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气体再燃技术在宝钢电厂 350 MW 锅炉机组上的工业应用

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摘 要: 煤炭是我国电力工业的主要燃料, 大量煤炭在燃烧中对环境造成了极大的破坏, 尤其是氮氧化物对环境的污染非常严重。作为一种有效且前景看好的降低 NO_x 排放的技术, 气体再燃在宝钢电厂的锅炉改造中得到了应用, 并取得了令人满意的效果。NO_x 的排放浓度可以达到 155 mg/m^3, 为国内 300 MW 以上机组的最好水平。再燃量为 10% 左右, 再燃区过量空气系数取 0.9 即能取得很好的效果。随着"西气东输"工程的完成, 应用天然气再燃大幅度降低燃煤电厂造成的 NO_x 污染, 是合理使用天然气这一优质清洁能源的良好途径。

关 键 词: 锅炉; 气体再燃; NO_x 还原; 工业应用

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1 前 言

大量的实验研究和工业应用表明, 燃料再燃可以大幅降低烟气中 NO_x 的含量, 其脱硝率可达 50%～85%, 是一种十分有效且很有前途的低 NO_x 燃烧技术[1－6], 目前, 国内有许多 300～600 MW 的大型燃煤机组, 是合理使用天然气这一优质清洁能源的良好途径。宝山钢铁公司利用其 COG(焦炉煤气)进行气体再燃的技术改造, 取得一些效果, 并对这一技术的推广有重要的意义。

2 锅炉简介

宝钢电厂锅炉是日本三菱重工制造的亚临界压力中间再热, 煤、煤气混烧的多次强制循环锅炉, 单炉体负压炉膛, 四角切向燃烧。锅炉主要设计参数见表 1。锅炉设计燃用大同煤, 设计煤种特性见表 2。

表 1 锅炉主要设计参数

	数值
汽包压力/MPa	17.6
主蒸汽流量/t·h^{-1}	1 160
主蒸汽温度/℃	541
给水温度/℃	279
再热器进/出口压力/MPa	4.07/3.89
再热器进/出口温度/℃	339/541

表 2 燃煤特性

		设计煤种(大同煤)
应用基水分(平均值)	M_{ar}/%	8
干燥基灰分	A_{ad}/%	10.52
干燥基灰发分	V_{ad}/%	27.47
干燥基固定碳	FC_{ad}/%	62.01
应用基低位发热量	$Q_{net.v.ar}$/kJ·kg^{-1}	26831
干燥基碳	C_{ad}/%	75.48
干燥基氢	H_{ad}/%	4.34
干燥基氮	N_{ad}/%	0.79
干燥基硫	S_{ad}/%	1.52
干燥基氧	O_{ad}/%	7.35

高炉煤气 BFG 的组成成份为: CO_2, 19%; CO, 24.8%; H_2, 3%; N2, 53.2%。低位发热量 3 470 kJ/m^3。COG 的组成成份为: CO_2, 2%; CH_4, 29.1%; C_2H_2, 2.8 %; CO, 7.5%; H_2, 53.5%; N_2, 4.9%; O_2, 0.1%。低位发热量 18 810 kJ/m^3。

本锅炉炉室为单炉膛结构。锅炉总高度 71.9 m, 汽包中心线高度 61.8 m; 锅炉宽度 28 m, 深度 36.5 m; 炉膛有效容积约 6 650 m^3。炉膛容积热负荷为 393.96 MJ/(m^3·h)。锅炉为四角布置燃烧器, 每角布置 11 只燃烧器。本锅炉使用煤粉、高炉

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煤气、焦炉煤气和重油等多种燃料的燃烧，燃烧方式为四角切圆燃烧，在炉膛的四角布置了 44 只燃烧器，上部每角布置 5 只煤粉燃烧器，燃烧器可上下摆动 30°，下部每角布置有 4 只高炉煤气燃烧器，中间的上排为焦炉煤气燃烧器，下排为焦炉煤气式重油燃烧器。燃烧系统示意图见图 1。煤粉燃烧器采用四角切圆燃烧方式，分 G、H、I、J、K 五段，布置在炉膛的四角风箱上，共 20 只。本锅炉的五层煤粉燃烧器喷口和相应的二次风喷口可以作 ±30°角度的变动，在运行中通常在 ±20° 角度的范围内调节，通常各层喷口的摆动角度是相同的，但若有需要也可调整各喷口连杆的长度来改变不同的倾角，但在同一层的 4 个燃烧器的倾角应相同，以形成良好的燃烧中心。BFG 燃烧器分 A、B、C、D 四段布置，共 16 只燃烧器，布置在整个燃烧器组的最下方。COG 燃烧器分 E、F 二段布置，共 8 只，布置在整个燃烧器标高的中部位置。其中 E 段与重油燃烧器合并成一体，F 段与作为 G 段煤粉燃烧器的二次风喷嘴合并成一体。

图 1 改造前燃烧器

图 2 改造后燃烧器

3 改造方案

“再燃(Reburning)”，也称为“燃料分级”或“炉内 NO_x 还原”，是一种 3 段燃烧方式，即沿炉膛高度，自下而上依次分为主燃区、再燃区和燃尽区 3 段。由 NO 的形成和破坏机理可知，已生成的 NO 在遇到烃根 CH_i 和未完全燃烧产物 CO、H_2、C 和 C_nH_m 时，会发生 NO 的还原反应，这些反应的总反应式为[7]：

$$4NO+CH_4\rightarrow 2N_2+CO_2+2H_2O$$

$$2NO+2C_nH_m+(2n+m/2-1)O_2\rightarrow N_2+2nCO_2+mH_2O$$

$$2NO+2CO\rightarrow N_2+2CO_2$$

$$2NO+2C\rightarrow N_2+2CO$$

$$2NO+2H_2\rightarrow N_2+2H_2O$$

利用这一原理，将 70%～90%的燃料送入主燃区，在 α 接近于 1 的条件下燃烧并生成 NO_x。其余 10%～30%的再燃燃料在再燃区中喷入，在 $\alpha<1$ 的条件下形成很强的还原性气氛，即生成大量的烃根(CH_i)，使得在主燃烧区中生成的 NO_x 在再燃区中还原成氮分子(N_2)，同时还抑制了新的 NO_x 的生成。最后在燃尽区中送入燃尽风，使未燃成份充分燃尽。在考虑宝钢电厂 350 MW 锅炉机组燃烧系统原有结构的基础上，为了尽可能减少改造成本，我们提出了实现气体再燃的方案：去掉底下一组 D 段 BFG 燃烧器；把 E 和 F 段 COG 燃烧器上移至煤粉燃烧器上方 1 m 处，以此作为再燃燃料喷口实现再燃；把煤粉燃烧器整体下移，以尽可能地增加再燃区的空间；最后，在再燃燃料上方布置一燃尽风(OFA，Over Fire Air)喷口。改造方案按 10%的再燃量来设计，即 COG 的发热量占燃料总发热量的 10%，并可在 5%～20%之间调节，此时，再燃区过量空气系数为 0.92，主燃区过量空气系数从 0.93 递增到 0.99，炉膛出口烟温为 1 405 K。改造的重点是对再燃燃料 COG 喷口和燃尽风喷口位置的布置。为了保证再燃区足够的停留时间，结合以前作过的模拟计算，方案中将燃尽风喷口上移，使再燃燃料 COG 喷口至燃尽风喷口的中心线之间的距离达到 5.5 m，再燃区停留时间在 0.7 s 左右[8～10]。

4 工业应用与试验

2004 年 4 月宝山钢铁公司热电厂在 1 号炉大修期间，对其进行了燃烧器的改造。为了使改造前后的污染物排放情况具有可比性，在改造以前，测定了在特定工况下的 NO_x 的排放参数及所用燃煤的工业与元素分析指标。在改造完成以后，先对 1 号炉的燃烧区域的空气动力场进行了冷态试验，并在锅炉投运后，在相同工况(320 MW)采用相同产地、指标相近燃煤进行了热态试验。试验入炉煤质分析值见表 4。

表 3　入炉煤质分析表　　(%)

	M_{ad}	V_{ad}	A_{ad}	FC_{ad}	H_{ad}	O_{ad}	S_{ad}	N_{ad}
数值	2.34	30.02	19.64	64.09	4.02	8.21	0.54	1.16

4.1　燃尽风与上移 COG 燃烧器特性试验

为了检验改造后的燃烧器的 NO_x 排放量是否能达到预期数值, 在本次试验中设定的机组负荷仍为 320 MW, 燃料配比为 21% 的 BFG, 15% 的 COG, 其余为煤粉; 并先预设 COG 燃烧器的角度为 24°, 水平摆放。试验结果如图 3 所示。

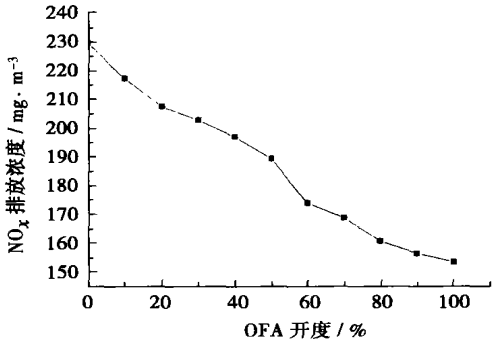

图 3　OFA 开度与 NO_x 排放量的关系

从图 3 可以看出, 燃尽风对 NO_x 排放量的影响较大, 燃尽风挡板位置全开时比全关时的 NO_x 排放量从 230 mg/m^3 降至 154 mg/m^3, 减少了 33%, 即 76 mg/m^3。这是因为随着燃尽风的增加, 再燃区的风量相应减少, 在再燃区处于还原性气氛中, 有利于烃根的产生, 从而增加了 NO_x 的还原率, 降低了 NO_x 的排放量。同改造前的平均 1 000 mg/m^3 相比, NO_x 的排放量最多可降低 85% 左右, 效果十分显著。另外, 从图中我们还能确定燃尽风的最佳开度为 80% 左右, 继续增加 OFA 开度对降低 NO_x 的效果趋于平缓。此时再燃区对应的过量空气系数为 0.9, 与模拟所作计算基本吻合[9]。

4.2　满负荷时不同燃料比的燃烧特性试验

在这次试验过程中, COG 燃烧器的角度我们仍选定为 24°, 水平摆放。燃尽风开度我们选择为 80%, 水平摆放, 机组负荷稳定在 350 MW。通过调整 COG 与煤粉的供给量来观察相应的 NO_x 排放量, 试验数据如图 4 所示。试验中, 我们并没有对 BFG 的量进行大幅度的调整, COG 所占总燃料量的调整幅度为 5% 到 22%, 当 F 段的四角燃烧器全部投用时, 大约可以达到 10% 左右; 若再增加 COG 则需投用 E 段的对角的两个燃烧器。

从图中可以清楚的看到, 随着 COG 量增加, NO_x 的排放量呈现明显的下降趋势, 这是由于随着 COG 投入量的增加, 再燃区内的烃根量增加, 从而加大了 NO_x 的还原量。由图 4 还可以看出, 当 COG 比例从 0% 增加到 10% 时, 还原效果最显著, 下降幅度明显; 继续增加到 20% 时, 下降趋势趋于缓和。本组数据的最低排放量在 COG 比例为 22% 时取得, 达到了 155 mg/m^3, 为国内目前 300 MW 以上机组的最佳值。我们认为 COG 为 10% 左右的燃料比例为最佳值, 此时 NO_x 的排放浓度为 173 mg/m^3。

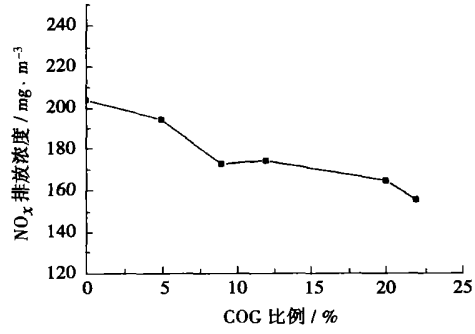

图 4　不同 COG 比例的 NO_x 排放数据

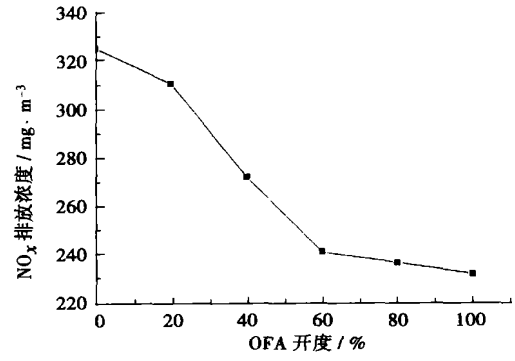

图 5　全燃烧煤满负荷工况时 OFA 与 NO_x 关系

4.3　全燃烧煤满负荷工况时燃尽风特性试验

由于宝钢电厂锅炉使用的是煤粉和气体等多种燃料燃烧, 且在运行中存在单独燃烧煤粉的运行工况, 鉴于宝钢电厂机组运行的这一特点, 为了进一步优化燃烧, 寻找各工况下的最佳燃烧方案, 在全燃烧煤的 350 MW 工况下, 再次对燃尽风开度进行调整, 试验数据表明了与前面相同的规律, 具体数据如图 5 所示。

本组数据是在没有气体再燃的情况下得到的，从中看出通过燃烧方式的重整，也可以达到较理想的环保效果，图中 NO_X 的排放量最低达到 232 mg/m^3，而且随着 OFA 开度的增加，NO_X 排放量减少了 28%。这是因为在总风量不变的情况下，燃尽风的增加使整个燃烧逐步形成分级燃烧，主燃区在缺氧的富燃料燃烧条件下燃烧，此时在还原性气氛中降低了 NO_X 的反应率，抑制了其生成量。这也给大型煤粉锅炉降低污染物排放提供了指导。

5 结 论

宝钢电厂 350 MW 锅炉机组燃烧系统的改造表明：

(1) 气体再燃技术能够大幅降低 NO_X 的排放量，最低可以达到 155 mg/m^{3}左右，再燃量为 10%左右，再燃区过量空气系数取 0.9 即能取得很好的效果。

(2) 改造后的燃烧系统在无气体再燃的情况下，NO_X 的排放量最低可达 232 mg/m^3，仍可以获得较好的降低 NO_X 排放浓度的效果。

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法进行计算。在迭代的过程中，采用温度 323.15 K 时的 5 个实验点关联相互作用系数 k_{aij} 和 k_{cijk}，计算值分别是 0.575 和 0.5。当外推到其它实验点时，由表 3 结果可知，预测结果的精度较高。因此式(1)及其混合法则可以用来预测湿空气的高压下相平衡性质。

5 结 论

(1) 采用新的立方型状态方程计算了纯质水在亚临界，近临界点处的相平衡参数，并和目前认为较好的其它立方型状态方程的计算结果进行了比较，新立方型方程在对饱和压力和气相比容的计算是较好的模型，液相比容的计算误差也较小。这个新方程可以用在工程上对纯质水进行相平衡参数预测估算，精度高于其它立方型模型，计算较 ISPWS—IF97 模型简单。

(2) 用这个新方程计算了湿空气在目前实验温度和压力范围内的相平衡性质，取得了较好的精度，具有好的外推性。

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by a direct sampling in a natural gas diffusion flame. Furthermore, candle soot, four kinds of commercial soot and a kind of anthracite coke were selected for comparison study purposes. On the basis of test results the parameters of combustion kinetics characteristics were determined along with an analysis of their combustion features. The soot obtained in a natural gas diffusion flame possesses the following combustion features: a relative ease of ignition, a comparatively low ignition temperature (compared with coke or coal with a relatively low volatile content), a relatively weak combustion during an earlier period, a relatively slow combustion at a later period, a fairly long time needed for burn-out, etc. These results and findings can provide a basis for utilizing the soot-generated intensified flame radiation characteristics and for their effective control in the natural gas combustion process. **Key words**: natural gas, soot, combustion characteristics, thermal analysis, reaction kinetics

链条锅炉的动态建模与仿真＝**The Dynamic Modeling and Simulation of a Chain Grate Boiler** [刊, 汉] /XU Hong-sheng (Thermo-electric Engineering &Research Institute under the Southeastern University, Nanjing, China, Post Code: 210096), ZHU Jin-rong (Simulation Department, Nanjing Engineering Institute, Nanjing, China, Post Code: 210013) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(5). —527 ~ 531

In consideration of the very frequent load fluctuations of chain grate boilers with a steam capacity of 10 t/h and lower a dynamic mathematical model was set up by using a modular modeling method for the steam-water system and combustion system of a 10 t/h chain grate boiler. Through simulation tests obtained were the real-time variation quantity and trend for the boiler combustion rate, steam flow rate, superheated steam temperature and boiler drum water level, all during the changes in chain-grate traveling speed and air feeding rate. The results of the simulation tests indicate that to better implement boiler load adjustments it is necessary to simultaneously change the chain-grate traveling speed and airflow rate. This and other findings can serve as a theoretical guide for the stable and economic operation of chain grate boilers. **Key words**: chain grate boiler, dynamic model, simulation test

高温高压湿空气气液相平衡 PVT 参数估算＝**Evaluation of the PVT (Pressure-volume-temperature) Parameters of Vapor-liquid Phase Equilibrium of High-temperature and High-pressure Humid Air** [刊, 汉] /YANG Zhi-yong, LIU Chao (Power Engineering Institute under the Chongqing University, Chongqing, China, Post Code: 400030) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(5). —532 ~ 534, 538

With the working medium in a humid air turbine and compressed-air energy storage system serving as an object of study a new cubic type of status equation is employed to compute the vapor-liquid phase equilibrium parameters of pure water at subcritical and near-critical status as well as the humid air in the current range of experimental temperature and pressure. Compared with the experimental data now available the average and maximum calculation error of pure water saturated pressure is respectively 0.09% and 0.44%. As for the saturated gas-phase specific volume the average and maximum calculation error is respectively 1.81% and 5.15%. The average and maximum calculation error for the saturated liquid-phase specific volume is respectively 2.30% and 5.47%. The average calculation error for vapor molar fraction in the humid air is 0.10% with its maximum error being 1.99%. This new cubic type of status equation currently represents a relatively good mathematical model for calculating the phase equilibrium parameters of water and the properties of saturated humid air. **Key words**: high temperature and pressure, humid air, status equation, phase equilibrium

气体再燃技术在宝钢电厂 350 MW 锅炉机组上的工业应用＝**The Industrial Application of Gas Reburning Technology in a 350 MW Boiler Unit at Bao Steel Works Power Plant** [刊, 汉] /WEI Hua-yan, ZHANG Zhong-xiao (Power Engineering Institute under the Shanghai University of Science &Technology, Shanghai, China, Post Code: 200093), ZHU Ji-mu (Shanghai Bao Steel Works Power Plant, Shanghai, China, Post Code: 200097) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(5). —535 ~ 538

Coal as a main fuel used in the power generation industry of China has led to extremely serious environmental pollution, especially by NO_x emissions resulting from the burning of an enormous quantity of coal. The use of gas reburning techn-

ology for the effective and highly promising reduction of NO_x emissions has been successfully implemented during the modification of boilers at Bao Steel Works power plant with an emission concentration of NO_x of 155 mg/m^3 being attained. The latter is the best result not achievable in China for power units of 300 MW or higher. At a reburning rate of about 10% and the excess air factor of the reburning zone selected at 0.9 excellent results can be obtained. With the completion of the project "natural gas in the west to be transported to the eastern regions" the use of natural gas for reburning can drastically reduce the NO_x emissions-related pollution caused by coal-burning power plants, initiating a good approach for the rational application of natural gas as a high-quality and clean energy source. **Key words**: boiler, gas reburning, reduction of NO_x, industrial application

高性能船舶动力定位系统技术分析= **Technical Analysis of a Dynamic Positioning System for High Performance Ships** [刊, 汉] / LI Nan, LIU Xiao-bing (Dalian University of Science & Technology, Dalian, China, Post Code: 116023), SUN Chang-jiang (Military Representative Office Resident at Dalian Shipyard, Dalian, China, Post Code: 116001) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(5). —539 ~ 541

An analysis and investigation is conducted of the issues concerning the insufficient precision of control and a rather slow response speed of the control process, which exist in the design scheme for the dynamic-positioning control system of a foreign vessel. As a result, an improved version for the above system has been put forward. Meanwhile, on the basis of the basic configuration of the equipment for the positioning control system the fundamental operating principles of the said system are analyzed with a basic mathematical model and transfer functions for the positioning control system being obtained. Furthermore, based on the working characteristics of the control system the authors have come up with a method for solving the above-mentioned problems. The method consists in the adoption in the control system of a neural network-based control algorithm to replace the algorithm of multivariable control system of the original version. A numerical simulation-based comparison of the control performance of the original version with that of the improved one indicates that in respect of control performance the improved version is much better than the original version. **Key words**: marine power plant, dynamic positioning system, design, improvement

裂解气压缩机透平真空度下降的原因及其改造措施= **An Analysis of the Causes Leading to the Lowering of Vacuum Level in a Cracking-gas Compressor Turbine and Relevant Measures Taken for its Modification** [刊, 汉] / LI Ruo-ping, HE Cheng-guang, ZHOU Dian-ying (China Petroleum Fushun Petrochemical Branch Company, Fushun, China, Post Code: 113008) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(5). —542 ~ 544

A comprehensive analysis was conducted of the causes leading to the reduction of vacuum level in a compressor-condensing turbine. It is believed that the cause of the low vacuum lies in an irrational structure. Through detailed thermodynamic calculations it was decided to modify the structure of the condenser and to use copper-nickel alloy tubes BFe10-1-1 featuring high heat transfer efficiency and good corrosion resistance. After the modification the vacuum level of the unit has been increased to 0.024 MPa, resulting in a steam saving of 10 t/h and significant economic benefits. **Key words**: surface type condenser, turbine vacuum level, measures taken for modification

压力式喷水装置= **Pressure-type Water Spraying Device** [刊, 汉] / HE Fu-dong, JIN Chun-nan, XU Heng, et al (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. — 2005, 20(5). —545 ~ 547

Pressure-type water spraying device is a new type of water-feeding spray nozzle. The difference between the pressure-type water spraying device on the one side and conventional mechanical spray nozzles and rotating membrane tubes on the other is expounded along with a description of the construction features of the pressure-type water spraying device. Measurement and test data of cold-state experiments are presented and the application prospects of the pressure-type water-spraying device analyzed. **Key words**: water spraying device, structure cold-state tests