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自然循环热水锅炉水动力回路分析法的计算原理

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摘 要: 自然循环热水锅炉长期使用图解法进行水动力计算, 计算误差较大, 影响了锅炉水动力的安全性。本文详细阐述了水动力回路分析法的计算原理, 给出了自然循环热水锅炉水冷壁和对流管束循环回路的水动力回路分析法等效管路图、水动力计算数学方程组及其相应的求解方法。采用水动力回路分析法, 不仅可以提高自然循环热水锅炉水动力计算的可靠性, 对保证热水锅炉水动力安全具有重要意义, 而且由于该方法采用计算机数值求解, 其计算效率也得到明显提高。此外, 为了便于应用水动力回路分析法对自然循环热水锅炉进行水动力计算, 推导给出了另外几种常见的自然循环热水锅炉水冷壁循环回路水动力回路分析法等效管路图, 并且介绍了自然循环热水锅炉水动力回路分析法对全炉水动力工作点的计算方法及其运算步骤。

关 键 词: 热水锅炉; 自然循环; 水动力计算; 水动力回路分析法

中图分类号: TK229 文献标识码: A

1 前 言

自然循环热水锅炉在我国得到了广泛的应用。为了保证热水锅炉的安全运行, 必须对其进行水动力计算。长期以来, 自然循环热水锅炉水动力计算使用的方法是图解法[1], 该方法将锅炉受热面划分成若干个管组, 假定每管组内的各单管具有相同的热负荷和结构参数, 然后对各个管组进行水动力计算, 由于其计算原理的限制, 该方法得到的是各个管组的平均水动力参数, 而不是受热面内的每个单管的水动力参数[2]。文献[3]最新研究并应用的自然循环热水锅炉水动力回路分析法, 在给定锅炉受热面各单管热负荷分布、结构参数及管内工质流动阻力系数的条件下, 可以准确地计算出各单管内的工质流量等水动力参数。本文则通过理论推导, 给出了自然循环热水锅炉水冷壁和对流管束循环回路的水动力回路分析法等效管路图、水动力计算数学方程组及其相应的求解方法, 阐述了水动力回路分析法的计算原理。

2 水冷壁循环回路的水动力回路分析法等效管路图、计算方程组及其求解方法

2.1 水冷壁循环回路的水动力回路分析法等效管路图

作为示例的自然循环热水锅炉水冷壁循环回路[4], 由锅筒、布置在分配集箱单侧端部的下降管、分配集箱、多根并联水冷壁上升管、汇集集箱以及布置在汇集集箱单侧端部的热水引出管所组成的水循环回路 1 的水循环回路图及水动力回路分析法等效管路图如图 1 所示。

2.2 水冷壁循环回路的水动力回路分析法计算方程组及其求解方法

如图 1 所示, 有 n 个独立回路, 各假想回路绕行方向设逆时针绕行为正。根据水动力回路分析法列方程:

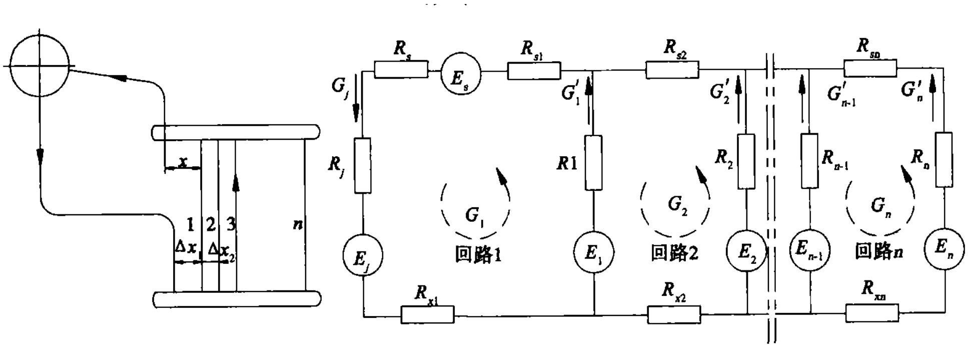

图 1 水冷壁循环回路 1 的水循环回路图及其水动力回路分析法等效管路图

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$$E_j-(E_1+E_s)=G_1[|G_j|R_j+|G_1|(R_{x1}+R_s+R_{s1})+|G_1'|R_1]-G_2|G_1'|R_1 \quad (1)$$

$$E_i-E_{i+1}=G_{i+1}[|G_{i+1}|(R_{x(i+1)}+R_{s(i+1)})+|G_i'|R_i+|G_{(i+1)}'|R_{(i+1)}]-G_i|G_i'|R_i-G_{i+2}|G_{(i+1)}'|R_{(i+1)} \quad i=1、2\cdots n-2 \quad (2)$$

$$E_{n-1}-E_n=G_n[|G_n|(R_{xn}+R_{sn})+|G_{n-1}'|R_{n-1}+|G_n'|R_n]-G_{n-1}|G_{n-1}'|R_{n-1} \quad (3)$$

式中：$G_j=G_1$ (4)

$$G_i'=G_i-G_{i+1} \quad i=1、2\cdots n-1 \quad (5)$$

$$G_n'=G_n \quad (6)$$

式中：G_i（$i=1,2\cdots n$）—第 i 个回路的回路工质流量；G_j—下降管中工质流量；G_i'（$i=1,2\cdots n$）—第 i 根水冷壁管中工质流量；R_j—下降管的流阻；R_{x1}—第一根水冷壁管与下降管间的流阻；R_i—每根水冷壁管的流阻；R_{xi}（$i=2\cdots n$）—分配集箱中第 $i-1$ 与第 i 根水冷壁管间的流阻；R_{si}—汇集集箱中第 $i-1$ 与第 i 根水冷壁管间的流阻；R_{s1}—第一根水冷壁管与引出管间的流阻；R_s—引出管流阻；$E_i=$（$i=1,2\cdots n$）—第 i 根水冷壁管的流动势；E_j—下降管流动势；E_s—引出管的流动势。

解方程：将式(4)～式(6)带入式(1)～式(3)，有：

$$E_j-(E_1+E_s)=G_1[|G_1|(R_j+R_{x1}+R_s+R_{s1})+|G_1-G_2|R_1]-G_2|G_1-G_2|R_1 \quad (7)$$

$$E_i-E_{i+1}=[-|G_i-G_{i+1}|R_i]G_i+[|G_{i+1}|(R_{x(i+1)}+R_{s(i+1)})+|G_i-G_{i+1}|R_i+|G_{i+1}-G_{i+2}|R_{i+1}]G_{i+1}+(-|G_{i+1}-G_{i+2}|R_{i+1})G_{i+2} \quad i=1、2\cdots n-2 \quad (8)$$

$$E_{n-1}-E_n=(-|G_{n-1}-G_n|R_{n-1})G_{n-1}+[|G_n|(R_{xn}+R_{sn})+|G_{n-1}-G_n|R_{n-1}+|G_n|R_n]G_n \quad (9)$$

此方程组即是非线性的水动力数学方程组，E 和 R 都是 G 的函数。其求解方法如下：

(1) 设定各假想回路的流量 $G_0(i)$，带入方程中的绝对值项；

(2) 设定下降管的入口温度 t_0，计算 E 和 R；

(3) 此非线性方程组即线性化为 $AG=b$ 的形式；

(4) 求解上述线性方程组得到 $G_1(i)$，判断 $\left|\dfrac{G_0(i)-G_1(i)}{G_0(i)}\right|<\varepsilon$ 是否满足，若满足，则 $G_1(i)$ 即为所求；若不满足则采用迭代法 $G_0(i)^{(n)}=G_0(i)^{(n-1)}+\alpha\,\overline{(G_1(i)^{(n-1)}-G_0(i)^{(n-1)})}$ 重新计算，直至满足 $\left|\dfrac{G_0(i)-G_1(i)}{G_0(i)}\right|<\varepsilon$；

(5) 各支路中的工质流量可按照式(4)～式(6)求得。

2.3 常见水冷壁循环回路的水动力回路分析法等效管路图

为了便于应用水动力回路分析法对自然循环热水锅炉进行水动力计算，推导给出了另外几种常见的自然循环热水锅炉水冷壁循环回路水动力回路分析法等效管路图。

(1) 由锅筒、布置分配集箱单侧端部的下降管、分配集箱、多根并联水冷壁上升管、直接引入锅筒的汇集集箱所组成的水冷壁循环回路 2 的水循环回路图和其等效管路图如图 2 所示。

(2) 由锅筒、布置分配集箱单侧端部的下降管、分配集箱、直接引入锅筒的多根并联水冷壁上升管所组成的水冷壁循环回路 3 的水循环回路图和其等效管路图如图 3 所示。

(3) 由锅筒、布置分配集箱双侧端部的下降管、分配集箱、多根并联水冷壁上升管、汇集集箱、布置在汇集集箱单侧端部的热水引出管所组成的水冷壁循环回路 4 的水循环回路图与其等效管路图如图 4 所示。

(4) 由锅筒、布置在分配集箱中部的下降管、分配集箱、多根并联水冷壁上升管、汇集集箱、布置在汇集集箱中部的热水引出管组成的水冷壁循环回路 5 的水循环回路图与其等效管路图如图 5 所示。下降管和引出管都在第 $n/2$(若是奇数根取整)与第(n

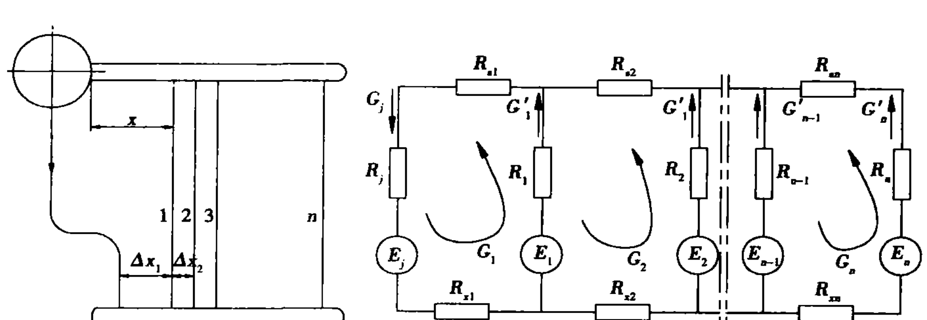

图 2 水冷壁循环回路 2 的水循环回路图及其水动力回路分析法等效管路图

/2)＋1 根水冷壁之间引入和引出。

3　对流管束回路的水动力回路分析法等效管路图、计算方程组及其求解方法

3.1　对流管束回路的水动力回路分析法等效管路图

回路分析法可以对每排排管中的各单管分别进行计算, 由于对流管束回路的水管数量大, 但每排水管的各单管热量和几何尺寸相差很小, 因此, 为了提高计算效率, 可以把每排排管等效为一根单管, 等效管的工质流通截面积等于每排水管的工质截面积。对流管束回路的水循环回路图及水动力回路分析法等效管路图如图 6 所示。

3.2　对流管束回路的水动力回路分析法计算方程组及其求解方法

如图 6 所示, 设虚拟回路逆时针绕行方向为正, 根据水动力回路分析法原理列方程:

$$E_0 - E_1 = G_1[|G_1|R_0 + |G_1'|R_1] - G_2|G_1'|R_1 \quad (10)$$

$$E_i - E_{i+1} = G_{i+1}[|G_i'|R_i + |G_{i+1}'|R_{i+1}] - G_i|G_i'|R_i - G_{i+2}|G_{i+1}'|R_{i+1} \quad i = 1, 2 \cdots n-2 \quad (11)$$

$$E_{n-1} - E_n = G_n(|G_{n-1}'|R_{n-1} + |G_n'|R_n) - G_{n-1}|G_{n-1}'|R_{n-1} \quad (12)$$

式中: $G_0 = G_1$　$G_i' = G_i - G_{i+1}$　$i = 1, 2 \cdots n-1$　$G_n = G_n'$

原方程可改写为:

$$E_0 - E_1 = [|G_1|R_0 + |G_1 - G_2|R_1]G_1 + (-|G_1 - G_2|R_1)G_2 \quad (13)$$

$$E_i - E_{i+1} = (-|G_i - G_{i+1}|R_i)G_i + (|G_i - G_{i+1}|R_i + |G_{i+1} - G_{i+2}|R_{i+1})G_{i+1} + (-|G_{i+1} - G_{i+2}|R_{i+1})C_{i+2} \quad i = 1, 2 \cdots n-2 \quad (14)$$

$$E_{n-1} - E_n = (-|G_{n-1} - G_n|R_{n-1})G_{n-1} + (|G_{n-1} - G_n|R_{n-1} + |G_n|R_n)G_n \quad (15)$$

此方程中, E 和 R 都是 G 的函数, 则此方程组是非线性方程组, 解法如下:

(1) 假设下降管、上升管的初始温度 t_0、t_s, 假定第一根上升管的位置 k;

(2) 假设每个回路的流量 $G_0(i)$, 带入方程组的绝对值项中, 此非线性方程组则转化为线性方程组, 即 $AG = b$;

(3) 解此线性方程组, 求得各回路流量 $G_1(i)$, 并计算第一根上升管的位置 k_1;

(4) 如果 $\frac{|G_0(i) - G_1(i)|}{G_0(i)} < \varepsilon$, 并且 $k = k_1$, 则所得到的 $G_1(i)$ 即为所求; 若不满足则采用迭代法 $G_0(i)^n = G_0(i)^{(n-1)} + \alpha\overline{(G_1(i)^{(n-1)} - G_0(i)^{(n-1)})}$, 并且 $k = k_1$, 计算上升管的入口水温即为每根下降管出口水温与流量的加权平均, 把这 3 个值重新带入计算, 直至 $\frac{|G_0(i) - G_1(i)|}{G_0(i)} < 10^{-4}$, 并 $k = k_1$ 且为止;

(5) 各回路流量求出后则可求出各支路流量即为每根管子的工质流量。

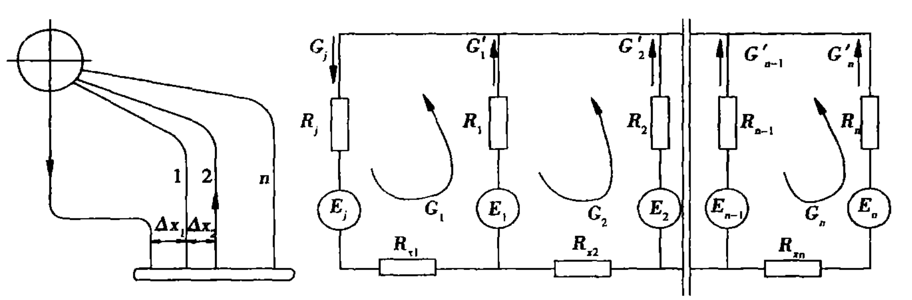

图 3　水冷壁循环回路 3 的水循环回路图及其水动力回路分析法等效管路图

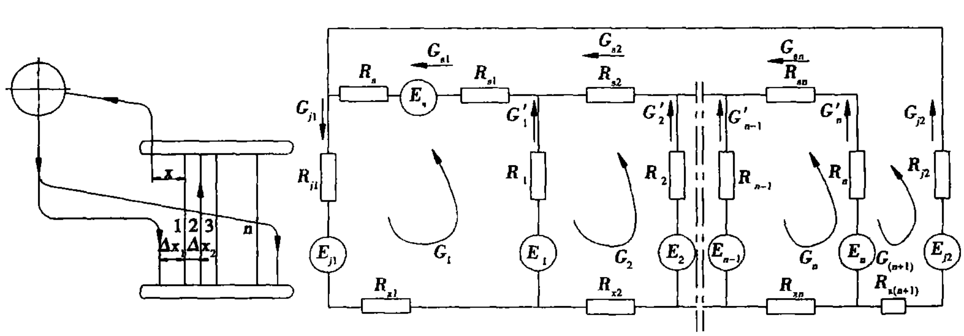

图 4　水冷壁循环回路 4 的水循环回路图及其水动力回路分析法等效管路图

4　全炉水动力工作点的计算方法及其运算步骤

根据水动力回路分析法的计算原理和各个回路的水动力计算数学方程组可以对自然循环热水锅炉全炉的水动力进行直接数值计算[5]，最终可求得全炉的水动力工作点，其主要水动力参数为下降管入口水温、全炉循环倍率、全炉循环流量、各单管的循环倍率、各单管的流量和流速。具体步骤如下：

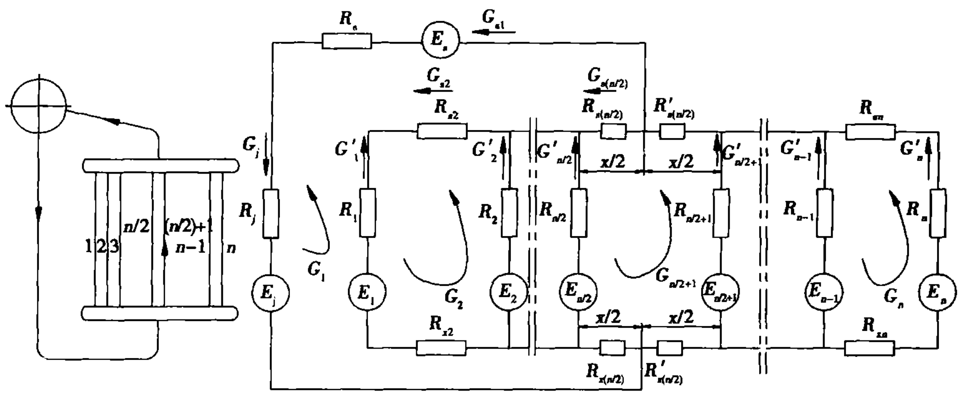

图 5　水冷壁循环回路 5 的水循环回路图及其水动力回路分析法等效管路图

(1) 假设下降管入口水温 t_0；

(2) 计算各回路中各单管的局部阻力系数；

(3) 选择水冷壁回路形式，进行各水冷壁回路水动力计算，在计算时需进行摩擦阻力系数和水冷壁吸热量分配计算；

(4) 如果锅炉回路形式中有对流管束回路，则需进行对流管束回路水动力计算，在计算时需进行摩擦阻力系数和对流管束吸热量分配计算；

(5) 计算各回路的循环流量，然后计算全炉循环倍率，最后求得下降管入口温度 t_0'；

(6) 若 $\left|\frac{t_0-t_0'}{t_0}\right|>\varepsilon$ 时，则采用迭代法：$t_0=t_0'$，重复计算步骤(3)～步骤(5)，再进行判断，直至满足 $\left|\frac{t_0-t_0'}{t_0}\right|\leqslant\varepsilon$，本文取 $\varepsilon=10^{-4}$。

5　结　论

(1) 水动力回路分析法是对自然循环热水锅炉进行水动力数值计算的新方法。采用水动力回路分析法对自然循环热水锅炉水冷壁进行水动力计算时，在各单管热负荷分布、结构参数及工质流动阻力系数给定的条件下，可以准确计算出水冷壁各单管内的工质流量；

(2) 与仅能求出循环回路内管组平均流量的图解法相比，水动力回路分析法不仅避免了图解法中由于曲线拟合产生的误差，而且是采用数值计算方法直接求解水动力计算数学方程组，其计算过程严格，计算结果准确，因此，水动力回路分析法的应用将会提高自然循环热水锅炉的设计质量以及对其水动力安全性预测的准确性。

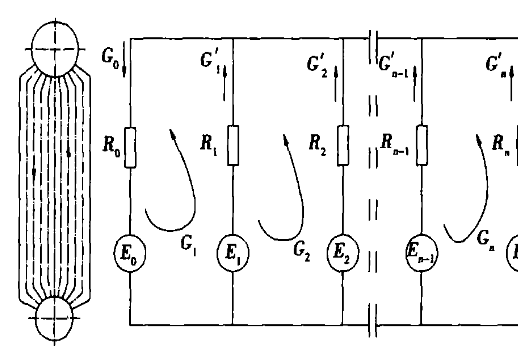

图 6　对流管束回路的水循环回路图及其水动力回路分析法等效管路图

参考文献：

[1] JB/T 8659—1997，热水锅炉水动力计算方法[S].

[2] 鲍亦龄，陆惠林. 锅炉水动力学及锅内设备[M]. 哈尔滨：哈尔滨工业大学出版社，1988.

[3] 董 [redacted] 徐艳英，兰日华. 采用水动力回路分析法进行自然循环热水锅炉水动力数值计算[J]. 工业锅炉，2006(2)：8–13.

[4] 冯俊凯，沈幼庭，杨瑞昌. 锅炉原理及计算[M]. 第三版. 北京：科学出版社，2003.

[5] 徐艳英. 自然循环热水锅炉水动力数值计算方法研究[D]. 哈尔滨：哈尔滨工业大学，2005.

（渠　源　编辑）

回转式空气预热器风烟焓增模型及其效率分析＝**An Air-and-Flue Gas Enthalpy-increase Model for a Rotary Air Preheater and an Analysis of the Preheater Efficiency**[刊,汉] /WANG Hong-yue, BI Xiao-long, SI Feng-qi, et al (Power Engineering Department, Southeast University, Nanjing, China, Post Code: 210096)//Journal of Engineering for Thermal Energy & Power. — 2006, 21(5). —465～469

Rotary air preheaters usually serve as tail heating surfaces of large-sized utility boilers. An analysis of the relationship between their air leakage rate and boiler unit efficiency plays a major role in guiding the modification of the whole seal system for a preheater. Based on the thermodynamic cycle of a working medium, an air and flue gas enthalpy-increase model for a rotary air-preheater is presented for analyzing the impact of air leakage rate in preheater thermal process on the boiler unit efficiency. Furthermore, the extent of the impact of air leakage from the hot end on the boiler unit efficiency is verified quantitatively. A preliminary conclusion has been reached that the reduction of total air leakage can not guarantee an increase in boiler unit efficiency. Finally, the rationality of a technical modification for a power plant by adopting "VN" seals is analyzed by using the air and flue gas enthalpy-increase model of the rotary air preheater. **Key words**: rotary air pre-heater, enthalpy increase, efficiency, air and flue gas, air leakage

船用增压锅炉热平衡计算＝**Heat Balance Calculation of a Turbo-charged Marine Boiler**[刊,汉] /WANG Jian-zhi, WU Shao-hua (Energy Source Science and Engineering College under the Harbin Institute of Technology, Harbin, China, Post Code: 150001), JI Qing-zhou (Harbin No.703 Research Institute, Harbin, China, Post Code: 150036)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(5). —470～472

Heat balance calculation is a basis for the thermodynamic performance calculation of turbo-charged marine boilers. As the turbo-charger unit participates in the thermodynamic process of the boiler, there may result a more complicated heat balance calculation of the turbo-charged marine boiler. A sectionalized calculation method is proposed for the heat balance calculation of the turbo-charged boiler along with an analysis and exploratory study of the direct heat-balance and sectionalized heat-balance calculation method. A general heat-loss formula applicable to the variable load calculation of the turbo-charged boiler is presented. A calculation formula of available heat quantity for fuel used to do work in an auxiliary steam turbine is given and a calculation and analysis of specific cases also performed. The sectionalized heat-balance calculation results are relatively satisfactory, thus providing a guide for the performance calculation and analysis of the turbo-charged marine boilers. **Key words**: turbo-charged boiler, heat balance, heat loss, available heat quantity

自然循环热水锅炉水动力回路分析法的计算原理＝**Principle of Calculations for Hydrodynamic-loop Analysis Method Used for Natural Circulation Hot Water Boilers**[刊,汉] /XU Yan-ying, DONG Peng, LAN Ri-hua (Energy Source Science and Engineering College under the Harbin Institute of Technology, Harbin, China, Post Code: 150001)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(5). —473～476

Over a long period of time a graphic method has been used for the hydrodynamic calculation of natural circulation hot water boilers, which involves a relatively large calculation error, thus affecting the hydrodynamic safety of boilers. The principles of calculation for hydrodynamic-loop analytic method is expounded in detail. Also given for natural circulation hot water boilers are the equivalent pipeline chart of hydrodynamic-loop analytic method for water walls and convection tube-bundle circulation loops, hydrodynamic-calculation mathematical equations set and their corresponding mathematical solution method. The adoption of hydrodynamic-loop analytic method can not only enhance the reliability of natural circulation hot-water boiler hydrodynamic calculation and guarantee the hydrodynamic safety of hot water boilers but can markedly enhance the calculation efficiency due to the use of a computer-based numerical solution. Moreover, to facilitate the application of the hydrodynamic-loop analytic method for performing the hydrodynamic calculation of the above-cited hot water boilers, through a derivation process given are the equivalent pipeline charts of the hydrodynamic-loop analytic method of a water-wall circulation loop for other commonly seen natural circulation hot-water boilers. In addition, also presented are the hydrodynamic-loop analytic method for the said boilers, the calculation method and operational procedures of hydrodynamic working points for the boiler as a whole. **Key words**: hot water boiler, natural circulation, hydrodynamic calculation, hydrodynamic-loop analytic method

双旋流气体燃烧器冷态流动特性的实验研究＝**An Experimental Study of Cold-state Flow Characteristics of Dual-swirl Gas Burners**[刊,汉] /JIA Qiong, LIU Ming, CHE De-fu, et al (Energy Source and Power Engineering College under the Xi' an Jiaotong University, Xi' an, China, Post Code: 710049)//Journal of Engineering for Thermal Energy &Power. —2006, 21(5). —477~481

An experimental study was conducted of the cold-state flow field of a dual swirl gas burner model through the use of an IFA300 type two-dimensional constant-temperature hot-wire anemometer system. The transient velocity distribution and turbulent flow intensity at different locations of the flow field were measured. The research results show that the said burner can organize a rational aerodynamic field and have a comparatively good adaptability to load changes. When the flow fields in different diffuser outlet structures are compared, it can be found that installing a convergent-divergent diffuser outlet of certain structure can better contribute to a stable, effective and clean combustion of fuel. A rotating jet flow assuming different directions can be detrimental to a uniform mixing of fuel and air and greatly reduce the length of the return flow zone. Such a structure should be avoided during the design of burners. **Key words**: swirl burner, gas combustion, hot-wire anemometer, cold state, convergent-divergent diffuser outlet

微细化煤粉再燃还原NO的反应动力学机制＝**Dynamics Mechanism Governing a NO Reduction Reaction During the Reburning of Superfine Pulverized Coal**[刊,汉] /LIU Zhong, YAN Wei-ping (Energy Source and Power Engineering College under the North China Electric Power University, Baoding, China, Post Code: 071003), SONG Qiang, YAO Qiang (Education Ministry Key Laboratory on Thermal Sciences and Power Engineering under Tsinghua University, Beijing, China, Post Code: 100084)//Journal of Engineering for Thermal Energy &Power. —2006, 21(5). —482~486

With blended coals (bitumite and lignite) in three kinds of fineness, Datong-origin bitumite in one kind of fineness and Xingtai origin lean coal in the form of superfine pulverized coal all serving as reburning fuel, and having prepared a simulation flue-gas by using N_2, O_2, CO_2 and NO, an experimental study was conducted of NO reduction by reburning in a 1 300 ℃ and 1 100 ℃ EFR (entrained flow reactor) along with an analysis of its chemical reaction dynamics mechanism. The experimental results show that the chemical reaction rate of superfine pulverized coal reburning involving NO reduction is jointly controlled by diffusion--reaction dynamics. Hence, raising the temperature in the reburning zone, using pulverized coal with a high reaction activity as reburning fuel or increasing the fineness of reburned pulverized coal, all these measures can significantly enhance the chemical reaction rate of NO reduction through reburning, thereby properly shortening the residence time of pulverized coal in the reburning zone. However, if the residence time of the pulverized coal in the reburning zone is shorter than 0.6 s, the efficiency of NO reduction will drop drastically. Meanwhile, the pulverized coal burn-out rate will also be reduced. It has been found that with superfine pulverized coal serving as a reburning fuel, the suitable residence time in the reburning zone should be about 0.8 s. **Key words**: superfine pulverized coal, reburning, NO, reaction dynamic mechanism, experiment

循环流化床脱硫塔内流场及气固分离特性数值模拟＝**Numerical Simulation of the Flow Field in a Circulating Fluidized Bed Desulfurizer and Its Gas-solid Separation Characteristics**[刊,汉] /GAO Jian-min, QIN Yu-kun, GAO Ji-hui, et al (Energy Source Science and Engineering College under Harbin Institute of Technology, Harbin, China, Post Code: 150001)//Journal of Engineering for Thermal Energy &Power. —2006, 21(5). —487~490

A numerical simulation was conducted of the gas-phase turbulent flow and particle-phase pulsating flow within the gas-sol-