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节流件阻力特性的 CFD 研究

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摘　要: 增加沸腾管入口段流动阻力是抑制沸腾管内流动不稳定性的主要措施之一。本文采用商用 CFD 软件 CFX 对带有微小节流件的沸腾管入口段进行计算分析, 得到了计算该段摩擦阻力的关系式, 并能与现有的实验数据吻合。

关　键　词: 沸腾管; CFX; 节流件

中图分类号: TK172　　文献标识码: A

1　引　言

在能源、化工和航天等工业经常采用沸腾管输送热量, 在沸腾管内流体经历液相到汽相的相变过程, 单相流动阻力和两相流动阻力构成了沸腾管的总阻力, 沸腾管的传热强度直接影响到沸腾管内单相区与两相区的分配比例, 使沸腾管的阻力特性随传热强度不断的变化。反之, 沸腾管阻力特性的改变引起流量的变化, 从而改变沸腾管的传热强度。在一定运行工况下, 沸腾管内流动与传热的强烈耦合引起流动的不稳定, 造成设备传热性能降低, 甚至危害设备的安全。因此, 在沸腾管入口插入节流件, 增加沸腾管单相区流动阻力在总阻力中的比重, 是抑制沸腾管内发生流动不稳定性的主要措施之一。

本文采用商用 CFX 程序计算分析管内节流件的阻力特性, 对管内入口节流件结构与沸腾管总阻力特性进行了研究。

2　计算模型

普通的沸腾管流动阻力很小(主要是沿程阻力), 随着传热强度的变化, 流动阻力也发生变化, 引起流动发生脉动。采用在沸腾管入口处插入节流件, 增加单相区阻力在整个阻力中所占的比重, 减弱沸腾管流动总阻力与传热强度的耦合, 可以抑制沸腾管内的流动脉动。但是本文需要模拟的沸腾管管径十分细小, 入口段插入节流件以后, 流道十分复杂和狭窄, 许多热工参数很难测量甚至无法用实验测量, 无法得知内部的流动特性。基于目前 CFD 技术和计算机的发展, CFD 程序已经可以采用细小的网格, 捕捉到流体在不规则细小流道里面的变化, 我们拟采用 CFD 的数值实验来解决这一问题。

本文研究的沸腾管前端直径为 2 mm, 长为 80 mm, 管内插入形状复杂的节流件, 如图 1 所示。该节流件长为 72 mm, 由 24 个同样的"葫芦串" 间隔反向串连而成。"葫芦串"为一个 1 mm 长的圆缺加上 2 mm 长的圆柱体构成。圆缺部分半径为 2 mm 的圆柱体, 在边缘处开一个半径为 1 mm 的半圆形槽。小圆柱体半径为 1 mm, 槽底部与小圆柱体的圆周相切。

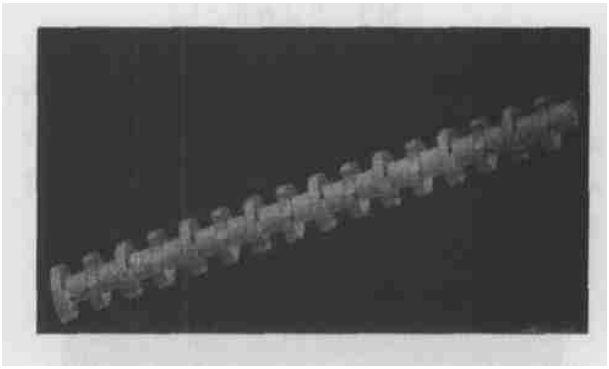

图 1　节流件图

这样, 将此节流件插入沸腾管, 使管内部形成不规则的狭窄空间, 最狭窄处只有 1 mm, 由于开槽方向间隔相反, 使流体经过沸腾管形成环流和绕流, 增加了流动的阻力和复杂性。图 2 为放大的流体经过单节"葫芦串"的流场模型。

为了保证沸腾管内流体在节流件入口不会形成急速流速转变, 加入了导流件, 如图 3。

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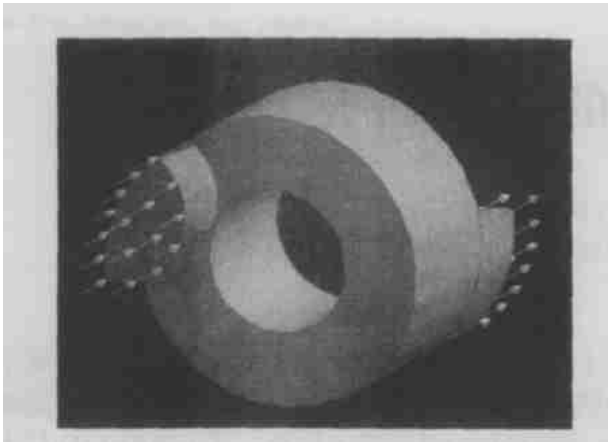

图 2 放大的局部(单节“葫芦串”)流场

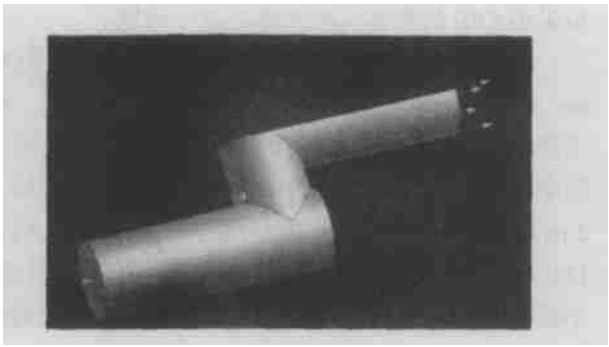

图 3 导流件图

其中导流件前端半径为 0.75 mm, 在长度为 4 mm 处 90° 的转弯, 连接导流件后端, 后端长度为 4 mm, 大小与节流件形成的入口一致。这样, 流体在沸腾管内的流场模型如图 4。

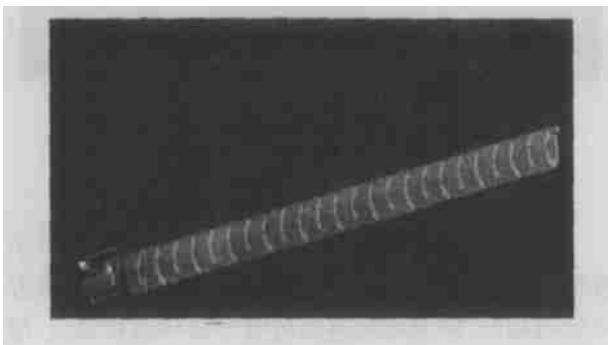

图 4 总沸腾管几何图

3 控制方程

工质为水, 对于不可压缩流体, 描述其三维稳态的 Navier-Stokes 方程为:

质量守恒方程(连续性方程):

$$\frac{\partial \rho}{\partial t} + \triangle \cdot (\rho U) = 0$$

动量守恒方程:

$$\frac{\partial \rho U}{\partial t} + \triangle \cdot (\rho U \times U) = \triangle \cdot \sigma + S_M$$

同样考虑稳态, $\frac{\partial \rho U}{\partial t} = 0$

能量守恒方程:

$$\frac{\partial \rho h_{tot}}{\partial t} - \frac{\partial \rho}{\partial t} + \triangle \cdot (\rho U h_{tot}) = \triangle \cdot (\lambda \triangle T) + S_E$$

考虑粘性后的方程为:

$$\frac{\partial \rho h_{tot}}{\partial t} - \frac{\partial \rho}{\partial t} + \triangle \cdot (\rho U h_{tot}) = \triangle \cdot (\lambda \triangle T) + \triangle \cdot \mu (\triangle U + (\triangle U)^T - \frac{2}{3} \triangle \cdot U \delta) U + S_E$$

紊流模型选用 κ-ε 方程来建立方程组, 动力粘性系数重新定义, 由温度差分得知。分别定义紊流脉动动能 k 和脉动动能耗散率 ε。紊流模型方程的其它相关系数取标准值分别为: $c_\mu = 0.09$, $c_{\varepsilon 1} = 1.44$, $c_{\varepsilon 2} = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$。

压力项、速度项、紊动能项和紊流粘性系数项均采用二阶迎风差分形式, 求解过程中各迭代松弛因子分别为压力项 0.3、速度项 0.7、紊流动能项和紊流粘性系数项 0.8。

沸腾管水平放置, 采用均匀入流条件, 给定入口速度, 为保证沸腾管管内流型为紊流, 根据入口的管径需保证雷诺数大于 2 000, 故入口速度依次从 1 ~ 20 m/s, 并给定沸腾管入口流体的进口温度为 20 ℃。壁面按照设计要求, 光滑管壁, 并设置为无滑移边界, 壁面稳定温度为 100 ℃。内部各局部点则通过 CFX 的后处理模拟来得知压力和速度等分布情况。

当沸腾管入口段插入节流件以后, 管内流动将趋于复杂化。因此, 在界面发生突扩和突缩, 工质开始绕着节流件绕动的情况下, 采用不规则网格划分沸腾管, 并在突扩和突缩的地方细分管道, 如图 5。

4 计算结果与分析

如图6和图7所示, 管内流动由于节流件的作用让水速度方向和大小不断变化, 尤其在管内的局部地方, 容易产生流动滞止区。

如图所示, 根据得到的数据, 我们采用 $f = 2\Delta p / \rho v^2 \times \frac{d}{l}$ 公式, 其中 f 为摩擦系数, d 为当量水

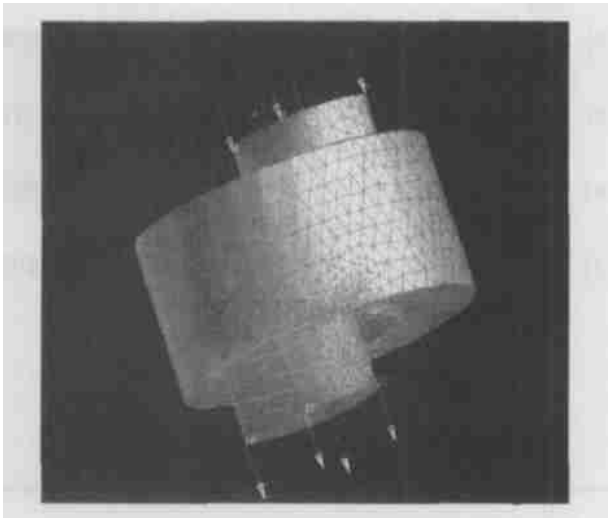

图 5　局部沸腾管网格模型

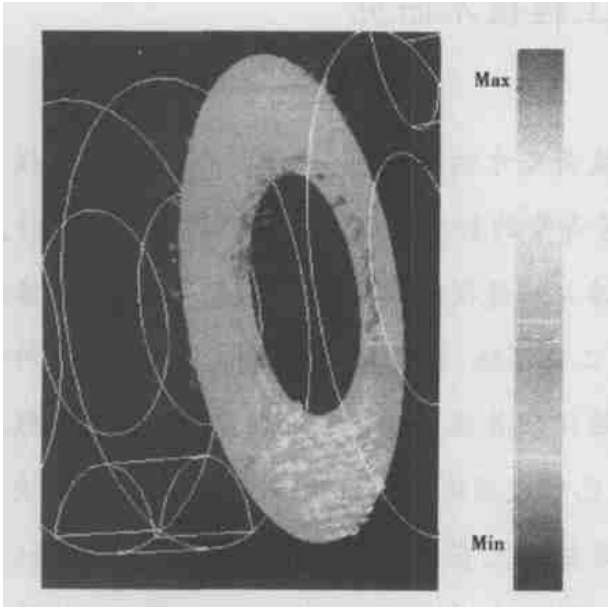

图 6　管内横截面速度矢量图

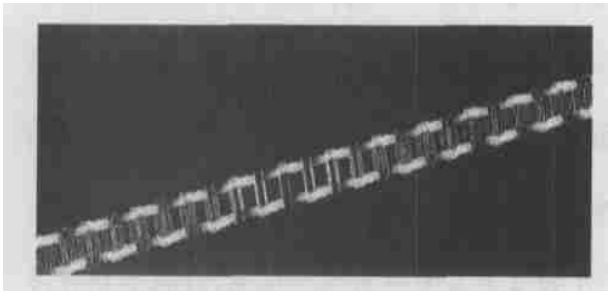

图 7　管内纵向截面速度矢量图

利直径, l 为管长, 求得了摩擦系数。图 8 为光滑管计算得出的 Re-f 图, 因为该换热器内管的粗糙度要求在 0.015 mm 以下, 我们又计算了该粗糙度的管内流动, 得出了 Re-f 图, 如图 9。

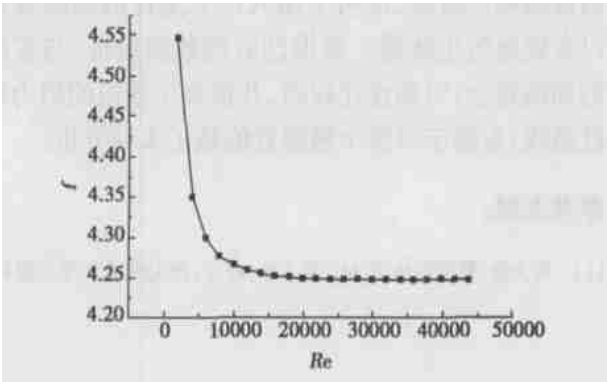

图 8　光滑沸腾管流动阻力图

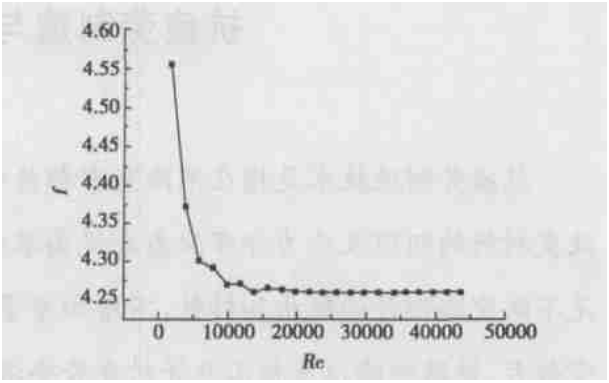

图 9　粗糙度为 0.015 mm 沸腾管的流动阻力图

我们发现, 因为节流件的作用, 管内的阻力急剧增大, 沿程损失几乎可以不用考虑。对带有节流件的模型, 当管内雷诺数大于 4 000 以后, 当流动进入紊流自模化区以后, 摩擦系数不再随雷诺数的改变而改变, 基本上保持在一定水平上, 沸腾管后段均为普通圆管, 只需要考虑沿程阻力。对于整个沸腾管来说, 绝大部分的阻力都来自于节流件, 说明该结构可以有效地防止单管脉动。

由数据拟合的 Re-f 关系曲线表达式为:

$$f = 4.247 + 180e^{-(Re/201)} + 52e^{-(Re/1\,800)}$$

在雷诺数大于 4 000 以后, f 用 4.427 或 4.428 即可, 误差很小。将以上所得到的数据和现有的数据对照, 发现 Re-f 曲线变化趋势一致。拟合出的公式对整个热工水利分析将起到必要的作用。

5　结　论

综上所述, 在无法用实验得知内部流动特性的

情况下, 我们运用商用 CFD 软件 CFX, 对该沸腾管带节流件的狭小前段进行了仿真模拟, 得出了内部的流动特性曲线, 证明了加入该节流件的沸腾管可以有效地防止脉动。根据已有的数据验证, 与实际的曲线符合, 可靠性比较高, 并拟合了该段的阻力特性曲线, 有助于对整个沸腾管的热工水利分析。

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抗疲劳制造与表面工程技术研究

抗疲劳制造技术是指在不改变零部件材料和截面尺寸的前提下, 通过在制造工艺过程中改变材料的组织及应力分布状态来提高零部件疲劳寿命的制造技术。该技术的一个突出特点是不改变零部件的结构和材料, 不增加重量, 但能够大幅度提高零部件的疲劳寿命, 对于像航空航天、铁路运输以及核工业等对疲劳要求很高的工业领域, 抗疲劳制造显得尤为重要。所开展的主要研究工作包括: 抗疲劳制造原理; 冷挤压强化改善疲劳性能; 高能束流强化改善微动疲劳性能; 抗疲劳制造设备研制等。所取得的成果已经成功地应用于国防装备研制中, 解决了重大关键技术难题。其中, 开发成功"双轴柔性滚弯技术", 在国内首次研制成功开缝衬套, 已提供了 800 余件合格产品, 其直径从 Φ27 ~ Φ70, 总共 10 个系列, 从而结束了该产品只能依赖进口的被动局面。

在膜技术研究领域, 开展了溶胶凝胶法金刚石膜的涂覆机理研究; 类金刚石膜过滤式真空阴极电弧沉积机理研究, 自行研制了沉积装置, 在硅片和高速钢基体材料上获得了类金刚石薄膜, SP^3 含量最高达 70%; 在 Ni 和 Cr 等电沉积过渡层上沉积金刚石膜机理的研究, 极大地提高了金刚石膜与基体材料间的结合性能, 为在硬质合金上获得粘附金刚石膜提供了一条新思路; EACVD 法金刚石薄膜与厚膜沉积技术研究, 设计并制造了金刚石膜沉积设备, 其技术指标达国际先进水平; PZT 陶瓷涂层沉积机理与技术的研究。

(翟国臣 供稿)

An analysis was performed of the variation relationship between the flow-straightening tube length and the steam-jet factor. The results of the analysis indicate that under identical operating conditions the nozzle structure of a straightened flow can effectively enhance the steam jet factor of the jet ejector. Meanwhile, there exists an optimum length of the flow-straightening tube corresponding to the maximum jet factor. In addition, the above-mentioned nozzle structure is conducive to effectively preventing the deterioration of equipment performance caused by a reduction of operating fluid pressure, thus increasing the stability of the steam jet pump operation. **Key words**: jet pump, nozzle, steam jet factor, numerical simulation

关于换热系统优化目标函数的探讨=**An Exploratory Study Concerning the Target Function of Heat Exchange System Optimization** [刊, 汉] / XU Wen-zhong (Department of Architectural Environment and Equipment under the Civil Engineering College of Shandong University of Science & Technology, Taian, Shandong Province, China, Post Code: 271019), ZHANG Kai (Energy & Power Engineering Institute under the Shandong University, Jinan, China, Post Code: 250061), YANG Dong (Air Conditioning Department, Shandong Architectural Engineering Institute, Jinan, China, Post Code: 250061) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(5). —510~512

Through an analysis of the various factors liable to affect expenses caused by the loss of available energy of an heat exchange system a comprehensive consideration has been given to the material consumption expenses of a heat exchanger. A target function based on the second law of thermodynamics was proposed for the optimization of the heat exchange system. Moreover, by making use of the theory of engineering thermodynamics, fluid mechanics and thermo-economics a derivation of the target function was carried out, resulting in the acquisition of a calculating formula for the target function. **Key words**: the second law of thermodynamics, heat exchange system optimization, target function, expenses due to the loss of available energy

液幕状气液两相流流动特性的实验研究=**Experimental Investigation of the Flow Characteristics of a Gas-liquid Two-phase Flow Assuming the Form of a Gas-liquid Screen** [刊, 汉] / ZHOU Qu-lan, SONG Hong-peng, HUI She-en, et al (Thermal Energy Engineering Department, Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(5). —513~516

A new flow pattern, the so-called "gas-liquid screen", is proposed and an experimental investigation of the gas-liquid two-phase flow characteristics based on this new flow pattern conducted. The investigation of the flow characteristics has been focused on the relationship between the above-mentioned bed layer height of the gas-liquid two-phase flow and resistance characteristics on the one hand and gas phase and liquid phase flow speed on the other. As a result, correlation equations for calculating equivalent bed layer height, actual bed layer height and the resistance factor of the gas-liquid screen bed layer were obtained. These correlation equations provide basic scientific test data for the research of the gas-liquid two-phase flow assuming the form of a gas-liquid screen. **Key words**: gas-liquid two-phase flow, fluid dynamics, experimental research

节流件阻力特性的 CFD 研究=**CFD (computational fluid dynamics) Research on the Resistance Characteristics of a Throttling Element** [刊, 汉] / FU Jian-qiang, CHEN Jun, YANG Yan-hua (Department of Nuclear Science and System Engineering, Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(5). —517~520

One of the major measures to suppress flow instability in a boiling tube consists in increasing the flow resistance at the boiling tube inlet section. With the help of a CFD (computational fluid dynamics) software "CFX" computations and analyses have been performed of a boiling tube inlet section fitted with a tiny throttling element and a formula for calculating the friction resistance of that inlet section was obtained. The calculation results agree well with the experimental data.

Key words: boiling tube, CFX, throttling element

转子蜂窝密封封严特性的试验研究＝**Experimental Investigation of the Sealing Characteristics of a Rotor Honeycomb Seal** [刊, 汉] / WANG Xu, ZHANG Wen-ping (Nuclear and Power Engineering Institute under the Harbin Engineering University, Harbin, China, Post Code: 150001), MA Sheng-yuan (Harbin No. 703 Research Institute, Harbin, China, Post Code: 150036) //Journal of Engineering for Thermal Energy &Power. — 2004, 19(5). —521 ~ 525

To study the sealing characteristics of a rotor honeycomb seal, five kinds of stator test piece for honeycomb seals and five kinds of rotor test piece were designed and fabricated. Tests were carried out on a rotor seal test rig to identify the impact on sealing characteristics of such factors as honeycomb core lattice size, seal clearance, rotor speed, honeycomb depth, and seal pressure ratio. Contrast tests were also conducted of the sealing characteristics of a seal structure composed of a honeycomb stator, labyrinth disc and smooth disc. Finally, the conclusions of the experimental study were presented.

Key words: rotor, honeycomb seal, labyrinth seal, sealing characteristics

五孔探针实验数据处理的线性插值法＝**Linear Interpolation Method for Processing the Test Data of Five-hole Probes** [刊, 汉] / YUE Guo-qiang, Han Wan-jin, Lu Wen-cai, et al (Institute of Energy Science &Engineering under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. — 2004, 19(5). —526 ~529

During the calibration of data by using five-hole probes a spline interpolation and least square fit are generally employed. For the calibration of curves by the use of identical probes the results of interpolation obtained by employing respectively the above-mentioned two methods may be quite different. Through a theoretical analysis of these two methods the authors have come up with a linear interpolation method, which is more practical for general use. For probes with good characteristics the recommended method can attain a precision close to that of the spline interpolation. As for probes with relatively poor characteristics the above method is capable of ensuring interpolation precision without the change of the probe characteristics, and relative to the spline interpolation and least square fit it enjoys a higher degree of adaptability. **Key words**: five-hole probe, linear interpolation, spline interpolation, least square method

循环流化床的物料平衡和运行中的物理现象＝**Mass Balance of a Circulating Fluidized Bed and Physical Phenomena Encountered in the Latter's Operation** [刊, 汉] / MA Su-xia, WANG Ming-min, YUE Guang-xi (Department of Thermal Engineering, Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy &Power. — 2004, 19(5). —530 ~533

Mass balance in a fluidized bed constitutes the core and basis of the combustion process in a circulating fluidized bed and is of utmost importance to the operation of the fluidized bed. A mass balance model is presented for a circulating fluidized bed in its steady state along with a discussion of various factors liable to influence the mass balance. The mass balance model was used to calculate the circulating mass flow rate, residue mass flow rate and fly ash flow rate (including its particle distribution) of a 75t/h circulating fluidized bed boiler. An analysis was conducted of the intrinsic causes of the physical phenomena and problems encountered in the operation of the fluidized bed boiler under the influence of the mass balance. Such phenomena include "bed quality" and the characteristics of the separator used for the circulating bed, etc. Some existing problems currently attracting the attention of a circle of theoretical and industrial workers are quantitatively explained. **Key words**: circulating fluidized bed, mass balance, model, physical phenomena

余热锅炉补燃装置的研究＝**A Study of the Supplementary-firing Burner Unit for a Heat Recovery Steam Generator** [刊, 汉] / YU Zhao-yang (Harbin Boiler Co. Ltd., Harbin, China, Post Code: 150046), WANG Jian-zhi (Harbin No. 703 Reseach Institute, Harbin, China, Post Code: 150036), HE Nian (Equipment Engineering Depart-