热力工程

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对冲旋流锅炉的配风调整试验研究

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摘 要:针对深度空气分级的低氮燃烧技术改造后的锅炉排烟中CO浓度高,飞灰含碳量偏高,减温水用量偏高和受热面容易超温等常见问题。在1台2 070 t/h对冲旋流燃烧锅炉上实施了配风调整优化试验,通过对运行氧量、燃尽风率和前后墙燃尽风配比的综合调整,获得了锅炉运行调节的最优参数。取得了锅炉效率上升1.88%,省煤器出口NO_x浓度下降15 mg/m³,过热减温水量下降95.2 t/h,再热减温水量下降10.6 t/h的综合优化成果。

关 键 词:旋流燃烧;对冲燃烧;低氮燃烧;配风调整;运行优化

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引 言

为应对日益严峻的NO_x(氮氧化物)减排形势,火力发电厂大量采用了深度空气分级的低氮燃烧技术改造现役煤粉锅炉[1~2]。深度空气分级低氮燃烧技术的特点是,在最上层燃烧器喷口以上布置一组燃尽风喷口,二次风中的一部分从燃尽风喷口给入。燃烧器喷口与燃尽风喷口之间形成一定高度的还原区,将锅炉燃烧室分隔为两个不连续的燃烧反应区段:下部燃烧器喷口所在区域称为主燃区,主燃区过量空气系数控制在1.0以下;上部燃尽风喷口所在区域称为燃尽区,燃尽区风量占总风量的20%以上。煤粉锅炉采用低氮燃烧技术后的NO_x减排效果首先取决于入炉煤的挥发分含量,挥发分含量越高,燃烧中NO_x的生成量也能做到越低[3]。除燃尽风和还原区的设置外,燃烧器中煤粉的浓淡分离方式,氧气浓度,内外二次风量分配和旋流强度的设计等[4~7],也都是影响旋流燃烧锅炉氮氧化物生成的重要因素。

低NO_x旋流燃烧器大致可分为:分级燃烧型旋流燃烧器和浓缩型旋流燃烧器[8~10]。分级燃烧型旋流燃烧器的特点是二次风分级供给且没有对一次风煤粉气流进行浓淡分离,它的原理是在燃烧初期减少二次风的供给,形成还原性气氛,从而抑制NO_x的生成。浓缩型旋流燃烧器特点是将煤粉气流分成浓淡的两股气流,结合燃烧器内空气分级技术,在燃烧器出口处形成合理的煤粉颗粒分布和空气动力场分布[11~12],使煤粉在低氧且富燃料条件下燃烧,以抑制NO_x的生成和保证燃料燃烧充分。

采用低氮燃烧技术改造后的现役锅炉,虽然NO_x排放水平相比改造前有明显下降,但也不同程度地出现了排烟中CO浓度高,飞灰含碳量增大,减温水用量偏高和受热面容易超温等一系列问题。电站锅炉试验研究表明[13~15],煤种、煤粉细度和燃尽风风量等运行操作参数对旋流燃烧器的燃烧特性有很大的影响,通过合理的燃烧调整优化试验,能够有效的降低NO_x排放,同时降低排烟中CO浓度和飞灰可燃物含量。

1 试验对象

某电厂2 070 t/h锅炉采用中速磨正压直吹式制粉系统,配6台HP1103型磨煤机,正常运行投运5台磨煤机,1台备用,设计煤粉细度$R_{90}=20\%$。投产时采用30只LNASB轴向旋流式煤粉燃烧器如图1所示[16],每台磨煤机对应5只燃烧器,分别布置于前后墙,形成对冲燃烧。为进一步降低炉膛内NO_x的生成,在加装尾部烟道脱硝装置的同时,采用中心给粉低氮旋流燃烧器对锅炉进行了改造如图2所示。

根据锅炉原有燃烧系统的结构、布置特点,以及降低工程项目技术风险的要求,低氮燃烧技术改造

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的内容分为两个主要部分: 首先，在原燃尽风喷口(OFA) 上再增设一层燃尽风喷口(OFA2) ，燃尽风喷口采用直流一次风在内，旋流二次风在外的结构，如图 3 所示，前、后墙各 5 只，并为其配备风箱、风道、风量调节及测量装置等; 其次，将锅炉 BCDEF 磨煤机对应的 25 只 LNASB 型煤粉燃烧器更换为中心给粉低氮燃烧器，其主要接口设计与原 LNASB 燃烧器保持一致，燃烧器数量、布置位置及旋转方向均保持不变，燃烧器喷口与水冷壁开孔的密封方式不变，不改变现有水冷壁结构。同时，原 A 层等离子燃烧器和(OFA) 燃尽风喷口不作改动，改造前后炉膛水冷壁结构如图 4 所示。

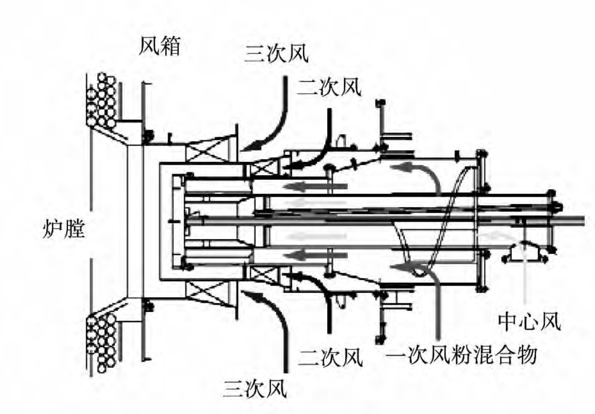

图 1　LNASB 轴向旋流式煤粉燃烧器结构示意

Fig. 1 Structure of Low NO_x Axial Swirl Burner (LNASB)

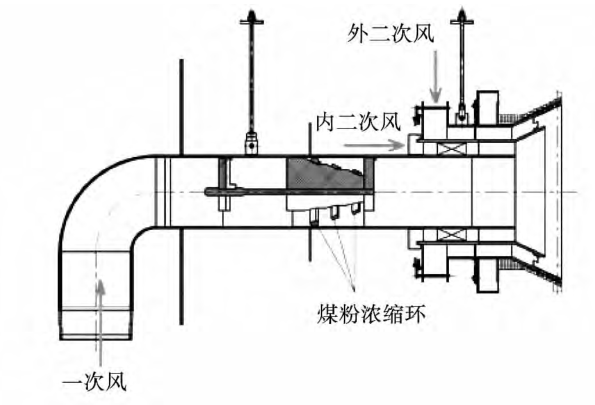

图 2　中心给粉低氮燃烧器结构示意

Fig. 2 Structure ofcentrally fueled and low NO_x swirl burner

锅炉的供风主要分为一次风和二次风两部分，改造后燃烧器的设计参数如表 1 所示。一次风经制粉系统送入炉膛，锅炉在一定负荷下运行时，运行磨煤机的数量也唯一确定，单台磨煤机的经济运行风量即决定了总一次风量的大小。深度空气分级的低氮燃烧技术中，二次风又分为主燃区二次风和燃尽风，根据燃烧器设置位置和结构形式，各层二次风量的大小一般也不完全相同。总二次风量的大小和各层二次风的分配都需要通过配风调整试验来确定[17~19]，在尽可能提高锅炉运行经济性的同时，还应降低炉膛内 NO_x 的生成量。

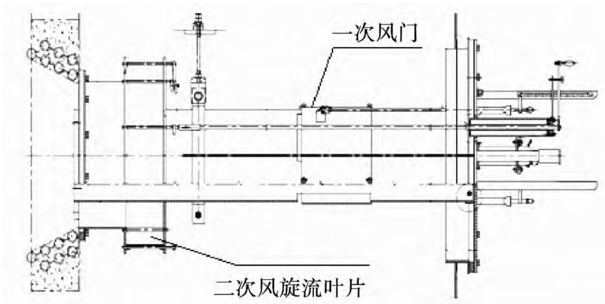

图 3　增设的旋流燃尽风喷口(OFA2) 结构示意

Fig. 3 Structure of Over Fire Air(OFA2) swirl nozzle

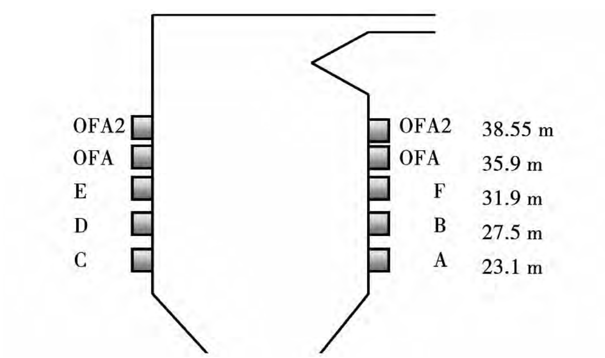

图 4　改造后的炉膛水冷壁结构示意

Fig. 4 Configuration of furnace water wall

表 1　燃烧器主要设计参数

Tab. 1 Design parameters of swirl burner

参　数	数　值
单只燃烧器输入热/kJ · h^{-1}	188.8×10^6
炉膛出口过量空气系数	1.2
二次风速/m · s^{-1}	19.2
二次风温/℃	327
二次风率/%	73.5
二次风中燃尽风比率/%	25.0
一次风速度/m · s^{-1}	19.2
一次风温度/℃	77
一次风率/%	21.5

试验中，通过测量省煤器出口的烟气成分来分析炉膛内的燃烧和污染物生成情况。烟气成分测点布置在省煤器出口(即脱硝系统入口) 烟道，取烟道截面上多点测量数据的平均值。以烟气中 CO 的浓度表征炉膛内燃料的燃尽程度; 以 NO_x 浓度表征炉膛内 NO_x 的生成量，按式(1) 将其折算至氧量为 6% 的条件下的浓度。

$$c^* = \frac{15}{21 - O_2}c \tag{1}$$

式中: c^* —折算后的 NO_x 或 CO 浓度，mg/m^3; c—实测的烟气中 NO_x 或 CO 浓度，mg/m^3; O_2—实测的烟气中氧气的体积浓度，%。

2　试验结果

2.1　氧量优化试验

锅炉设计中，通常在省煤器出口烟道内布置多个在线测点，测量烟气中氧气的体积浓度(氧量) 。日常的运行调整中，氧量表征了进入锅炉的总空气量，氧量越大，越有利于炉膛内燃料的燃尽。但是烟气量的增加又会使锅炉的排烟热损失增大，同时氧量增加也会削弱炉膛内的还原性气氛，导致炉膛内 NO_x 生成量增加。因此，理论上存在一个最优的运行氧量，使燃烧效率较高的同时抑制 NO_x 的生成。

如图 5 所示，锅炉在 ECR(额定工况主汽流量约 1 880 t/h) 下运行时，随着氧量的增加，CO 浓度先快速下降，NO_x 浓度变化不明显; 氧量大于 2% 后，CO 浓度的下降幅度明显变小; 氧量大于 2.5% 时，NO_x 浓度快速上升。据此判断，锅炉氧量在 2% ~2.5% 区间运行时，其燃烧效率和 NO_x 排放的综合效果最优。

2.2　燃尽风率优化试验

在燃烧器以上一定高度设置燃尽风，是深度空气分级低氮燃烧技术的最显著特征。燃尽风的设置使燃尽区以下形成较强的还原性气氛，有利于抑制主燃区中 NO_x 的生成，燃尽风风量与总风量的比值称为燃尽风率。过大的燃尽风率一方面导致燃料中的焦碳无法在主燃区完全燃尽，飞灰含碳量增加; 另一方面焦炭内残留的部分燃料氮会在燃尽区被重新氧化，使炉膛内 NO_x 的生成量增加。此外，燃尽区内的燃烧份额过大还会导致炉膛内火焰中心上移，蒸汽受热面的减温水用量增大。因此，最佳的燃尽风率是既保证燃料中焦炭在主燃区内充分燃尽，又使主燃区形成适宜的还原性气氛，还能维持炉膛内火焰中心的合理高度。

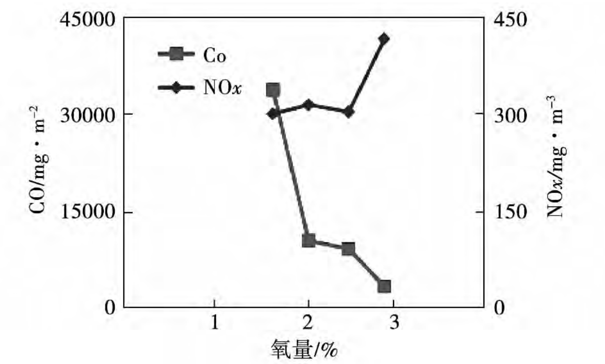

图 5　运行氧量对烟气中 CO 和 NO_x 浓度的影响

Fig. 5 Effect of Oxygen oncarbon monoxide (CO) and nitrogen oxides (NO_x) in flue gas

如图 6 所示，锅炉在 ECR 工况下运行，燃尽风门在可调范围变化时，下层燃尽风率(3% ~8%) 对烟气中 NO_x 浓度的影响不明显。下层燃尽风率小于 7% 时，烟气中 CO 浓度的变化较小; 下层燃尽风率大于 7% 时，烟气中 CO 浓度随燃尽风率的增加出现明显增大。随着上层燃尽风率(7% ~15%) 的增加，烟气中 CO 浓度近似呈线性增大，NO_x 浓度近似呈线性减小。

2.3　前后墙燃尽风分配优化试验

在 ECR 工况下，ABCDF 磨煤机运行时，改变前后墙下层燃尽风比例，对省煤器出口烟气中 CO 和 NO_x 的浓度的影响情况如图 7 所示，图中横坐标为前墙下层燃尽风量与后墙下层燃尽风量的比值。当前墙燃尽风量小于后墙燃尽风量时，烟气中 CO 和 NO_x 的浓度均较低，这是由于此次前墙投入的燃烧器数量少于后墙，燃尽风从后墙补入更有利于主燃区生成的还原性气体与燃尽风的混合，既有利于提高燃烧效率又能有效抑制 NO_x 生成。

2.4　试验前后锅炉性能对比

在锅炉配风优化调整试验前后，在 ECR 工况下分别测试了锅炉效率、省煤器出口 NO_x 浓度和过再热减温水量等主要性能指标，如表 2 所示，其中各数值均为两小时稳定负荷下的平均值。通过配风的调

整优化,使锅炉效率上升 1.88%,省煤器出口 NO_x 浓度下降 15 mg/m³,过热减温水量下降 95.2 t/h,再热减温水量下降 10.6 t/h。锅炉的经济性能和环保性能均有明显提升。

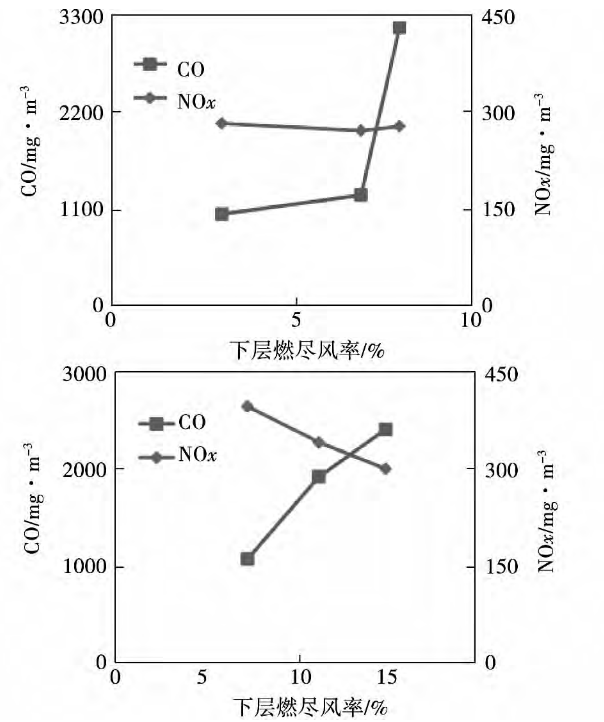

图 6　燃尽风率对烟气中 CO 和 NO_x 浓度的影响

Fig. 6 Effect of OFA rate oncarbon monoxide (CO) and nitrogen oxides (NO_x) in flue gas

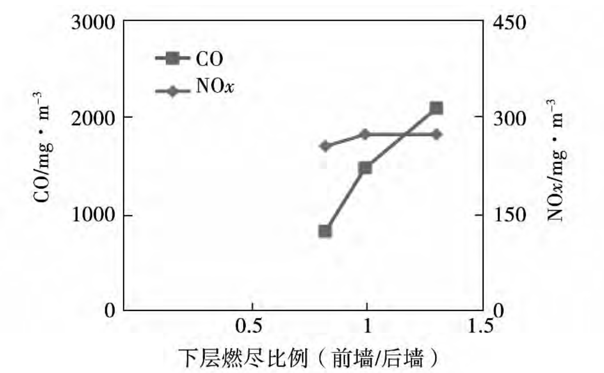

图 7　前后墙燃尽风分配对烟气中 CO 和 NO_x 浓度的影响

Fig. 7 Effect of OFA feeding location oncarbon monoxide (CO) and nitrogen oxides (NO_x) in flue gas

表 2　优化调整前后锅炉主要性能对比

Tab. 2 Comparison of performances before and after optimization

参　数	调整前	调整后
锅炉效率/%	90.40	92.28
NO_x/mg·m^{-3}	241	226
过热减温水量/t·h$_{-1}$	270.3	175.1
再热减温水量/t·h^{-1}	21.8	11.2

3　结　论

以深度空气分级为特征的低氮燃烧技术,存在一个范围较窄的最优运行区间,使其在获得高燃烧效率的同时有效抑制 NO_x 的生成。以省煤器出口的 CO 和 NO_x 浓度分别作为炉膛内燃烧效率和污染物排放的指标,可以方便地判别出低氮燃烧的最佳配风方式,从而实现锅炉运行经济性和环保性能的综合优化。基于 2 070 t/h 旋流燃烧锅炉的配风调整试验,获得如下结论:

(1) 合适的氧量应保证燃料燃烧所需过量空气的同时,维持炉膛内一定强度的还原性气氛,并尽量减少排烟热损失。锅炉氧量在 2% ~2.5% 区间运行时,其燃烧效率和 NO_x 排放的综合效果最优;

(2) 最佳的燃尽风率是既保证燃料中焦炭在主燃区内充分燃尽,又使主燃区形成适宜的还原性气氛,还能维持炉膛内火焰中心的合理高度,ECR 工况下的最佳燃尽风率在 14% 左右;

(3) 根据燃烧器投运数量的差异调整前后墙燃尽风量的分配,有利于燃尽风与主燃区生成的还原性气体混合,既有利于提高燃烧效率又能有效抑制 NO_x 生成。

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Power. －2016，31(8). －44～50

In the low pressure turbine of aero-engines，especially the power turbine of turbo-shaft and turbo-prop engines，the rotor blades are usually shrouded and pre-twisted. The introduced pre-twist in power turbine rotor blades is inevitable to bring certain effects on the aerodynamic performance and flow status of the turbine parts. This paper，taking the whole turbine part of a certain engine as the research object，numerically investigated the aerodynamic effects of the pre-twist in two-stage power turbine rotor blades on the turbine part under ground take-off and max cruise conditions. The results showed that the pre-twist in two-stage power turbine rotor blades has evident effects on the performance and flow status of the LP turbine and power turbine in the turbine part，and the effects produced by the two-stage rotor blades respectively can be overlaid. As the power turbine operation status is distinct on ground and in the air，the pre-twist effect on the aerodynamic loss in the power turbine is also distinct. **Key words:** power turbine，blade，pre-twist，aerodynamic effects，ground takeoff，max cruise

液压型风力发电机组功率追踪及功率平滑多目标控制研究＝Research on Multi-objective Control of Maximum Power Point Tracking and Power Smoothing in Hydraulic Wind Turbine [刊，汉] ZHANG Yin (School of Mechanical Engineering of Yanshan University，Qinhuangdao，China，Post Code：066004)，KONG Xiang-dong (Hebei Provincial Key Laboratory of Heavy Machinery Fluid Power Transmission and Control，Yanshan University，Qinhuangdao，China，Post Code：066004)，CHEN Li-juan (School of mechanical engineering of Yanshan University，Qinhuangdao，China，Post Code：066004)，CHEN Li-jian (School of Mechanical Engineering of Yanshan University，Qinhuangdao，China，Post Code：066004)，AI Chao (Hebei Provincial Key Laboratory of Heavy Machinery Fluid Power Transmission and Control，Yanshan University，Qinhuangdao，China，Post Code：066004) // Journal of Engineering for Thermal Energy & Power. －2016，31(8). －51～58

In this paper，the control of maximumpower point tracking and power smoothing in the hydraulic wind turbine and under low wind speed conditions was investigated. The inverse system model of hydraulic wind turbine was first established，followed by the analysis of the nonlinearization of the model and the determination of the decoupling method of inverse system. Then the method of inverse system was used to design the hydraulic system torque controller for the maximum power point tracking. And finally the multi-objective optimal controller for power tracking and power smoothing was designed based onthe method of linearity quadratic formoptimal control. Corresponding simulation and experimental studies were conducted based on the 30 kVA hydraulic wind turbine experiment platform，and the feasibility of the method was verified. Both simulation and experimental results showed that the presented method has achieved the control goal，and the maximum power point tracking control is guaranteed while the power smoothing control is also ensured. These research results are believed to provide a theoretical and experimental reference for the further research in the hydraulicwind turbine. **Key words:** wind power，power tracking，power smoothing，hydraulic transmission，inverse system，multi-objective optimization

对冲旋流锅炉的配风调整试验研究＝Optimization on Air Supplication of Pulverized Coal Fired Boiler with

Swirling Counter-flow Combustion [刊,汉] LI Jin-jing, ZHAO zhen-ning, ZHANG Qing-feng, LI Yuan-yuan (North China Electric Power Research Institute Co. Ltd., Beijing, China, Post Code: 100045) //Journal of Engineering for Thermal Energy & Power. -2016, 31(8). -59~63

The reform of pulverized coal fired boiler with low-NO_x combustion technology causes a series of shortages, such as increase in carbon content in fly ash, rise in spraying water flow rate in steam heater, and frequent overheating of steam heater. In this paper, the total air flow rate, separated overfire air flow rate, and difference of separated overfire air between front and rear walls, were investigated on a 2 070 t/h pulverized coal fired boiler with swirling counter-flow combustion, and the optimized air supplication was obtained. Results showed that with the optimized air supplication, the boiler efficiency increases by 1.38% point, NO_x formation in furnace decreases by 15 mg/m^3, and the spraying water in super heater and reheater also reduces by 95.2 t/h and 10.6 t/h, respectively. **Key words:** Swirling combustion, counter-flow combustion, low-NO_x combustion, air supplication adjustment, operation optimization

某核电厂风冷器对称排列子风机共振特性 = Resonance Character of Wind-cooler's Sub-Fans Symmetrically Arranged in a Nuclear Power Station [刊,汉] YANG Zhang, WANG He-xu, JIANG Yan-long (Department of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China, Post Code: 210016) //Journal of Engineering for Thermal Energy & Power. -2016, 31(8). -64~68

In this paper, the wind-cooler vibration beyond its limitation in a large-size diesel genset of a nuclear power station was investigated and resolved. The genset is mainly composed of 8 axial-flow fans in symmetry arranged. It was found that the main vibration spectrum component was 12.5 Hz, as wind-fan´s rotation frequency through vibration measurement and spectrum analysis was 12.33 Hz. It was also found that the 12.5 Hz is near to the second-order resonance frequency of axial flow fan-supporting system which was 13.6 Hz. The main cause of fan vibration beyond the limitation was too low rigidity of the axial flow fan-supporting system, and structural resonance happened near the rotation frequency of fans, leading to severe and periodic fluctuation in vibration. When the sub-axial flow fan was switched from signal-running mode to all 8 fans running mode in synchronism, the spectrum component of 12.5 Hz increased sharply. With some reinforced measures added in field, the fan vibration drops back to the allowable range. **Key words:** symmetry, axial flow fan, vibration, structural resonance

添加剂对五彩湾煤中钠在燃烧过程中析出的影响 = The Influence of Additive on the Emission of the Sodium Contained in Wucaiwan Coal During Combustion [刊,汉] TU Sheng-kang, ZHANG Shou-yu (Department of Thermal Engineering, School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai, China, Post Code: 200093), SHI Deng-yu (Shanghai J. E Power Plant Equipment Co., LTD, Shanghai, China, Post Code: 200437), PEI Yu-feng (Northeast Electric Power Design Institute of China Power Engineering Consulting Group, Changchun, China, Post Code: 130021) //Journal of Engineering for Thermal Energy & Power. -2016, 31(8). -69~74