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船用增压锅炉旋流蒸汽机械喷油器的雾化特性

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摘　要: 采用 LPI-3 衍射式激光粒子测径仪与 LE-3 雾化角测量仪对船用旋流蒸汽机械雾化喷油器进行了试验研究, 得到了雾化油滴索特平均直径及喷油量与压力的变化关系; 利用 Realizable $k-\varepsilon$ 模型模拟气体湍流流动, 随机轨道模型模拟液滴运动; 并用 LISA 模型和 TAB 模型模拟液滴变形和破碎, 对旋流蒸汽机械雾化喷油器的雾化过程进行了数值模拟, 分析了喷油器内雾化空气和油质量流量对雾化特性的影响, 模拟的结果与试验结果吻合得较好。研究表明, 在喷油压力高于 1.1 MPa 时, 喷油器特性符合机械雾化喷嘴的一般规律, 但当喷油压力较低时, 雾化规律相反, 喷油压力越低, 雾化粒度越细。由此表明, 旋流蒸汽机械雾化喷油器可以极大地改善低工况雾化质量, 具有较大的调节比, 气耗量也优于常见的气动雾化喷油器。

关　键　词: 增压锅炉; 喷油器; 雾化特性; 数值模拟
中图分类号: TK229　　文献标识码: A

前　言

船用增压锅炉采用了增压燃烧, 具有尺寸小、重量轻、机动性好等特点[1], 是船用锅炉的发展方向。船用增压锅炉喷油器一般要求单只容量大, 结构简单可靠, 调节比大; 在可调范围内燃油雾化质量好; 燃烧产生的火炬直径小, 长度短; 一般喷油器很难满足这种要求[2]。

国内外对燃烧器及炉内流场已经做了大量的研究工作, 多数集中在煤粉燃烧器和水煤浆领域, 对 Y 型喷嘴、机械雾化喷嘴等油燃烧器的雾化特性也有一定的研究, 但对于增压锅炉大容量喷油器的研究还很少[3], 对船用同轴式旋流蒸汽机械雾化喷油器雾化特性的研究还未见报导。

采用 LPI-3 衍射式激光粒子测径仪与 LE-3 雾化角测量仪对某增压锅炉用大容量旋流蒸汽机械雾化喷油器进行了试验研究, 并建立数学模型进行了数值模拟分析, 为进一步开展增压条件雾化及燃烧的研究奠定了基础。

1　旋流蒸汽机械雾化喷油器

旋流同轴式蒸汽机械雾化喷油器不同于常见的机械雾化喷嘴和蒸汽机械雾化喷嘴, 该型喷油器同时采用了机械雾化和气体辅助雾化两种雾化手段, 具有雾化蒸汽耗量低、雾化效果好、调节比大等优点, 适用于对变负荷能力要求较高的船用锅炉。该型喷油器的雾化片具有双面旋流切向槽, 燃油和雾化气分别经过切线槽旋转加速后同轴从喷口喷出, 旋流空气冲击已经过压力雾化的燃料液滴, 达到更好的雾化效果。常用的气体辅助雾化喷油器要求气体压力大于喷油压力, 且汽液比也较大。本文研究的喷油器则有较大的不同, 雾化气压力较低, 额定工况下汽耗量不超过喷油量的 1%, 喷油器结构见图 1。

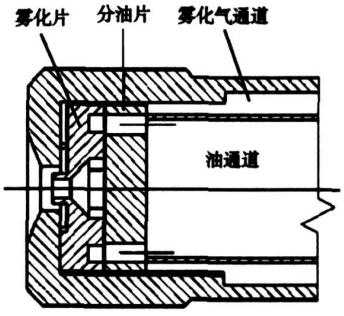

图 1　喷油器结构示意图

2　喷油器雾化特性的冷态试验研究

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建立了图 2 所示的喷油器特性试验系统, 试验系统包括油系统和压缩空气系统两部分。主要部件包括油箱、喷油罐、储气罐、空气压缩机、油泵、流量计、压力表以及各种阀门等。

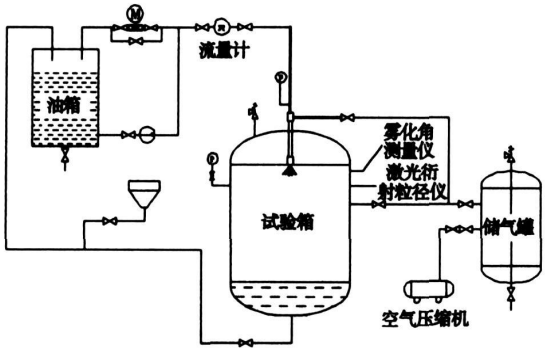

图 2　喷油器实验系统

测量装置采用 LPI-3 型激光衍射粒径仪以及 LE-3 雾化角测量仪。测量位置距喷油器出口 150 mm。LE—3 雾化角测量仪主要是利用高像素的数码相机对雾化炬进行拍照, 然后利用液滴和空气的感光不同原理, 利用雾化炬与空气交界处灰阶的不同对雾化角的测量。其测量范围是 0 ~ 180°, 测量精度为 1%, 重复度为 1°。

雾化粒径采用 LPI-3 激光衍射粒径仪测量。可测颗粒直径范围为 10 ~ 1 000 μm。雾化平均粒径(SMD)及粒度分布(N)测量结果可以由计算机自动处理。为排除随机脉动的影响, 实验中每个实验点重复测量 20 次, 最后取其算术平均值。

油滴粒径分布模式采用 Rosin-Rammler 分布拟合:

$$R=1-\exp\left[-\left(\frac{D}{X}\right)^{N}\right] \tag{1}$$

其中: R—累积分布, 即直径大于 D 的液滴的累积重量分数; X—尺寸参数, 液滴尺寸分布中的某个特征尺寸, 大于这个尺寸的液滴的累积重量占 36.8%。X 值的大小反映了液滴尺寸的大小。N—分布参数, 表征液滴尺寸分布的均匀性。N 值越小, 尺寸分散度越大; N 值越大, 尺寸就越均匀, 如果 N 值趋向无穷大, 则雾化所形成的是单一尺寸的理想液滴。LPI-3 激光衍射式测粒仪对尺寸参数 X 的测量精度为 3%, 重复性 1 μm; 分布参数 N 的精度为 1%, 重复性为 0.1。

实验采用柴油作为燃料, 空气作为雾化气体。物性参数为: $\rho_{oil}=860\ kg/m^3$; $\sigma_{oil}=0.03\ N/m$; $\nu_{oil}=0.03\ kg/(m\cdot s)$; $\rho_{air}=1.225\ kg/m^3$。

3　试验结果及分析

在常压环境下, 对有雾化气和无雾化气条件下的雾化特性进行了试验研究, 试验结果见图 3 ~ 图 5。试验结果表明: 在常压环境下, 当没有雾化气辅助雾化时, 喷油量随着喷油压力的升高而升高, 燃油雾化粒径随着喷油压力的升高而减小; 油压较低时, 雾化粒径随压力的变化明显, 雾化角基本不随喷油

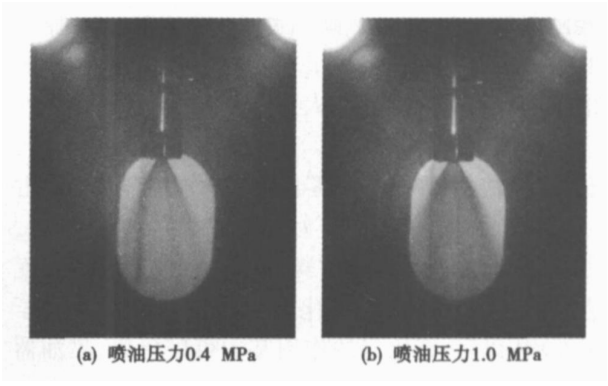

图 3　雾化炬照片

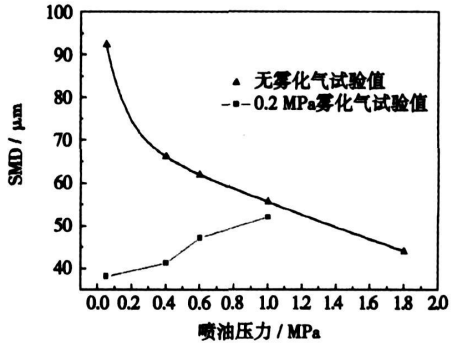

图 4　喷油器雾化特性

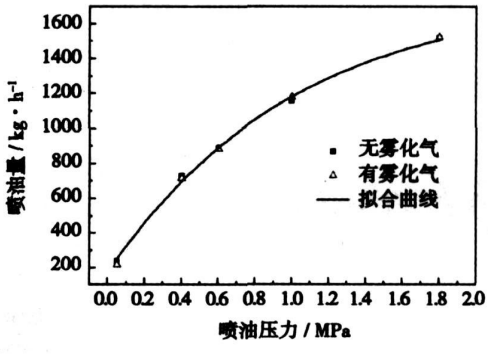

图 5　喷油器流量特性

压力变化。这与一般压力雾化喷油器的特性是一致的。

当加入 0.2 MPa 压力的雾化空气时，喷油量依旧随着喷油压力的升高而升高，但略有差异，主要是由于雾化气占据了一定的流通通道，影响了燃油的流通面积所致。喷油压力高于 1.1 MPa 时，雾化粒径随着喷油压力的升高而减小，但喷油压力降到 1 MPa以下时，粒径规律出现逆转，燃油雾化粒径随着喷油压力的升高而增大，但粒径比同等压力条件下没有雾化气时小得多。分析认为，当喷油压力较低时，气液比相对增加，雾化空气的辅助雾化作用占主导地位，使雾化效果更好，随着喷油压力的增加，加大了燃油的流量，实质就是减小了气液质量比，逐步弱化了辅助气的雾化作用；当喷油压力大于 1.1 MPa以后，雾化气的作用基本可以忽略，喷油器特性开始符合机械雾化的规律。

试验表明，该型蒸汽机械雾化喷油器具有下述特性：在有雾化气的条件下，喷油量随喷油压力的增高而增大；在压力较低时，雾化粒度随喷油压力的增高而增大，当达到一定压力时，粒径随着压力的增大而逐渐变小，即在压力较大条件下符合压力雾化规律，而在低压条件下，由于雾化气的作用而使雾化效果大幅度提高，该型喷油器可以具有较大的调节比，且保证其具有良好的雾化效果。

4 数值模拟计算

4.1 物理模型及网格划分

在实际使用中，喷油器都与调风器配合使用，由于本计算主要研究喷油器的雾化性能及辅助雾化气的影响，可以暂不考虑调风器的影响，因此，建立的计算模型不考虑调风器区域，以喷油器雾化片的旋流通道入口作为模型入口边界，考虑到实际炉膛的几何尺寸，计算区域选定为直径 1 m，长度 2 m 的圆柱形区域。网格化分以结构化网格为主，在雾化片区域采用非结构化网格，并作局部细化（见图 6 和图 7）。

假设雾化空气与油滴之间不存在热量传递，不考虑油滴的蒸发，进口采用质量进口边界，出口采用压力边界，雾化气流量约为油量的 1%。

4.2 数学模型的建立

考虑到旋流雾化的特点，选用 Realizable $k-\varepsilon$ 模型模拟气体湍流旋流流动，随机轨道模型计算液滴流动，线性不稳定液膜雾化模型（Linearized Instability Sheet Atomization，LISA 模型）、泰勒类比破碎模型（Taylor analogy breakup model，TAB 模型）对气液同轴式喷油器的雾化过程进行了数值模拟计算。控制方程参见文献[4~5]，这里不再赘述。

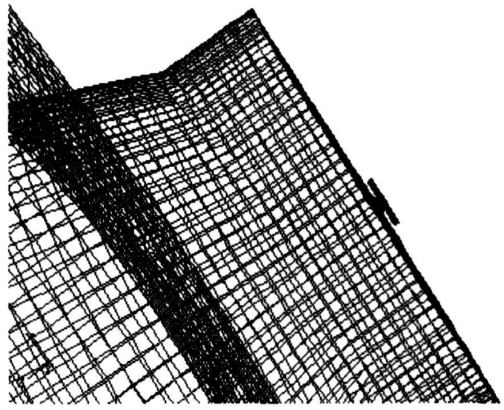

图 6 计算区域模型

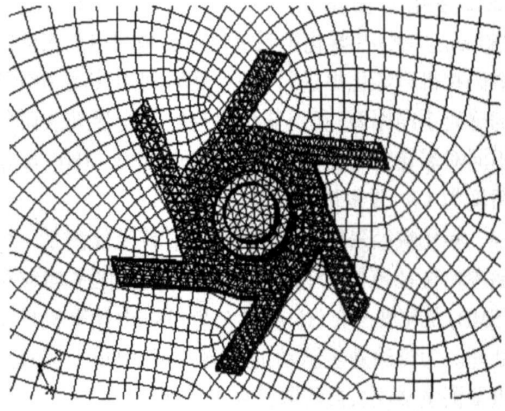

图 7 入口部分模型及网格

4.3 计算结果和分析

根据试验工况进行了数值模拟计算，出口压力设为0 MPa。计算结果见图 8 和图 9。

根据图 8 可以看出，在雾化空气流量一定的情况下，在油压低于 1 MPa 的范围内，随着喷油压力的增加，液滴雾化的索特平均直径（SMD）随之增加，从 29.2 μm 增加到 71.1 μm。计算结果与图 4 试验研究结果比较可知，虽然在具体数值上有所差异，但得到的雾化特性规律是一致的，数值的差异主要是由于试验和计算误差所致；喷油压力较低时，喷油流量小，辅助雾化气的作用占主导地位，喷油器特性类似气动喷嘴；随着喷油压力的提高，增加了燃油的质量流量，气液比减小，导致 SMD 增加，当压力增加到 1.1 MPa 以上时，雾化气的作用逐步被燃油压力的

作用所掩盖, 喷油器呈现出压力雾化特性。计算结果与试验结果的一致性也说明计算模型对于研究旋流蒸汽机械雾化喷油器的雾化特性规律是适用的。

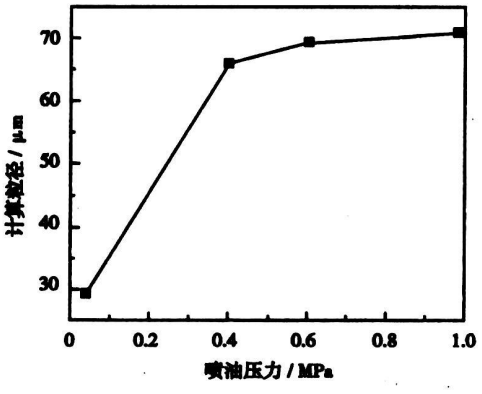

图 8　液滴索特平均直径随喷油压力的变化

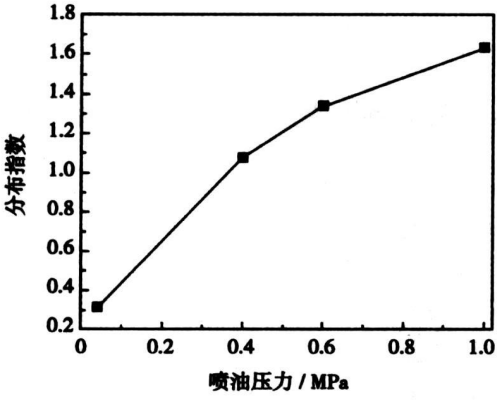

图 9　均匀度分布指数与喷油压力的关系

5　结　论

对旋流蒸汽机械雾化喷油器进行了试验研究和数值模拟分析, 研究结果表明, 该型喷油器兼具机械雾化喷油器和气体辅助雾化喷油器的优点, 当喷油压力高于 1.1 MPa 时, 油滴的雾化粒径随喷油压力的提高而减小, 喷油量随喷油压力的提高而增大, 变化规律基本符合压力雾化喷嘴的特性规律; 当喷油压力低于 1.1 MPa 时, 燃油的雾化粒径随喷油压力的提高而增大, 但总体上仍小于机械雾化的细度。雾化粒径的分布指数随喷油压力的增高而增大。

旋流蒸汽机械雾化喷油器具有气耗低、低负荷雾化特性好、调节比大等特点, 可以满足船用锅炉的要求。

建立的计算模型适用于旋流雾化喷油器的数值模拟, 为后续开展增压雾化特性研究奠定了基础。也为船用大容量蒸汽机械喷油器的研制提供了参考依据。

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(编辑　何静芳)

能源利用

烧高炉煤气的联合循环装置

据《Gas Turbine World》2005 年 11～12 月号报道, 南源钢铁集团已与日本(三菱重工)签约一项合同, 该合同是 MHI 将提供一台为燃烧高炉煤气已经过改型的燃气轮机。

该机器将安装在湖南省中部卢迪市南源集团现有钢铁厂内, 供联合循环发电装置用。

燃气轮机将以来自钢铁厂高炉的低热值煤气作为燃料, 以联合循环方式工作, 它将生产 50 MW 电力。MHI 将在其 Takasago 机械工三制造该燃气轮机。

与杭州汽轮机厂一起, MHI 也将装备用于联合循环的辅助设备。

南源钢铁集团称, 它将在当地采购余热锅炉和汽轮机。

全套装置计划于 2007 年 5 月投入运行。

(吉桂明　供稿)

rious coupling among various variables and it is very difficult to achieve an ideal effect by employing a PID (proportional, integral and differential) control. In the light of these specific features, the authors have applied for the above milling system a new type of control strategy, namely, a combination of auto-disturbance-rejection controller (ADRC) and a multivariable decoupling control. In the meantime, the authors have also made a partial improvement of the ADRC. An auto-disturbance-rejection-based multivariable control system has been designed for a ball-mill milling system and a comparison performed between a reverse-frame normalization design method and Smith forecasting compensation method. The simulation results demonstrate the validity, disturbance rejection and strong robustness of the control algorithm proposed by the authors. Hence, the control strategy under discussion enjoys a very high potential for engineering applications. **Key words**: ball mill, auto-disturbance-rejection controller (ADRC), decoupling control, reverse-frame normalization (RFN), Smith forecasting compensation method

考虑凝汽器压力的火电厂循泵出口阀启闭规律优化＝**Optimization of Open-close Mechanism of Circulation-pump Outlet Valves for a Thermal Power Plant with Condenser Operating Pressure being Considered** [刊, 汉] / YANG Zhi, LIU De-you (College of Water Conservancy and Hydropower Engineering under the Hehai University, Nanjing, China, Post Code: 210098), CHEN Fu-shan (Jiangsu Provincial Engineering Consultancy Center, Nanjing, China, Post Code: 210003)// Journal of Engineering for Thermal Energy &Power. — 2007, 22(3). —301 ~305

When a transient hydraulic change occurs to the circulation water system of a thermal power plant, the condenser may be subjected to a loss of cooling water, leading to an increase of operating pressure of the condenser, and thereby affecting the operating stability and safety of a steam turbine unit. The optimized setting of the open-close mechanism of circulation pump outlet valves can play a definite role in controlling the maximal water loss amount to the condenser. The authors have proposed a method for combining the calculation of a hydraulic transition process with that of the off-design conditions of the condenser to optimize the setting of the valve open-close mechanism. The practical application of the above method for a 300 MW steam turbine unit shows that under the optimized mechanism determined by the method, the minimal flow rate of the condenser has increased from 1.991 m^3/s to 2.271 m^3/s while the highest pressure of the condenser decreased from 22.111 kPa to 16.911 kPa. As a result, the hydraulic safety of the circulation water system has been ensured with a simultaneous consideration of the dynamic characteristics of the condenser during the transient process, thus contributing to a safe and steady operation of the steam turbine unit. **Key words**: thermal power plant, circulation water system, transient hydraulic change, open-close mechanism of valves, condenser operating pressure

船用增压锅炉旋流蒸汽机械喷油器的雾化特性＝**Atomization Characteristics of Swirling Steam-based Mechanical Oil Sprayers for a Supercharged Marine Boiler** [刊, 汉] /WANG Jian-zhi, WU Shao-hua, QIN Yu-kun (College of Energy Science and Engineering under Harbin Institute of Technology, Harbin, China, Post Code: 150001), WANG Yong-tang (Harbin No.703 Research Institute, Harbin, China, Post Code: 150036)// Journal of Engineering for Thermal Energy &Power. — 2007, 22(3). —306 ~309

By using a LPI-3 diffraction type caliper gage of laser particles and a LE-3 atomizing-angle measuring device an experimental study has been conducted of the above-mentioned oil sprayer for marine use. Identified was the variation relationship between the Sauter mean diameter of atomized oil droplets and sprayed oil quantity on the one hand and its oil pressure on the other. By utilizing the Realizable k-ε model, the turbulent gas flow was simulated followed by a simulation of the droplet movement by using a random orbit model. The deformation and fragmentation of droplets were also simulated by employing the LISA and TAB models. A numerical simulation was performed of the atomization process of the above-mentioned oil sprayer along with an analysis of the effect of the atomized air and oil mass flow rate in the oil sprayer on the atomization characteristics. The simulation results are in comparatively good agreement with the test ones. The research indicates that when the oil spray pressure is above 1.1 MPa, the oil sprayer characteristics comply with the general

law of mechanical atomizing nozzles. But when the oil spray pressure is relatively low, the atomization mechanism will take a reverse course, i.e. the lower the oil spray pressure, the finer the atomized particles. From the foregoing it can be shown that the swirling steam-based mechanical atomized-oil sprayer can maximally improve the atomization quality under a low-load operating condition and has a relatively large turndown ratio with a steam consumption rate lower than that of an often-used pneumatic atomized-oil sprayer. **Key words**: supercharged boiler, oil sprayer, atomization characteristics, numerical simulation

基于粗糙集理论的火焰图像处理与状态识别=**Flame Image Processing and Status Discrimination Based on Rough Sets Theory** [刊, 汉] /WU Guang-fu, LU Zhen-zhong (College of Energy Source and Environment under the Southeast University, Nanjing, China, Post Code: 210096)// Journal of Engineering for Thermal Energy & Power. —2007, 22(3). —310 ~313, 321

A flame status discrimination method based on rough sets theory has been presented in the light of the main problems concerning the flame detection of an entire furnace. The method makes use of the classification principle in the rough sets theory to identify the high temperature zone of flame combustion. In combination with other flame image characteristic values, a knowledge decision-making system was employed based on the rough sets theory to set up flame-status discrimination rules and establish a basic model for the discrimination of entire furnace combustion status to make a judgement of the latter. As the decision-making table is of a simple attribute expression, it lends itself to be easily understood by operators and provides operation guidance for boiler combustion regulation. The on-site tests indicate that the characteristic magnitudes of flame images have a close bearing on the quality of combustion process. The processing based on the rough sets theory can lead to a higher effectiveness and the quantitative classification by adopting attribute sets should help realize a qualitative discrimination of the output values, thus resulting in a precise and reliable discrimination of the system status. **Key words**: rough set, image processing, status discrimination, flame detection, decision-making table

基于混沌理论的 PID 参数自整定锅炉汽包水位控制系统设计=**Design of a Water Level Control System for the Drum of a PID Parameter and Self-tuning Boiler Based on Chaotic Theory** [刊, 汉] /LU Ning, JI Qiu-yun, XIA Zeng-gang (College of automation under the Harbin University of Science and Technology, Harbin, China, Post Code: 150080)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —314 ~316

The water level in a boiler drum is an important index for the safe and steady operation of an industrial steam boiler. Nowadays, for the water level control usually adopted are feed-forward cascade three-impulse controllers. The control effectiveness is heavily dependent on the proper selection of PID (proportional-integral-differential) parameters of the controller. However, the commonly used parameter-adjusting method involves complicated and tedious steps, resulting in a relatively low searching efficiency. Furthermore, the method is not always an optimized one and big oscillations and overshoots often occur to the control system. By making use of the ergodicity specific to the chaotic theory, one can improve the chaotic-searching optimization method based on Logistic mapping. Presented was a new chaotic PID-parameter optimization method by using one-dimensional iterative chaotic self-mapping which features infinite collapses in a finite region. The simulation results obtained by using the boiler drum models show that the relevant algorithm has a relatively high searching efficiency and accuracy, capable of realizing an optimized adjustment of PID parameters. **Key words**: drum water level, chaos, optimization, PID control

低热值煤层气燃烧器的数值模拟=**A Numerical Simulation of a Low-heat-value Coal-bed Gas Burner** [刊, 汉] /LUO Yu-dong, ZHANG Li, TANG Qiang, et al (College of Power Engineering under the Chongqing University, Chongqing, China, Post Code: 400030)// Journal of Engineering for Thermal Energy & Power. — 2007, 22(3). —