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换热器可靠性三维热－力耦合概率有限元模拟

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摘　要: 应用概率有限元 Monte Carlo 法、反应面法, 基于三维热－力耦合(TMC)模型对换热器可靠性模拟中的一些核心问题进行了研究, 发现直接模拟法能够更准确地模拟换热器整体结构可靠性。提出了复杂边界条件和 TMC 过程中诸多变量的不确定性处理技巧, 通过定义多维表格数据函数, 应用分段线性插值实现了随机变化温度边界条件施加; 将疲劳寿命经对数变换后可提高模拟精度。工业换热器实例模拟计算表明: 有限元随机模拟技术应用于复杂结构可靠性计算和疲劳寿命预测, 能够给出完全再现实际结构服役载荷与材料、几何非均匀特性的高可信度结果。

关　键　词: 换热器; 概率有限元分析; 可靠性; 热力耦合
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引　言

随着现代工业设备向着高参数方向发展, 对换热器设计提出了更高要求。不仅要求其传热效率高、成本低, 而且要求在各种工况下具有足够的安全可靠性。换热器设计参数, 如压力、温度、流量、热负荷、换热系数和制造公差等都具有不确定性, 很多参数的分散性还相当大。采用确定性设计法给出的结果常常和实际状态相差较远, 因此, 有必要采用先进的概率设计技术[1~2]。限于参数内禀不确定性以及信息搜集有穷特征, 使得精确的可靠性分析比较困难。单纯应用数学解析很难解决千变万化的工程可靠度评定问题, 采用概率统计方法研究结构可靠性最为适宜。所以, 采用计算机统计试验手段对这类问题进行数值模拟是目前研究的热点。

管壳式换热器介质温差大, 结构中存在显著的热应力, 与机械应力相叠加后给设备造成机械损伤。对其进行安全评定时必须考虑热应力与机械应力的组合, 同时, 还应考虑危险工况组合。通过三维热－力耦合(TMC)分析获取结构中的真实应力分布, 为可靠性评估提供准确的应力值。本文基于三维 TMC 概率有限元分析模型, 对换热器结构静强度和疲劳可靠性进行了模拟, 并据此结果对结构参数进行了改进。

1　基于随机模拟技术的可靠性预测

有关有限元分析和 Monte Carlo 随机模拟技术的原理和方法可参阅有关文献[3~4], 此不赘述。直接 Monte Carlo 模拟技术具有直观、简单、可靠等优点, 但是计算效率低。因此, 近年发展了一些新的计算机随机模拟试验算法, 如反应面法。下面简要说明一下反应面法要点。

1.1　反应面分析法[4~5]

反应面法基于随机输入变量对随机输出参量的影响能够用数学函数逼近这一假设。反应面法在随机输入变量空间定位抽样点, 能够最有效地建立普适逼近函数, 其典型形式是二次多项式。

可取逼近函数 Y:

$$Y = C_0 + \sum_{i=1}^{NRV} C_i X_i + \sum_{i=1}^{NRV}\sum_{j=1}^{NRV} C_{ij} X_i X_j \qquad (1)$$

式中: C_0－常数; C_i, $i=1, \cdots NRV$ 为线性项系数; C_{ij}, $i=1, \cdots NRV$ 和 $j=i, \cdots, NRV$ 为二次项系数, NRV 为随机变量个数。采用最小二乘法通过拟合回归模拟结果与近似函数可以确定这些系数。就工程分析而言, 二次多项式给出的计算精度已足够精确。对于疲劳寿命, 直接拟合精度较差, 可先进行对数变换, 然后再拟合。当随机输入变量很多、随机输出参量不是随机输入变量的光滑函数时, 反应面法则不适用。

1.2　反应面 Monte Carlo 模拟样本生成

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应用反应面法，首先要生成含有某(些)个随机输出参量反应面的反应面集。然后，利用这些反应面集实施 Monte Carlo 模拟生成概率结果。它能够在较短时间内完成大规模随机样本循环模拟，只要几千次循环就能获得相当好的模拟精度。

1.3 热—力耦合概率有限元模拟步骤

首先建立耦合温度场和结构应力分析模块能够求解的 TMC 有限元分析模型，然后进行概率设计模拟。主要步骤如下：

(1) 生成循环分析文件，包括参数化模型、解算、设定输入变量、输出参量；

(2) 声明随机输入、输出变量及其相关性；

(3) 选择概率设计方法并执行模拟循环；

(4) 若采用反应面法则执行拟合反应面操作；

(5) 概率分析结果评价。

对于大型复杂问题，概率分析设计耗费时间非常多，可以采用多处理器并行计算技术。

2 换热器结构可靠性随机模拟

2.1 应力强度安全性分析原则

换热器属于典型压力容器，除常规设计法外，还可应用美国 ASME 规范中应力分析设计方法，通过应力分类评估设备强度安全状态[6]，该方法基于极限设计和安定状态概念，准确性较高。对结构中某截面，通过积分单元应力线性化处理后得到薄膜、弯曲应力分量，结合等效、最大剪应力和总应力分别进行可靠度评价。

2.2 典型换热器三维 TMC 可靠性模拟

根据经验和实际测量数据，可以确定换热器随机变量及其分布类型，必要时还要考虑材料性能离散性与温度之间的变化关系。

2.2.1 固定管板管壳式换热器结构模型

某型号工业换热器主要结构、工艺和物性参数如下：公称直径 900 mm，壳程与管程筒体壁厚分别为 17 mm 和 19 mm，管板厚 100 mm，均为 16MnR 材料；换热管为 ϕ25×2.5 mm，管心距 32 mm；管程与壳程设计压力分别为 2.0 MPa 和 0.6 MPa；壳程、管箱、换热管内侧和空气给热系数均值分别为 1 768、192、553 和 7.6 W/(m^2·K)；管程与壳程流体温度分别为 260 和 140 ℃，环境温度 20 ℃；16MnR 与保温石棉导热系数分别为 18 和 0.2 W/(m·K)；16MnR 许用应力 250 ℃下为 147 MPa，150 ℃下为 163 MPa。该换热器两端为椭球形封头、壳体为圆柱形筒体。为使问题简化而又不影响主要内容，构建换热器三维研究模型时省掉进出口接管段，并不计进出口段温度非均匀性影响。模拟时选取管程温度、壳程温度、环境温度、壳程压力、管程压力、壳程给热系数、管程给热系数，换热管内介质给热系数、环境空气换热系数、保温层热导系数和材料屈服应力等为随机输入变量，其它材料性能参数在工作温度范围内变化不大，可作为确定量处理。选取危险截面最大剪应力、主应力、等效应力以及线性化膜应力、弯曲应力等作为随机输出变量，然后按照规范计算可靠度。

复杂温度边界条件施加有一定技巧。一般给定温度边界只能作用在节点上，且为固定值，沿结构表面变化的温度边界条件一般程序不能直接设定，需进行二次开发。本文通过定义带自变量的参数化多维表格数据，应用分段线性插值技术解决动态随机变化温度边界的施加问题。

2.2.2 模拟结果

概率设计模拟提供的结果中包括了随机抽样样本、输出变量灵敏度、输出变量相对于输入变量的离散图和一定置信度下的概率值等内容。这里仅给出正常运行工况下的部分模拟结果。图 1 和图 2 分别为换热器三维温度场和等效应力场分布，危险部位位于管板与管箱连接处。

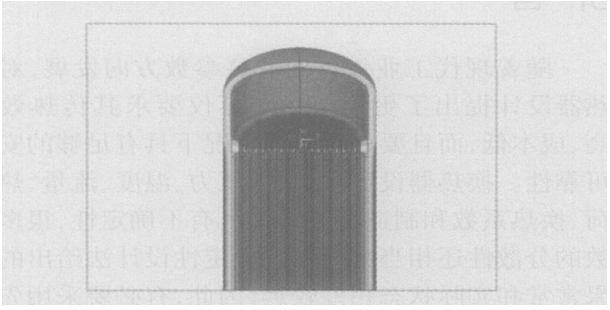

图 1 换热器三维温度分布

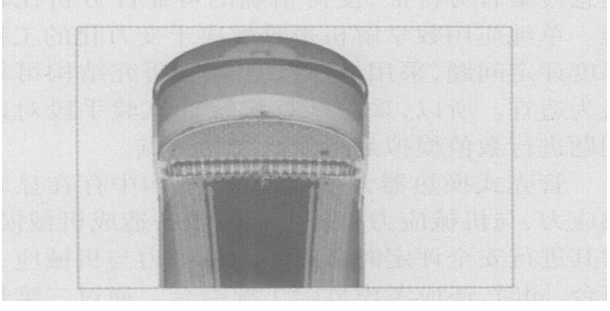

图 2 换热器等效应力分布

图 3 为最大剪应力参数敏感度分布。最大剪应

力对许用应力、管程温度、压力最敏感, 而最大等效应力则对管程、壳程温度, 换热管内介质给热系数和管程压力最敏感。正常工况置信度 95%水平下, 概率有限元模拟给出换热器强度可靠度如下: 一次、二次应力可靠度均为 1.0, 即不会发生失效。如果取 1.5 倍许用应力按照最大等效应力评估, 则可靠度只有 38%, 且上、下限分别为 45%和 32%。根据概率可靠性设计结果, 特别是参考灵敏度分析结果, 对结构和可调参数进行优化控制, 即可得到满足可靠度要求的最佳参数。

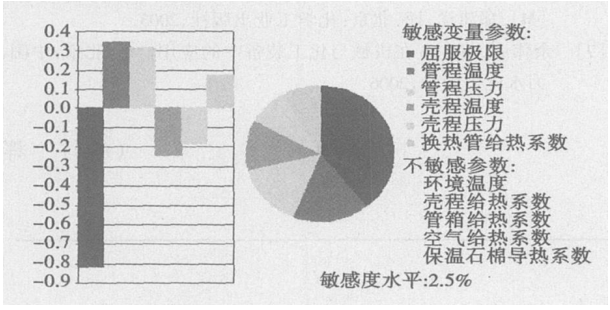

图 3　最大剪应力参数敏感度

2.3　复杂结构概率有限元模拟方法与效率讨论

尽管 Monte Carlo 直接模拟计算效率相对较低, 但它对内存的需求比反应面法要少得多, 而且具有很强的鲁棒性、普适性, 1 GB 物理内存计算机上可模拟百万自由度、数十个随机变量的大型工程问题。而反应面法虽然计算效率高, 但内存需求大, 对问题中的变量变化关系有要求。选择模拟算法时要综合考虑评估这些因素。

3　换热器 TMC 耦合疲劳可靠性模拟

换热器受到的交变机械载荷主要有低周起停和高周瞬态变化负荷。根据换热器 TMC 随机模拟应力结果, 基于材料 $S-N$ 曲线, 仍应用概率模拟技术, 即可对换热器疲劳可靠性进行模拟[6~7]。

换热器筒体、管板材料设计 $S-N$ 方程为:

$$\lg N = C + m\lg S_a \qquad (2)$$

式中: N—疲劳寿命; S_a—应力幅, C 和 m 为材料常数, m 符合正态分布 $m \sim N[-3.50, 0.111]$, C 符合对数正态分布 $\lg C \sim N[12.539, 0.256]$。

换热器三维 TMC 概率有限元模拟给出的疲劳计算应力均值和标准差分别为 203 和 32 MPa。再结合材料 $S-N$ 方程, 采用直接模拟法或反应面法随机模拟即可得到疲劳可靠性。疲劳分析选择位于管板、管箱连接表面最大主应力作为疲劳寿命计算应力, 考虑其随机性分布, 同时引入设计 $S-N$ 曲线离散性。图 4 为 $\lg N \sim (C, m)$ 反应面, 图 5 为 $\lg N \sim (S_a, m)$ 反应面。五万次概率有限元模拟给出的换热器疲劳可靠性结果见表 1。

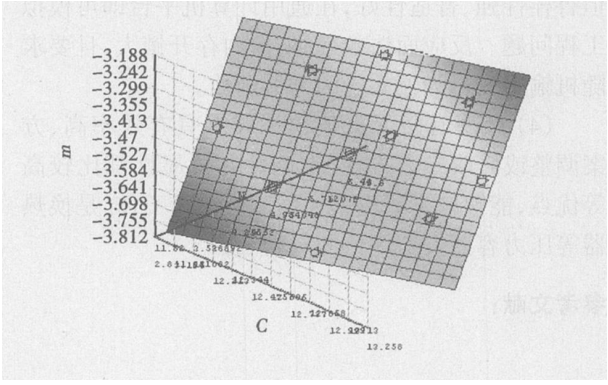

图 4　$\lg N \sim (C, m)$ 反应面

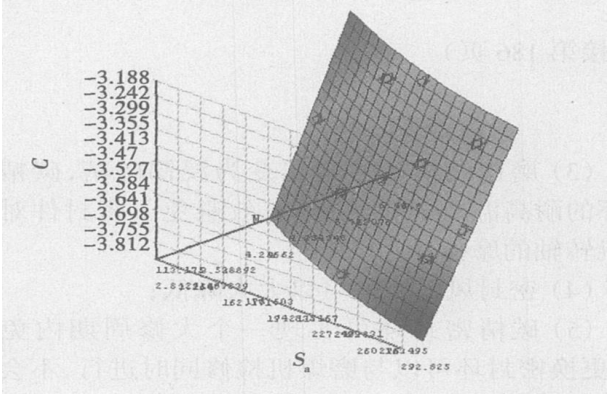

图 5　$\lg N \sim (S_a, m)$ 反应面

表 1　换热器可靠性概率有限元 5 万次模拟结果　(千次)

	平均值	最大值	最小值	对数标准差
反应面法	30.34	3400.00	0.36	0.43
直接模拟	30.37	4200.00	0.48	0.44

两种方法所得结果基本相同。从对数寿命标准差和最大最小值变化范围可见换热器疲劳分散性还是比较大的。另外, 按照 95%置信度计算寿命低于 2 万次的发生概率为 35%。

4　结　论

(1) 换热器可靠度评定应采用三维热—力耦合模型, 建立符合实际结构、工况的概率有限元随机模拟模型。数值模型应尽量复现边界条件和过程中诸

多变量的不确定性。

(2) 以换热器结构应力和疲劳可靠性为优化目标,通过随机有限元模拟获得最佳结构形式和尺寸,对换热器安全运行有着重要意义。

(3) Monte Carlo 直接模拟法虽然计算效率低,但鲁棒性强、普适性好,在通用计算机平台即可模拟工程问题。反应面法效率高,但内存开销大,且要求随机输出变量为输入量的光滑函数。

(4) 概率有限元数值模拟技术具有效率高、方案调整或修改参数方便、准确性和可靠性都比较高等优点,能够减少或省去大量试验测量工作,是换热器等压力容器安全评估的有利工具。

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(3) 磨擦副从硬质金属变为浸锑碳精,碳精密封环的耐高温、自润滑特性有效避免了密封件对磨煤机转轴的摩损和啃蚀;

(4) 密封风的能耗可以大大降低;

(5) 碳精密封环可实现一个大修周期内免维护,更换密封环可以与磨煤机检修同时进行,不会增加维护难度;

(6) 磨煤机内部磨损也有所下降,磨煤机耗能减少;

(7) 节省了开支。以连云港新海电厂为例,2×200 MW, 2×300 MW 机组共有 ZGM95 型中速磨煤机 18 台,据估算,改造后一个大修周期内可节省原有迷宫密封装置 4 套,备品费用按每套 1.8 万元计算,材料费用按每套 2000 元计算,一台磨煤机仅此一项可节约 8 万元。一套制粉系统将节约 30 多万。

5 结 语

中速磨煤机漏粉是电厂常见的通病,其原因可以追溯到制造厂的设计本身不完善,存在设计缺陷。

目前,江苏徐塘电厂、彭城电厂以及连云港新海电厂已采用浸锑碳精密封环和弹簧组成的浮动式密封代替了原有的金属迷宫密封对中速磨煤机进行改造。经过改造后的磨煤机,不但提高了运行的经济性,改善了磨煤机的运行工况,而且对存在类似问题的其它磨煤机,该经验也值得借鉴和参考。

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status quo of seal systems of race pulverizers is described with the causes of pulverized-coal leakage being pinpointed and corresponding modification schemes proposed. In the meantime, a contrast analysis is conducted of two cases, i.e. before and after the modification of the pulverizer. Through the modification, the air and pulverized-coal leakage phenomena have been effectively eliminated with the working environment being improved and operation cost-effectiveness enhanced. Therefore, it is of major significance to conduct a modification of the seal system for the race pulverizer. **Key words**: boiler milling system, race pulverizer, pulverized-coal leakage, seal system modification

不同动态叶片倾角下动静态分离器的试验研究= **Experimental Study of a Static/Dynamic Pulverized Coal Separator with Different Dynamic Blade Inclination Angles**[刊, 汉] / YANG Long-bin, WU Shao-hua, QIU Peng-hua (Combustion Engineering Research Institute under Harbin Institute of Technology, Harbin, China, Post Code: 150001), GAO Zhen-sen (Clean Coal Technology Research Center under Heilongjiang College of Science and Technology, Harbin, China, Post Code: 150027) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(2). —187 ~189

A test stand to determine the performance of a dynamic/static rotor separator is described. An experimental study has been conducted of the separator at different dynamic blade inclination angles and rotor rotating speeds with pulverized coal serving as a raw material. Through a sorting-out and analysis of the test results, it has been found that the separator has a best comprehensive performance when its dynamic blade inclination angle is set at 45 degrees. In such a case, R_{45} can be as high as 3.95% with the comprehensive separation efficiency being 55.32% and the resistance head 846 Pa. An increase of the dynamic blade inclination angle and rotor rotating speed can both increase the fineness of the pulverized coal at the outlet of the separator. Furthermore, there exists a maximal value of the comprehensive separation efficiency but there is a minimal value for the resistance head. **Key words**: pulverized coal, separator, gas-solid flow, experimental study

连续螺旋折流板管壳式换热器动态特性研究及预测= **A Study and Forecast of Dynamic Characteristics of Heat Exchangers with Continuous Spiral Baffle Plates**[刊, 汉] / WU Feng, WANG Qiu-wang, Chen Qiu-yang, et al (National Key Laboratory on Multiple-phase Flow in Power Engineering under Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(2). —190 ~196

A system has been established to conduct the experimental study of dynamic characteristics of shell-and-tube heat exchangers. Through experimental methods, an experimental study has been performed of the dynamic characteristics of heat exchangers with continuous spiral baffle plates, which have water and oil to serve as heat exchange working media. With the inlet flow disturbance representing equal percentage flow rate characteristics, studied were the dynamic responses to water and oil temperature at the outlet in four modes of flow rate disturbance. In the meantime, the effect of fluid disturbing quantity on the temperature rise at heat exchanger inlet and outlet at a certain *Re* number was also studied with a correlation equation between the temperature rise at the inlet and outlet of the heat exchanger and fluid disturbing quantity being obtained. The tests show that the dynamic response to the temperature of a liquid-liquid heat exchange system needs a comparatively long time. It has been found through the study that under a disturbance with a positive or negative flow rate, the change of temperature at the inlet and outlet of spiral-baffle plate heat exchangers assumes a linear relationship and the variation curve featuring temperature rise at the inlet and outlet has a symmetric feature at a positive or negative flow rate disturbance. A finite-difference numerical forecast model and artificial neural network one have been established respectively to dynamically forecast the outlet temperature at the heat exchanger oil side. The forecast results are in good agreement with the test values. The forecast results obtained from the neural network is better than those from the numerical simulation with the absolute value of the deviation being less than 1.3%, indicating that artificial neural network has a definite merit for engineering reference and applications when performing the discrimination of complicated systems. **Key words**: shell-and-tube heat exchanger, continuous spiral baffle plate, dynamic characteristics, numerical forecast, artificial neural network, dynamic forecast

换热器可靠性三维热—力耦合概率有限元模拟= **Three Dimensional Thermal-mechanical Coupled Probability-based Finite Element Simulation of Heat Exchanger Reliability**[刊, 汉] / LIU Tong, LIU Min-shan, DONG Qi-wu

(Thermal Energy Engineering Research Center under Zhengzhou University, Zhengzhou, China, Post Code: 450002) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(2). — 197 ~ 200

On the basis of a three dimensional thermal-mechanical coupled model, a study has been conducted of some key issues concerning the reliability simulation of heat exchangers by using probability finite-element Monte Carlo method and reaction surface method. It was found that a direct simulation method can more accurately simulate the reliability of the integral structure of a heat exchanger. Presented were uncertainty treatment skills for multiple variables under complicated boundary conditions and the TMC (thermal-mechanical coupled) process. By giving a definition of multi-dimensional tabular data functions, a sectioned linear interpolation method was adopted to realize an application of randomly-changed temperature boundary conditions. The simulation accuracy of fatigue life can be enhanced through a logarithmic transformation. A practical example of simulation calculation of industrial heat exchangers indicates that finite-element random simulation technology applied to the reliability calculation and fatigue life prediction of complicated structures can bring about a high confidence result regarding loads and materials as well as geometric uneven characteristics entirely reproducing the actual structures in service. **Key words**: heat exchanger, finite-element probability analysis, reliability, thermal-mechanical coupled

非均匀截面自激振荡流热管内热传输特性实验研究= **Experimental Study of Heat Transmission Characteristics inside Self-excitation Oscillation Flow Heat-pipes of Non-uniform Section**[刊, 汉] / SHANG Fu-min, LIU Deng-ying, XIAN Hai-zhen, et al (Education Ministry Key Laboratory on Power Plant Equipment Condition Monitoring and Control under the North China Electric Power University, Beijing, China, Post Code: 102206) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(2). —201 ~ 204

For two kinds of loop type self-excitation oscillation flow heat-pipes with different sectional structures, i.e. one of a uniform section with an inner diameter of 3 mm and another, on the basis of the above-mentioned uniform section, having an elliptical non-uniform section obtained by machining its heating and adiabatic segments into a vertically staggered arrangement, studied was the internal heat transmission performance of the above loop type heat-pipes of non-uniform section under the condition of being heated by laser with various power ratings. The study has been conducted by adopting and experimental study method and through an acquisition and analysis of temperature data monitored from the heat-pipe wall. To perform the above study, various temperature measurement points were arranged at different locations on the heat pipe wall. Furthermore, a contrast analysis has been conducted with respect to the performance of the uniform section self-excitation flow heat pipes. The results of the analysis show that the pulsation mechanism and heat transmission characteristics of the self-excitation oscillation-flow heat-pipes of non-uniform section are quite different from those of uniform section heat pipes. At medium and high loads, non-uniform section structured heat pipes can obviously strengthen heat transfer effect. Compared with heat pipes of uniform section, they can increase the heat transmission power by 13.6%. **Key words**: self-excitation oscillation flow heat-pipe of non-uniform section, heat transmission characteristics, experimental study

液—液射流雾化的数值模拟与实验研究= **Numerical Simulation and Experimental Study of Liquid-liquid Jet-flow Atomization**[刊, 汉] / PENG Zheng-biao, LIANG Kun-feng, YUAN Zu-lin (College of Energy Source and Environment under the Southeast University, Nanjing, China, Post Code: 210096) // Journal of Engineering for Thermal Energy & Power. — 2007, 22(2). —205 ~ 212

A platform for numerical simulation of liquid-liquid atomization mechanism and another one for experimental study have been established. By employing the above platforms, water jet atomization mechanism in indissolvable solutions has been studied and its atomization process numerically simulated by using a VOF-CSF multi-phase flow model. An experimental verification and comparison was performed under identical working conditions. The study shows that the mathematical model set up by the authors can successfully simulate a continuous jet-flow atomization process and the simulation results are in extremely good agreement with the experimental ones. Through a combination of numerical simulation and experiments an exploratory study has been conducted of the influence of such key factors as jet-flow cone height, jet flow speed, indissolvable working-medium velocity etc. As a result, the following relevant law has been identified: under a certain