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注蒸汽对涡轮增压器的影响

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摘　要: 水蒸气与燃气混合后的混合气体注入涡轮后, 涡轮增压器会出现运行状态的变化。经对注蒸汽后的涡轮增压器进行了热力学的分析, 认为: 汽气比的增大使增压器的转速、压气机空气流量和压气机压比增高; 注汽温度对压气机压比有较小影响; 低工况时, 水蒸气的注入使涡轮的折合流量、膨胀比皆增大; 在高工况时, 膨胀比、折合流量能够增大的幅度减小; 不同的汽气比对涡轮效率特性曲线影响较小。

关　键　词: 涡轮增压器; 注蒸汽; 汽气比

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1　前　言

涡轮增压柴油机是柴油机与涡轮增压器所组成的复合式发动机, 在各种工况下, 涡轮增压装置应该向柴油机提供足够的空气量, 如果涡轮增压器的供气量不足, 就会引起工作过程的恶化。通常是涡轮增压柴油机在低工况运行时会出现增压压力不足, 燃烧过量空气系数小和废气排温较高等固有特性, 其直接表现就是涡轮增压器不能提供运行条件所要求的压比, 满足对空气量的要求。在涡轮增压器的涡轮前注蒸汽是改善涡轮增压柴油机低工况性能的方法之一, 而注蒸汽后涡轮增压器的变化是必须要关注的。

涡轮增压器的主要工作参数有压气机和涡轮的等熵效率、压气机压比、涡轮膨胀比、气体流量和涡轮增压器转速等, 并以这些参数及其相互关系来表示涡轮增压器的工作性能。在涡轮注入水蒸气后, 由于气体流量增大, 气体工质改变, 并且气体的作功能力增强, 导致涡轮增压器的工作点发生变化, 涡轮折合流量、涡轮等熵效率、涡轮膨胀比、压气机压比和涡轮增压器转速等都发生了改变。

2　燃气物性的变化

注水蒸气影响涡轮增压器性能的根本原因是由于燃气中所含有水蒸气参数的变化。湿燃气作为燃气和水蒸气的混合气体, 被认为符合"高温、低压"的条件, 可以按理想气体处理[2]。

对应于燃料系数为 β 的燃气, 汽气比(水蒸气与空气质量比)为 g_s, 则对于由 $C_xH_yO_zN_uS_v$ 燃气和水蒸气组成的湿燃气, 其任意同名摩尔热力性质为($x_{n,\beta,s}$、$x_{n,\beta}$、x_s 分别表示湿燃气、燃气、水蒸气的摩尔热力性质):

$$x_{n,\beta,s} = r_{n,\beta} \cdot x_{n,\beta} + r_s \cdot x_s$$

式中:

$$r_{n,\beta} = [(1+d)(x+y/4+v-z/2)+\beta(y/4+z/2+u/2)] / [(1+d)(x+y/4+v-z/2)+\beta(y/4+z/2+u/2)+(M_a/M_s)g_s(1+d)(x+y/4+v-z/2)]$$

$$r_s = [(M_a/M_s)g_s(1+d)(x+y/4+v-z/2)] / [(1+(M_a/M_s)g_s)(1+d)(x+y/4+v-z/2)+\beta(y/4+z/2+u/2)]$$

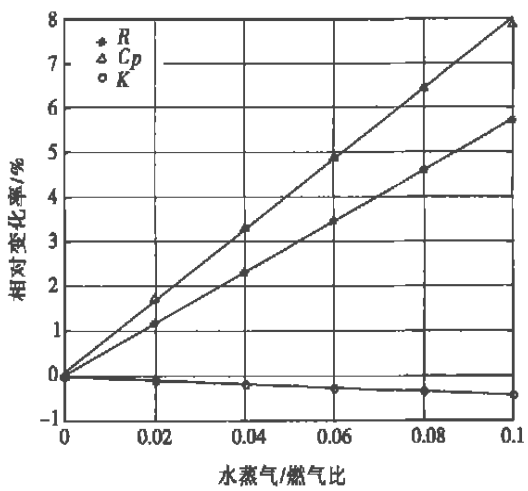

图 1　水蒸气与燃气混合气体物性的变化

其中: $d = 3.77382$, 大气中氮氧摩尔成分之比。

图 1 给出了燃气与水蒸气的混合气体的气体常

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数 R、定压比热 Cp、绝热指数 k 随水蒸气 / 燃气比（水蒸气质量与燃气质量比）的变化关系。此时，燃气与水蒸气的混合气体（湿燃气）的温度为 800 K、压力为 0.3 MPa。

由图中可以看出，混合气体的气体常数、定压比热随水蒸气 / 燃气比的改变而变化较大，并且随着水蒸气/ 燃气比的增加而增大；绝热指数随水蒸气/ 燃气比的改变而变化较小，并且随着水蒸气 / 燃气比的增加而减小。

3　增压器的变化

对于某型涡轮增压器，进行了涡轮前注水蒸气后的计算。

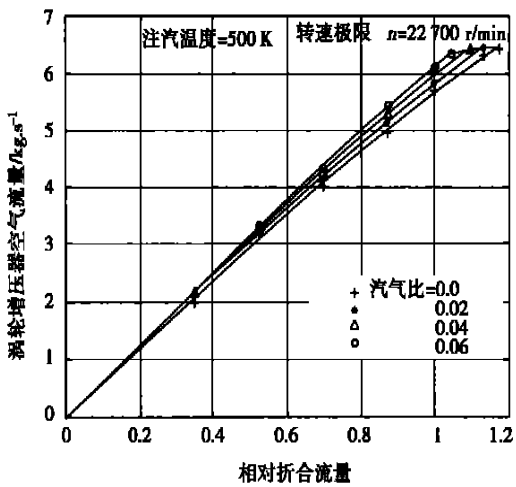

图 2　汽气比对涡轮增压器空气流量的影响

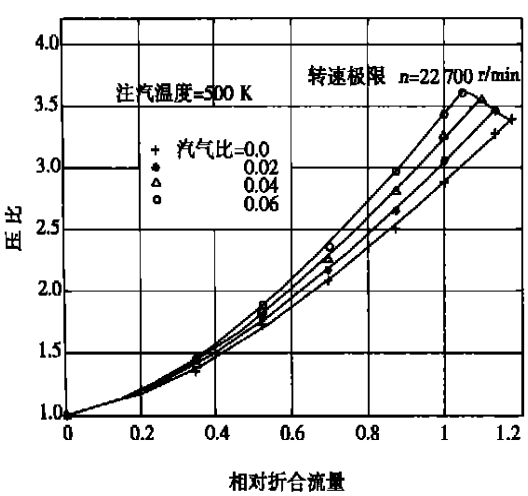

图 3　汽气比对涡轮增压器压比的影响

图 2 ~ 图 4 表示不同水蒸气流量对增压器空气流量、增压器压比和增压器转速的影响。由图可以看出，汽气比越高，注汽对增压器压比的影响越大。此时涡轮内工质作功能力增强，涡轮增压器转速增加，增压器压比增大，体积流量增加。但在某一相对折合流量时，当涡轮增压器转速达到自身的极限转速时，汽气比不可再增大。因此，在涡轮增压柴油机低工况运行时，压比不能满足流量要求的情况下，在满足涡轮增压器转速极限要求时，可通过改变注水蒸气流量的大小，来获得所需的压比和空气流量。

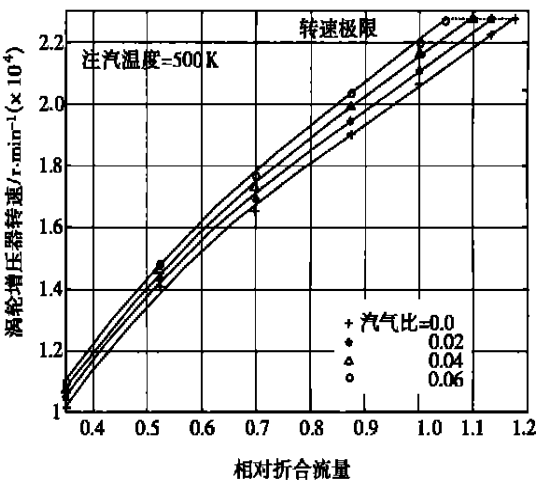

图 4　汽气比对涡轮增压器转速的影响

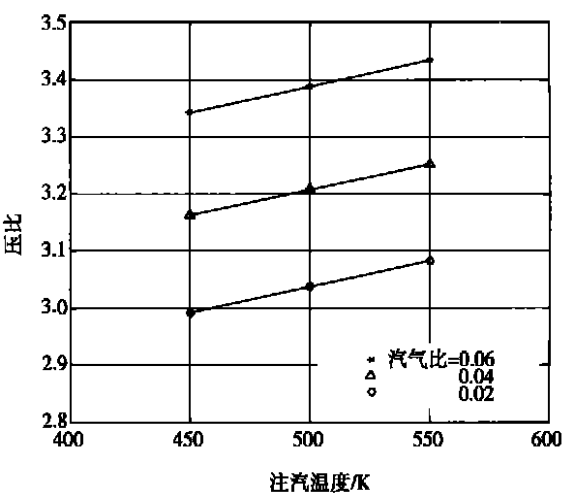

图 5　注汽温度对涡轮增压器压比的影响

图 5 表示注汽温度对涡轮增压器压比的影响。由图中可以看出，注汽温度对压气机压比有一定的影响，并且温度越低，压比增加越小。这是因为，如果蒸汽的温度过低，导致蒸汽和燃气混合气体的温度过低，其在涡轮内做功减小，直接影响压气机压比；并且注蒸汽的温度不能过低，否则会直接影响涡轮

的做功能力，但相对于注蒸汽量对压比的影响，注蒸汽温度对压比的影响较小。因此，在注蒸汽时应考虑注蒸汽量和注蒸汽温度的协调，使得涡轮增压器的性能达到最佳改善效果。

4 涡轮性能的变化

涡轮性能曲线表示了各种工况下涡轮主要工作参数间的变化关系，是确定涡轮与发动机匹配合理与否的重要依据。对于注水蒸气后的涡轮来说，由于水蒸气的注入，表征涡轮的通流能力的流量特性曲线变化较大。流量特性曲线是以折合流量 $q_{mT}\sqrt{T_T^*}/P_T^*$ 为横坐标，膨胀比 P_T^*/P_2 为纵坐标，折合转速 $n_T/\sqrt{T_T^*}$ 为参变量的一组曲线。图 6 表示了某型涡轮增压器的涡轮在相同涡轮入口条件下，不同汽气比时的涡轮流量特性曲线。

如图 6 所示，在涡轮中注入水蒸气后，涡轮的工作点随着汽气比的增大，折合流量增大，膨胀比升高，折合转速增加。在相同的膨胀和折合转速下，汽气比增加，相应的折合流量减小。如果要使折合流量保持不变，必须使涡轮的膨胀比增加，并且折合转速一定时，折合流量随膨胀比的增大而增加，直至达到最大流量。若再继续增大膨胀比，涡轮流量也不会再增加，此时涡轮喷嘴处气流速度已达到了当地声速，发生了流量阻塞。由图中可以看出，在低折合转速时，即低工况时，涡轮内注入水蒸气后，涡轮的折合流量、膨胀比皆增大。但在高折合转速时，即高工况时，涡轮内注入水蒸气后，工作点向阻塞点移动。

同时，对图 6 所示涡轮进行了在 0.3 工况下对于不同汽气比的涡轮效率曲线计算。计算结果表明，由于注小流量水蒸气后混合气体的物性变化较小，同时涡轮的膨胀比增加，因此汽气比的增大使涡轮的效率产生较小变化，如图 7 所示。

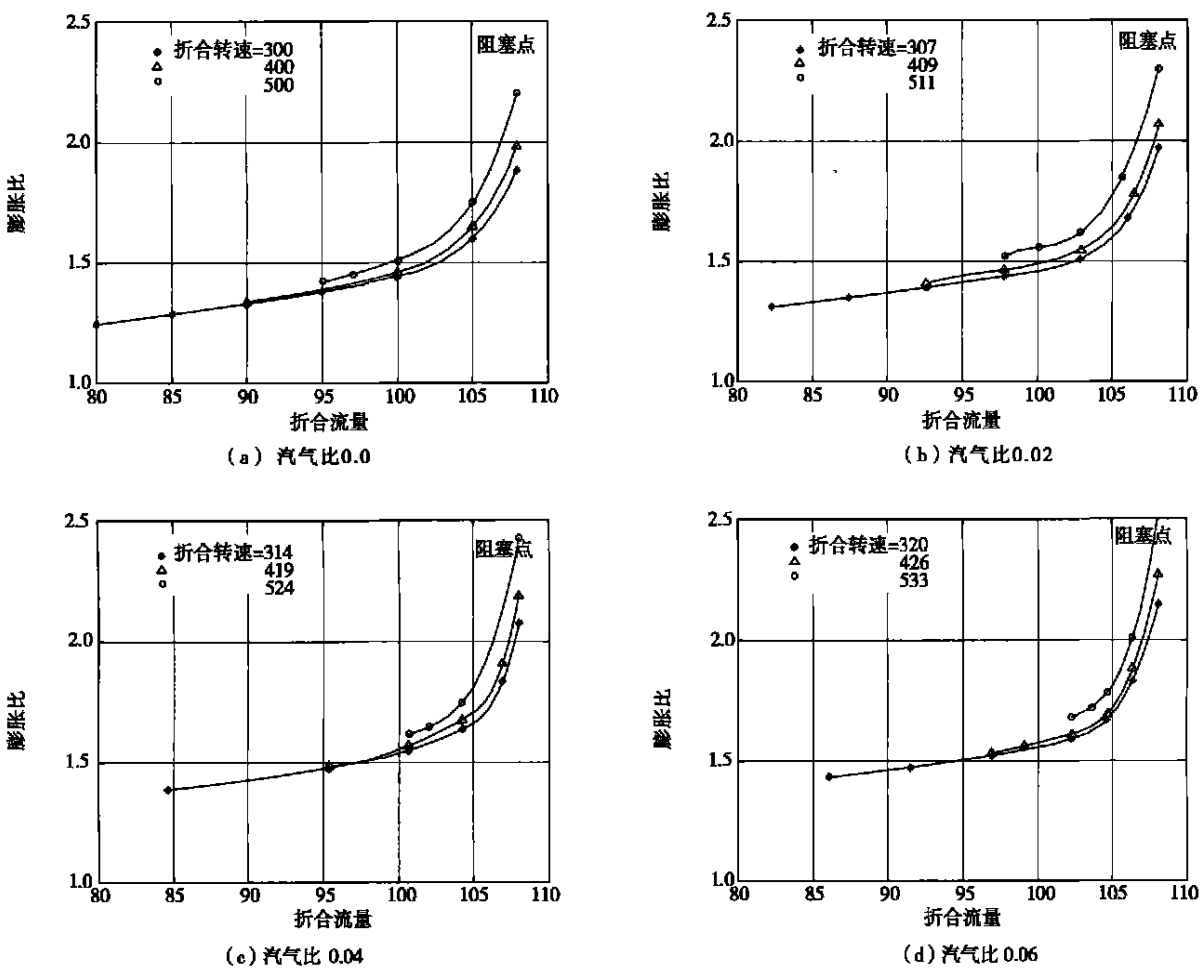

图 6 汽气比对涡轮流量特性的影响

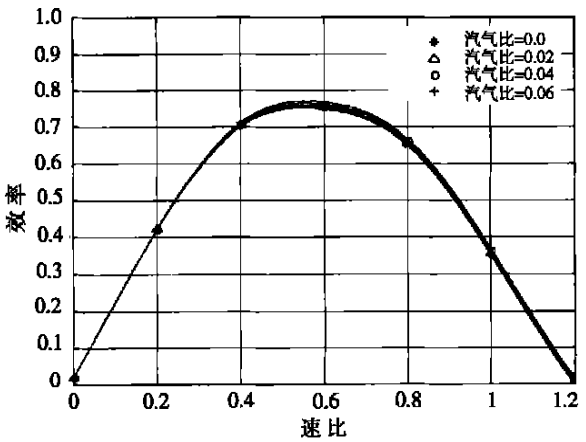

图 7　汽气比 对涡轮效率的影响

5　结　论

(1) 给出燃气和水蒸气混合气体的摩尔热力性质的计算公式。并指出燃气和水蒸气混合气体的气体常数、定压比热随水蒸气/燃气比的改变而变化较大, 绝热指数随水蒸气/燃气比的改变而变化较小。

(2) 对于某型涡轮增压器, 进行了涡轮前注水蒸气后的计算, 得出了不同水蒸气流量对增压器空气流量、增压器压比和增压器转速的影响: 汽气比越大, 增压器的转速越高, 压气机空气流量越大, 压气机压比越高; 但汽气比不能过大, 否则涡轮增压器的转速会超出极限。

注汽温度对压气机压比有一定的影响, 并且温度越低, 压比增加越小。

(3) 对某型涡轮增压器进行了计算, 得出了不同汽气比时的涡轮流量特性曲线, 计算结果表明: 低工况时, 涡轮内注入水蒸气后, 涡轮的折合流量、膨胀比皆增大, 能够满足涡轮增压器对涡轮的要求。在高工况时, 涡轮内注入水蒸气后, 工作点向阻塞点移动, 并且汽气比越大、折合转速越高, 其膨胀比、折合流量能够增大的幅度越小。

对同一涡轮增压器的涡轮得出了效率特性曲线, 计算结果表明: 不同的汽气比对涡轮效率特性曲线影响较小。

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(何静芳　编辑)

新结构

涡轮机蜂窝状密封优化的方法

据《ИВУЗ Энергетика》2002 年 5～6 月号报道, 提高涡轮和压气机经济性和可靠性的方法之一是减少与工质沿装置旋转零件和静止零件之间各种间隙漏泄有关的损失。

与传统的曲径式密封相比, 蜂窝状密封具有许多优点。它在最小的材料质量下能保证密封具有最大的强度, 从而允许在高压降下应用, 而不增加密封的尺寸。此外, 它还简化了涡轮机组安装和修理时的装配工作。

蜂窝状密封内过程的特点是由气流在具有蜂窝壁的槽道内流动的物理本质决定的。蜂窝状结构的几何形状应该根据能反映这些结构因素和状态参数影响的多因素试验进行优化。在涡轮机械通流部分内利用蜂窝状密封在减少径向间隙值时, 而且借助于优化密封蜂窝室几何参数的关系显著提高了涡轮机械的经济性。

(吉桂明　供稿)

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

Industry Co., Tangshan, Hebei Province, China, Post Code: 063502) // Journal of Engineering for Thermal Energy & Power. — 2003, 18(3). — 272 ~ 275

After the injection of a gaseous mixture of steam and gas into a turbine a change in turbocharger operating condition will take place. In this connection the authors have performed a thermodynamic analysis of the turbocharger after steam injection. It is concluded that the increase in steam-gas ratio will lead to an increase in turbocharger speed, compressor airflow rate and pressure ratio. The impact of injected steam temperature on compressor pressure ratio is relatively small. During part-load operating conditions the injection of steam will result in an increase in turbine corrected flow rate and expansion ratio. During high-load operating conditions the range of increase in expansion ratio and corrected flow rate diminishes. Different steam-gas ratios have a relatively small influence on turbine efficiency characteristics. **Key words**: turbocharger, steam injection, steam-gas ratio

电站煤粉锅炉飞灰浓度模型 = **Fly-ash Concentration Model for a Utility Pulverized Coal-fired Boiler** [刊, 汉] / XUAN Yi-min, FENG Chang-qing, LI Qiang (Power Engineering Institute under the Nanjing University of Science and Technology, Nanjing, China, Post Code: 210094) // Journal of Engineering for Thermal Energy &Power. — 2003, 18(3). — 276 ~ 279

On the basis of the basic theory of boiler thermal balance and combustion theory set up is an online monitored parameters-based fly-ash concentration calculation model. The model has a definite practical engineering value for the online measurement of fly-ash carbon content. **Key words**: pulverized coal-fired boiler, fly-ash carbon content, fly-ash concentration, thermal efficiency

基于小波变换的离心风机弱失速特征分析 = **Analysis of Weak Rotating-stall Characteristics of a Centrifugal Fan Based on Wavelet Transformation** [刊, 汉] / HOU Jun-hu, WANG Song-ling, WANG Qiang, et al (Power Engineering Department, North China Electric Power University, Baoding, Hebei Province, China, Post Code: 071003) // Journal of Engineering for Thermal Energy &Power. — 2003, 18(3). — 280 ~ 284

A rotating-stall test was conducted of a lab 4-73 No. 8d fan with harmonic wavelet transformation being introduced into the study of rotating stall. Through a time-frequency analysis of fan-casing pressure signals during a weak rotating-stall stage determined were the rotating-stall energy intermittency, frequency characteristics and sensibility of regulation function at that stage. This indicates that the weak rotating-stall stage of the centrifugal fan is a major region worthy of close attention on the part of operational and maintenance personnel. In addition, the foregoing also has laid a firm basis for the further in-depth research of centrifugal fan rotating-stall. **Key words**: harmonic wavelet, centrifugal fan, rotating stall, weak rotating stall, analysis of characteristics

石门电厂 300 MW 机组引风机振动分析 = **An Investigation on Inducd-draft Fan Vibrations in a 300MW Unit of Shimen Power Plant** [刊, 汉] / WANG Yun-min, XIAO Han-cai (Changsha Electric Power Institute, Changsha, Hunan Province, China, Post Code: 410077), ZHAO Shi-chang, et al (Hunan Shimen Power Plant, Shimen, Hunan Province, China, Post Code: 415300) // Journal of Engineering for Thermal Energy &Power. - 2003, 18(3). — 285 ~ 288

The vibrations of an induced-draft fan installed at Shimen Power Plant are analyzed and tested. The cause of the excessive vibrations has been identified and proper measures were taken to alleviate them. The results of operation thereafter indicate that the vibration performance of the induced-draft fan has significantly improved, fundamentally resolving the problem of safe and economical operation of the power plant caused by the excessive vibrations of the fan. **Key words**: power plant, induced-draft fan, vibration