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# 汽液相变系统的平衡稳定性分析

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摘 要: 以非平衡热力学理论为基础, 通过引入可用能这个汽液相变换热过程的一个重要的功势函数, 对汽液相变系统的可用能进行了分析, 得到了汽液相变系统的可用能变化的计算式, 并以此为判据来分析汽液相变系统的稳定性, 得到了汽液相变系统的相平衡条件、力学稳定性条件和热稳定性条件, 并给出了有关物理意义; 定义了汽液相变时的汽、液相的力稳边际曲线。结果表明, 汽液相变系统的力稳条件不同于简单可压缩单相系统的力稳条件, 相变力稳边际曲线是相变时不可逾越的界限。

关 键 词: 非平衡热力学; 汽液相变系统; 可用能; 平衡稳定性

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## 1 引 言

相变换热现象是工程上常常遇到的极为重要的物理现象, 长期以来它吸引着研究者们广泛的关注。任何实际相变换热过程都是不可逆热力学过程, 经典热力学, 尤其是非平衡热力学为它的研究提供了必要的理论依据[1]。特别是功势函数的出现, 为汽液相变换热过程的热力学理论分析提供了重要的基础。其中可用能即为汽液相变换热过程的一个重要的功势函数, 通过汽液相变过程的可用能分析, 可以得到汽液相变过程的相平衡条件、相转变条件以及一些重要的有关核化机理的重要参数, 如临界半径、汽液相变过程的唯象系数等[2]。对于单相的简单可压缩系统, 大多采用内能、焓、自由能、自由焓等判据来研究其平衡的稳定性, 并得到其热稳定性条件和力学稳定性条件[3]; 而对于具有相变的复相系统, 由于各相的质量在变, 而且除了膨胀功外还有表面功的参与, 因此用内能、焓、自由能、自由焓等判据就不好判定其平衡与平衡稳定性条件。由于可用能判据的通用性, 因此本文采用可用能判据来分析研究汽液相变系统的稳定性。

## 2 汽液相变系统的可用能分析

根据实际过程的相变条件, 假定在一定环境压力 $p_0$ 及环境温度 $T_0$ 下发生相变(如图 1 所示), 取系统可用能 Φ 为功势函数。

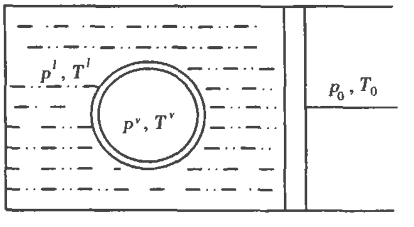


图 1 汽液相变系统

即:
$$\Phi = U + p_0 V - T_0 S \tag{1}$$
$$\delta\Phi = \delta U + p_0 \delta V - T_0 \delta S \tag{2}$$
式中: $U$—内能, J; $V$—体积, $m^3$; $S$—熵, J/K。

把上式分别应用到液相(用上标"l"表示)、汽相(用上标"v"表示)和汽液界面相(用上标"I"表示), 有:
$$\delta\Phi^l = \delta U^l + p_0 \delta V^l - T_0 \delta S^l \tag{3}$$
$$\delta\Phi^v = \delta U^v + p_0 \delta V^v - T_0 \delta S^v \tag{4}$$
$$\delta\Phi^I = \delta U^I + p_0 \delta V^I - T_0 \delta S^I \tag{5}$$
$$\delta\Phi = \delta\Phi^l + \delta\Phi^v + \delta\Phi^I \tag{6}$$

对汽液界面, 利用 Gibbs 关系有:
$$T^I dS^I = dU^I - \sigma dA \tag{7}$$
即:
$$dU^I = T^I dS^I + \sigma dA \tag{8}$$
式中: σ—汽液界面表面张力, N/m; $A$—汽液界面表面积, $m^2$。

把上式代入式(5), 并假定汽液界面的体积 $V$ 极小, 有:

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$$\delta\Phi^l = (T^l - T_0)\mathrm{d}S^l + \sigma\mathrm{d}A \tag{9}$$

利用 $G = U + pV - TS$；$G = mg = m\mu$；$V = mv$，则式(3)变为：

$$\delta\Phi^l = \delta G^l + \delta[(p_0 - p^l)V^l] - \delta[(T_o - T^l)S^l]$$
$$= m^l\delta\mu^l + \mu^l\delta m^l + \delta[(p_0 - p^l)V^l] - \delta[(T_0 - T^l)S^l] \tag{10}$$

假定 $p_0 = p^l$，$T_0 = T^l$，且液相状态不变，即有 $\delta\mu^l = 0$，于是上式变为：

$$\delta\Phi^l = \mu^l\delta m^l \tag{11}$$

式中：$G$—自由焓，J；$m$—质量，kg；$g$—比自由焓，J/kg；$v$—比容，kg/m$^3$；$\mu$—化学势，J/kg。

同理，对汽相有：

$$\delta\Phi^v = m^v\delta\mu^v + \mu^v\delta m^v + \delta[(p_0 - p^v)V^v] - \delta[(T_0 - T^v)S^v] \tag{12}$$

利用 $\mathrm{d}\mu^v = -s^v\mathrm{d}T^v + v^v\mathrm{d}p^v$，则上式化为：

$$\delta\Phi^v = \mu^v\delta m^v - m^v s^v\mathrm{d}T^v + m^v v^v\mathrm{d}p^v + (p_0 - p^v)\times\delta V^v - m^v v^v\mathrm{d}p^v - \delta[(T_0 - T^v)S^v]$$
$$= \mu^v\delta m^v + (p_0 - p^v)\delta V^v - m^v s^v\mathrm{d}T^v + S^v\mathrm{d}T^v - (T_0 - T^v)\delta S^v$$
$$= \mu^v\delta m^v + (p_0 - p^v)\delta V^v - (T_0 - T^v)\delta S^v \tag{13}$$

式中：$s$—比熵，J/(kg·K)。对汽液界面，由上述假定有 $V^I \approx 0$，忽略其它热力学参量，则式(9)变为：

$$\delta\Phi^I = \sigma\mathrm{d}A \tag{14}$$

又由 $\delta m^l = -\delta m^v$，则系统的总可用能变化为：

$$\delta\Phi = \delta\Phi^l + \delta\Phi^v + \delta\Phi^I$$
$$= (\mu^l - \mu^v)\delta m^l + (p_0 - p^v)\delta V^v - (T_0 - T^v)\delta S^v + \sigma dA \tag{15}$$

## 3　汽液相变系统的平衡稳定性分析

假定汽泡为球体，有 $V^v = \frac{4}{3}\pi\cdot r^3$，则 $\delta V^v = \frac{r}{2}\times\mathrm{d}A$，代入式(15)得：

$$\delta\Phi = (\mu^v - \mu^l)\delta m^v + (p^l - p^v + 2\sigma/r)\mathrm{d}V^v - (T^l - T^v)\delta S^v \tag{16}$$

式中：$r$—汽泡半径，m。

由上式可知：$\Phi$ 是 $m^v$、$V^v$、$S^v$ 的函数，$\Phi = \Phi(m^v, V^v, S^v)$，故有：

$$\left(\frac{\partial\Phi}{\partial m^v}\right)_{V^v, S^v} = \mu^v - \mu^l \tag{17}$$

$$\left(\frac{\partial\Phi}{\partial V^v}\right)_{m^v, S^v} = (p^l - p^v) + 2\sigma/r \tag{18}$$

$$\left(\frac{\partial\Phi}{\partial S^v}\right)_{V^v, m^v} = -(T^l - T^v) \tag{19}$$

$$\left(\frac{\partial^2\Phi}{\partial m^{v2}}\right)_{V^v, S^v} = \left[\frac{\partial(\mu^v - \mu^l)}{\partial m^v}\right]_{V^v, S^v} \tag{20}$$

$$\left(\frac{\partial^2\Phi}{\partial V^{v2}}\right)_{m^v, S^v} = \left[\frac{\partial(p^l - p^v + 2\sigma/r)}{\partial V^v}\right]_{m^v, S^v} \tag{21}$$

$$\left(\frac{\partial^2\Phi}{\partial S^{v2}}\right)_{V^v, m^v} = -\left[\frac{\partial(T^l - T^v)}{\partial S^v}\right]_{m^v, V^v} \tag{22}$$

$$\left(\frac{\partial^2\Phi}{\partial m^v\partial V^v}\right)_{S^v} = \left[\frac{\partial(\mu^v - \mu^l)}{\partial V^v}\right]_{m^v, S^v} = \left[\frac{\partial(p^l - p^v + 2\sigma/r)}{\partial m^v}\right]_{V^v, S^v} \tag{23}$$

$$\left(\frac{\partial^2\Phi}{\partial m^v\partial S^v}\right)_{V^v} = \left[\frac{\partial(\mu^v - \mu^l)}{\partial S^v}\right]_{m^v, V^v} = -\left[\frac{\partial(T^l - T^v)}{\partial m^v}\right]_{V^v, S^v} \tag{24}$$

$$\left(\frac{\partial^2\Phi}{\partial S^v\partial V^v}\right)_{m^v} = -\left[\frac{\partial(T^l - T^v)}{\partial V^v}\right]_{m^v, S^v} = \left[\frac{\partial(p^l - p^v + 2\sigma/r)}{\partial S^v}\right]_{V^v, m^v} \tag{25}$$

系统的可用能在平衡时达到最小，任何离开平衡态的虚变动 $\Delta\Phi$ 都必须大于零，这就是系统的平衡稳定性判据，即：$\Delta\Phi > 0$。把 $\Delta\Phi$ 在平衡态做泰勒展开并忽略二阶以上项得：

$$\Delta\Phi = \delta\Phi + \delta^2\Phi > 0 \tag{26}$$

在平衡时 $\Phi$ 的一阶虚变动 $\delta\Phi$ 等于零，则有二阶虚变动：

$$\delta^2\Phi > 0 \tag{27}$$

把上式左边展开，其正定的充分必要条件是系数矩阵：

$$\begin{pmatrix} \left(\frac{\partial^2\Phi}{\partial m^{v2}}\right)_{V^v, S^v} & \left(\frac{\partial^2\Phi}{\partial m^v\partial V^v}\right)_{S^v} & \left(\frac{\partial^2\Phi}{\partial m^v\partial S^v}\right)_{V^v} \\ \left(\frac{\partial^2\Phi}{\partial m^v\partial V^v}\right)_{S^v} & \left(\frac{\partial^2\Phi}{\partial V^{v2}}\right)_{m^v, S^v} & \left(\frac{\partial^2\Phi}{\partial V^v\partial S^v}\right)_{m^v} \\ \left(\frac{\partial^2\Phi}{\partial m^v\partial S^v}\right)_{V^v} & \left(\frac{\partial^2\Phi}{\partial V^v\partial S^v}\right)_{m^v} & \left(\frac{\partial^2\Phi}{\partial S^{v2}}\right)_{m^v, V^v} \end{pmatrix} \tag{28}$$

的各阶主子式都大于零。先展开其一阶主子式得：

$$\text{(a)}\quad \left(\frac{\partial^2\Phi}{\partial m^{v2}}\right)_{V^v, S^v} = \left[\frac{\partial(\mu^v - \mu^l)}{\partial m^v}\right]_{V^v, S^v} > 0 \tag{29}$$

这是系统的相稳定性条件，它的物理意义是：随着汽泡内蒸汽量的增加，蒸汽的化学势须增加(但总是要小于液体的化学势)，液、汽相的化学势差减小，即驱动相变的热力学力减小，到达平衡时，两相的化学势相等。

$$\text{(b)}\quad \left(\frac{\partial^2\Phi}{\partial V^{v2}}\right)_{m^v, S^v} = \left[\frac{\partial(p^l - p^v + 2\sigma/r)}{\partial V^v}\right]_{m^v, S^v}$$

$$= -\frac{2\sigma}{r^2} / \left(\frac{\partial V^v}{\partial r}\right)_{m^v, S^v} - \left(\frac{\partial p^v}{\partial V^v}\right)_{m^v, S^v}$$

$$= -\frac{2\sigma}{2\pi r^4} - \left(\frac{\partial p^v}{\partial V^v}\right)_{m^v, S^v} > 0 \quad (30)$$

由于 $m^v$ 一定，所以下标 $S^v$ 可以换为 $s^v$，故有：

$$-\frac{\sigma}{2\pi r^4} - \frac{1}{m^v}\left(\frac{\partial p^v}{\partial v^v}\right)_{s^v} > 0 \quad (31)$$

由热力学基本关系知：

$$\gamma = \frac{c_p}{c_v} = \left(\frac{\partial p}{\partial v}\right)_s / \left(\frac{\partial p}{\partial v}\right)_T \quad (32)$$

把式(32)代入式(31)得：

$$\frac{m^v \sigma}{2\pi r^4 \gamma} + \left(\frac{\partial p^v}{\partial v^v}\right)_{T^v} = \frac{\rho^v V^v \sigma}{2\pi r^4 \gamma} + \left(\frac{\partial p^v}{\partial v^v}\right)_{T^v}$$

$$= \frac{2\rho^v \sigma}{3r\gamma} + \left(\frac{\partial p^v}{\partial v^v}\right)_{T^v} < 0 \quad (33)$$

或：
$$\left(\frac{\partial p^v}{\partial v^v}\right)_{T^v} < -\frac{2\rho^v \sigma}{3r\gamma} \quad (34)$$

其中：$\gamma = c_p^v / c_v^v$，上式即为汽相的力学稳定条件。

(c)
$$\left(\frac{\partial^2 \Phi}{\partial S^{v2}}\right)_{V^v, m^v} = -\left[\frac{\partial (T^l - T^v)}{\partial S^v}\right]_{m^v, V^v}$$

$$= \left(\frac{\partial T^v}{\partial S^v}\right)_{m^v, V^v} = \frac{1}{m^v}\left(\frac{\partial T^v}{\partial s^v}\right)_{v^v} = \frac{T^v}{m^v c_v^v} > 0 \quad (35)$$

即有：
$$c_v^v > 0 \quad (36)$$

上式即为汽相的热稳定性条件。

展开系数矩阵式(28)的二阶和三阶主子式，得到的仅是式(29)、式(34)和式(36)的各种组合，并不能得到独立的判据。

同理，对蒸汽凝结成液滴的相变系统进行推导，同样可以得到液相的平衡稳定性条件。

相稳定条件：

$$\left[\frac{\partial (\mu^l - \mu^v)}{\partial m^l}\right]_{V^l, S^l} > 0 \quad (37)$$

即随着液滴的长大，液滴的化学势必须增加（但总要小于蒸汽的化学势），蒸汽与液滴的化学势差减小，即驱动凝结的热力学力减小，平衡时两相化学势相等。

力学稳定性条件：

$$\left(\frac{\partial p^l}{\partial v^l}\right)_{T^l} < -\frac{2\rho^l \sigma}{3r\gamma} \quad (38)$$

其中：$\gamma = c_p^l / c_v^l$。

热稳定条件：

$$c_v^l > 0 \quad (39)$$

通过以上分析并比较可知，由式(34)和式(38)所确定的汽液相变系统的力稳条件与简单可压缩单相系统的力稳条件 $(\partial p / \partial v)_T < 0$ 是不一样的。于是，为区别起见，如把 $(\partial p / \partial v)_T = 0$ 定义为 Spinodal 线[3]，则把式(38)和式(34)分别定义为汽液相变中液相和汽相的力稳边际曲线。如图 2 所示，汽液相变的液相力稳边际曲线相对于 Spinodal 线左移，而汽相力稳边际曲线相对于 Spinodal 线右移。相变力稳边际曲线是相变时不可逾越的界限，因而液体过热或蒸汽过冷不可能达到 Spinodal 线，而是在力稳边际曲线上就已经失稳。

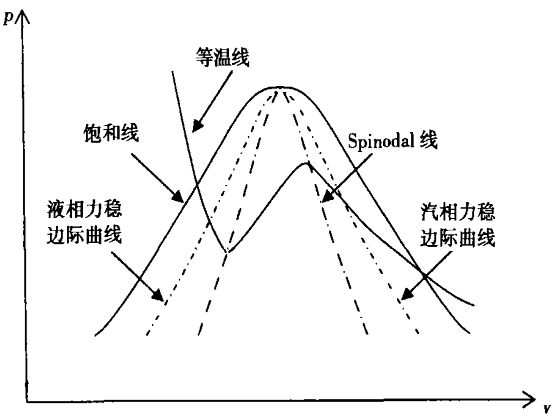


图 2 相变力稳边际曲线与 Spinodal 线的比较

## 4 结 论

以非平衡热力学理论为基础，用可用能判据分析了汽液相变系统的稳定性，导出了汽液相变系统可用能变化的计算式；得到了汽液相变系统的相平衡条件、力学稳定性条件和热稳定性条件；定义了汽液相变时的汽、液相的力稳边际曲线。结果表明，汽液相变系统的力稳条件不同于简单可压缩单相系统的力稳条件，相变力稳边际曲线是相变时不可逾越的界限，因而液体过热或蒸汽过冷不可能达到 Spinodal 线。

参考文献：

[1] 曾丹苓. 工程非平衡热力学[M]. 北京：科学出版社，1991.

[2] 吴双应，曾丹苓. 汽液相变换热过程唯象系数的计算[J]. 热能动力工程，2004，**19**(6)：593－596.

[3] 苏长荪，谭连城，刘桂玉. 高等工程热力学[M]. 北京：高等教育出版社，1987.

**clined Tube** [刊, 汉] /GAO Feng, YIN Fei, CHEN Ting-kuan, et al (National Key Laboratory of Multi-phase Flow in Power Engineering under the Xi' an Jiaotong University, Xi' an, China, Post Code: 710049) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(5). —478 ~481

Taking into account the impact of natural convection on the fluid heat transfer in an inclined riser tube the outer wall temperature and heat load are assumed as boundary conditions. Meanwhile, with the internal heat source being treated as a parallel-connected network resistance heat-release a two-dimensional mathematical model was set up for assessing the temperature field distribution in an electrically heated inclined tube. A controlled-volume differential method based on spatial node advance was used to solve the inverse problem of a two-dimensional temperature field heat conduction in an electrically heated inclined tube, which is determined by the coupling of fluid heat exchange and tube wall heat conduction. A computation program was prepared and the calculation of tube-wall temperature field conducted for the tube type of the spiral tube-coil water-wall of the first supercritical-parameter boiler in China. Under the operating condition of subcritical and supercritical pressures the calculation results can all truly reflect the wall-temperature distribution law of the inclined tube with a fairly good computation convergence being attained. **Key words**: temperature field, source item, inclined tube, thermal load

辐射离散传播法在三维圆柱腔体辐射传热计算中的应用＝**The Application of a Radiation Discrete Transfer Method for the Radiation Heat Transfer Calculation of a Three-dimensional Cylindrical Cavity Body** [刊, 汉] / GU Ming-yan, ZHANG Ming-chuan, FAN Wei-dong, et al (Mechanical &Power Engineering Institute under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200240) //Journal of Engineering for Thermal Energy &Power. — 2005, 20(5). —482 ~485

By employing a method combining spatial analytical geometry theory with numerical calculations a radiation discrete transfer method (DTM) was implemented for the radiation heat transfer calculations in a three-dimensional cylindrical cavity body. Through the use of coordinate transformation a radiation ray equation was set up. By directly solving the intersection points of the radiation rays in various three-dimensional angles with various radiation unitary bodies at all emission points determined were the path traversed by the rays and the distance between the various intersecting points and emission points. Then, with the intersecting points being arranged in proper order, and taking into account the magnitude of the above-mentioned distance, one can obtain the intersecting point sequence for solving the radiation energy transfer equation in adaptation to the DTM method. The above-mentioned method was used to perform a three-dimensional calculation of the radiation heat exchange in the cylindrical cavity body and the computation results are in basic agreement with those of a precision solution. The DTM method was employed for calculating the radiation heat exchange in a pulverized-coal combustion flame. The temperature field being obtained basically agrees with that of experimental results and the surface radiation heat-flux density assumes a rational distribution. This shows that the method designed by the authors is feasible. **Key words**: radiation transfer equation, discrete transfer method, three-dimensional cylindrical cavity body

汽液相变系统的平衡稳定性分析＝**Equilibrium Stability Analysis of a Liquid-vapor Phase Transition System** [刊, 汉] /WU Shuang-ying, ZENG Dan-ling, LI You-rong (Power Engineering College under the Chongqing University, Chongqing, China, Post Code: 400044) //Journal of Engineering for Thermal Energy &Power. 2005, 20(5). —486 ~488

On the basis of the theory of non-equilibrium thermodynamics and through the introduction of an important work /potential function in the heat exchange process of a liquid-vapor phase transition, the so-called available energy, an analysis was conducted of the available energy of the liquid-vapor phase transition system. As a result, a calculation formula for the available energy variation of the liquid-vapor phase transition system was obtained, and using this as criteria an analysis was performed of the stability of the liquid-vapor phase transition system. Thus, obtained were the phase equilibrium conditions of the above-mentioned system, mechanics stability conditions and thermal stability conditions with relevant physical meanings being also given. Furthermore, a definition is provided for the liquid and vapor phase force-stable marginal curves during the liquid-vapor phase transition. It can be shown that the force-stable condition of the liquid-vapor phase 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