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基于辐射能检测的智能燃烧进化优化系统研究

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摘　要: 辐射能信号能够更加直接地反映燃料量或燃烧品质的变化, 在此建立基于辐射能检测的智能燃烧进化优化系统, 实现热力控制系统参数的进化优化整定。设计了由烟气含氧量与炉膛总辐射能的模糊自寻优控制器和风煤比进化优化器组成的燃烧优化回路。仿真结果和开原热电厂的现场运行结果证实了该方法的实用性和优越性。

关　键　词: 炉膛辐射能; 进化优化

中图分类号: TK223; TP273　　文献标识码: A

1　前　言

锅炉的燃烧控制关系到安全、经济、清洁利用煤炭资源和为国民经济发展提供强大电力, 同时保护环境的大问题[1]。锅炉燃烧控制系统中的负荷(一般是主蒸汽压力)调节回路包括: 给煤调节回路和送风调节回路。给煤调节回路的作用是保证主蒸汽压力稳定, 而送风调节回路保证进入炉膛燃料。因而该控制系统存在动态品质调节和经济燃烧两个方面的问题, 燃烧优化的真正内涵是: 如何使得主蒸汽压力具有良好的动态特性, 而且又能使入炉燃料得以充分燃烧(即高效燃烧问题)。这不仅是一个亟待解决的问题, 同时也是燃烧控制的一大难点。为了节约能源和保护环境, 无论是在稳定燃烧状态还是在过渡燃烧状态, 都必须将空气和燃料的比值(风/煤比)控制在正常值上, 就是说, 调整风煤比是高效燃烧的关键。

寻优对象的特性决定了寻优过程的时间响应过程和效果, 而对于锅炉燃烧过程的优化来说, 需要选择一个能够快速准确反映锅炉燃烧状况、效率等参数作为寻优参量, 而且该参数应该能够准确测量, 易于控制, 以实现在线寻优的目的。燃料在炉内燃烧时立即释放出能量, 这个过程很快。例如, 煤粉炉内的煤粉在炉膛内停留的时间一般在 2 s 左右, 因此, 炉内辐射能信号能够快速反映入炉燃料的变化, 获得燃烧火焰的详尽而准确的信息已成为现实, 采用炉膛断面辐射能量作为调节变量的燃烧控制思想的实现成为可能。

2　炉膛辐射能作为控制系统辅助调节变量的选取

炉内传热主要通过燃烧火焰对冷壁的辐射换热进行的, 所以辐射是锅炉燃烧过程的重要特征, 而火焰辐射能量是炉内主要可以利用的有效能量, 现场火焰检测系统测到的能够代表火焰辐射能量的量化参数值可以作为炉膛断面辐射能量, 因而炉膛断面辐射能量可以作为表征燃烧效率的特性指数。

由于火焰辐射能量的多少取决于燃料总发热量以及烟气的吸热。可以证明炉膛火焰辐射能量表征了燃烧率的变化, 表征了燃料数量变化的同时也表征了燃料质量的变化。而燃烧总发热量越高, 烟气的吸热能量越少, 辐射能量越多。当负荷一定时, 在煤质和给煤量都保持不变的情况下, 燃料的总发热量直接受机械不完全燃烧损失的影响, 而机械不完全燃烧损失的大小又主要决定于风煤比。因此, 燃料总发热量与风煤比密切相关。同时, 烟气的吸热随风煤比的增加而线性增加。通过燃料总发热量和烟气的吸热量都取决于风煤比, 火焰辐射能量多少最终决定于风煤比的合适与否。

研究表明: 锅炉最高燃烧效率总出现在炉膛总辐射能量高的情况下, 而且此时必定对应着最佳风煤比, 同时也应该对应着最佳烟气含氧量。这就为采用炉膛总辐射能作为辅助变量来间接调节风煤比, 提高燃烧效率提供了理论依据。

为配合锅炉燃烧控制系统, 针对辐射能测量等核心问题提出了基于改进比色测温法的全炉膛火焰监测和燃烧诊断方法。

3　基于辐射能检测的智能燃烧进化优化系统设计

锅炉在某一负荷下, 燃烧效率与炉膛总辐射能量成正比, 而且炉膛总辐射能量随风煤比的变化存在一个极值点, 该极值点受锅炉入炉煤质以及锅炉

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热负荷变化的影响会产生漂移。在锅炉的实际运行过程中，为排除煤质及负荷变化等不可测因素的干扰，使得锅炉运行在最佳燃烧状态，可利用风煤与炉膛总辐射能量间的峰值特性，采用调节送风量寻找炉膛总辐射能量的最大值，而不采用定量的指标来搜索最佳风煤比，从而达到在线优化燃烧的目的。

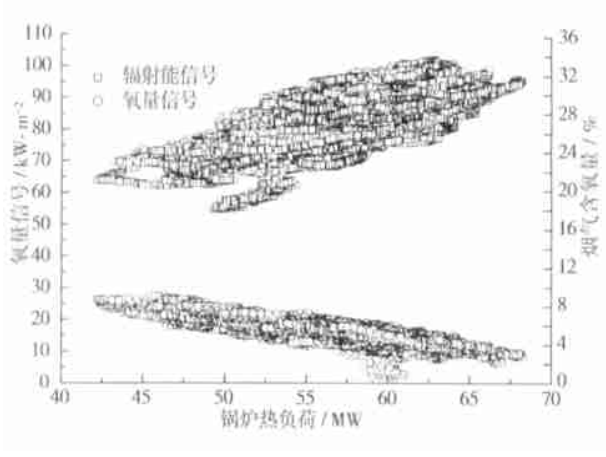

图 1 辐射能信号和氧量信号对比图

从锅炉实际运行数据中得到图 1 所示的在某个煤种下的辐射能信号和氧量信号对比图，由图看到，随着锅炉热负荷的增大，烟气含量总体在减小，而辐射能信号总体在增大。这与锅炉燃烧理论是相符合的。而对于任意范围内的热负荷，其烟气含量的辐射能信号都在一个比较宽的范围内，说明其中必存在一个对应于该负荷和煤种下的最优烟气含氧量，也证明了燃烧具有优化的潜力。

3.1 系统介绍

对于锅炉燃烧对象来说，从送风量到炉膛总辐射能调节通道的滞后比较小(大约几秒的量级)，远远小于送风量至主蒸汽压力调节通道，而且该通道受外界、负荷等变化的干扰影响很小。所以，通过炉膛辐射能对送风阶跃摄动信号的响应来寻找最佳燃烧状态，建立了基于辐射能检测的燃烧进化优化系统(见图 2)。

3.2 系统工作过程

本系统综合应用了热力控制系统进化优化体系，在基于辐射能检测的燃烧进化优化系统研究中，对常规控制器(如给煤控制器)进行了在线进化优化。针对系统各个部分，分别说明其工作过程：

传统控制部分——经煤控制器和送风控制器采用传统 PID 控制，用于稳定主蒸汽压力和调节送风量，维持锅炉的正常进行。将进化优化体系应用于这两个控制器，按照各自的优化指标分别优化各自的控制参数，并将优化结果应用到实际控制系统中。

开关控制部分——判断锅炉燃烧系统是否处于稳定状态，判断项目包括主蒸汽压力、汽包压力、一次风箱压力、送风压力是否处于正常的工作范围内，而且在比较稳定的状态。若满足条件，则进行优化；否则，就不进行优化。

模糊自寻优控制器部分——建立模糊自寻优控制器是确认送风摄动强度变化与炉膛总辐射能量变化之间规律，达到快速确定最佳燃烧工作点的目的。自寻优方法采用远离最优点时用大步长，接近最优点时用小步长的变步长搜索方法。具体实现是根据工人的实际操作经验和现场运行数据，应用模糊集合理论，通过模糊逻辑推理，建立模糊自寻优控制规则表，达到根据实际工况和燃烧状态改变寻优步长的变步长策略，以提高搜索速度，减少搜索损失，提高本系统对不可控干扰因素的自适应能力。在实际应用中，为了保证寻优过程的稳定性，适当加入停步判断环节[2]。若在寻优过程中，由于外部干扰使锅炉出现不稳定现象或者超限等，则退出寻优过程，启动常规调节器部分，调节给粉量、送风量等，使锅炉回到稳定状态。

风煤比进化优化器——对于锅炉的燃烧过程，其典型的热力过程具有变量多、大滞后等特点，而且各变量参数间存在不同程度的时变性，几乎无法建立燃烧过程的精确数学模型。在模糊自寻优控制器作用下，可以得到不同负荷、不同煤质下的最佳风煤比(本系统中是最佳烟气含氧量)，以这些数据作为原始数据，采用遗传规划的方法在风煤比进化优化器中建模，得到的模型就是锅炉的燃烧优化控制模型，其输入量为锅炉负荷、发热量等参数，输出量为特定负荷、煤质下的最佳烟气含氧量。该优化器实际上是一个学习系统，将模糊自寻优控制器得到的优化结果进行总结学习。

综上所述，本系统工作过程如下：

(1)当锅炉处于变工况下，开关控制不启动模糊自寻优控制器，保证不加入送风摄动信号，由常规控制器调节负荷，维持锅炉的稳定运行，满足生产需要。此时的送风控制回路的含氧量给定值采用的是风煤比进化优化器中对应负荷、煤种下的烟气含氧量值。

(2)在锅炉运行状态满足条件时，开关控制启动模糊自寻优控制器，加入送风摄动信号。摄动强度由根据工人操作经验和现场实际数据整理出来的模糊自寻优控制表规则确定。

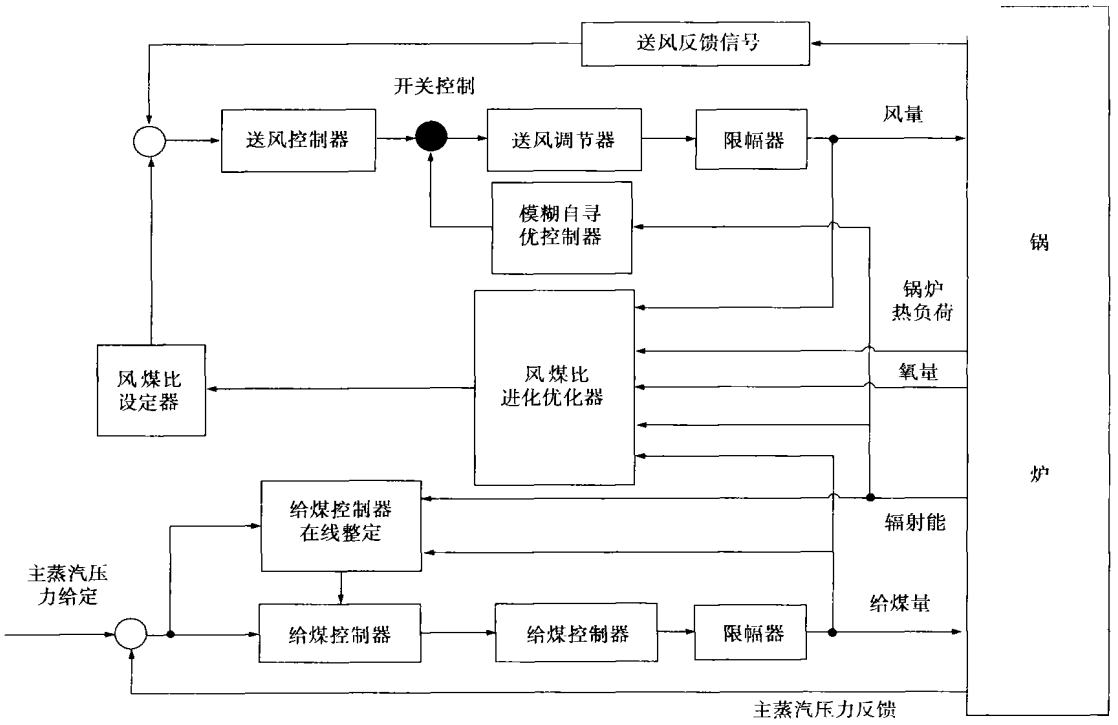

图 2　基于辐射能检测的燃烧进化优化系统

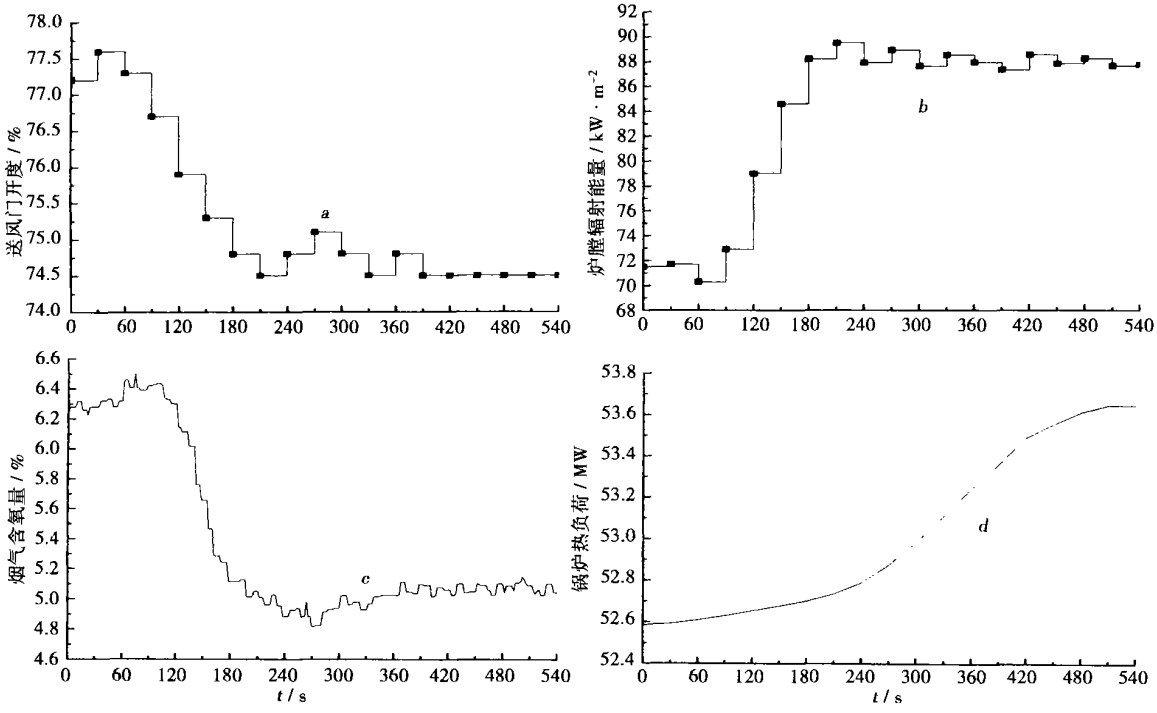

图 3　实际优化过程

(3)当搜索到最佳工作点后, 记忆此时烟气含氧量等锅炉实际运行数据, 启动风煤比进化优化器, 更新燃烧优化控制模型和风煤比设定器设定值(烟气含氧量)。

(4)在模糊自寻优控制器工作期间,随时判断锅炉运行状况是否出现不稳定现象,是否超限等,如果不满足条件,则退出寻优过程,启动常规调节器部分,调节锅炉至稳定范围。模糊自寻优控制器作用时,常规调节器也在正常工作,仅仅是送风控制回路处于开环控制状态。整个过程是一个在线优化过程,可以克服工况变化所造成的影响。

4 仿真试验研究

模糊自寻优控制器的输入量为上次寻优步长 ΔF_{k-1} 和本次锅炉炉膛总辐射能变化量 ΔE_k,在每个周期测量炉膛总辐射能增量 ΔE_k,根据 ΔE_k 和上次寻优步长 ΔF_{k-1} 决定本次寻优步长。首先,运用模糊集合理论和现场经验,建立模糊自寻优控制表。然后,应用模糊逻辑推理,再根据现场情况加以人工修正,就得到了实际自寻优模糊规则表。在实际寻优过程中,根据该表实现变步长寻优工作。图 3 所示为对实际煤粉锅炉进行风煤比模糊自寻优过程曲线。其中 a、b、c、d 曲线分别对应该优化过程的送风门开度、炉膛辐射能信号、烟气含氧量和锅炉热负荷曲线。从图 3 的 b 中看到,炉膛辐射能总体上在增大,表明了锅炉的燃烧效率提高,燃烧状况变好,因此,相应的锅炉热负荷也会增大;从图 3 的 d 所示,寻优结束后,锅炉热负荷也增大到 53.64 MW。

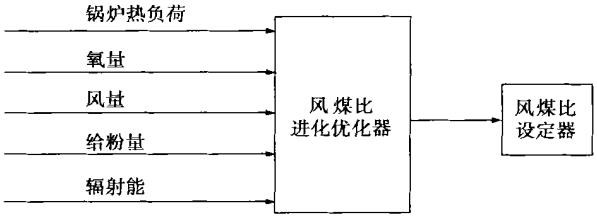

图 4 风煤比进化优化控制器

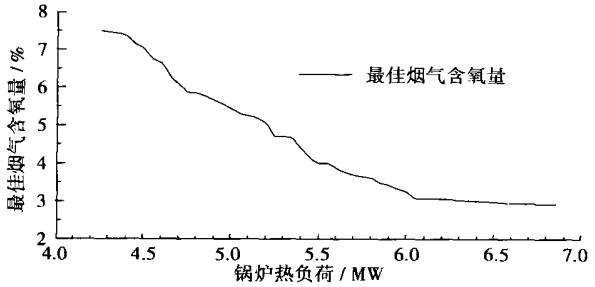

图 5 不同负荷下最佳烟气含氧量曲线

经过这样的一系列的优化过程,得到该锅炉在不同负荷、不同煤种下的最佳烟气含氧量以及对应的炉膛辐射能等一系列信息。在此基础上,可以在风煤比进化优化控制器建立锅炉燃烧优化模型。

寻优过程结束后,得到单点最佳燃烧状态,将表征工作点燃烧状态的参数送入图 4 所示的风煤比进化优化控制器中,风煤比进化优化器输入量为锅炉热负荷、氧量、风量信号、给粉量和输出量为给定煤种,给定热负荷下的风煤比(最佳烟气含氧量)设定值。如前分析,对应于最高炉膛辐射能量的风煤比为锅炉燃烧效率最高点。在得到不同热负荷下的根据最高炉膛辐射能量寻找的最优风煤比后,采用遗传规划方法,建立锅炉燃烧优化模型,寻找不同煤种、不同热负荷下的最佳烟气含氧量设定值曲线。

经过这五个月优化运行后(见图 5),得到的不同负荷下最佳烟气含氧量曲线,从曲线中可以看出,随着锅炉热负荷的增大,最佳烟气含量减小,符合锅炉燃烧理论。

5 工程应用

本系统在开原某电厂 75 t/h 煤粉锅炉现场长期运行后,锅炉的飞灰含碳量明显降低。现场实际应用证明,基于炉膛辐射能信号的智能燃烧进化优化系统可以明显提高锅炉燃烧控制的效果。由于锅炉现场实际运动情况,只得到了锅炉在煤种下的最佳烟气含氧量曲线。当实际运行的煤种发生变化时,只需要将煤质分析结果引入本系统中,就可以将所得的各个煤种下的最佳含氧量曲线,按照煤种(低位发热量等)、锅炉负荷,在风煤比进化优化器作用下,建立起更详细的锅炉燃烧优化模型,以此模型的输出,作为锅炉实际运行送风控制回路的烟气含氧量设定值。

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(渠源 编辑)

三维内肋螺旋管内强化换热实验= **Experimental Research on Intensified Heat Exchange in a Three-dimensional Internally Finned Helical Pipe** [刊, 汉] / LI Long-jian, XIN Ming-dao CUI Wen-zhi (Power Engineering Institute under the Chongqing University, Chongqing, China, Post Code: 400044) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 270 ~ 273

Tests and measurements were performed to investigate the flow and heat transfer performance in a three-dimensional internally finned helical pipe with a curvature of 0.066 3 and measurement section length of 1.15 m. With water serving as a working medium tests were carried out in a spiral bare pipe and a three-dimensional internally finned pipe of two different structural dimensions. The range of Reynolds number is Re = 1 000-8 500. The test results indicate that a relatively high intensification of convection heat exchange can be achieved in the spiral pipe by the use of three-dimensional inner fins, which is accompanied by a moderate increase in flow resistance. In comparison with bare spiral pipes without fins the average intensification ratio of heat exchange for the two kinds of three-dimensional internally finned pipe within the range of measured flows can reach 1.71 and 2.03 respectively with the thermodynamic performance factor being assessed at 1.2 - 1.66. **Key words**: spiral tube, ribbed tube, intensified heat transfer

大加速度场中层流扩散火焰流场的数值计算= **Numerical Calculation of Laminar Flow Field of a Diffusion Flame in a High Acceleration Field** [刊, 汉] / DONG Zhi-guang (Department of Urban Construction, Hubei Engineering Institute, Handan, China, Post Code: 056038), WU Jin-xiang, LIU Zhi-kai (Department of Thermal Energy Engineering, Hubei Polytechnical University, Tianjin, China, Post Code: 300130), DONG Zhi-hui (Handan Municipal Planning Design Institute, Handan, China, Post Code: 056006) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 274 ~ 277

A numerical calculation method is proposed for calculating the laminar flow field of a combustor in a high acceleration field and a mathematical model for two-dimensional laminar flow combustion in the high acceleration field was set up. A control equation group was discretised. A SIMPLE algorithm and a staggered grid design were adopted and the relevant program was debugged. On the basis of the successfully debugged program a numerical simulation of the diffusion combustion process was performed of methane and air in the high acceleration field. The results of the calculation indicate that the uniform and high acceleration field along the axis of the combustor will exercise a significant influence on the velocity and temperature fields of the diffusion flame. On the one hand, it has intensified the diffusion/mixing process of the fuel and air, resulting in a length-reduction and thickening of the diffusion flame shape and a rise in flame surface temperature and thus enhancing its combustion speed. On the other hand, due to a floating force action the high-temperature air flow will assume a direction opposite to that of the fuel jet flow, which would produce a unstable flow field structure, triggering a unstable combustion process. **Key words**: high acceleration field, combustion, numerical simulation

微细微量螺旋加料器的试验研究= **Experimental Research on a Micro-particle and Micro-quantity Screw Feeder** [刊, 汉] / ZHANG Jie, GAO Tie-yu, HUI Shi-en (College of Energy & Power Engineering under the Xi' an Jiaotong University, Xi' an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 278 ~ 280, 291

An experimental study of several types of self-designed micro-particle and micro-quantity solid-particle feeder has resulted in the identification of micro-quantity feeding rod types suitable for materials of different particle diameters. It is found that when carborundum particles have a Sauter mean diameter around 90 μm the pressure screw-feeding rod can accommodate a minimum flow of 0.4 g/min. With the carborundum particles assuming a Sauter mean diameter of 40 μm the two-wire relaxation screw feeder rod can attain a minimum flow rate of 0.6 g/min. A micro-particle and micro-quantity solid particle feeder featuring simple and reliable operation with an accurate quantification can be crucial for a uniform, continuous and stable feeding of powder during the experimental study of gas-solid two-phase flows. **Key words**: gas-solid two-phase flow, screw, feeding rod, relaxation, multi-wire

基于辐射能检测的智能燃烧进化优化系统研究= **A Study of the Optimization System of Radiation Energy Detection-based Intelligent Combustion Evolution** [刊, 汉] / MA Tao, XU Xiang-dong, WANG Xin-xin (Department of

Thermal Energy Engineering, Tsinghua University, Beijing, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 281 ~ 284

Radiation energy signals are capable of more directly reflecting the variation of fuel flow rate or combustion quality. An optimization system of radiation energy detection-based intelligent combustion-evolution has been set up to implement the evolution-optimization adjustment of the parameters of a thermodynamic control system. A combustion optimization circuit was designed, which consists of two parts: a fuzzy self-optimizing controller of flue-gas oxygen content and furnace total radiation energy, and an air/coal ratio evolution optimizer. The results of a simulation and the on-site operation results at Kaiyuan Thermal Power Plant have demonstrated the practicality and superiority of the adopted method. **Key words**: furnace radiation energy, evolution optimization

喷水塔饱和器的动态建模与仿真= **Dynamic Modeling and Simulation of a Water-spray Tower Saturator** [刊, 汉] / LIU Yong-wen, SU Ming, WENG Shi-lie (Education Ministry Key Laboratory for Power Machinery & Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 285 ~ 287

A method of building a one-dimensional dynamic model for a water-spray tower saturator is discussed. Under this method the saturator has been divided along its height into several segments, each being represented by gas and water-drop modules. The setting-up of an explicit simulation model makes it possible to clarify the variation mechanism of parameters of the saturator under a steady state and during a dynamic process. According to the data of the model under a steady state the variation of pressure along the main flow direction of gas basically assumes a linear relationship, while the variation of other parameters has been found to be nonlinear. The results of the model dynamic simulation indicate that the interaction between gas pressure and water in the saturator features a rapid process, thus exhibiting the characteristics different from those of a heat exchanger. **Key words**: humid air turbine, saturator, dynamic simulation

熔融碳酸盐燃料电池动态性能数值模拟= **Numerical Simulation of the Dynamic Performance of Molten Carbonate Fuel Cells** [刊, 汉] / YU Li-jun, JIANG Xiu-min, YUAN Jun-qi (Institute of Mechanical & Power Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200240), CAO Guang-yi (Fuel Cell Research Institute under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 288 ~ 291

A dynamic three-dimensional mathematical model of fuel cells featuring variable parameters was set up, which can give an accurate description of heat generation, mass transfer and electrochemical reaction characteristics. By using a numerical simulation method it is possible to forecast such performance properties as fuel cell temperature and speed distribution, etc. Through an experimental investigation test data, such as fuel cell power-generation system output performance and temperature distribution, etc can be acquired. The comparative analysis of numerical calculation results with those of experimental tests has confirmed the precision of the numerical simulation, testifying to the relatively high reliability of the adopted mathematical model. **Key words**: fuel cell, computational fluid mechanics, numerical simulation

热力系统新型纵流壳程换热器 CAD 技术的研究= **Research and Application of CAD Technology for a New Type of Heat Exchanger with a Longitudinal Flow of Shell-side Fluid in a Thermodynamic System** [刊, 汉] / LIU Min-shan, DONG Qi-wu, GU Xin (Thermal Energy Control Center under the Zhengzhou University, Zhengzhou, China, Post Code: 450002) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 292 ~ 294

Through the research on some key items of CAD technology, such as parametric graphic design, data configuration and processing, and system integration, etc implemented was the CAD technology integration for a new type of tubular heat exchanger with a longitudinal flow of the shell-side fluid (NTTHELFSF). The CAD technology integration entails fabrication technology, machine components and parts. In addition, resolved were two key issues, namely, information integration and general assembly drawing integration. As a result, it is possible to dramatically enhance the design efficiency and quality of the NTTHELFSF, blazing a new path for the further research and popularization of the latter. **Key words**: thermodynamic system, new type of tubular heat exchanger with a longitudinal flow of shell-side fluid, parametric graphic