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并联蒸发管内两相流密度波型脉动线性分相模型

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摘　要：两相流密度波型脉动理论分析方法可以分为两大类：一类是数值解析法，另一类是近似分析法。数值分析法已经有很多学者进行了大量研究，而近似分析法研究相对少一些，特别是运用系统控制原理的方法来分析两相流密度波型脉动就更少，本文运用系统控制原理的方法来研究两相流密度波型脉动，提出了描述并联沸腾管内两相流密度波型脉动的线性分相模型，导出了描述系统稳定性的状态空间表达式，计算了质量流速、热负荷和系统压力的变化对系统特征方程式的特征根的影响。结果表明：各个参数对密度波型脉动界限值的影响规律与实验值是一致的。

关　键　词：并联蒸发管；两相流；密度波；分相模型

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1　前　言

由于数学上的困难，到目前为止还不能对描述两相流体的质量守恒方程、动量守恒方程和能量守恒方程以及两相流体补充方程所组成的偏微分方程组进行解析求解，因此理论分析方法可以分为两大类：一类是数值解析法，另一类是近似分析法。数值分析法已经有很多学者进行了大量研究[1~2]，而近似分析法研究相对少一些，特别是运用系统控制原理的方法来分析两相流密度波型脉动就更少。因此本文试图运用系统控制原理的方法来研究两相流密度波型脉动，提出了描述并联沸腾管内两相流密度波型脉动的线性分相模型。

2　数学模型建立

用分相模型求解两相流的动态问题，提出以下假设：采用一元分相流动，忽略流体的可压缩性；热负荷分布均匀，忽略流体的轴向导热。

基于上述基本假设，根据管路内两相流守恒定律，考虑汽液两相流的滑动比，可得到描述两相流体的质量守恒、动量守恒和能量守恒方程式：

$$\frac{\partial}{\partial t}\rho+\frac{\partial}{\partial z}W+\left[(\rho_L-\rho_g)\frac{\partial}{\partial t}K_1\right]=0 \tag{1}$$

$$\frac{\partial}{\partial t}\rho h+\frac{\partial}{\partial z}Wh+\left[(\rho_L h_L-\rho_g h_g)\frac{\partial}{\partial t}K_1\right]=q_v \tag{2}$$

$$\frac{\partial}{\partial t}W+\frac{\partial}{\partial z}\frac{G^2}{\rho}+\frac{\partial}{\partial z}\frac{W^2}{\rho}K_2=-\frac{\partial}{\partial z}P-F-\rho g\sin\theta-\left[(\rho_L-\rho_g)gK_1\sin\theta\right] \tag{3}$$

式中：$K_1=\frac{\rho(s-1)(1-x)x}{s\rho_g(1-x)+\rho_L x}$

$$K_2=\frac{-\rho(s-1)(\rho_L-s\rho_g)(1-x)}{s\rho_L\rho_g}$$

$$F=fW^2/D2\rho$$

加入的热量可由壁面传热方程和壁面能量方程得到：

$$\rho_w C_{pw}\frac{\partial T_w}{\partial t}=q_w\ \ \frac{4D\alpha}{(D_0^2-D^2)}(T_w-T_f) \tag{4}$$

传热方程：

$$q_v=\frac{4\alpha}{D}(T_w-T_f) \tag{5}$$

能量守恒方程用质量守恒方程来进行整理得到：

$$\frac{\partial}{\partial t}h+\frac{W}{\rho^*}\frac{\partial}{\partial z}h=\frac{q_v}{\rho^*} \tag{6}$$

式中：$\rho^*=\rho\left[1-\frac{\rho_L\rho_g}{\rho^2}\left(\frac{\partial K_1}{\partial x}\right)\right]$

对式(4)整理得：

$$\frac{\partial}{\partial t}T_w=\frac{q_w}{\rho_w C_{pw}}-\frac{D^2}{\rho_w C_{pw}(D_0^2-D^2)}q_v \tag{7}$$

在上述分相模型中，还有一些两相流特性参数如截面含气率以及结构参数如摩擦阻力系数和放热系数需要根据具体情况确定，形成两相流补充方程。

3　系统状态空间表达式

假设系统具有线性的特性，根据模型的基本假

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设，使用小偏差法，对系统的基本方程线性化，得到描述系统动态特性的线性化增量方程。假定系统变量可以用下式表示：

$$W(z,t)=W^0(z)+\delta W$$
$$\rho(z,t)=\rho^0(z)+\delta\rho$$
$$h(z,t)=h^0(z)+\delta h \tag{8}$$
$$p(z,t)=p^0(z)+\delta p$$
$$T_W(z,t)=T_W{}^0(z)+\delta T_W$$

将式(8)分别代入到式(1)、式(6)和式(2)，整理得：

$$\left[1+(\rho_L-\rho_g)\frac{\partial K_1}{\partial\rho}\right]\frac{\partial}{\partial t}\delta\rho+\frac{\partial}{\partial z}\delta W=0 \tag{9}$$

$$\frac{\partial}{\partial t}\delta h+\left(\frac{q_v}{\rho^*}\right)^0\frac{\partial}{\partial z}\delta h-\frac{1}{\rho^*}\left(\frac{\partial q_v}{\partial h}\right)^0\delta h+$$
$$\left[\frac{q_v^0}{\rho^{*0}W}-\frac{1}{\rho^{*0}}\left(\frac{\partial q_v}{\partial W}\right)^0\right]\delta W+\left[\frac{q_v^0}{\rho^{*0}}\frac{\partial\rho^*}{\partial P}-\left(\frac{q_v}{\rho^*}\right)^0\frac{\partial\rho^*}{\partial\rho}\right]\times$$
$$\delta\rho-\frac{1}{\rho^*}\left(\frac{\partial q_v}{\partial T_w}\right)^0\delta T_w=0 \tag{10}$$

$$\frac{\partial}{\partial t}\delta W+\frac{\partial}{\partial z}\left(\frac{2W^0}{\rho^0}\delta W-\frac{W^0}{\rho^2}\delta\rho\right)+$$
$$\frac{\partial}{\partial z}\left[\frac{2W^0}{\rho^0}K_2^0\,\delta W-\frac{W^2}{\rho^2}K_2^0\,\delta\rho+\frac{W^2}{\rho}\left(\frac{\partial K_2}{\partial\rho}\right)^0\delta\rho\right]$$
$$=-\frac{\partial}{\partial z}\delta P-\left(\frac{\partial F}{\partial\rho}\right)^0\delta\rho-\left(\frac{\partial F}{\partial W}\right)\delta W-g\sin\theta\,\delta\rho-$$
$$(\rho_L-\rho_g)g\sin\theta\left(\frac{\partial K_1}{\partial\rho}\right)^0\delta\rho \tag{11}$$

假定在稳定状态下，两相区截面含汽率呈线性分布：

$$\varphi=\frac{\varphi_0}{L_b}z$$

则 $\frac{\partial}{\partial z}\rho^0=-\frac{\varphi_0}{L_b}(\rho_L-\rho_g)$

代入式(11)，整理得：

$$\frac{\partial}{\partial t}\delta W+\frac{2W^0}{\rho^0}(K_2+1)\frac{\partial}{\partial z}\delta W+$$
$$\left[\frac{2W^0\varphi_0}{\rho^2L_b}(\rho_L-\rho_g)+\frac{\partial F}{\partial W}\right]\delta W+\left(\frac{W}{\rho^2}\right)^0\left[\rho\frac{\partial K_2}{\partial\rho}-K_2-1\right]\frac{\partial}{\partial z}\delta\rho+$$
$$\left[\frac{\partial F}{\partial\rho}+g\sin\theta+(\rho_L-\rho_g)g\sin\theta\left(\frac{\partial K_1}{\partial\rho}\right)\frac{2W^2\varphi_0}{\rho^3L_b}(\rho_L-\rho_g)\right]\delta\rho-$$
$$\left[\frac{W^2K_2\varphi_0}{\rho^3L_b}(\rho_L-\rho_g)+\frac{W^2\varphi_0}{\rho^2L_b}\frac{\partial K_2}{\partial\rho}(\rho_L-\rho_g)\right]\delta g$$
$$=-\frac{\partial}{\partial z}\delta p \tag{12}$$

将式(12)代入式(7)得：

$$\frac{\partial}{\partial t}\delta T+\frac{D^2}{\rho_wC_{pw}(D_0^2-D^2)}\left(\frac{\partial q_v}{\partial T_w}\right)^0\delta T_w+$$
$$\frac{D^2}{\rho_wC_{pw}(D_0^2-D^2)}\left(\frac{\partial q_v}{\partial W}\right)^0\delta W+\frac{D^2}{\rho_wC_{pw}(D_0^2-D^2)}\times$$
$$\left(\frac{\partial q_v}{\partial h}\right)^0\delta h=\frac{q_w}{\rho_wC_{pw}} \tag{13}$$

引入无因次参数：

$$\tau=\frac{t}{t_c},\ y=\frac{z}{L},\ \delta\eta=\frac{\delta\rho}{h_c},\ \delta H=\frac{\delta h}{h_c},\ \delta G=\frac{\delta W}{W},$$

$$\delta T=\frac{\delta T_w}{T_{sat}}$$

并代入到式(9)～式(10)、式(12)～式(13)，整理得出以下式中为简单计算，略去了稳定状态下的肩标“0”：

$$\left[1+(\rho_L-\rho_g)\frac{\partial K_1}{\partial\rho}\right]\frac{\partial}{\partial\tau}\delta\eta+\frac{Wt_c}{L\rho_L}\frac{\partial}{\partial y}\delta G=0 \tag{14}$$

$$\frac{h_c}{t_c}\frac{\partial}{\partial\tau}\delta H+\frac{\mathrm{h_c}}{\mathrm{L}}\left(\frac{q_v}{\rho^*}\right)\frac{\partial}{\partial y}\delta H-\frac{h_c}{\rho^*}\left(\frac{\partial q_v}{\partial h}\right)\delta H+$$
$$\left(\frac{q_v}{\rho^*}-\frac{W}{\rho^*}\frac{\partial q_v}{\partial W}\right)\delta G+\rho_L\left[\frac{q_v}{\rho^{*2}}\frac{\partial\rho^*}{\partial\rho}-\left(\frac{q_v}{\rho^*}\right)\frac{\partial\rho^*}{\partial\rho}\right]\times$$
$$\delta\eta-\frac{-T_{sat}}{\rho^*}\left(\frac{\partial q_v}{\partial T_w}\right)\delta T=0 \tag{15}$$

$$\frac{W\partial}{t_c\partial\tau}\delta G+\frac{2W^2}{L\rho}(K_2+1)\frac{\partial}{\partial y}\delta G+$$
$$\left[\frac{2W^2\varphi_0}{\rho^2L_b}(\rho_L-\rho_g)+W\frac{\partial F}{\partial W}\right]\delta G+$$
$$\frac{W^2\rho_L}{L\rho^2}\left[\rho\left(\frac{\partial K_2}{\partial\rho}\right)-K_2-1\right]\frac{\partial}{\partial y}\delta\eta+$$
$$\rho_L\left[\left(\frac{\partial F}{\partial\rho}\right)+g\sin\theta+(\rho_L-\rho_g)g\sin\theta\left(\frac{\partial K_1}{\partial\rho}\right)-\frac{2W\varphi_0}{\rho^3L_b}(\rho_L-\rho_g)\right]\times$$
$$\delta\eta-\left[\frac{W^2K_2\varphi_0}{\rho^3L_b}(\rho_L-\rho_g)+\frac{W^2\varphi_0}{\rho^3L_b}\frac{\partial K_2}{\partial\rho}(\rho_L-\rho_g)\right]\delta\eta$$
$$=-\frac{1}{L}\frac{\partial}{\partial y}\delta p \tag{16}$$

$$\frac{T_{sat}}{t_c}\frac{\partial}{\partial\tau}\delta T+\frac{D^2T_{sat}}{\rho_wC_{pw}(D_0^2-D^2)}\left(\frac{\partial q_v}{\partial T_w}\right)\delta T+$$
$$\frac{D^2W}{\rho_wC_{pw}(D_0^2-D^2)}\left(\frac{\partial q_v}{\partial W}\right)\delta G+\frac{D^2h_c}{\rho_wC_{pw}(D_0^2-D^2)}\left(\frac{\partial q_v}{\partial h}\right)\delta H$$
$$=\frac{q_w}{\rho_wC_{pw}} \tag{17}$$

对上述方程式(14)～式(17)在 $0<y<1$ 区间内积分，并且假定在 y 方向上 $\delta\eta$，δH，δG，δT 呈线性变化。

$$\delta\eta=\delta\eta_0(t)y,\ \delta H=\delta H_0(t)y$$
$$\delta G=\delta G_i(t)-[\delta G_i(t)-\delta G_0(t)]\,y$$
$$\delta T=\delta T_0(t)y \tag{18}$$

把式(18)代入到式(14)～式(17)，并在 $0<y<1$ 区间内积分，整理得：

$$\frac{\partial}{\partial\tau}\delta\eta_0=A_1\,\delta G_i-A_1\,\delta G_i \tag{19}$$

$$\frac{\partial}{\partial\tau}\delta H_0 = -B_1\delta m_0 - B_2\delta H_0 - B_3\delta G_i - B_4\delta T_0 + \delta\phi_1 \tag{20}$$

$$\frac{\partial}{\partial\tau}\delta G_i = -C_1\delta m_0 - C_2\delta G_i + \delta\phi_2 \tag{21}$$

$$\frac{\partial}{\partial\tau}\delta T_0 = -D_1\delta H_0 - D_2\delta G_i - D_3\delta T_0 + \delta\phi_3 \tag{22}$$

式中: A_1、B_1、B_2、B_3、B_4、C_1、C_2、C_3、D_1、D_2、D_3、$\delta\phi_1$、$\delta\phi_2$、$\delta\phi_3$ 均为积分系数, 具体请参考文献[3]。

式(19)~式(22)组成了分相模型系统动态特性的状态空间表达式, 即:

$$M = FM + Eu \tag{23}$$

M 为由状态变量 δm_0、δH_0、δG_i、δT_0 组成的状态向量, 即:

$$M = [\delta m_o, \delta H_o, \delta G_i, \delta T_o]^T \tag{24}$$

F 为 4×4 阶矩阵:

$$F = \begin{bmatrix} F_{11} & F_{12} & F_{13} & F_{14} \\ F_{21} & F_{22} & F_{23} & F_{24} \\ F_{31} & F_{32} & F_{33} & F_{34} \\ F_{41} & F_{41} & F_{43} & F_{44} \end{bmatrix}$$

矩阵的元素分别为:

$F_{11}=0$, $F_{12}=0$, $F_{13}=A_1$, $F_{14}=0$

$F_{21}=-B_1$, $F_{22}=-B_2$, $F_{23}=-B_3$, $F_{24}=-B_4$

$F_{31}=-C_1$, $F_{32}=0$, $F_{33}=-C_2$, $F_{34}=0$

$F_{41}=0$, $F_{42}=-D_1$, $F_{43}=-D_2$, $F_{44}=-D_3$

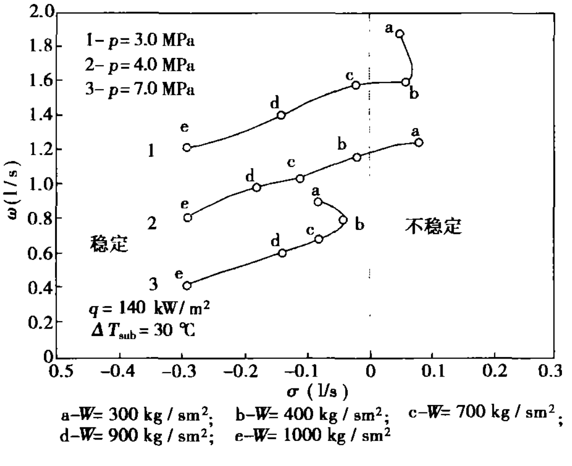

图 1　质量流速对特征值的影响

4　理论结果与实验结果比较

判断系统是否稳定, 可以通过判别系统特征方程式的特征根实部的符号来得到。对于式(23)所组成的动态系统状态空间表达式。它的特征方程式分别为:

$$\det(\lambda I - F) = 0 \tag{25}$$

特征方程的特征根为:

$$\lambda_i = \sigma_i + J\omega_i \quad (i = 1, 2, \cdots\cdots N) \tag{26}$$

通过判断式(26)特征根实部 σ_i 的符号就可以判断系统的稳定性。为了解系统的稳定性, 计算了各个参数对特征值的影响。图 1 为计算得到的质量流速对特征值的影响。由图可见, 随着质量流速增加, 特征值的实部逐渐减小, 表明系统稳定性逐渐增强。图 2 为计算得到的系统压力对特征值的影响。由图可见, 随着系统压力增加, 在复平面上特征值的实部向左移动, 表明系统稳定性增强。图 3 为计算得到的热负荷对特征值的影响。由图中可见, 随着

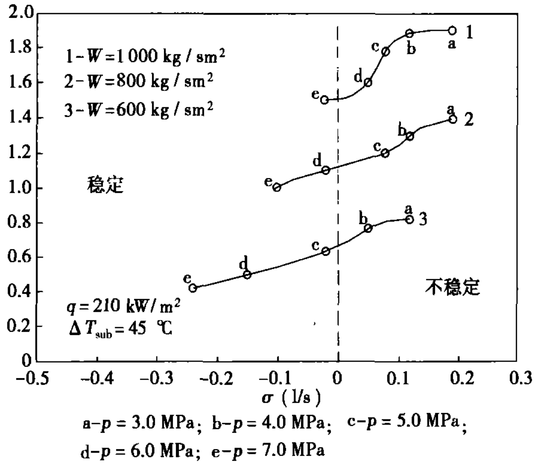

图 2　系统压力对特征值的影响

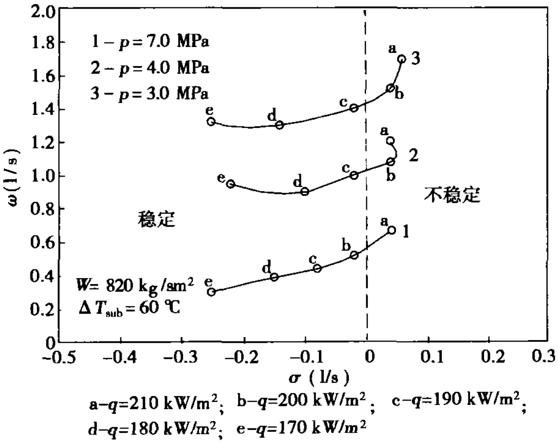

图 3　热负荷对特征值的影响

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喷嘴雾距方向液滴团聚对喷雾干燥的影响[6]，并计算了不同烟气条件、不同喷嘴情况下液滴团聚对喷雾干燥塔所需高度的影响。计算表明，当湿球温度为50 ℃，烟气温度由140 ℃降到70 ℃，在没有液滴团聚时完全蒸发需要的喷雾干燥塔高度为5.6 m；有液滴团聚时的高度为11 m，也就是说在相同条件下，液滴团聚使得喷雾干燥塔的高度增加了80%。

在本研究中，液滴的干燥时间基本维持在1.5～2.0 s，这主要是由于脱硫灰的再循环对浆液滴的干燥有利，使得烟气循环流化床具有较好的干燥性能。烟气循环流化床中由于脱硫灰的再循环，使得塔内的脱硫灰浓度很高，有时高达$600\ \mathrm{g/m^3}$。虽然流化床内也存在液滴团聚现象，但是液滴的团聚增加了液滴的粒径，使得它更容易粘附脱硫灰颗粒，同时由于高浓度脱硫灰的存在，使得液滴极易与脱硫灰颗粒碰撞并粘附，加大了液滴的蒸发面积，提高了蒸发速率。

5　结　论

(1)在烟气脱硫循环流化床内，烟气的绝热饱和温度近似等于湿球温度，可用屏蔽热电偶测量烟气温度，用裸露热电偶测量湿球温度。

(2)在烟气循环流化床中，在喷入增湿水后，存在烟气温度逐渐降低和增湿水温逐渐升高两个不同的温度场。烟气温度经过快速降温及缓慢降温两个阶段；而增湿水温度快速升高并蒸发。烟气温度与增湿水温度在液滴干燥完毕时趋于一致。

(3)烟气循环流化床内雾化液滴的干燥时间约为1.5～2.0 s

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热负荷的增强，在复平面上特征值的实部向右移动，表明系统稳定性逐渐减弱。这一结果与作者的实验结果得出的结论是一致的[3～4]。

5　结　论

(1)提出了描述两相流不稳定性的线性分相模型，运用系统控制原理的方法来预测两相流密度波型脉动。

(2)根据分相模型导出了描述系统稳定性的状态空间表达式，计算了质量流速、热负荷和系统压力的变化对系统特征方程式的特征根的影响，计算结果表明：各个参数对两相流密度波型脉动界限值的影响规律与实验值是一致的。

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transition system is different from that of a simple compressible single-phase system. The phase transition force-stable marginal curves constitute a limit or boundary which cannot be overstepped during a phase transition. **Key words**: non-equilibrium thermodynamics, liquid-vapor phase transition system, available energy, equilibrium stability

并联蒸发管内两相流密度波型脉动线性分相模型= **Linear Phase-separation Model for the Two-phase Flow Density-wave Type Pulsations in Parallel-connected Evaporating Tubes** [刊, 汉] /ZHOU Yun-long, HONG Wen-peng, ZHAO Xue-feng, et al (Energy &Mechanical Engineering College under the Northeast China Electric Power Institute, Jilin, China, Post Code: 132012) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(5). —489 ~491, 496

Methods for the theoretical analysis of two-phase flow density-wave type pulsations can be divided into two categories: 1. numerical analysis method and 2. approximate analysis method. Many academics have conducted a huge amount of research on the first method, while relatively little research has been undertaken on the second method. In particular, even less research by using the method of system control theory has been conducted to analyze the two-phase flow density-wave type pulsations. In view of this, the authors have employed the method of system control theory to study the above-mentioned pulsations, proposing a linear phase-separation model for describing the two-phase flow density-wave type pulsations in parallel-connected boiling tubes. A status-space expression for describing system stability has been derived. Calculations were performed to determine the impact of the variation of mass flow velocity, thermal load and system pressure on the characteristic root of a system characteristic equation. The results of the calculation indicate that the law governing the impact of various parameters on the density-wave type pulsation limit values is in agreement with that of the experimental values. **Key words**: parallel-connected evaporating tubes, two-phase flow, density wave, phase-separation model

烟气脱硫循环流化床内的温度分布与干燥特性= **Temperature Distribution and Drying Characteristics in a Flue Gas Desulfurization-based Circulating Fluidized Bed** [刊, 汉] /DONG Yong, MA Chun-yuan, WANG Wen-long, et al (Institute of Energy &Power Engineering under the Shandong University, Jinan, China, Post Code: 250061) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(5). —492 ~496

The adiabatic saturation temperature in a flue-gas circulating fluidized bed was analyzed. A device was designed for measuring the temperature in a flue gas desulfurization-based circulating fluidized bed. With the help of this device and on the flue-gas desulfurization pilot test rig measurements were taken of the temperature distribution of the flue gas and wet ball temperature distribution in the fluidized bed. The results of the measurements indicate that after the injection of humidifying water there exist in the circulating fluidized bed two different temperature fields, i.e., one being characterized by a gradual lowering of flue gas temperature and another one featuring a gradual rise of the humidifying water temperature. The flue gas temperature underwent two stages, namely, a rapid reduction and a slow reduction of temperature. However, the humidifying water experienced a rapid rise in temperature and then evaporated. Upon completion of the liquid-droplet drying process the flue gas temperature and the humidifying water temperature tend to coincide. Test results also indicate that the drying time of the atomized liquid droplet in the flue gas circulating fluidized bed is approximately 1.5 ~2.0 seconds. **Key words**: flue gas desulfurization, circulating fluidized bed, temperature distribution, drying time

循环流化床脱硫塔直/旋流复合流化下的两相流场试验研究= **Experimental Study of Two-phase Flows under the Composite Fluidization of Desulfurizer Straight/rotating Flows in a Circulating Fluidized Bed** [刊, 汉] /HAO Xiao-wen, MA Chun-yuan, ZHANG Li-qiang (Institute of Energy &Power Engineering under the Shandong University, Jinan, China, Post Code: 250061), HUANG Sheng-zhu (The School of Energy Science &Engineering under the Harbin Institute of Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(5). —497 ~500, 505

The Venturi straight-flow fluidization speed of a circulating fluidized bed desulfurizer will change with a change in boiler load. This has a negative influence on desulfurization efficiency. The authors have come up with a straight/rotating flow