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电站锅炉神经网络燃烧诊断系统应用研究

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摘　要: 先进的燃烧诊断技术可以有效地提高电站锅炉运行的经济性和安全性。本文通过对炉膛火焰的图像采集, 利用计算机数字图像处理技术及人工神经网络模型分析方法, 开发了永安火电厂 5 号炉的火焰图像燃烧诊断系统。该系统为运行人员提供了有意义的定量化特征参数, 并对燃烧状况辨识的机理进行了富有成效的探索, 为电站锅炉的燃烧诊断和优化控制提供新方法和新途径。

关　键　词: 电站锅炉; 燃烧诊断; 数字图像; 人工神经网络

中图分类号: TP183; TK227.1　　文献标识码: A

1　前言

燃烧诊断是电站锅炉安全生产和高效运行的迫切要求。电站锅炉燃烧状况的优劣, 直接影响到整个电厂运行的经济性及安全性。在燃用劣质或低品位煤种时, 燃烧的稳定性问题尤为突出。同时, 由于某些电站燃用煤种的多样性, 使燃烧工况的调节更为复杂, 加剧了熄火及火焰冲墙等事故的发生。许多电厂现有的 FSSS 或工业电视等火焰检测装置具有很大的局限性[1], 仅能起到灭火保护和点火时肉眼观察的作用。所以, 电厂迫切需要开发出一套智能化的火焰燃烧工况诊断系统, 以实时监测炉内燃烧状况, 为锅炉的优化控制提供有力保证。

电站锅炉内的煤粉燃烧过程极其复杂, 燃烧的诊断问题长期得不到很好解决。现代光测技术、计算机数字图像处理技术、人工智能等新技术和新理论的飞速发展, 推动了真正意义上的燃烧诊断技术的实现。20 世纪 90 年代初, 图像处理技术被应用到了电站锅炉的燃烧诊断上, 目前已经在火焰图像采集和处理、温度场测量和重构等方面取得了初步的进展[2~4], 多探头火焰图像及人工神经网络燃烧诊断和控制系统在实验室中也得到了开发[5]。在国内, 首次将人工神经网络应用到燃烧诊断中去[6], 在实验室获得了良好的结果。在此基础上, 本文作者开展了人工神经网络火焰图像燃烧诊断技术的工程化应用研究。

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2　系统

电站煤粉锅炉火焰图像燃烧诊断系统的构成如图 1 所示。将特制的高温光学镜头插入到 31 m 标高的炉膛内, 俯视的全炉膛燃烧火焰图像, 视频信号通过视频电缆实时传入数字化图像处理器, 转化为数字化图像, 然后应用专门开发的软件对图像信息进行分析与处理, 得出各种反应炉内燃烧状况的特征量, 再经过人工神经网络模型的分析, 由终端输出诊断结果。为了保证光学镜头在高温环境下正常工作, 还配有冷却、吹扫、进退、安全保护等伺服系统, 以实现探头的进退控制和安全保护。当冷却水或吹扫风压力太低而起不到应有的冷却和吹扫效果、或

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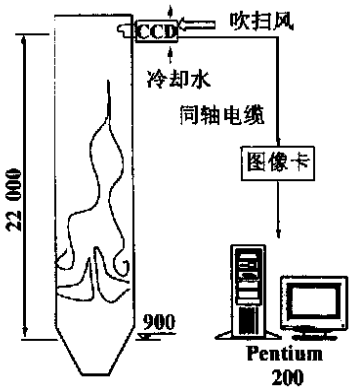


图 1 永安火电厂 5 号炉(125 MW)火焰图像燃烧诊断系统

镜头温度太高时,伺服系统自动将探头从炉膛内退出,从而使探头免遭损坏。

图 2(a)为采集到的满负荷 125 MW 情况下的火焰原始图像,(b)为对应的处理后的具有不同辐射强度区域的边界。从左至右的边界曲线所对应的灰度等级分别为 80、130、180、210 和 245。

3 人工神经网络在火焰诊断中的应用

人工神经网络是新兴的智能理论,它实现了并行处理的机制;具有联想与记忆的能力和很高的自适应能力;对缺损信息具有高度的容错能力;具有十分强大的学习功能等。人工神经网络现已在模式识别、图像处理等领域得到了应用。

Back— Propagation(B—P 网络)即反向传播网络,其学习算法采用的是新颖的反向传播算法,其基本思想是构造一个类似于感知机的非线性系统,并让该系统的决策能力与最小均方误差函数和梯度下降联系起来,从而解决了普遍存在的多层神经网络的学习不易收敛的问题,是现今实用程度最高的一类。

3.1 网络结构和算法

B—P 网络的属于多层前馈式,如图 3 所示[7]。Robert Hesht-Nielson 证明了对于任何在闭区间内的一个连续函数都可以用一个隐含层的 B—P 网络来逼近,因而一个三层 B—P 网络可以完成任意的 n 维空间到 m 维的映射,故本文所采用的网络为三层网络,中间只有一层隐含层。最下面一层神经元组成了输入层,此层的主要作用是接收输入矢量,在此我们设输入矢量为 $X \in R^n$, $x = (x_0, x_1, \cdots, x_{n-1})^T$,此层神经元个数为 n_1,其输出矢量为 $X' \in R^n$, $x' = (x_0', x_1', \cdots, x_{n1-1}')^T$。

中间一层为隐含层,共由 n_2 个神经元组成,接受由输入层神经元的输出矢量 X',其输出矢量为 X'', $x'' = (x_0'', x_1'', \cdots, x_{n2-1}'')^T$。

最上一层为输出层,共由 m 个输出神经元组成,接受来自隐含层的输出矢量 X'',其输出矢量为 $Y \in R^m$, $y = (y_0, y_1, \cdots, y_{m-1})^T$。

在输入矢量和输入层之间的权值为 W_{ij}。在输入层和隐含层之间的权值为 W_{jk}'。在隐含层和输出层之间的权值为 W_{kl}'。

B—P 网中的每个神经元的输入输出采用非线性变换,其输出函数是采用连续可微的 S 型函数:

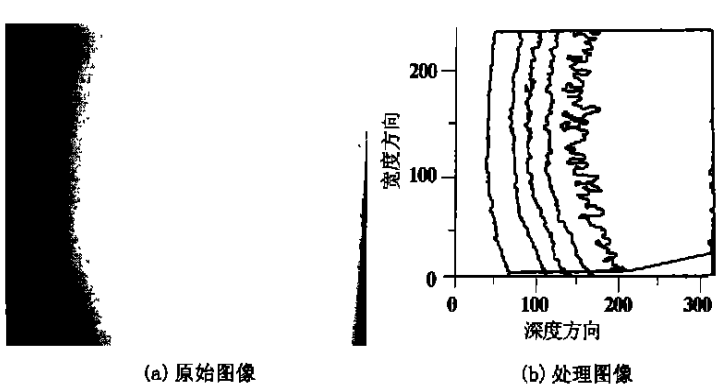
$$f(x) = \frac{1}{1 + e^{-x}} \tag{1}$$

这样各层神经元的输出满足下列各式:

$$y_i = f\left(\sum_{k=0}^{n2-1} W''_{kl} \cdot x''_k - \theta''_l\right) \tag{2}$$

$$x''_k = f\left(\sum_{j=0}^{n1-1} W'_{jk} \cdot x'_j - \theta'_k\right) \tag{3}$$

$$x'_i = f\left(\sum_{k=0}^{n2-1} W_{ij} \cdot x_i - \theta_j\right) \tag{4}$$



(a) 原始图像 (b) 处理图像

图 2 炉膛火焰图像及处理

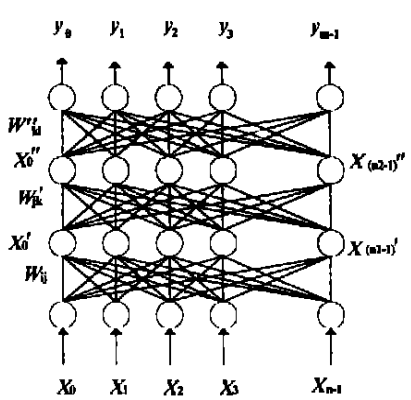


图 3 B—P网络结构简图

B－P 的学习算法属于 δ学习律,是一种有教师的学习算法,设其总共有 p 个学习样本$\vec{x^1}$, $\vec{x^2}$, …, $\vec{x^p}$,已知对应的教师应为$\vec{t^1}$, $\vec{t^2}$, …, $\vec{t^p}$,学习算法是用实际的输出$\vec{y^1}$, $\vec{y^2}$, …, $\vec{y^p}$ 与$\vec{t^1}$, $\vec{t^2}$, …, $\vec{t^p}$ 的误差来修改联接权和阈值,使训练后的$\vec{y^p}$ 与$\vec{t^p}$ 尽可能的相近。

3.2　火焰图像特征向量

Back－Propagation 神经网络模型非常适合于对不同特征向量的分类识别。每一幅火焰图象包含了巨大的信息量,由于实时性的要求,必须提取诸个最能反映出不同燃烧状态的本质特征参数,作为神经网络辨识分类的判据。通过大量的现场试验,本文作者利用图像处理技术对不同燃烧状态下火焰图像的特征参量进行了提取和筛选,构成了人工神经网络赖以工作的基础特征向量。

限于篇幅,图 4 所示为其中三种特征参数在不同燃烧工况下的脉动时序图,(a),(b),中,由上向下所示曲线分别代表负荷为 100、90、60、50 MW 时的情况。(c)图中由下向上分别代表负荷为 100、90、60、50 MW 时的情况。图中灰区域所示为稳定燃烧区域。

图 5 所示为在负荷突变时火焰燃烧不稳定性试验的动态数据记录曲线,很明显在工况突然调节时特征参数发生了明显的阶越。

3.3　网络的结构设计

B－P 网络的输入采用了以下方法,即对同一种工况下的火焰连续采集五幅瞬态图像,每幅图像从中提取了五个特征值,所以一次输入共有 25 个特征值,作为该工况下的一个输入样本。同样,可按时序对该工况下的火焰进行同样采集、处理,每工况获得 50 组样本。

网络的输出结点数目设计为数字式输出,若拟判别的类别为 3 类,则输出结点数目为 3,如 A 状态期望输出设为{0.1, 0.1, 0.1},B 状态期望输出设为{0.5, 0.5, 0.5},C 状态期望输出设为{0.9, 0.9, 0.9}。最终的判据则取这三点输出的平均值。用这种输出,可以在 0.0 ~ 1.0 区间上划分 3 个带状区域,即 0.0 ~ 0.2, 0.4 ~ 0.6, 0.8 ~ 1.0。凡是输出平均值落于 0.0 ~ 0.2 之中的即为 A 类,凡是输出平均值落于 0.4 ~ 0.6 区间的,认为属于 B 类,凡是输出平均值落于 0.8 ~ 1.0 之间的,认为属于 C 类。这样就完成了火焰状态识别的目的。

3.4　锅炉变负荷工况的诊断

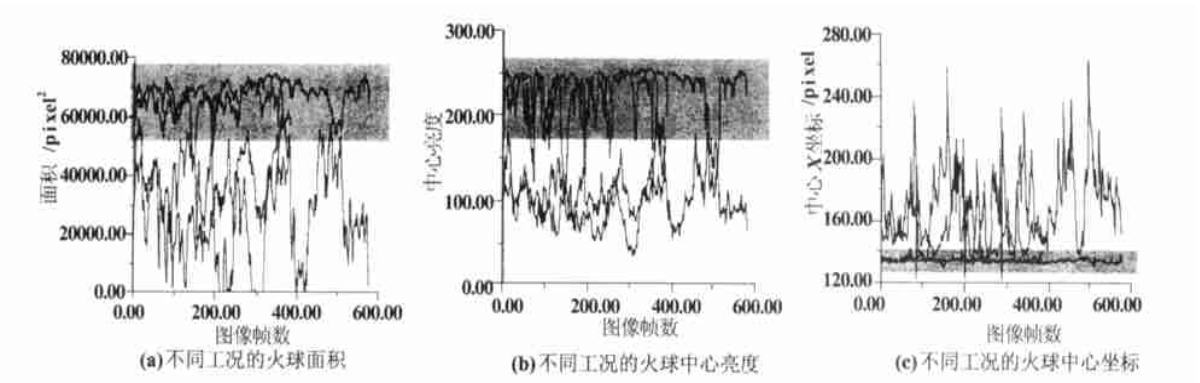


图 4　不同工况下的燃烧火焰特征参数脉动变化

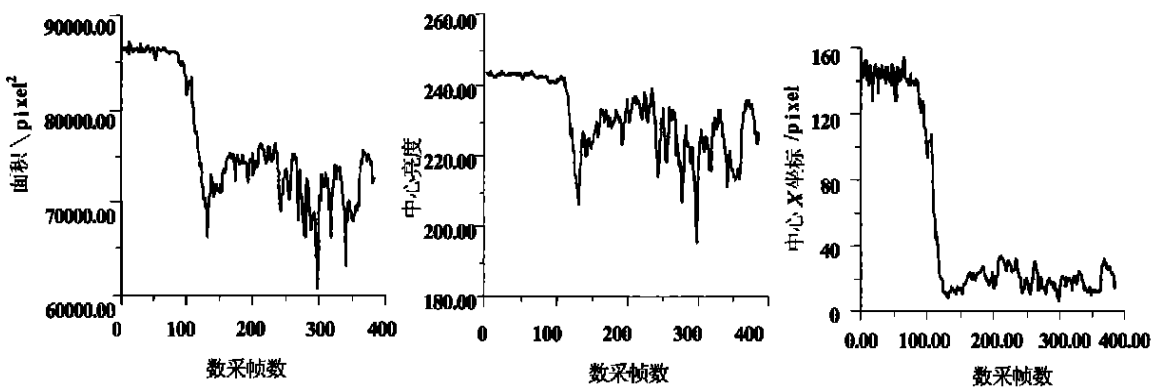


图 5　稳态到不稳态的突变过程

针对诊断锅炉变负荷的要求，作者进行了变工况的研究。它们的训练样本分别取自负荷为 125、80、50 MW 时的火焰图像，在此分别计作 A、B、C 工况。每个工况采 40 个样本，所以共 120 个训练样本，对 A 工况的样本输入，期望值设计为 0.1；对 B 工况的样本输入，期望值设计为 0.5；对 C 工况期望值设计为 0.9；经过 1950 次训练之后，网络输出结果如图 6 所示。

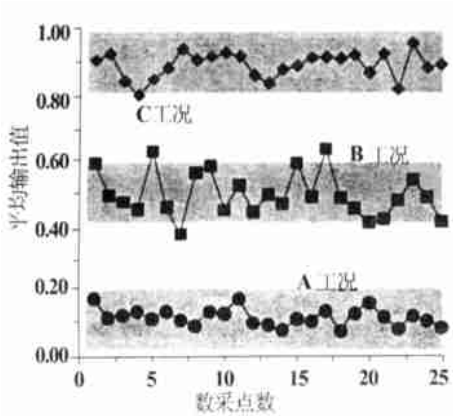


图 6 训练样本工况输出值

图 6 中，每幅图由三种不同标号连成了三条曲线，分别代表三种不同工况。图中每个工况的 25 个采样点是从录像带上存贮的三个工况火焰图像中随机采的，利用前文已训练好的权值矩阵，计算出每个采样点的网络输出值。对图中的圆点，它们主要集中于 0 ~ 0.2 之间。这正是它们所代表的工况 A 所期望的输出值，也就是说，B－P 网络通过有教师的学习训练，已经正确认识了工况 A 的火焰图像。当然对于其它的两个工况，如 B 工况的输出集中于 0.4 ~ 0.6 之间，C 工况的输出集中于 0.8 ~ 1.0 之间，也同样具有了辨识功能，另外可以发现在三条曲线之间存在着一很宽的空白区域，可以认为是介于两个工况之间的过渡工况，这个过渡区域的宽度越大，网络的识别效果越好。

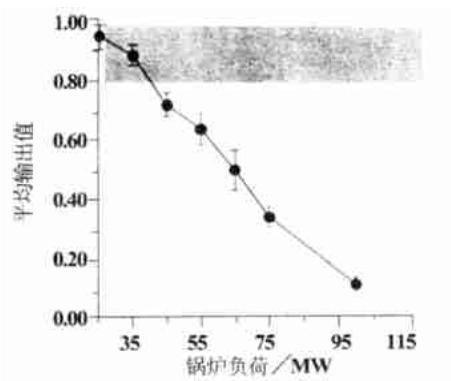


图 7 不稳定工况诊断

3.5 锅炉火焰燃烧不稳定及熄火预警功能

这里所述及预警功能，是针对锅炉运行过程中燃烧不稳定的问题，准确及时地进行预警。为此，在电站进行了一系列连续变工况试验。工况调整系列为 125、100、75、60、55、40、35 和 30 MW 滑负荷，来模拟火焰熄灭的动态过程，设定工况 60 MW 时的燃烧状态作为最终不稳定临界状态。

对动态火焰工况进行实时采样诊断，其诊断结果如图 7 所示。正常工况的网络输出值均在灰色危险区域以下，随着负荷的不断降低，网络输出从 0.1 渐近爬升到 0.9。另外，网络对于介于工况 A 和 B 之间的火焰状态，可以联想识别，将它们分别内插于工况 A 和工况 B 之间。当连续有 2－3 点落在了报警区，即输出为 0.8 ~ 1.0 时，计算机以屏幕的闪动和声音信号加以提示，从而实现了熄火实时报警功能。

4 结论

根据所开发的锅炉火焰图像燃烧诊断系统的现场应用情况，可以得到以下结论：该系统相对于传统的工业电视和光敏元件监控方法具有本质性的提高，为运行人员提供了更直观、更丰富、更准确、更可靠的燃烧控制信息，已具备了初步的指导燃烧的作用。

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Based on a gas-solid two-phase theory and taking into account the pressure loss effect in the air-coal combined flow process a method was proposed for measuring the pulverized coal concentration in primary air pipe after the mixing of air and the pulverized coal. The above measurement was carried out through the use of an energy balance method. Also described are the method and procedures for conducting the on-line and real-time monitoring of the pulverized coal and air speed in the primary air pipe with the use of a dynamic link library technique. The above-cited on-line monitoring method has been found to be very effective for its intended purposes when used on-site at thermal power plants. **Key words**: two-phase flow, pulverized coal concentration, on-line monitoring, dynamic link library technique

循环流化床锅炉在线监测与状态诊断专家系统= **An Expert System for the On-line Monitoring and Condition Diagnosis of Circulating Fluidized Bed Boilers** [刊, 汉] / LU Ji-dong, HUANG Yi-hua, SHEN Kai, CHEN Jiao-shun (National Key Lab of Coal Combustion under the Huazhong University of Science and Technology, Wuhan, China, Post Code: 430074) // Journal of Engineering for Thermal Energy &Power. —2001, 16(6)—628 ~631

In the light of the special characteristics and system requirements of circulating fluidized bed boilers (CFBB) an expert system for on-line monitoring and condition diagnosis of such boilers has been designed. On the basis of analyzing commonly seen faults of CFBB and frequently used diagnostic techniques the authors expound in detail the design process, software realization and system functions of the above-mentioned expert system. The feasibility of the latter has been verified by engineering practice on site. **Key words**: boiler, circulating fluidized bed, on-line monitoring, condition diagnosis, expert system

Visual Basic 编程语言用于热电厂在线监测与资源共享= **The Use of Programming Language Visual Basic for On-line Monitoring and Resource Sharing in Thermal Power Plants** [刊, 汉] / WANG Shi-zhong, QIU Jing-hui, YU Shi-sheng (Department of Aeronautic Engineering and Mechanics, Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy &Power. —2001, 16(6)—632 ~634

Through the adoption of an advanced 893 network intelligent distribution type of data acquisition device IDCB the problem of millivolt voltage signal interference (analog magnitude), which has troubled a factory for years, was successfully resolved. With Windows 98 serving as an operating system and Visual Basic 6.0 as a programming language, software Heatwork.Vbp has been prepared and operated on a "Pentium 586" industrial control machine, thus realizing an on-line monitoring and resource sharing. **Key words**: thermal power plant, power generating unit, on-line monitoring, resource sharing

压缩机中间冷却器采用不锈钢波纹管的试验研究= **Experimental Research of the Use of Stainless Steel Corrugated Tubes for a Compressor Intercooler** [刊, 汉] / CHEN Jia-xin, TAN Yu-fei (Electromechanical School under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—635 ~636

The modification of a compressor intercooler was conducted by replacing the straight tubes of a shell-tube heat exchanger with a new type of stainless steel corrugated tubes. Furthermore, measurements and tests were performed during the operation of the intercooler followed by a comparative analysis. It has been found that the natural gas outlet temperature of the corrugated tube heat exchanger can attain the compressor design value and even lower. The compressor enjoys a normal and stable operation with its heat exchange efficiency higher than that of an in-tube layout heat exchanger by 61%. The considerable reduction in maintenance work can contribute to a long-cycle operation of the intercooler. **Key words**: compressor intercooler, new type of stainless steel corrugated tube, high-efficiency heat exchanger, experimental research

电站锅炉神经网络燃烧诊断系统应用研究= **Applied Research of a Neural Network-based Combustion Diagnostic System for a Utility Boiler** [刊, 汉] / YANG Hong-min, MA Wei-min, GU Fan, XU Yi-qian (Research Insti-

tute of Thermal Energy Engineering under the Southeastern University, Nanjing, China, Post Code: 210096) //Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—637 ~ 640

The use of an advanced combustion diagnostic system can be conducive to an effective enhancement of utility boiler operation economy and safety. Through the collection of furnace flame images and by utilizing computer-based digital image processing techniques as well as the analysis method of an artificial neural network model a combustion diagnostic system of flame images has been developed for boiler No. 5 of Yongan Thermal Power Plant in Fujian Province. This system has provided meaningful quantified characteristics parameters, performing a highly effective probing of the combustion condition identification mechanism. As a result, a new method and approach for combustion diagnosis and optimized control is provided for utility boilers. **Key words**: utility boiler, combustion diagnosis, digital image, artificial neural network

火电机组锅炉过热汽温的约束模型预测控制研究=**A Study of the Constrained Model Predictive Control for the Boiler Superheated Steam of a Thermal Power Plant** [刊, 汉] / JU Gang, CHEN Shao-bing, XU Zhi-gao (Power Engineering Department, Southeastern University, Nanjing, China, Post Code: 210096) //Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—641 ~ 643

Presented is a model predictive control algorithm with an input of hard constraints. With no need for on-line iteration solution or on-line matrix inversion the recommended algorithm features a simplified calculation method with a low on-line computation load. It has been employed for the simulation study of boiler superheated steam control of thermal power plants and proved to be highly effective. **Key words**: predictive control, constraint, boiler, superheated steam temperature

75 t/h 树皮—煤粉复合燃烧系统的建模与仿真=**Model Building and Simulation of a 75 t/h Bark and Pulverized Coal-fired Boiler** [刊, 汉] / BAO Gang, DENG Su-bi, WANG Zu-wen (Pneumatics Technology Center under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—644 ~ 645, 649

A 75 t/h boiler with a composite firing system operates on bark and pulverized coal. A model of the firing system has been set up with the combustion system serving as an object model. Meanwhile, a simulation of its control system was also conducted. **Key words**: fluidized bed boiler, simultaneous burning of bark and pulverized coal, mathematical model, control system simulation

压水堆核电机组二回路的反平衡单元分析法=**Inverse-balance Element Analysis for the Secondary Circuit of a Pressurized Water Reactor-based Nuclear Power Plant** [刊, 汉] / LI Yun-ze, YAN Jun-jie, LIN Wan-chao (Power System Engineering Research Institute under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049), DENG Shi-min (Thermal Engineering Research Institute of National Electric Power Co., Xi'an, China, Post Code: 710032) //Journal of Engineering for Thermal Energy & Power. —2001, 16(6)—646 ~ 649

On the basis of analyzing the effect of additional components on the incoming water factor of a heating unit derived is a general expression for the incoming water factor of the high-pressure heating unit of a secondary circuit. Through a detailed theoretical analysis and mathematical deduction an inverse-balance mathematical model was set up for the secondary circuit of a pressurized water reactor-based nuclear power plant. The foregoing has laid a theoretical basis for the inverse-balance element analytical method of the above-mentioned secondary circuit. Such an analytical method features a simplified calculation and an accuracy of the calculated results. Being convenient for manual calculations and programming-based electronic calculations, it represents one of the effective tools for the secondary circuit system design and energy-saving diagnosis. **Key words**: pressurized water reactor-based nuclear power plant, secondary circuit, heating unit, incoming water factor, heat release factor, inverse-balance element analytical method

利用 Monte Carlo 方法对循环流化床锅炉炉膛传热的数值计算=**Numerical Calculation of Heat Transfer in a**