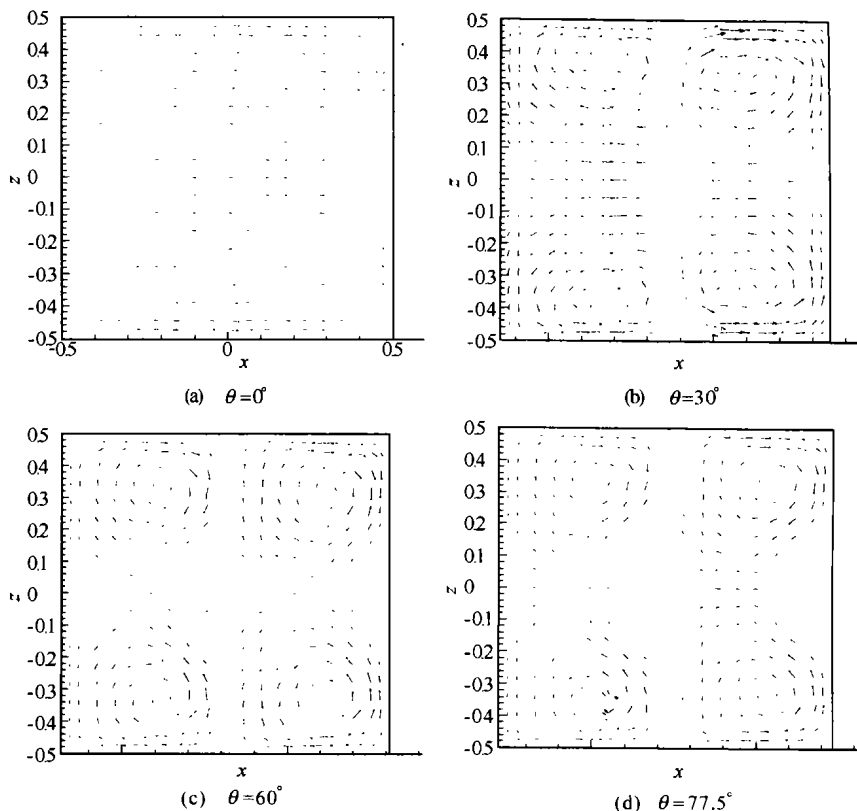


图 7 典型截面处的平均速度矢量图 (含导流叶片)

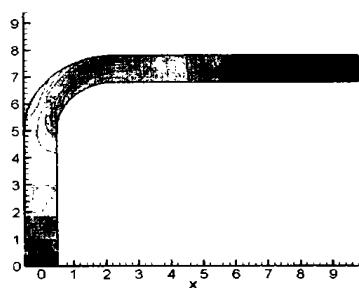


图 8 $X-Z$ 平面的流线 (含导流叶片)

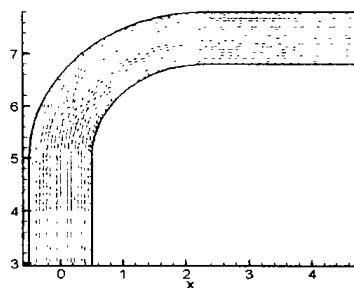


图 9 $X-Z$ 平面的压力等值线 (含导流叶片)

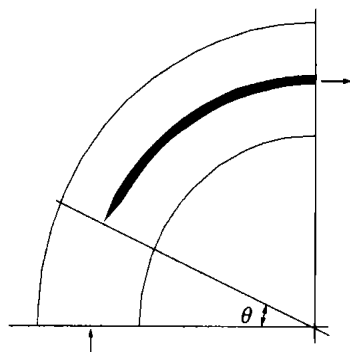


图 6 加装导流叶片时的结构示意图

计算发现, 在 $\theta = 27^\circ$ 附近沿流动方向产生较大范围的分离, 为此, 在弯道处加装一个导流叶片, 叶片厚度为 2.2 mm, 安装起始角度为 $\theta = 27^\circ$, 如图 6 所示。在这种情况下下的计算条件与未加装叶片时完全相同。图 7 给出垂直总流方向在 $\theta = 0^\circ$ 、 $\theta = 30^\circ$ 、 $\theta = 60^\circ$ 和 $\theta = 77.5^\circ$ 四个典型截面上的面内流动速度矢量图。图 8 和图 9 给出 Y

$= 0$ 处的平面, 即 $X-Z$ 平面的流线和压力等值线图。

结果表明, 加设导流叶片后, 从 $\theta = 27^\circ$ 始至 $\theta = 90^\circ$ 弯道出口止, 形成了两对二次流, 而且该二次流强度较低且沿程变化不大。这是由于叶片的作用, 外侧流体对管壁冲击以及内侧流体的惯性作用均减弱, 造成弯道内侧边界层脱离程度降低, 外侧的冲击范围减小。这样就使得弯道部分的压力分布趋于合理, 截面上的速度分布变得均匀。

4 结 语

应用湍流大涡模拟方法对弯道内的二次流动进行了数值模拟; 采用有限元法对控制方程和计算域进行高密度时空离散求解; 用编制的三维湍流场 LES 计算程序对方管内的流动进行了数值计算。加装叶片后, 形成了两对二次流, 而且该二次流强度较低且沿程变化不大, 改善了流动状况, 有效地抑制了弯道出口速度偏转以及流场压力畸变。完全有理由相信, 随着计算机的进一步发展, 对于解决和优化热能动力工程领域中的管道与设备内的流动问题大涡模拟将发挥更大的作用。

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(何静芳 编辑)

电站设备

真空除气器的改进

据《Элект Рические станции》2001 年 5 月号报道, 真空除气器的经济性取决于被除气水的加热。水在除气器内加热越小, 除气工况越经济。但是水在除气器内的加热不仅影响工况的经济性, 而且还影响到除气的质量, 更具体说, 水在除气器内加热越大, 除气质量越好。

对真空除气器工作提出的一个要求是保证被除气水中氧的含量不大于 $50 \mu\text{g}/\text{kg}$ 。就此而论, 水在除气器内的最佳加热是保证被除气水中要求氧含量的最小加热。

水的气蚀强度是决定水在热力除气器内除气过程强度的一个因素。安装在不同对象上的真空除气器除气特性的差别是由被除气水在这些对象上气蚀强度的差别引起的。在除气器工况温度和液力参数不改变的情况下, 改变水的气蚀强度将导致除气特性改变。

在真空除气器内应用带导向螺旋叶片的喷嘴, 改进了除气器的除气特性, 即

—减少了水在除气器内需要的最小的加热, 从 24°C 减少到 16°C ;

—降低了加热水允许的最小温度, 从 $85 \sim 90^\circ\text{C}$ 降低到 70°C 。

在未除气水温度为 30°C 以及加热水温度不低于 70°C 时, 结构中采用改造的带导向螺旋叶片喷嘴的除气器的生产率为 950 t/h 。

(思娟 供稿)

静电旋风分离器的流场分析= **Flow Field Analysis of an Electrostatic Cyclone Separator** [刊, 汉] / ZHANG Ji-guang, SHEN Heng-gen (East China University, Shanghai, China, Post Code: 200051), LI Hua (Qingdao Architectural Engineering Institute, Qingdao, China, Post Code: 266033) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). — 499 ~ 501

A three-dimensional speed distribution was tested respectively for two versions of CLT type (C - dust remover, L - centrifuge, T - cylinder) of electrostatic cyclone-separator, i. e., with and without a corona electrode being installed. The above-cited distribution was compared with that of two versions of XCY type (X - cyclone, C - long cone, Y - flue gas) of electrostatic cyclone separator, i. e., with and without a corona electrode being installed. After an analysis of the effect of corona electrode installation on the three-dimensional speed distribution the authors made the following observations. With the rational selection of a cyclone separator and the installation of a corona electrode at a specified location the favorable speed distribution in the cyclone separator will be conducive to enhancing the separation function of a centrifugal force and lowering the resistance in the electrostatic cyclone separator. The authors also discussed how to achieve a rational configuration of the electrostatic cyclone separator. **Key words:** electrostatic cyclone separator, separation effect, pressure loss, flow field

燃气机热电冷联供系统技术经济分析= **Technical and Economic Analysis of a Gas Engine-based process heat, electricity and cooling energy Cogeneration System** [刊, 汉] / YANG Zhao, ZHANG Shi-gang, TONG Chun-rong (Thermal Energy Research Institute under the Tianjin University, Tianjin, China, Post Code: 300072) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). — 502 ~ 505

In an effort to seek a rational approach of energy utilization, the authors have made a technical and economic analysis with regard to a gas engine-driven total energy system incorporating the triple supply of process heat, electricity and cooling energy. Its comparison with a motor-driven air-cooled heat pump shows that the recommended total energy system is technically feasible and economically rational. **Key words:** total energy system, technico-economics, heat pump

MSF 多级闪蒸海水淡化系统的建模与仿真= **Modeling and Simulation of a Multi-stage Flash (MSF) Seawater Desalination System** [刊, 汉] / ZHOU Shao-xiang, HU San-gao, SONG Zhi-ping (North China Electric Power University, Beijing, China, Post Code: 102206) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). — 506 ~ 509

Through the mechanism analysis of a multi-stage flash (MSF) process a comprehensive and dynamic mathematical model was set up for a MSF seawater desalination system. The model is different from those as reported in current literature in that it has taken into account the influence of steam density and flow rate changes of interstage-flash brine-water. The results of simulation calculations truthfully reflect the nonlinearity characteristics of the MSF system dynamic process. **Key words:** dynamic process, modeling, simulation, multi-stage flash, seawater desalination

方形截面弯管二次流数值模拟= **Numerical Simulation of the Secondary Flow in a Curved Duct of Square-shaped Cross-section** [刊, 汉] / FAN Hong-ming, LI Xian-ting, JIANG Yi (Department of Architectural Science, Tsinghua University, Beijing, China, Post Code: 100084), HE Zhong-yi (Department of Architectural and Thermal Energy Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). — 510 ~ 513

With the help of a large eddy simulation (LES) method for turbulent flows a numerical simulation was performed of the secondary flow in ninety degree curved ducts of a square-shaped cross-section with and without flow-guide blades. Meanwhile, presented is a Taylor-Galerkin finite-element discrete scheme. Two pairs of secondary flow were formed after the

duct has been fitted with flow-guide blades. Owing to the low intensity of the secondary flow and its small change along the ducts the flow condition has been improved. **Key words:** turbulent flow, large eddy simulation, flow field, finite element method, curved duct flow, flow-guide blade

确定船用蒸汽动力装置辅机余度系数的新方法 = **A New Method for Determining the Redundancy Factor of Auxiliary Machines for a Marine Steam Power Plant** [刊, 汉] / SHU Li-wei, JIN Jia-shan (Naval Engineering University, Wuhan, China, Post Code: 430033), JI Guang (Military Representative Office Stationed at Harbin Steam Turbine Works, Harbin, China, Post Code: 150046) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). — 514~516

With a turbine-driven feedwater pump serving as an example discussed is a method for determining the rated performance-based redundancy factor of auxiliaries for a marine steam power plant. The method under discussion takes into account in a comprehensive way several factors. They include: the discrete character of equipment rated performance during its manufacture, the degeneration mechanism of the rated performance with the passage of usage time, the discrete character as demanded of the equipment, etc. With performance-reliability serving as an objective the redundancy factor can be determined in a more rational way. This may provide guidance for the design of the thermodynamic system of a marine steam power plant as well as the type selection of other similar equipment items. **Key words:** performance reliability, degeneration, redundancy factor, marine steam power plant, turbine-driven feedwater pump

自动可调浓淡燃烧器低负荷稳燃特性 = **Low-load Stable Combustion Characteristics of an Automatic-adjustable Bias-combustion Pulverized-coal Burner** [刊, 汉] / LI Yong-hua, CHEN Hong-wei (North China Electric Power University, Baoding, China, Post Code: 071003), LIANG Hua-zhong, et al (Shandong Luneng Development Company, Jinan, China, Post Code: 250000) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). — 517~520

A new type of automatic-adjustable bias-combustion pulverized-coal burner is presented along with its service conditions in a power plant. The results of its operation has shown that the burner features an ability to regulate the distribution of air and pulverized coal during boiler operation, thus achieving the aim of operating at a drastically reduced load. **Key words:** burner, boiler, load

300 MW 机组 UP 型直流锅炉变压运行探讨 = **An Exploratory Study of the Variable-pressure Operation of an UP-type Once-through Boiler for a 300MW Unit** [刊, 汉] / KUANG Jiang-hong (College of Mechanical Engineering under the Shanghai University of Engineering & Technology, Shanghai, China, Post Code: 200336) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). — 521~523

Through a thermal calculation and analysis investigated are the operating characteristics of a UP-type once-through boiler and its feedwater pumps during its variable-pressure and peak-shaving operation. The authors concluded that a Chinese-made 300MW unit employing UP type once-through boilers basically possesses the ability to conduct a variable-pressure and peak-shaving operation. **Key words:** peak shaving, variable-pressure operation

TCDF-33.5 型 300 MW 汽轮机首次大修中的故障处理 = **Fault Treatment during the First-time Overhaul of a Model TCDF-33.5 300 MW Steam Turbine** [刊, 汉] / ZHANG Cai-wen, HUANG Hai-zhou, WANG Shu-shen (Hubei Provincial Electric Power Testing Research Institute, Wuhan, China, Post Code: 430077) // Journal of Engineering for Thermal Energy & Power. — 2002, 17(5). — 524~526

Described are the following main faults detected during the first-time overhaul of a model TCDF-33.5 300MW steam tur-