文章编号: 1001－2060(2006)04－0405－04

火电机组先进控制与优化软件的设计与应用

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摘 要: 为改善国内火电机组控制效果、提高运行经济性, 采用面向对象技术及模块化设计方法, 开发了一套先进控制与优化软件。该软件在 DCS 工作站后台运行, 并利用 DCS 的组态工具制作操作界面, 充分利用现有 DCS 的强大功能, 其操作方法易于被运行人员熟悉; 统一的数据预处理机制和对心跳信号的监测保证了安全性; 内嵌多种通信机制使其适用于各种现场情况, 既独立又可相互协作的算法模块结构使其配置灵活, 可扩展性好。已实现了一种经过改进的广义预测控制算法和一种简化后的自适应在线稳态优化算法。使用该软件对一个电站锅炉烟气含氧量实施先进控制, 显著改善了控制效果。结果表明, 该软件投资少、效果好、现场应用方便。

关 键 词: 火电机组; 先进控制与优化软件; DCS; 氧量校正
中图分类号: TP273 文献标识码: A

1 引 言

在我国, 火电机组是目前主要的发电设施, 其装机容量占总数的 75%左右, 每年消耗的煤占总消耗量的 60%, 提高电厂锅炉的能源利用率、降低其有害气体排放量对节约能源、改善环境有非常重要的意义。为此, 通常有两方面的考虑: (1)改善部分重要控制回路, 提高运行安全性, 不仅可以保证高效的热力循环, 还可以为一些在线优化系统的运行建立基础。国内外在这方面已经取得了一定的成果[1~4]。(2)在线调节烟气含氧量、配风等对燃烧影响比较大的参数以提高锅炉热效率, 降低污染物排放, 近年来这方面的算法和实践上也出现了不少尝试[5~9]。除了对算法的探讨, 迫切需要一种适用于火电机组的先进控制与优化软件, 国内使用的此类软件大多是引进的国外产品, 成本高, 不符合我国国情, 国内研究机构也开发了一些软件, 但在工程推广上还有不少问题[10], 把先进控制与优化功能结合起来并在火电机组成功应用的软件尚未见报道。

作者开发了一套适用于火电机组的先进控制与优化软件, 它集先进控制与优化算法于一体, 并可实现一些性能计算功能。作为例子, 使用本软件对山东石横电厂 2 号机组的氧量校正回路实施先进控制, 应用结果表明本软件投资少, 效果好, 现场应用方便。

2 系统要求

针对我国火电机组的具体情况, 先进控制与优化软件除算法及性能满足要求外, 要想在实际运行中推广, 还需具有如下特点:

(1)安全性。这是工业系统的基本要求;

(2)灵活易用性。系统的直接用户是现场操作人员, 操作方式须符合他们的习惯, 这有利于软件系统的现场投用和推广;

(3)适用性。软件需要考虑各种现场 DCS 软硬件条件及数据质量;

(4)可移植与可扩展性。对一个具体项目, 往往需要软件运行在特定软硬件平台上, 对多个回路进行调节和控制, 甚至需要新开发一个特定的功能模块, 这些都是事先难以明确的, 因此软件需要具有较好的可移植性与可扩展性。

3 软件设计

3.1 软件结构

软件结构及各部分的数据传输关系如图 1 所示, 图中箭头表示数据流动方向。软件从各个配置文件读取配置信息, 并通过数据接口从 DCS 读取数据和操作指令, 处理完成后向 DCS 发回计算或处理结果, 并在日志文件里面记录一些程序运行的信息, 各个部分的功能及实现特点如下:

3.1.1 主程序协调各个部分的工作

作为直接和 DCS 交互的部分, 负责根据配置文件在 DCS 与各个模块之间传输命令和数据。

3.1.2 算法模块

收稿日期: 2005－09－15; 修订日期: 2006－03－29
基金项目: 山东电力研究院基金资助项目(2003－A19)
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参考 WINDOWS 程序设计中的 COM 技术[11]，主程序与算法模块之间采用插件式结构，从而使得软件组态灵活，具有很好的可扩展性。新加入一个算法甚至不用编译原有的程序代码。

目前主要有 4 个模块：锅炉计算模块，进行一些开环计算；先进控制模块，实现了 γ 增量型阶梯广义预测控制（γ－SGPC）算法，这是我们在实践过程中对阶梯式广义预测控制算法（SGPC）的改进[12]；优化模型辨识模块，为动态优化模块在线辨识当前模型；动态优化模块，简化并实现了文献[13]提出的在线优化算法。

3.1.3 数据采集服务程序

针对不同的现场条件，提供两种数据通信方式：网络接口与内部接口，可满足不同现场条件需求。安装在单独的先进控制与优化工作站上时，用网络接口，而安装在现场工作站上时，两种接口均可用，后者更简单。

当主程序从 DCS 读取数据时，需要经过数据采集服务程序。对于网络接口，该服务程序进行 UDP 协议到 TCP 协议的转换；对于内部接口，解决数据读取时可能会出现的某次读取失败而暂时中断读数的问题。

3.1.4 DCS 端程序

这部分程序包括两部分：一、DCS 端操作界面，这是操作人员与本软件的交互接口；二、当数据采集采用网络接口时，DCS 端的一个工作站上需要运行一个网络数据收发服务程序，采用 UDP 协议，每个周期向网络上指定端口发送所有需要的数据。

3.1.5 配置文件和日志文件

配置文件功能相当于一些图形界面软件中的配置窗口，其中主程序和数据采集服务程序的配置文件主要用来指定程序的运行模式及参数等，各个算法模块的配置文件用于指定算法参数、数据采集及预处理参数等。日志文件记录软件运行过程中的重要信息，主要用于工程人员调试和查阅。

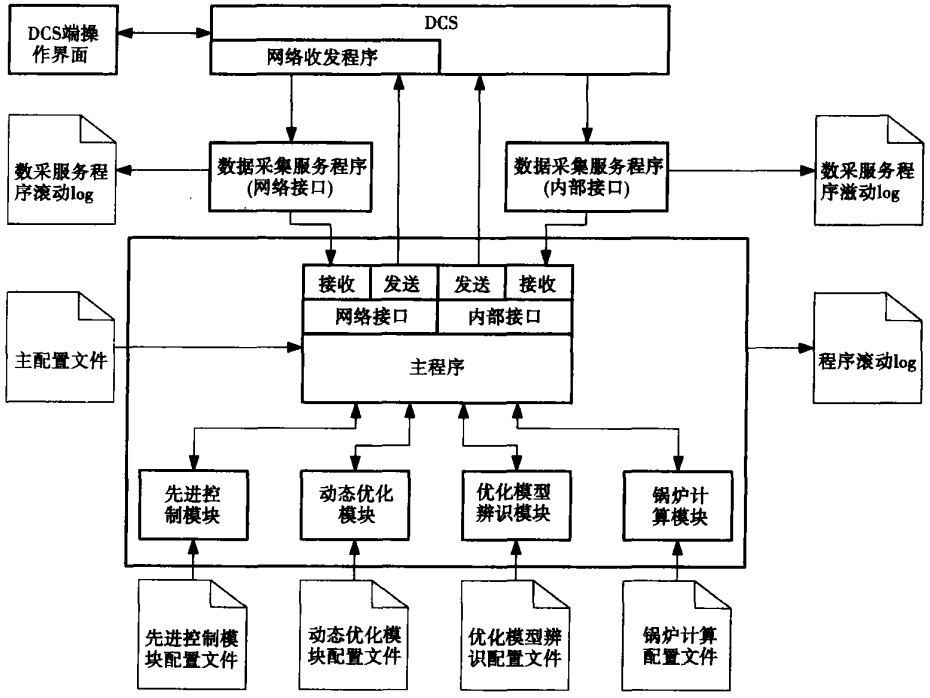

图 1 软件结构

3.2 系统功能及特点

3.2.1 与 DCS 无缝结合

现有火电机组基本上都已投用 DCS。本软件与 DCS 无缝结合，充分利用现有 DCS 的强大功能，投资少，易于现场实施，主要表现在以下方面：

（1）基于 Solaris 操作系统。与国内大容量火电机组广泛采用的 DCS 产品系统兼容。

（2）后台运行，无扰切换。软件作为后台服务

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程序运行, 程序的跟踪功能保证了算法之间的切换是无扰的。

(3) 采用 DCS 的界面工具。这一点使得软件看起来像是 DCS 的扩展。

3.2.2　有一套统一的数据预处理机制

模块每个模拟量数据的输入输出都通过一个数据预处理管道, 实现归一化、上下限、速度限制和数字滤波等, 通过合理配置, 可以适应现场复杂的数据环境, 默认情况下数据不作处理。

3.2.3　安全逻辑

软件设计了心跳信号(HEARTBEAT), 只要本软件运行, 就产生一个方波信号, DCS 可以知道本软件是否处于运行状态, 从而在必要的情况下可以自动采取切除措施。

4　应用实例

4.1　对象系统简介

本软件配置灵活, 根据具体需要, 可以选择全部或者部分功能。作为例子, 这里用本软件对山东石横电厂 2 号机组的氧量校正回路实施先进控制。该机组装机容量为 330 MW, DCS 型号为 FOXBORO I/A Series。

在对该机组的锅炉实施在线燃烧优化调节过程中, 把烟气含氧量的设定值作为一个在线调节量, 这就要求氧量控制回路快速平稳, 同时为保证负压稳定, 控制量不宜变化过快, 这也有利于执行机构的安全高效。

烟气含氧量的控制实际上是对风煤比的微调, 设计为一个串级控制系统。协调控制系统(CCS)根据一个粗略风煤比给出一个总风量参考值, 外环氧量校正回路的目标是使氧量测量值跟踪设定值, 输出控制量为一个对于总风量参考值的校正量, 通过代数运算校正总风量设定值在参考值的 0.8 ~ 1.2 倍范围内, 内环送风控制系统的目标是使总风量测量值跟踪其设定值。原系统两个回路的均用 PID 控制器实现。

为了达到在线燃烧优化调节的要求, 我们对氧量校正回路实施先进控制, 采用 γ－SGPC 算法来实现, 送风控制回路保持不变。

4.2　组态与界面设计

为了便于运行人员投用 γ－SGPC, 同时保证原控制方案可用, 氧量校正控制器面板(如图 2 所示)是在原有面板基础上修改而来, 加入了“GPC”和“PID”两个按钮, 用于在两种控制算法间切换。当 MOD 为“AUTO”时, 可以选择两种算法之一进行控制, 通过按钮的底色来指示当前投用的算法, 未投用的算法处于跟踪状态以保证无扰切换; 当 MOD 为“MANUAL”时, 不论选择哪种算法都不起作用, 它们都处于跟踪状态。另外, GPC 按钮的可用性受到 HEARTBEAT 信号的限制。

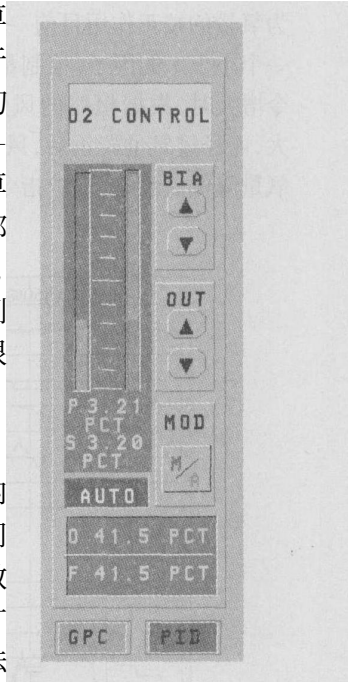

图 2　氧量校正控制面板

4.3　投用效果曲线

数据通信选用内部接口。取采样时间为 2 s, 利用机组运行数据, 采用渐消记忆的广义最小二乘辨识算法可得到对象近似模型(如式(1)所示):

$$G(z^{-1}) = \frac{0.0005}{1-0.995z^{-1}} \cdot z^{-36} \qquad (1)$$

考虑到对象模型特性, 并结合实际调节效果, 选定参数为: $p = 15$, $p_u = 8$, $\alpha = 0.98$, $\beta = 1.0$, $\gamma = 1.0$, 各个参数的含义参考文献[12], 参数 γ 可参照文献[13]中的 β, 控制效果如图 3 所示。

该图为 DCS 现场运行截图, 横坐标为时间(小时: 分钟), 每格 3 min, 图中对每条曲线标注了名称、坐标轴范围和单位。其中, 锅炉指令是 CCS 根据机组当前负荷给出的一个量, 煤量和风量参考值都是由它算出, 以保证粗略的风煤比。

在 9:33 左右, 设定值向上变化, 经过一小段纯时延, 测量值慢慢跟踪, 在 9:45 左右达到设定值并保持在附近, 在 10:00:32, 当时正同时进行的 MIS 系统改造项目造成数据读写严重阻塞, 软件与 DCS 的通信出现问题, 因此程序保护逻辑起作用, 把控制策略切回到原来的 PID 控制, 在 10:09:42, 人为切回到 γ－SGPC 算法, 这种问题在机组正常运行时不会发生。

由曲线可以看出: (1)当设定值发生变化后, 氧量可以较快速地跟踪设定值; (2)在切到 PID 控制方式的约 10 min 时间里, 由于控制器反应迟钝, 造成测量值与设定值之间偏差明显要大一点, 说明 γ－SGPC 的优越性, 本身这个切除过程也表明了软件在安全上具有很好的保障; (3)每当锅炉指令变化较大时, 氧量值会有反方向的扰动, 这一方面是因为锅炉在负荷高的时候炉内燃烧比较完全; 另一方面是因

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为氧量的校正作用目前一直是对总风量参考值乘以一个小于 1 的因子(控制量小于 50),所以当锅炉指令增大时,根据粗略的风煤比,风量参考值也会增大,而经过氧量校正后,风量的增大幅度偏小,造成氧量降低。反之,锅炉指令减小时,氧量会紧接着有向上的扰动,控制器的作用就是抑制这些扰动。由曲线可以看出,在锅炉指令变化较大时,扰动误差被控制在 0.2 以内,而锅炉指令变化较小时,误差基本上控制在 0.05 之内。综上可知,氧量控制回路改造后,可以满足在线优化调整和燃烧调整试验的要求。

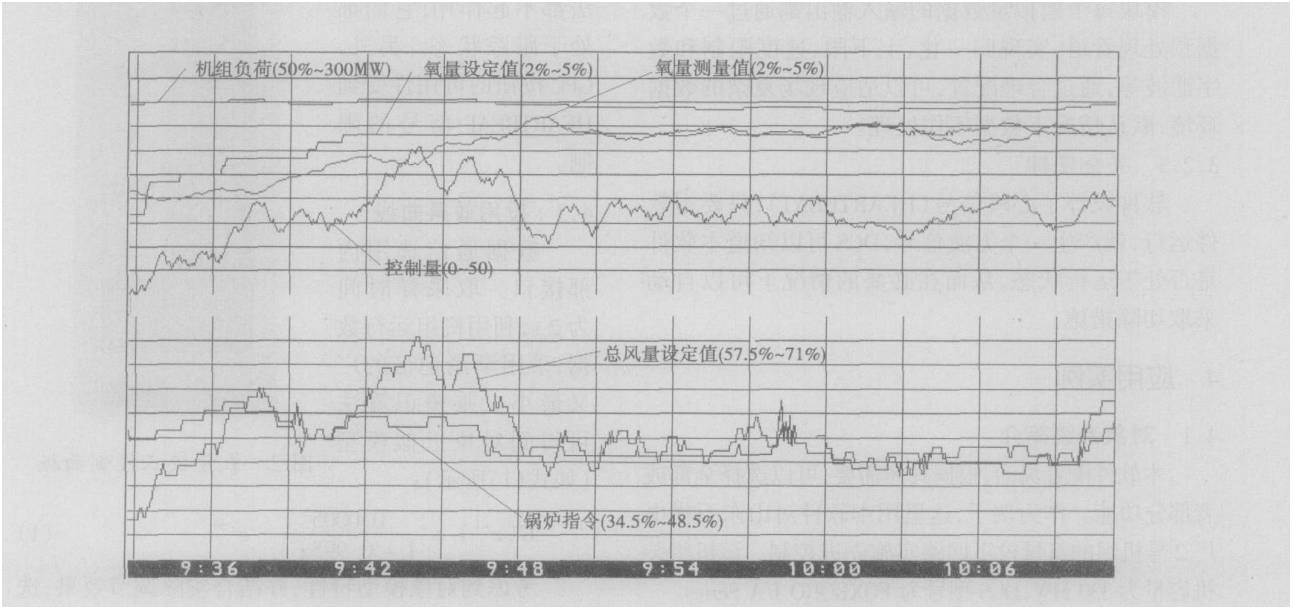

图 3 氧量校正先进控制效果曲线

在该软件进行氧量校正的投用过程中,不论从安全性、操作的便利性,还是在性能方面,都可以看出该软件具有较好的工业应用价值。

5 结束语

本软件采用面向对象技术设计,既最大限度地利用 DCS 强大的交互与逻辑处理功能,又保持灵活性,可以方便地应用于不同目标以及进行二次开发。现场使用结果表明,该软件可以作为 DCS 的扩展,操作方便,进一步的试验开发还可以提高实际工业过程的自动化及运行水平。

需要指出的是,本软件虽然针对大型火电机组设计,但同时兼顾通用性,通过合理配置,可以应用于其它工业过程。

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ature quickly increase and the amount being separated out far exceeds the amount released from the raw coal and coal-water slurry. The amount of NH_3 released from the raw coal will with an increase in temperature first increase and then decrease and a peak value will emerge at about 1 000 ℃. If the temperature continues to go up, the amount of NH_3 will not increase, but on the contrary begin to decrease. The amount of NH_3 separated out from the coal-water slurry will increase with an increase in temperature. Although the change proceeds slowly, the NH_3 amount released is still larger than that released from the raw coal. In the vapor atmosphere, with a rise in temperature, the amount of NH_3 all along exhibits a tendency to increase and after the temperature reaches 1 000 ℃, such an increase will go on still more rapidly with the amount released to be larger than that released from the raw coal and coal-water slurry. When the amount of HCN and NH_3 released as well as the ignition and combustion of fuel are taken into account in a comprehensive way, it can be clearly seen that the combustion of coal-water slurry is superior to that of pulverized coal alone and of pulverized-coal with steam injection. **Key words**: HCN, NH_3, pyrolysis, coal-water slurry

添加剂调质下脱硫剂活性影响因素的实验研究=**An Experimental Study of Various Factors Affecting the Activity of Desulfuration Agents Modified by Additives**[刊, 汉] /ZHANG Hu, TONG Hui-ling, DONG Shan-ning, et al (Education Ministry Key Laboratory on Thermal Sciences and Power Engineering under the TSinghua University, Beijng, China, Post Code: 100084) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —397 ~400

Through fixed bed experiments, the effect of different preparation conditions on the activity of additive-modified calcium-based desulfuration agents was investigated. It was found during the tests that at a hydration temperature of 70 ℃ the solubility of $Ca(OH)_2$ in the hydrate solution attains an optimum value, increasing the generated amount of desulfuration active substance in the hydrated product. Under the compound modification of NaOH and Na_2CO_3, the crystal in the product layer contains relatively more defects, thus promoting the diffusion of Ca^{2+} in the desulfuration agent to the product layer and gas phase and enabling the desulfuration agent exhibit its optimal sulfur retention effectiveness in a relatively short hydration time (2.5 hours). The desulfuration agent made in the natural drying mode has a relatively high water content. Through an analysis of pore structures it was found that the average pore diameter is relatively small and the pore surfaces can maintain a relatively high humidity for a long time, making its desulfuration activity higher than that of desulfuration agents obtained under the condition of baking and steam reforming process. **Key words**: desulfuration, additive, preparation, fixed bed

CO_2 活化 $CaCO_3$ 浆液对半干法烟气脱硫影响的实验研究=**An Experimental Study of the Effect of CO_2-activated $CaCO_3$ Slurry on Flue Gas Desulfuration by Using a Semi-dry Method**[刊, 汉] /ZHANG Li, WANG Jian-bao, LIU Yun-yi (Chemical Engineering School under the Shenyang Chemical Engineering College, Shenyang, China, Post Code: 110142) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —401 ~404

$CaCO_3$ desulfuration agent slurry is activated by gas CO_2 to enhance the reaction activity of $CaCO_3$ with SO_2, thus achieving a higher efficiency of the flue gas desulfuration process based on a fluidized semi-dry method. Through experiments in a fluidized reactor with a height of 1.1 m and an inner diameter of 12.5 cm, the effect of such factors as activation time, saturation proximity, calcium-sulfur ratio and desulfuration agent particle diameter etc. on desulfuration efficiency is investigated with coarse sand having a diameter of 275 μm and motionless bed height of 98 mm to serve as the fluidized medium. The experimental results show that when calcium-sulfur ratio is 1.2, saturation proximity at 15 ~18 ℃ and desulfuration agent particle diameter 64 μm, the $CaCO_3$ desulfuration agent after being activated by CO_2 gas can attain a desulfuration efficiency of 92%, approaching that of $Ca(OH)_2$ under the same conditions. **Key words**: flue duct gas, flue gas desulfuration, fluidized bed, sulfur dioxide

火电机组先进控制与优化软件的设计与应用=**Design and Applications of Advanced-control and Optimization Software for Thermal Power Plants**[刊, 汉] / YANG Bing, SUN De-min, GONG Dai-wei (Automation Department, China National University of Science and Technology, Hefei, China, Post Code: 230027), HAO Wei-dong (Shandong Electric Power Research Institute, Jinan, China, Post Code: 250002) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —405 ~408

To improve the control effectiveness of thermal power plants in China and enhance their operational efficiency, the authors have developed a set of advanced-control and optimization software through the adoption of an object-oriented technology

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and a modularized design method. The software can operate at the rear platforms of DCS work stations and prepare operational interfaces with the help of DCS configuration tools. It can make full use of powerful functions of existing DCS and its operation methods are easy for operators to get acquainted with. Unified data pretreatment mechanism and monitoring of heart-beat signals can guarantee required safety. Multiple built-in communication mechanisms make it suitable for various on-site conditions. The algorithm module structure, which can be either independent or mutually cooperative, yields a flexible configuration with a good expandability. Two kinds of improved generalized prediction control algorithm and a kind of simplified self-adaptive on-line steady-state optimization algorithm have been realized. The use of this software for implementing the advanced-control of the flue gas oxygen-content of a utility boiler has markedly improved control effectiveness. It has been found that the software under discussion involved less investment outlays and has facilitated on-site applications, achieving good results in general. **Key words**: thermal power plant, advanced-control and optimization software, DCS, oxygen-content correction

基于多层 BP 神经网络的回转窑内物料传输模型研究＝**A Study of the Transmission Model of Materials in Rotary Kilns Based on a Multi-layer BP Neural Network**[刊, 汉] /LOU Bo, LUO Yu-he, MA Xiao-qian (Electric Power College under the South China University of Science and Technology, Guangzhou, China, Post Code: 510640) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —409～413

Through experiments conducted on a rotary-kiln test rig and under the circumstances of rotary kiln speed and inclination angle changes the following law governing the variation of MRT (mean residence time) of materials for five kinds of solid waste materials with different physical-property parameters has been revealed: with an increase in rotary-kiln rotating speed and inclination angle as well as an air speed increase inside the kiln, the MRT will decrease. Among the physical-property parameters of the materials, the repose angle has a relatively great impact on the MRT. A greater repose angle will lead to a shorter MRT. The change of density, however, has a relatively minor effect. The various influencing factors mentioned above will give rise to a relatively big difference in sensitivity to the MRT. The rotary kiln speed is comparatively sensitive to the MRT, while the sensitivity of the kiln inclination angle assumes a relatively uniform character. As regards air speed in the kiln, a combination of low kiln speed and low air speed in the kiln is rather sensitive to the MRT. Taking account of the characteristics that there exist numerous influencing factors in the transmission process of materials in the rotary kiln and an intense nonlinear mechanism, a multi-layer BP neural network has been used to simulate the mapping relationship between the MRT and the various factors, establishing a nonlinear transmission model. The results predicted for 40 groups of experimental data in the model show that the values predicted by the model are in relatively good agreement with experimental results with an average relative error being assessed at 4.1%. This indicates that the model can correctly reflect the material transmission process in the rotary kiln. **Key words**: rotary kiln, BP neural network, transmission model, mean residence time (MRT), nonlinear

水平管内两相流动网丝电容层析成像＝**Wire-Mesh Capacitance Tomography of Two-Phase Flows in a Horizontal Tube**[刊, 汉] /HUANG Shan-fang, ZHANG Xiu-gang, WANG Dong, et al (State Key Laboratory on Power Engineering Multi-Phase Flows under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2006, 21(4). —414～417

A wire-mesh capacitance tomography of two-phase flow distribution is presented. Thermocouple wires with an insulation film on their surface are used as capacitive transducers. The electrolyte of the capacitor is an insulation film with the two poles being respectively metal cores of thermocouple wires and electroconductive fluid film covering the surface of thermocouple wires. The capacitance is directly proportional to the length of the electroconductive fluid film and independent of the latter's distribution and shape. The wire-meshes are parallel and uniformly arranged on a pipeline section. The inner diameter of the test pipeline is 70 mm and the capacitance of each mm long mesh wire being used is 4.82 pF with the spacing of mesh wires being 4 mm. The measurement was performed by use of horizontal and vertical two-direction capacitive transducers. On the basis of knowledge about flow patterns, it is not necessary to reestablish algorithm and the phase distribution can be readily obtained. The steady-state tests show that with this method one can realize the reestablishment of flow patterns, and the section water content as calculated based on the foregoing has a maximal error of 3.9%. **Key words**: wire-mesh capacitance tomography, phase distribution, dual directional measurement, rate of water content

不同油膜力模型下转子椭圆轴承系统的动力学分析＝**A Dynamic Analysis of a Rotor-Elliptic bearing System**

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