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周期性模型在管壳式换热器数值模拟中的应用

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摘 要: 根据管壳式换热器的结构特点, 提出了周期性全截面计算模型用于其流场和温度场的数值模拟。采用该模型的计算结果与壳程整体模型的计算结果对比, 误差在 10% 以内, 证明了该模型的合理性和模拟结果的正确性, 为实现具有复杂壳程结构的管壳式换热器的数值模拟提供了一种新方法。基于周期性全截面模型的计算结果, 提出了对折流杆换热器周期性单元流道模型的修正算法, 改进和完善了周期性单元流道模型的实用性和适用性。

关 键 词: 管壳式换热器; 周期性; 计算模型; 数值模拟; 修正算法

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引 言

高效节能过程装备及其现代设计研究方法的开发是当今工程节能的重要手段。重大过程装备一换热设备广泛用于石油、化工、化肥、动力、冶金、原子能、航空航天等国家基础和支柱产业中, 是诸多工业部门中广泛使用的一种通用设备, 其强化传热及相关性能的优劣对于工业过程节能降耗具有重要影响。

管壳式换热器是目前国内外换热设备的主要结构形式。采用数值模拟方法对换热设备进行性能研究与新型高效换热设备的开发, 已经成为当今换热设备研究的一个重要方面。数值模拟具有费用低、速度快、重复性好、能模拟较复杂或较理想工况下的流动现象和流动特性等优点, 还可观察不同操作参数对求解问题的影响, 获得所有相关变量的详细信息以及潜在的物理过程等, 可以弥补理论分析和实验测量方法的不足[1]。

管壳式换热器内零部件繁多, 几何结构和流动形态复杂, 在兼顾数值计算规模和效率的同时, 确定能够描述换热器真实结构和工作状态的建模方案, 对客观、准确、详尽地反映换热器内流场和温度场的特性至关重要。

1 管壳式换热器数值模拟的建模形式及其适用性

目前, 主要的管壳式换热器数值模拟建模形式有以下 3 种。

1.1 多孔介质模型

管壳式换热器的数值模拟大多采用多孔介质模型来处理管束及支撑装置等固体物对壳程流体流动和传热性能的影响[2~6]。将壳程的管、挡板、隔板等视为多孔介质, 引入分布阻力的概念, 采用体积多孔度表示流体占有空间与壳程整体空间的比值, 采用表面渗透率表示管束多孔度的表面特性, 易于从宏观上模拟换热器的流体流动和传热性能。

采用多孔介质模型过于简化了换热器的内部结构, 模拟结果并不能准确反映局部区域的真实流动和传热状况等详细信息, 而且部分重要输入参数与换热器的结构形式、几何尺寸和流经的介质有关。通常, 通过实验确定参数, 若根据经验来确定这些参数, 不易确保数值模拟的准确性。故在使用范围上有局限, 尤其是进行新型壳程支撑结构的流场局部细节的流态分布和强化传热机理研究时, 往往难以应对。

1.2 实体模型

文献[7]与目前换热器数值模拟中常用的多孔介质模型不同, 在作出相应简化和假设后, 采用了实体模型对纵向流换热器的流动和传热特性进行了数值模拟, 定性分析了纵向流换热器的传热与流动特性, 但未给出实验验证用以考核网格划分方法等因素对数值模拟结果准确性的影响。

1.3 周期性单元流道模型

文献[8]提出了纵流壳程换热器周期性单元流

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道模型简化计算方法, 忽略筒体壁面附近布管区流体流动和传热的特殊性对壳程流动和传热总体性能的影响, 取正方形布管时, 4 根管所包围的流体流动空间为一个“单元流道”作为计算模型, 可以有效地简化纵流壳程换热器的数值模拟计算, 如图 1 所示。然而, 单元流道模型适用于换热管束和管束支撑结构呈对称分布的某些纵流壳程换热器, 对于不具备上述结构特征的管壳式换热器, 如折流板换热器、螺旋板换热器等是无法予以这样简化的; 对于壳体直径较小的管壳式换热器, 即使符合单元流道对称性的简化要求, 由于筒体壁面附近布管区的流体对壳程流动和传热总体性能的影响较大而不可忽略, 单元流道模型模拟结果与实际工况有较大偏差。

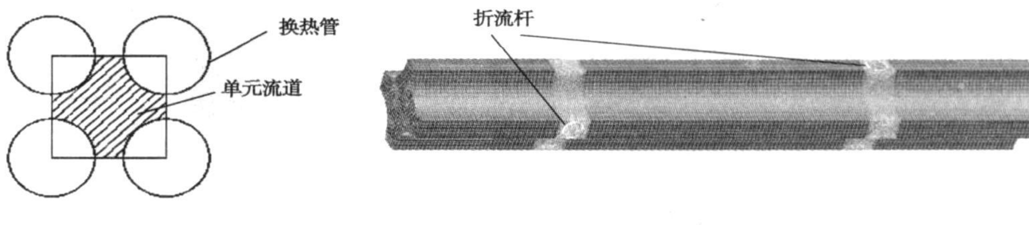


图 1　周期性单元流道模型示意图

可见, 目前已有的各类换热器数值模拟方法及建模形式在适用对象等方面尚有不足, 对管壳式换热器的数值模拟研究还未尽完善。

2　基于周期性全截面计算模型的管壳式换热器数值模拟

2.1　流体流动和传热的控制方程[9~10]

质量守恒方程(连续性方程):

$$\frac{\partial \rho}{\partial t}+\mathrm{div}(\rho U)=0$$

动量守恒方程:

$$\frac{\partial(\rho u)}{\partial t}+\mathrm{div}(\rho u U)=\mathrm{div}(\mu\,\mathrm{grad}\,u)-\frac{\partial p}{\partial x}+S_u$$

$$\frac{\partial(\rho v)}{\partial t}+\mathrm{div}(\rho v U)=\mathrm{div}(\mu\,\mathrm{grad}\,v)-\frac{\partial p}{\partial y}+S_v$$

$$\frac{\partial(\rho w)}{\partial t}+\mathrm{div}(\rho w U)=\mathrm{div}(\mu\,\mathrm{grad}\,w)-\frac{\partial p}{\partial z}+S_w$$

能量守恒方程:

$$\frac{\partial(\rho T)}{\partial t}+\mathrm{div}(\rho U T)=\mathrm{div}\left(\frac{\lambda}{c_p}\mathrm{grad}\,T\right)+S_T$$

2.2　几何模型

管壳式换热器核心部件是由换热管束和各类管束支撑物(或折流构件)构成, 支撑构件按照一定的方式沿管长方向等间距交替排布, 使得壳程几何结构呈现周期性的变化规律; 换热管一般采取对称的布置方式。因此, 从几何结构上看, 常规管壳式换热器壳程流道呈周期性变化, 且某些类型兼具对称性。

管壳式换热器壳程沿流体流动方向可以划分为进口段、周期性充分发展段和出口段。一般来说, 换热器壳程大部分换热段处于周期性充分发展段, 周期性充分发展段的流体流动和传热性能, 很大程度上反映了换热器的整体性能, 数值模拟应该选取最能代表换热器特征参数变化规律的区域进行分析求解。因此, 充分利用其流动和传热的周期性特征, 建立周期性计算模型, 是快捷、高效地对管壳式换热器进行数值模拟研究的重要方法。

鉴于此, 根据管壳式换热器的结构特点, 以及流体在壳程中的流动和传热特性, 在作出适当假设和简化的基础上, 提出了管壳式换热器“周期性全截面计算模型”, 采用基于管壳式换热器真实三维实体模型的几何建模形式, 截取管壳式换热器壳程流体流动和传热的充分发展区域的一个周期段作为数值模拟对象, 以此表述流动和传热充分发展区域的特征参数的变化规律。相对于周期性单元流道模型仅取 4 根管所包围的流体流动空间作为计算区域而言, 该模型包含一个周期段内全部几何信息, 可更为准确详尽地反映管壳式换热器壳程局部区域的真实流动和传热状况等详细信息, 显著提高模拟结果的准确性和计算精度。

对于周期性充分发展流动, 如果温度变化有限, 物性参数不变时, 则有周期性的流动特性:

$$u(x,y,z)=u(x,y,z+L)=u(x,y,z+2L)=\cdots$$

$$p(x,y,z)-p(x,y,z+L)=p(x,y,z+L)-p(x,y,z+2L)=\cdots$$

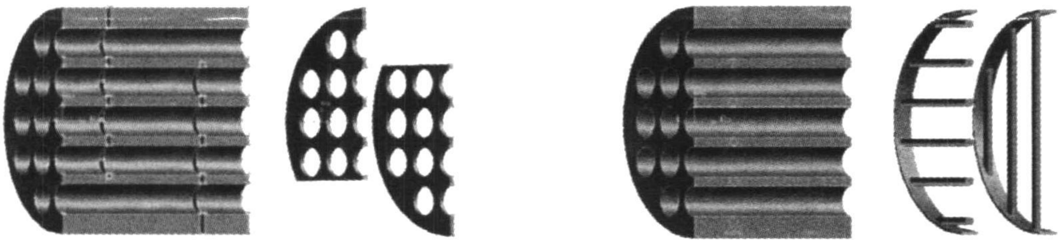
对于充分发展的换热, 取流动方向为坐标 z 轴, 当管壁是恒温时, 设壁温为 T_w, 流道内流体的平均温度为 T_b, 定义无因次温度:

$$\Theta=\frac{T-T_w}{T_b-T_w}$$

则有：

$$\Theta(x,y,z)=\Theta(x,y,z+L)=\Theta(x,y,z+2L)=\cdots$$

在对其几何结构作出了一定简化后，可建立典型管壳式换热器的周期性全截面计算模型（由于结构的对称性，建模时取相对称的半个实体即可），如图 2 所示。



(a) 折流板换热器　　　　(b) 折流杆换热器

图 2　管壳式换热器周期性全截面计算模型

2.3　计算方法和边界条件

采用分块划分、结构化和非结构化网格相结合的方式对计算区域进行网格划分，近壁节点采用壁面函数法处理，稳态隐式格式求解，采用标准 $k-\varepsilon$ 湍流模型计算湍流参量的影响；控制体积界面的物理量均应用二阶迎风差分格式获取；采用 SIMPLE 算法处理压力和速度的耦合问题；假定换热管壁恒温，壳程介质为水或空气，物性参数取定性温度下的常量；给定壳程流体的进口质量流量及相应的温度和湍流条件；壳程整体计算模型的进、出口分别为质量进口和压力出口边界条件，周期性模型的进、出口为周期性边界条件；壳体壁面和管束支撑装置采用不可渗透、无滑移绝热边界条件。

2.4　计算结果与分析

采用周期性全截面计算模型的某管壳式换热器数值模拟结果如表 1 所示。

表 1　管壳式换热器周期性全截面计算模型的计算结果

	计算结果
进口面平均流速/ $m·s^{-1}$	1.113
出口面平均流速/ $m·s^{-1}$	1.116
压差/Pa	6.31
进口面平均温度/ ℃	93.6
出口面平均温度/ ℃	99.41
温差/ ℃	5.86
平均传热系数/ $W·m^{-2}·℃^{-1}$	23.65

建立管壳式换热器壳程整体计算模型，将其计算结果作为参照，提取其各个周期段的相关数据，将这些数据与周期性全截面计算模型的计算结果进行对比，验证周期性全截面计算模型及其计算结果的可靠性。

图 3～图 6 所示为管壳式换热器壳程整体计算模型的数值模拟结果。

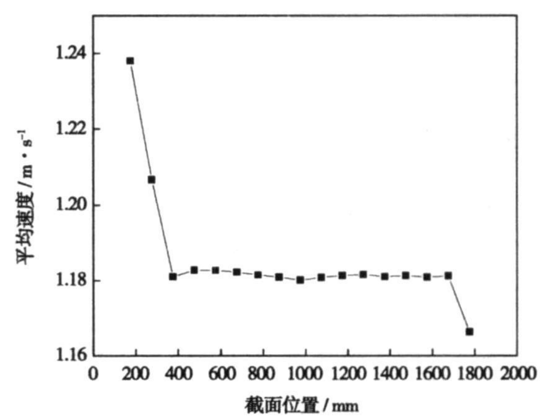


图 3　各截面的平均流速

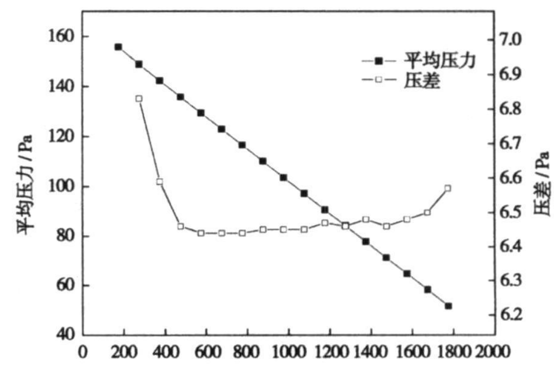


图 4　各截面的平均压力和截面间的压差

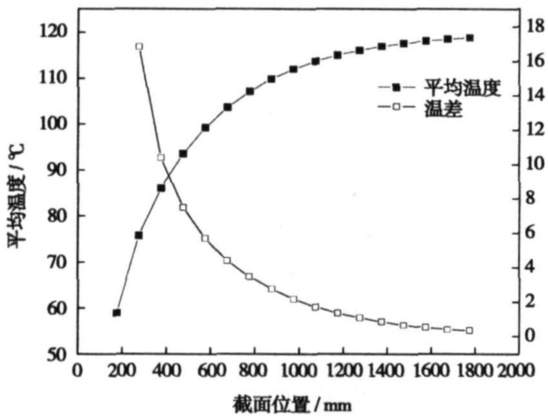


图 5　各截面的平均温度和截面间的温差

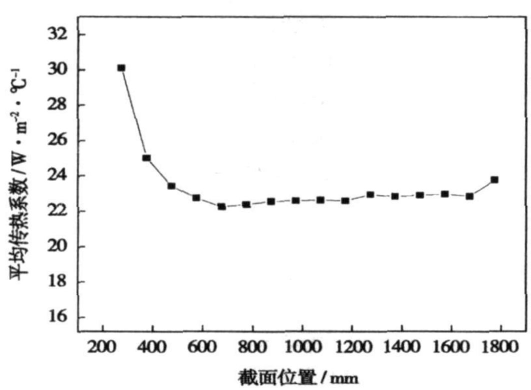


图 6　各段的平均传热系 数

为便于对比, 表 2 列出壳程整体计算模型与周期性全截面计算模型的计算结果。

表 2　两种计算模型计算结果对比

	平均流速 / $m·s^{-1}$	误差 / %	平均压差 / Pa	误差 / %	平均传热系数 / $W·m^{-2}·℃^{-1}$	误差 / %
整体模型	1.181	－5.59	6.47	－2.47	22.90	3.28
周期性模型	1.115		6.31		23.65	

由表 2 可见, 采用两种计算模型, 计算结果的误差相当小。理论分析和计算数据均表明, 管壳式换热器数值模拟计算模型的周期性简化是成立的, 以一个周期段的流动与传热相关参量来表征充分发展段的平均参量是合理的。

3　折流杆换热器周期性单元流道模型计算结果的修正算法

对于周期性单元流道模型在适用性方面的一些不足, 结合折流杆换热器周期性全截面计算模型, 提出了对前者计算结果的修正算法, 以进一步完善和发展周期性单元流道计算模型。图 7 和图 8 所示为采用两类计算模型在同一工况下的计算结果。

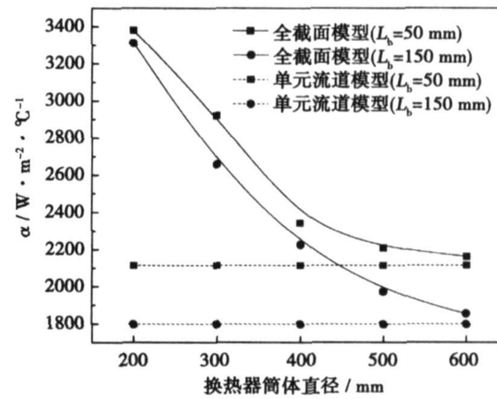


图 7　传热系 数随筒体直径的变化关系

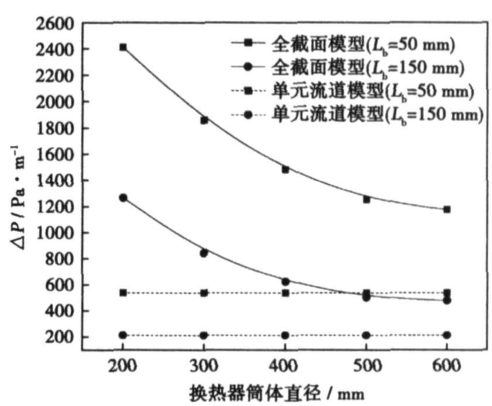


图 8　压力梯度随筒体直径的变化关系

随着换热器筒体直径的增加, 周期性全截面计算模型的对流传热系数和压力梯度的计算结果越来越与周期性单元流道的模拟结果相接近。当换热器筒体直径较大时, 采用周期性单元流道模型的模拟结果表征壳程流体流动和传热的总体性能是有实际意义的, 然而筒体直径较小时, 周期性单元流道模型的计算结果与实际工况有较大差别, 须予以修正。

利用最小二乘法原理, 应用多元线性回归对周期性单元流道模型和不同直径的周期性全截面计算模型在不同 Re 下的数值模拟结果进行拟合, 可以得到周期性单元流道模型的对流传热系数和压力梯度的修正关联式分别为:

$$h_h = \frac{\alpha'}{\alpha} = A\left(\frac{D}{d_e}\right)^{-0.528}\left(\frac{L_b}{d_e}\right)^{0.082}(Re)^{0.096} \quad (1)$$

$$h_p=\frac{\Delta P'}{\Delta P}=B\left(\frac{D}{d_e}\right)^{-0.813}\left(\frac{L_b}{d_e}\right)^{0.146}(Re)^{0.094} \qquad (2)$$

式中：h_h—周期性单元流道模型的对流传热系数修正因子；α'、α—实际对流传热系数和周期性单元流道模型的对流传热系数，W/(m^2·℃)；h_p—周期性单元流道模型的压力梯度修正因子；$\Delta P'$、ΔP—实际压力梯度和周期性单元流道模型的压力梯度，Pa/m；D—换热器筒体内径，mm；L_b—折流栅的间距，mm；d_e—定性长度，此处代表当量直径，mm；A、B—修正系数，由换热器筒体直径而定。

为验证修正公式的合理性，本文以常温状态下的水作为壳程介质，换热管壁温保持 120 ℃恒温，对内径为 300 mm，折流栅间距为 50 mm 的折流杆换热器进行传热性能实验，提取 Re 分别为 4 000、6 000、8 000、10 000、12 000 时的壳程对流传热系数，同时采用单元流道模型对相同工况进行数值模拟，并根据以上修正公式计算修正后的对流传热系数，比较三者的关系，如图 9 所示，可见筒体直径较小时单元流道模型的计算结果与实验值存在较大偏差，根据修正公式计算的壳程对流传热系数与实验值吻合较好，最大误差小于 15%。由线性回归结果，此处修正系数 A 可取为 2.189，不同 Re 下的修正因子 h_h 由式(1)计算，结果如表 3 所示。

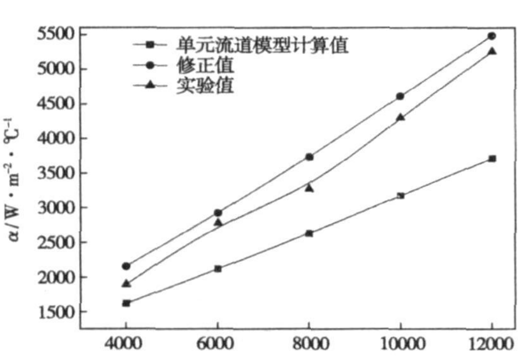


图 9　修正值与实验值的关系

表 3　不同 Re 下的修正因子

Re	h_h
4 000	1.330
6 000	1.382
8 000	1.422
10 000	1.453
12 000	1.478

4　结　论

(1) 根据管壳式换热器结构特征，提出了周期性全截面计算模型进行管壳式换热器数值模拟，弥补了现有数值模拟建模方式的一些不足，实现了具有复杂壳程结构的管壳式换热器壳程流场和温度场的数值模拟，为发现和解决管壳式换热器中与局部位置流体流动和传热细节相关的深层次问题提供了良好的辅助手段；

(2) 基于管壳式换热器周期性全截面计算模型，在综合考虑折流杆换热器壳程流体流动与传热的多方面影响因素下，提出了对折流杆换热器周期性单元流道模型的修正算法，给出了壳程流体传热系数和压降的修正关联式，改进和提高了折流杆换热器周期性单元流道模型的实用性和适用性，为新型高效节能换热设备的开发和以数值模拟方法进行具有工业规模换热设备的传热和流阻性能预估和性能改进，提供了理论与工程应用的依据。

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（编辑　滨）

Power University, Baoding, Post Code: 071003)//Journal of Engineering for Thermal Energy &Power.—2008, 23(1).—50~54

Under an operating condition of desulfurization with or without CaO, studied was the nano-TiO_2-catalyzed combustion effectiveness of Wen-nan lignite and Inner-Mongolia bituminous coal. Through thermogravimetric curves an analysis was conducted of the experimental results from such combustion properties as ignition temperature, weight loss and heat release rate etc. The analytic results show that during the desulfurization without CaO, the nano-TiO_2 can lower the ignition temperature of the bituminous coal by 15 ℃ and the burn-off temperature of the lignite, by 32 ℃. During the desulfurization with CaO, however, the nano-TiO_2 can lower the ignition temperature of the lignite by 17 ℃, and the burn-off temperature of the bituminous coal, by 8 ℃. In the meanwhile, the activation energy of both coals from combustion reaction has decreased by 5.9 kJ/mol and 1.3 kJ/mol respectively, and calorific power of the lignite, increased. No new substance being generated in the XRD (X-ray diffraction) spectrum also proves the catalyzed combustion effectiveness of the nano-TiO_2. The above result can provide a theoretical basis for the simultaneous implementation of desulfurization and the combustion efficiency enhancement, resulting in sizable coal savings. **Key words**: nano-TiO_2, catalyzed combustion, thermogravimetric analysis, X-ray diffraction analysis

220 MW 燃煤机组飞灰对汞的吸附特性研究= **A Study of the Mercury Adsorption Characteristics of Flyash in a 220 MW Coal-fired Power Plant**[刊, 汉] /JIANG Yi-man, DUAN Yu-feng, WANG Yun-jun, et al (Education Ministry Key Laboratory on Clean Coal Power Generation and Combustion Technology, Southeast University, Nanjing, Post Code: 210096)//Journal of Engineering for Thermal Energy &Power.—2008, 23(1).—55~59

The specific surface area, pore diameter, pore volume, pore distribution and fractal dimension of flyash in four electric fields of an electrostatic precipitator (ESP) in a 220 MW coal-fired power plant were measured by use of nitrogen isothermal adsorption (at a constant temperature of 77.35 K). By employing a scanning electron microscope the visual morphological characteristics of flyash particles were analyzed. The results show that the smaller the particle diameter and the greater the specific surface area, the higher the mercury content in flyash. The carbon and mercury content in flyash exhibits a positive correlation. With an increase of load, the mercury adsorption tends to be weakened. There exists an optimum fractal dimension, at which the physical and chemical adsorption of mercury by flyash attains a maximum value. The broader the pore distribution and the greater the effective utilization rate of the pore volume, the more favorable condition for the adsorption of mercury. The adsorption capacity of mercury by a sub-micron level particle depends on its pileup morphology and the utilization rate of its specific surface area. **Key words**: coal-fired plant, mercury, flyash, adsorption, surface utilization rate, fractal dimension

带预测有效约束的优化法对燃烧室构件的设计= **Design of Structural Members of a Combustion Chamber by Adopting an Optimization Method Featuring a Predictable Effective Restraint**[刊, 汉] /ZHANG De-xin, AN Wei-guang (Aerospace Engineering Department, Harbin Engineering University, Harbin, Post Code: 150001)//Journal of Engineering for Thermal Energy &Power.—2008, 23(1).—60~63

By adopting a fully analytic sensitivity analysis method with a predictable effective restraint, an optimization design was conducted of the structural members of a combustion chamber shell in order to better improve the stress concentration condition of the shell in question, prevent any damage from thermal distortion and enhance its load bearing capacity. During the optimization design of the shell members, a fully analytic sensitivity analysis technology, incorporating the above restraint, was established. By a combination of the above technology with a general-purpose shape optimization design algorithm, a shape optimization design of the structural members under a plane stress in the combustion chamber shell was conducted, thus reducing the maximal shear stress of the inner holes and finally achieving a satisfactory result. **Key words**: combustion chamber shell, effective restraint, boundary element, optimization design

周期性模型在管壳式换热器数值模拟中的应用= **Application of a Periodic Model in the Numerical Simulation**

of Shell-and-tube Heat Exchangers[刊, 汉] /GU Xin, DONG Qi-wu, LIU Min-shan (Thermal Energy Engineering Research Center, Zhengzhou University, Zhengzhou, Post Code: 450002)// Journal of Engineering for Thermal Energy & Power. —2008, 23(1). —64~68

In the light of the structural characteristics of shell and tube heat exchangers, a periodic whole-section calculation model was presented for use in the numerical simulation of the exchanger flow and temperature fields. A comparison of the calculation results obtained by using the model under discussion with those of an integral model for a shell side shows that the error is less than 10%, indicating that the model in question is rational and its simulation results are correct. As a result, it provides a new approach for performing the numerical simulation of shell-and-tube heat exchangers with a sophisticated shell-side structure. On the basis of the calculation results obtained by using the periodic whole-section model, the modified algorithm of a periodic unit flow-passage model was presented for baffle-rod type heat exchangers, thus improving and perfecting the practicability and applicability of the above periodic model. **Key words**: shell and tube heat exchanger, periodicity, calculation model, numerical simulation, modified algorithm

自抗扰控制器串级三冲量汽包水位控制系统=**Three-element Drum Water-level Cascade Control System Featuring a Self-disturbance-resistant Controller**[刊, 汉] /CHENG Qi-ming, DU Xu-feng, GUO Run-qing (College of Electric Power and Automation, Shanghai University of Electric Power, Shanghai, Post Code: 200090), ZHENG Yong (Automation College, Shanghai University, Shanghai, Post Code: 200072)// Journal of Engineering for Thermal Energy & Power. —2008, 23(1). —69~72

In the light of the specific features of boiler-drum water level control, a self-disturbance-resistant controller-based drum water-level control system was presented, which adopts a three-element cascade control plus a feedforward control. The inner ring of the cascade control employs a PID (proportional-integral-differential) control while the outer ring uses a self-disturbance-resistant controller with a feedforward compensation. The self-disturbance-resistant controller comprises three elements, i. e. a tracking differentiator, an extension-state observer and a non-linear status error feedback control gear. The simulation results show that the control scheme proposed by the authors enjoys a better control quality and stronger robustness compared with those of a conventional PID control scheme. **Key words**: boiler drum water level, self-disturbance-resistant control, tracking differentiator, extension state observer, PID (proportional, integral and differential) control

液幕式湿法脱硫中喷嘴竖直射流液体回落特性实验=**Experiments on Falling-back Characteristics of an Upright-jet-flow Liquid from Nozzles in Liquid-curtain Type Wet-method Desulfurization**[刊, 汉] /ZHANG Wei (Thermal Energy Engineering Department, China University of Petroleum, Dongying, Post Code: 257061), ZHOU Qu-lan, HUI Shi-en (Thermal Energy Engineering Department, Xi' an Jiaotong University, Xi' an, Post Code: 710049)// Journal of Engineering for Thermal Energy & Power. —2008, 23(1). —73~77

During the liquid curtain type wet-method desulfurization the distribution of the falling-back liquid quantity of an upright-jet-flow directly determines the desulfurization efficiency. The distribution law of the upright jet-flow falling-back liquid from three kinds of nozzle profile and the relationship between the jet flow height and jet pressure have been studied. On the basis of the experimental data, derived was the "non-dimensional volume-flow rate formula of a falling-back liquid curtain". It has been found during the experiment that the distribution law of the falling-back liquid in different nozzle profiles differ relatively little, because at a same jet flow height, the parameters A, n and R_0 derived from the formula very approximate to one another. Formulae showing the correlation of jet flow height and jet pressure as well as non-dimensional averaged radius and jet flow height have undergone a fitting. Through experiments of the nozzle groups it has been proven that the falling-back liquid quantity of the nozzle groups can be regarded as a simple superimposition of jet flow falling-back liquid quantity obtained simultaneously from many a single nozzle, and the distribution uniformity is a function of the nozzle spacing and jet flow height. **Key words**: nozzle, upright jet flow, falling-back liquid curtain

两种不对中在线补偿控制算法的比较=**A Comparison of Two Kinds of Out-of-alignment On-line Compensa-**