

海水脱硫散堆填料塔流体流动及传热研究

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摘 要: 在大型可移动式海水脱硫试验台上进行了中试规模的试验, 在体积平均法的基础上, 结合试验数据获得的压损拟合公式建立了描述散堆填料塔内气、液两相的流动及传热模型; 通过计算, 获取了在不同液气比下塔内流体速度、孔隙率分布、压力分布及海水温度分布, 并就压力损失和海水出口温度与试验值进行了对比, 预测值与试验值吻合较好。分析计算结果发现, 靠近壁面处存在着显著的壁流现象, 其形成原因是近壁面处的孔隙率明显高于中间区域。海水温度在顶部分布较不均匀, 靠近壁面处海水温度波动较大, 向塔中心处逐渐趋于均匀, 沿塔高度从上到下, 温度逐渐下降均匀, 到塔高一半处基本不再变化 ($\Delta T < 0.1$ K), 说明在塔高一半处气液间的热交换已基本完成。

关 键 词: 海水脱硫; 散堆填料; 数值模拟; 传热

中图分类号: X01; X55 文献标识码: A
符号说明

γ —孔隙率分布函数
 γ_{∞} —无塔壁限制时的填料平均孔隙率
 R —塔半径
 r —径向位置坐标
 p_d —振荡周期
 E_r —指数衰减函数
 h_L —液相总持液量
 h_s —液相静持液量
 h_d —液相动持液量
 σ_L —液体表面张力
 α_T —填料比表面积
 U —主流时均流速
 g —重力加速度矢量
 F_{LS} —散堆填料施加给液体的阻力
 F_{LG} —气液两相流动时气液两相间的相互作用力
 Δp_t —总压力
 Δp_d —干填料时气体压力降
 Δp_L —存有液体时气液间相互作用导致的压力降
 U_{slip} —滑移速度
 U_G —气相表观速度
 T_g —混合气温度
 λ'_g —考虑了多孔介质热弥散作用后修正的气体导热系数
 ρ_g —气相密度
 C_p —流体恒压热容
 λ_g —气体导热系数

T_L —液相温度
 h_p —体积换热系数
 λ_{eff} —单位体积内有效传质面积
 Re_{dp} —基于液相表观速度的液相雷诺数
 d_H —散堆填料水力直径

引 言

对填料塔以及固定床内的流体流动分布的试验以及理论研究一直是化学工程科研技术人员的重要研究内容^[1~6]。尽管文献上提供了许多描述散堆填料塔内液相流动分布的数学模型^[7~10], 但都是纯经验的, 不能正确的描述液相分布。本研究以国电环境保护研究院在秦皇岛热电厂的中型海水脱硫试验塔为模型, 采用 3 种工业型填料进行了大量的海水脱硫各种变工况试验, 以试验中测量的压损数据拟合获得 3 种填料的干损及湿损公式。在平均体积法的基础上, 将 Brinkman 方程与上述获得的压损方程相结合, 并且用孔隙率分布函数替代 Ergun 方程中的平均孔隙率, 建立流体力学及传热模型, 获得海水在填料塔内表观流速的径向分布及海水温度分布。

1 试验方法

本研究以国电环境保护研究院在秦皇岛热电厂的中型海水脱硫试验塔为模型进行模拟计算。试验装置如图 1 所示, 整个试验台搭建于秦皇岛热电厂脱硫塔旁边。

试验台吸收塔直径 1.2 m, 高 6 m。海水来源为秦皇岛热电厂脱硫海水箱, 采用电磁流量计调节海水流量, 在填料塔上方布置四个喷嘴, 通过喷淋泵以喷淋方式进入填料层。原烟气从热电厂脱硫塔的原烟气引进, 从吸收塔底部进入, 通过原烟气挡板门对烟气流进行调节, 以孔板流量计测量烟气流。在吸收塔底部装有隔栅, 对填料起支承作用, 同时对气体起均布作用。在烟气的进出口以及在海水箱内及

收稿日期: 2011 - 02 - 25; 修订日期: 2011 - 07 - 01

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填料塔底部装有温度感应器,以测量原烟气及海水进出口温度。在原烟气进口及净烟气出口中心处装有德国 MRU 生产的 MRU VARIO PLUS “工业增强型”烟气分析仪,以检测进出口 SO₂ 浓度。在原烟气进口和净烟气出口以及除雾器前后侧装有压力感应器,以获取装置压损。

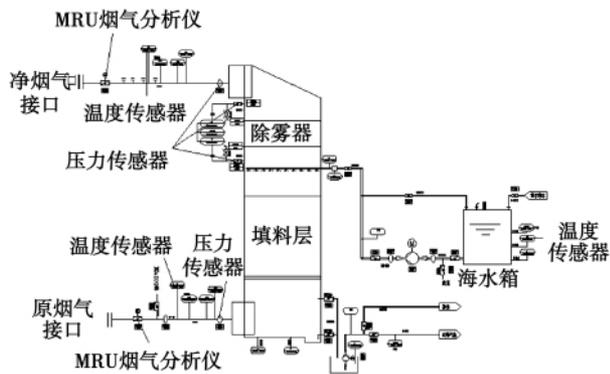


图 1 试验装置图

Fig. 1 Drawing of the test device

2 模型的建立

2.1 体积平均计算流体力学模型

模型基本假设: (1) 液相在散堆填料塔内流动为稳态的、轴对称; (2) 流体不可压缩; (3) 气体为活塞流运动。

根据体积平均连续性方程及体积平均动量守恒方程式建立流体力学模型^[11]。模型中的散堆填料床的孔隙率分布函数 γ 采用式 (1) 的关联式进行计算^[12] 即:

$$\gamma = \gamma_{\infty} + \frac{(1 - \gamma_{\infty})}{2} Er [(1 - 0.3p_d) \times \cos(\frac{2\pi}{c_r + 1.6Er^2 p_d d_p} R - r) + 0.3p_d] \quad (1)$$

在文献上有许多关于散堆填料截内气液两相逆流操作持液量的研究及其预测关联式,这里采用 Engel 的关联式计算静持液量 h_s , 采用 Stichlmair 关联式计算动持液量 h_d ^[13-14] 则:

$$h_s = 0.033 \exp(-0.22 \frac{g\rho_L}{\sigma_L a_T}) \quad (2)$$

$$h_d = 0.555 (\frac{a_r U^2}{g\gamma^{4.65}})^{1/3}$$

体积平均动量守恒方程中^[11]的 F_{LS} 代表散堆填料施加给液体的阻力, F_{LG} 为气液两相流动时气液两

相间的相互作用力。

根据填料表面被液体完全覆盖的假设,可以采用 Ergun 提出的半经验公式计算填料对液体流动造成的阻力 F_{LS} ^[15]。

至于气液两相流动时气液两相间的相互作用力 F_{LG} 的计算,现有的计算方法如 Robbins 根据大量试验数据总结出气体通过湿填料塔时总压力 Δp_t 可表示为^[16]:

$$\Delta p_t = \Delta p_d + \Delta p_L \quad (3)$$

气液间的相互作用力 F_{LG} 可以表示为:

$$F_{LG} = \frac{\Delta p_L}{|U_{slip}|} U_{slip}$$

其中,滑移速度 $U_{slip} = U_G - U$ 。

2.2 体积平均计算传热学模型

由于散堆填料塔内孔隙率很大(高于 0.9),可认为固体填料全部被液体覆盖,进而把气、液、固三相之间的传热问题简化为气、液两相之间的传热。根据下述的两点假设,可导出体积平均计算传热学模型。

计算传热学模型假设:

- (1) 填料表面全部被液相覆盖,假设液体与填料固体温度相等,只考虑气、液间的换热过程;
- (2) 忽略 SO₂ 的溶解热。

根据体积平均温度方程建立传热模型^[11]:

填料层内气体能量方程:

$$\nabla \cdot (\rho_g c_p \vec{u}_g) = \nabla \cdot [(\gamma - h_L) \lambda'_g \nabla T_g] + h_p (T_L - T_g) \quad (4)$$

$$\lambda'_g = [h + 0.1 \left(Pr \left(\frac{\rho_g u d_p}{\mu} \right) \right)] \lambda_g + (1 - \varepsilon) \lambda_L$$

填料层内液体能量方程:

$$\nabla \cdot (\rho_L c_L \vec{u}_L) = \nabla \cdot [(1 - \gamma + h_L) \lambda_{eff} \nabla T_L] - h_p (T_L - T_g) \quad (5)$$

式中: $\frac{h_p d_p^2}{\lambda_g} = [0.0426 + \frac{1.236}{L/d_p}] Re_{dp}$, $\lambda_{eff} = \lambda_L (1 - \gamma + h_L)$, $Re_{dp} = \rho u d_p / \mu$ 。

3 模拟过程

图 1 为计算区域示意图,整个区域为轴对称结构,塔顶、塔底分别为海水入口和烟气入口条件,右边界为墙壁条件。塔顶设为海水入口,塔底为海水出口,在塔顶设置海水初始温度,塔底分别设置烟气初始温度及 SO₂ 的初始浓度。

3.1 塔顶

塔顶处设置为速度进口边界,需定义海水速度及湍流特性参数。海水速度由试验中所测海水流量而得,湍流特性参数由下列经验公式得出:

$$k_{in} = 0.003 U_{in}^2 (r)$$

$$\varepsilon_{in} = 0.09 \frac{k_{in}^{1.5}}{d_H}$$

其中,散堆填料水力直径 d_H 表示为 $d_H = \frac{4\gamma_\infty}{a_T(1-\gamma_\infty)}$ 。对于烟气温度与 SO_2 浓度方程的求解,在此边界上取充分发展条件,设定海水的入口温度。

3.2 塔底

对海水流动方程,此边界设为压力出口边界,规定此处的静压值。为求解添加的 3 个 UDS 方程,需要在这些边界上规定 SO_2 的初始浓度值、烟气的初始温度,并认为海水温度在此充分发展。

3.3 对称轴

在对称轴边界上,所有变量的径向能量变化率为零,即 $\partial\phi/\partial r = 0$ 。

3.4 墙壁条件

墙壁处认为无滑移边界,即速度、湍动能及湍动能耗散率都等于零。采用标准壁面函数计算近壁区的速度及湍流变量的分布。

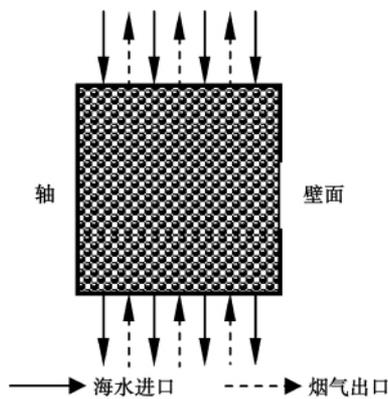


图 2 计算区域示意图

Fig. 2 Schematic diagram of the calculation zone

4 模拟结果

采用了 3 种填料作为研究对象,分别为多面球填料、雪花环填料和蜂窝环填料。它们的特性参数如表 1 所示。

由于所研究的几种填料为新型填料,不能应用已有的经验公式来获得总压损。在试验中测量了应

用 3 种不同散堆填料时,一定的气体流量下不同液气比的气体压力损失,根据这些数据可以得出气体通过这几类类型填料时的压力损失特性。把气体总压力损失分为干损与湿损两部分,干损即为气体流过干填料床时的压力损失,湿损为气体流过被海水浸湿的填料床时的压力损失。

表 1 填料特性参数

Tab. 1 Characteristic parameters of the packing

填料名称	尺寸规格/mm	比表面积 / $m^2 \cdot m^{-3}$	孔隙率	堆重 / $kg \cdot m^{-3}$	堆积个数 / $个 \cdot m^{-3}$
多面球	$\phi 50 \times 50 \times 1.5$	237	0.9	82.8	11500
雪花环	$\phi 90 \times 34 \times 1.5$	138	0.97	49	4900
蜂窝环	$\phi 88 \times 22 \times 1.25$	142	0.92	67	5500

对于这 3 种不同填料,认为干损相等,而湿损随着填料的变化会发生相应的改变。在直径为 1.2 m,床高 0.6 m 的雪花环填料塔上,分别测量了不同烟气流速时,气体流过干床的压力损失,表 2 为不同烟气流速下烟气流经填料塔的单位长度压力损失测量值,对此表的数据按照 Ergun 公式进行拟合,图 3 为此组数据的拟合图。

表 2 雪花环填料干床压力损失测量值

Tab. 2 Measuring value of the dry-bed pressure loss of the snowflake ring packing

烟气流速 / $m \cdot s^{-1}$	单位长度压损 / $Pa \cdot m^{-1}$
1.46	24.3
2.16	31.2
2.36	70.7
2.75	173.8
3.50	188.9

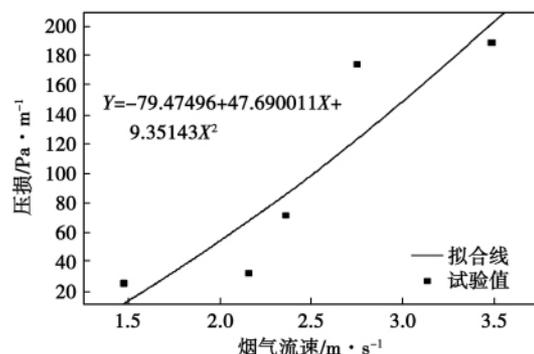


图 3 雪花环填料压力损失随速度分布图

Fig. 3 Chart showing the pressure loss distribution of the snowflake ring packing with the velocity

此干压损公式同时适应于其它两种填料。向填料塔内通入海水之后,由于海水流过填料塔内孔隙会造成烟气压力损失的大幅提高,因此还需计算出填料塔在不同液气比操作条件下的烟气流动的压力损失。图4为根据试验数据拟合出的填料塔湿床烟气压损随液气比升高的变化图,其中雪花单位湿压损(Pa/m)的计算式为:

$$Y = 139.84 \exp(X/5.465) - 166.2$$

此式同样适用于蜂窝环填料。而多面球单位湿压损的计算公式为:

$$Y = 357.2 \exp(X/7.737) - 213.54$$

式中: X—液气比; Y—单位长度上压力损失, Pa/m。

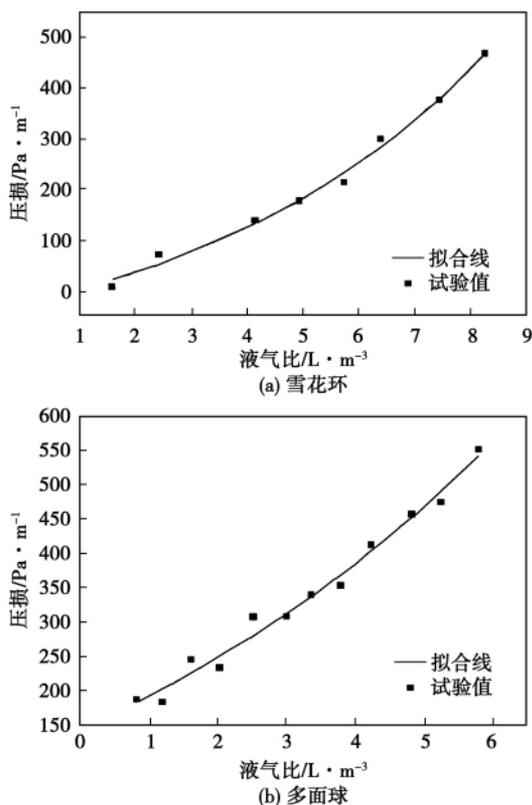


图4 单位湿压损与液气比的关系
Fig. 4 Relationship between the unit wet pressure loss with the liquid/gas ratio

4.1 压损

图5为在不同液气比下,压力损失的预测值与试验值对比图。图5(a)为雪花环填料高度为0.6m、当烟气流量11000m³/h时,在不同液气比下烟气压力损失的对比图;图5(b)为多面球填料高度为1.2m,当烟气流量12000m³/h时,不同液气比下烟气压力损失的对比图;图5(c)为蜂窝环填料高度为1.2m,当烟气流量12000m³/h时,不同液气

比下烟气压力损失的对比图。从图5中可看出,压损数值计算结果与测量结果吻合较好,试验值与计算值略有偏差,这是由于试验测量的压损值是取进出口的中心处的压强计算,而计算值是取的进出口的平面加权平均值计算的。从图5可看出,预测结果与试验值的趋势完全一致,从而说明以试验数据进行拟合获得压损公式进行数值模拟计算的方法是可行的。

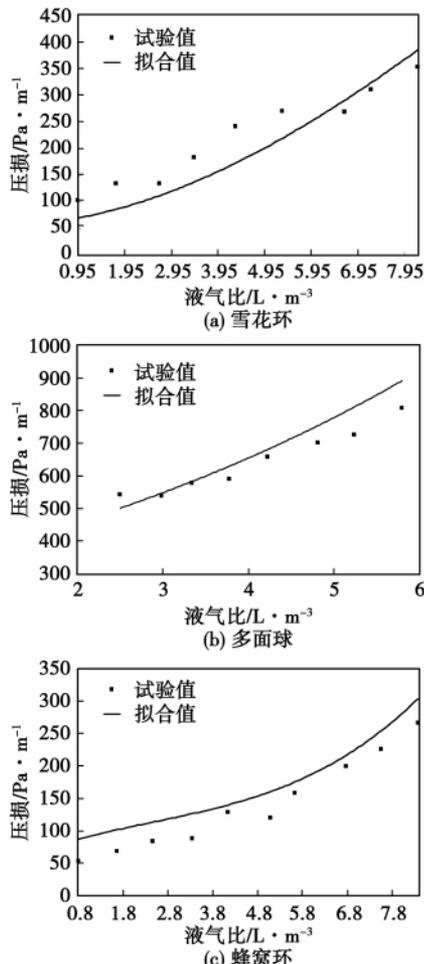


图5 压力损失的预测值和试验值对比图
Fig. 5 Chart showing the contrast of the predicted values of the pressure loss with the test ones

4.2 海水速度分布

图6为填料塔中间高度断面上的速度分布图。从图6可看出靠近壁面处存在着显著的壁流现象,并且沿着液体的流动方向上,液体有向塔壁区附近积聚的趋势,壁流现象变得更严重。图7为径向方向上的孔隙率分布图,从图上可看出在靠近处的孔隙率明显高于中间区域,这是形成壁流的原因所在。

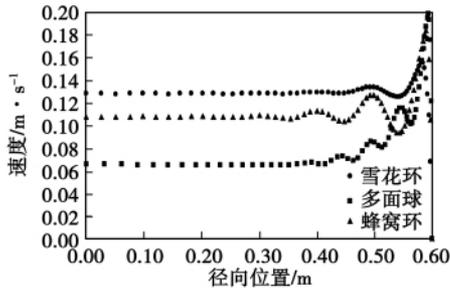


图 6 中间高度断面速度分布图

Fig.6 Chart showing the velocity distribution in the section at the half height

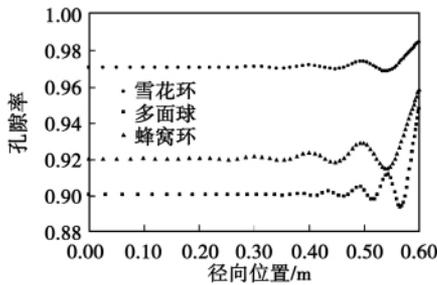
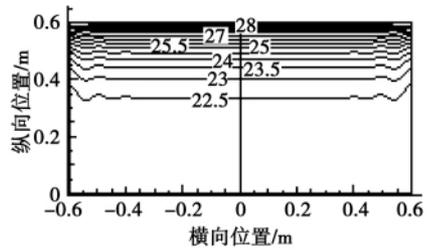
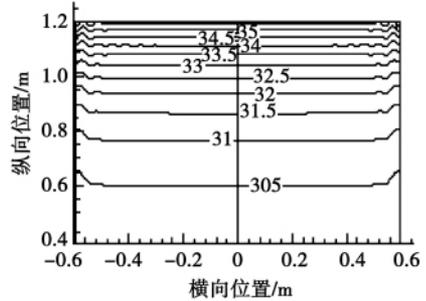


图 7 径向孔隙率分布图

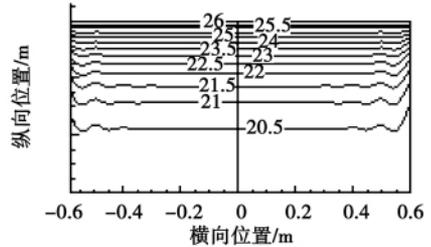
Fig.7 Chart showing the radial porosity distribution



(a) 雪花环



(b) 多面球



(c) 蜂窝环

图 9 海水温度分布图

Fig.9 Chart showing the seawater temperature distribution

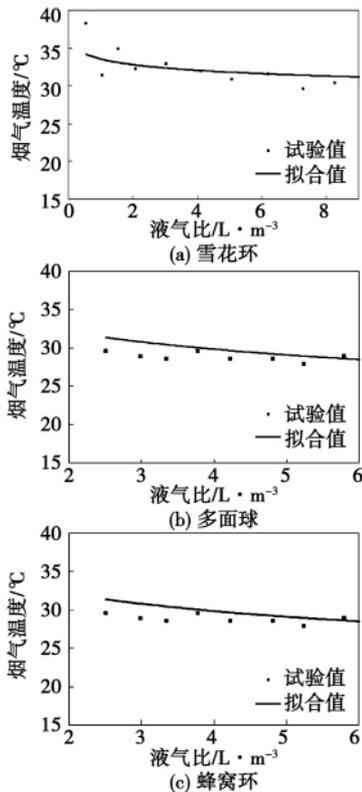


图 8 烟气出口温度的预测值和试验值对比图

Fig.8 Chart showing the contrast of the predicted values of the flue gas temperature at the outlet with the test ones

图 8 为烟气流量 $9\ 500\ \text{m}^3/\text{h}$, 气体进口温度为 $140\ \text{°C}$ 海水入口温度为 $30\ \text{°C}$ 时, 不同液气比下烟气出口温度的试验值与计算值对比图, 图 8(a) 为 0.6 米塔装填雪花环填料的对比图; 图 8(b) 为 1.2 米塔装填多面球填料的对比图; 图 8(c) 为 0.6 米塔装填蜂窝环填料的对比图。从图 8 可看出, 在低液气比时预测值与试验值偏差较大, 这是由于模型中假设进入填料中的海水可以均匀分布于填料表面, 而在试验中低液气比时, 海水量较少, 不能均匀分布于填料表面, 造成气液之间的热量交换不充分。预测值是求取整个出口界面的加权平均值, 而试验数据是以出口中心处的测量值为出口温度, 这是造成在低液气比时预测值与试验值偏差较大的原因。而在较高液气比时(大于 3) 预测值与试验值偏差很小, 说明建立的气、液两相传热模型能够很好地预测热烟气在流经填料床过程中气、液间所发生的热量交换。图 9 为海水温度分布图, 从图 9 可以看出, 海水温度在顶部分布较不均匀, 靠近壁面处海水温度

波动较大,向塔中心处逐渐趋于均匀。沿塔高度从上到下,温度逐渐下降,且波动也逐渐减小,到塔高一半处已基本不再变化($\Delta T < 0.1 \text{ K}$),说明在塔高一半处气液间的热交换已基本完成。

5 结 论

(1) 在国内大型可移动式海水脱硫试验台上进行了一系列海水脱硫试验,在体积平均法的基础上,结合试验数据获得的压损拟合公式建立了描述散堆填料塔内气、液两相的流动及传热模型。通过数值计算,获得了在不同液气比下塔内流体速度、孔隙率分布、压力分布及海水温度分布,并就压力损失和出口海水温度与试验数据对比。预测值与试验值吻合较好,趋势完全一致。说明在模型中采用试验数据拟合压损公式的方法是可行的,建立的气、液两相传热模型能够很好地预测热烟气在流经填料床过程中气、液间所发生的热交换。

(2) 根据应用3种填料塔内海水在填料塔中间高度断面上的速度分布图,发现近壁面处存在着显著的壁流现象,并且沿液流方向上,液体有向塔壁区附近积聚的趋势,壁流现象变得更严重。同时根据3种填料径向方向上的孔隙率分布图可看出在靠近壁面处的孔隙率明显高于中间区域,说明这是形成壁流的原因所在。

(3) 分析海水温度分布图,发现海水温度在顶部分布较不均匀,靠近壁面处海水温度波动较大,向塔中心处逐渐趋于均匀,而沿塔高度从上到下,温度逐渐下降均匀,到塔高一半处已基本不再变化($\Delta T < 0.1 \text{ K}$),说明在塔高一半处气液间的热交换已基本完成。

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action of SO_4^{2-} will mainly dominates to contain the corrosion to the stainless steel ,thus enhancing the corrosion-resistant property of the material. At a high temperature SO_4^{2-} will become corrosive ions to quicken the pitting of the material ,thus forming pittings with serrated rims ,of which the critical pitting concentration will be 1 mg/L. At a normal temperature ,the mechanism to contain the Cl^- pitting by SO_4^{2-} lies in its competitive adsorption while at a high temperature ,the mechanism to promote the pitting by SO_4^{2-} lies in its local acidification theory. **Key words:** waterwall tube ,15CrMo SO_4^{2-} pitting

电厂用阳离子交换树脂高温分解特性研究 = **Study of the Pyrolytic Characteristics of Power-plant-purposed Cation Exchange Resin** [刊,汉] JING Ling-ling , ZHU Zhi-ping , ZHANG Hui , XIONG Shu-hua (College of Chemical and Biological Engineering , Changsha University of Science and Technology , Changsha , China , Post Code: 410076) // Journal of Engineering for Thermal Energy & Power. -2012 27(1) . -96 ~ 100

The pyrolysis by SO_4^{2-} leaked into a thermal system to break up cation resin represents one of the causes that the SO_4^{2-} content in a water-steam system of a power plant exceeds the standard. To solve such a problem ,the authors have studied the SO_4^{2-} pyrolysis characteristics of the commonly-used cation resin polished by condensate water in an autoclave. The research results show that after a pyrolysis of the cation resin ,its exchange functional group ($-\text{SO}_3\text{H}$) will fall off from the resin skeleton and produce a great quantity of acidic substances. The quantity of SO_4^{2-} produced by the pyrolysis will increase with the pyrolytic temperature and a surge phenomenon will emerge after the temperature exceeds 200 °C. The quantity of SO_4^{2-} produced by the old resin will be slightly less than that produced by the new resin ,however ,more acidic substances will be generated. At 280 °C ,the quantity of SO_4^{2-} produced by the cation resin will increase with an elapse of time. Both actually measured SO_4^{2-} and the result obtained from the infrared spectrum show that a certain quantity of resin is almost completely decomposed after 24 hours. **Key words:** cation exchange resin ,pyrolysis SO_4^{2-} ,ion chromatography ,infrared spectrum

海水脱硫散堆填料塔流体流动及传热研究 = **Study of the Fluid Flow and Heat Transfer in a Seawater Desulfurization Bulk Packing Tower** [刊,汉] GAO Mei-shan , WANG Shi-he (College of Civil Works , Southeast University , Nanjing , China , Post Code: 210096) , WANG Xiao-ming (Guodian Environmental Protection Research Institute , Nanjing , China , Post Code: 210013) , GUO Ming-chun (Shanghai Huolin Chemical Equipment Engineering Co. Ltd. , Shanghai , China , Post Code: 200127) // Journal of Engineering for Thermal Energy & Power. -2012 27(1) . -101 ~ 106

On a large-sized movable type seawater desulfurization test rig , a pilot-scale test was performed. On the basis of the volumetric average method , in combination with the pressure loss fitting formula obtained from the test data , a mod-

el for depicting the gas-liquid two-phase flow and heat transfer in a bulk packing tower was established. Through calculation, the speed, porosity, pressure and seawater temperature distribution of the fluid inside the tower at different liquid-gas ratios were acquired and the pressure loss and seawater outlet temperature were compared with the test values. The predicted values are in relatively good agreement with the test ones. The analytic and calculation results show that a wall-surface flow phenomenon conspicuously exists in places nearing the wall surface, of which the causes lie in that the porosity nearing the wall surface is obviously higher than that in the central area. The seawater temperature distribution at the top portion is not comparatively uniform while that nearing the wall surface has a relatively big fluctuation and gradually tends to be uniform towards the central area of the tower. From the top to the lower portion along the height of the tower, the seawater temperature gradually decreases and no longer changes (basically) when reaching the half height of the tower ($\Delta T < 0.1 \text{ K}$), indicating that the heat exchange at the half height of the tower has been basically completed. **Key words:** seawater desulfurization, bulk packing, numerical simulation, heat transfer

超临界碳氢燃料流动换热的仿真研究 = **Simulation Study of the Flow and Heat Exchange of a Supercritical Hydrocarbon Fuel** [刊 汉] BAO Wen, LI Xian-ling, XU Zhi-qiang, ZHOU Wei-xing (College of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. - 2012 27(1). - 107 ~ 111

Established was a one-dimensional model for studying the supercritical hydrocarbon fuel heat exchange characteristics when the temperature and pressure are changing in a wide range. The reliability of the model in question has been verified by the test. Moreover, the influence of such factors as the mass flow rate, heat exchange state conversion and pressure etc. on the heat exchange characteristics of the supercritical hydrocarbon fuel was also analyzed based on the model. It has been found that at a low pressure of 4.0 MPa, an intensified heat transfer phenomena of the supercritical hydrocarbon fuel exists at places nearing the pseudo-critical temperature while at a high pressure of 7.0 MPa, the above-mentioned intensified heat transfer disappears. No matter what the mass flow rate is, the heat transfer coefficient at 4.0 MPa is invariably higher than that at 7.0 MPa. Furthermore, the magnitude of the pressure has an even conspicuously influence on the heat exchange performance in the steam-phase heat exchange zone of the supercritical hydrocarbon fuel. At a low mass flow rate of $40 \text{ kg}/(\text{m}^2 \cdot \text{s})$, the conversion of the heat exchange state from the liquid-phase heat exchange zone to the steam-phase heat exchange zone will lead to a heat transfer deterioration around the heat exchange zones, however, to increase the mass flow rate can avoid the problem. **Key words:** supercritical hydrocarbon fuel, heat exchange state conversion, pressure, mass flow rate, heat transfer characteristics