赵良 举, 高丽娟, 袁悦祥, 曾 丹苓

(重庆大学 动力工程学院, 重庆 400044)

: 建立了基于两 相流音速的气 固两相流激波模型, 并进行了计算分析。 与基于单 相流音速的激波模型的计算结果比较发现, 当气 相体积比较大时, 两种模型所计算的音速差别较小, 激波的结果是吻合的; 当气 相体积比较小时, 两相音速模型所计算的音速值与实际值更接近, 其激波结果更合理。 因此本文基于两 相流音速模型的激波分析更具通用性。

:   ;   ;

: O359   : A

1

(CSC),

(CGDS),
[1~3]

,

[4]

[5]

[6]。 Jack-
son
[6]

Jackson

,   [6]

2

[7~9]

[4]

[7]

Laplace   :

$$a_s = \sqrt{(\partial p / \partial \rho)_s} \tag{1}$$

:

$$a = v\left[-\left((v_g - v_p)\left(\frac{\partial(1-x)}{\partial p} \right)_s + (1-x)\frac{dv_g}{dp} + x\frac{dv_p}{dp} \right) \right]_s^{-1/2} \tag{2}$$

: v—   ; h—   ; p—   ; x— 。

: g、p—   。 α, $x = \alpha\rho_p/[\alpha\rho_p + (1-\alpha)\rho_g]$, ρ 。 $h = (1-x)h_g + xh_p$:

$$x = \frac{h - h_g}{h_p - h_g} \tag{3}$$

(2),   :

$$a = v\left[-\left((v_g - v_p)\left(\frac{dh/dp}{h_g - h_p} - \frac{(h_g - h)dh_p/dp + (h - h_p)dh_g/dp}{(h_g - h_p)^2} \right)_s + (1-x)\frac{dv_g}{dp} + x\frac{dv_p}{dp} \right) \right]_s^{-1/2} \tag{4}$$

, $p_g v_g = R_g T$,

, $dh_p/dp = 0$, $dv_p/dp = 0$,

:

$$a = v\left[-(v_g - v_p)\frac{c_{pg}v_g}{R_g}\left(1 - \frac{1}{k_g} \right) \times \right.$$

$$\left(\frac{1-x}{h_{\mathrm{g}}-h_{\mathrm{p}}}-\frac{(h-h_{\mathrm{p}})}{(h_{\mathrm{g}}-h_{\mathrm{p}})^{2}}\right)+\frac{(1-x)v_{\mathrm{g}}}{kp}\right)^{-1/2} \qquad (5)$$

：c_{pg}—　　　　　　　　；k_{g}—　　　　　　。

　1　　2　　　　　　　　，　　　　　　　　　。　　　　　　　　　x　　　　　　　　　　，σ
$10\% \sim 95\%$　，　　　　　　　　　　　　　　，m　　　　　　，u　　　　　；
　　　　　　　　　　　50%　，　　　　　p、g　　　　　　　　　，a、b
$20\,\mathrm{m/s}$。　　　　　　　　　　，　　　　　，　：

　　　　，　　　　　　1　，　　　$$x=\frac{m_{\mathrm{p}}}{m_{\mathrm{p}}+m_{\mathrm{g}}} \qquad (6)$$

　　　　　　　　　　[7]　　，　　　1　　$$\sigma=u_{\mathrm{p}}/u_{\mathrm{g}} \qquad (7)$$

　，　　　　　　　。　　　　　　：

　　　　　　　，　　　　　　100%　，$$\rho_{\mathrm{g,b}}u_{\mathrm{g,b}}=\rho_{\mathrm{g,a}}u_{\mathrm{g,a}} \qquad (8)$$

　，　　2　　。　　　　　　：

$$\tilde{u}=u/u_{\mathrm{g,b}} \qquad (9)$$
$$\tilde{T}=T/T_{\mathrm{g,b}} \qquad (10)$$
$$\tilde{p}=p/p_{\mathrm{g,b}} \qquad (11)$$
$$\tilde{\rho}=\rho/\rho_{\mathrm{g,b}} \qquad (12)$$

（8）　　　：
$$\tilde{\rho}_{\mathrm{g,a}}\tilde{u}_{\mathrm{g,a}}=1 \qquad (13)$$

$$p_{\mathrm{g}}=\rho_{\mathrm{g}}R_{\mathrm{g}}T_{\mathrm{g}}, \qquad ：$$
$$\tilde{P}_{\mathrm{g,a}}=\tilde{\rho}_{\mathrm{g,a}}\tilde{T}_{\mathrm{g,a}} \qquad (14)$$

图 1　不同压力下的气固两相流音速

　　　　　　　：
$$(p_{\mathrm{b}}-p_{\mathrm{a}})A=(u_{\mathrm{g,a}}-u_{\mathrm{g,b}})\rho_{\mathrm{g,b}}u_{\mathrm{g,b}}A+(u_{\mathrm{p,a}}-u_{\mathrm{p,b}})\rho_{\mathrm{p,b}}u_{\mathrm{p,b}}A \qquad (15)$$

　　（6）　：
$$x=\frac{m_{\mathrm{p}}}{m_{\mathrm{p}}+m_{\mathrm{g}}}=\frac{\rho_{\mathrm{p,b}}u_{\mathrm{p,b}}}{\rho_{\mathrm{p,b}}u_{\mathrm{p,b}}+\rho_{\mathrm{g,b}}u_{\mathrm{g,b}}} \qquad (16)$$

　　　　　：
$$\rho_{\mathrm{p,b}}=\rho_{\mathrm{p,b}}\frac{x}{\sigma_{b}(1-x)} \qquad (17)$$

　　　　（15）　：
$$p_{\mathrm{b}}-p_{\mathrm{a}}=(u_{\mathrm{g,a}}-u_{\mathrm{g,b}})\rho_{\mathrm{g,b}}u_{\mathrm{g,b}}+(\sigma_{\mathrm{a}}u_{\mathrm{g,a}}-\sigma_{\mathrm{b}}u_{\mathrm{g,b}})\rho_{\mathrm{g,b}}u_{\mathrm{g,b}}\frac{x}{1-x} \qquad (18)$$

图 2　不同温度下的气固两相流音速

$\rho_{\mathrm{g,b}}u_{\mathrm{g,b}}^{2}$　：
$$\frac{p_{\mathrm{b}}}{\rho_{\mathrm{g,b}}u_{\mathrm{g,b}}^{2}}-\frac{p_{a}}{\rho_{\mathrm{g,b}}u_{\mathrm{g,b}}^{2}}=(\frac{u_{\mathrm{g,a}}}{u_{\mathrm{g,b}}}-1)+(\sigma_{\mathrm{a}}\frac{u_{\mathrm{g,a}}}{u_{\mathrm{g,b}}}-\sigma_{\mathrm{b}})\times$$

3　

　　　　Jackson　$$\frac{x}{1-x} \qquad (19)$$
[6]　　，　　　　　　　　　　　，
　，　　　　，　　　　　　　　　　，η_i
，　　　　　。　　　　　　　　：
$$\eta_i=a_i/a_{\mathrm{g}\,i} \qquad (20)$$

: a_i —　　　　　; $a_{g\,i}$ —　　　　, i　　　　a b,　　　　　　　　。

　　Ma,　　　　　　　:

$$M_{g,b} = \frac{u_{g,b}}{a_b} = \frac{u_{g,b}}{a_{g\,b}\,\eta_b} \qquad (21)$$

　　　　(19)　　　　　　:

$$\frac{1}{M_{g,b}^2\,\eta_b\,\gamma_g} + \left(1 + \sigma_b\frac{x}{1-x}\right) = P_{g\,a}\frac{1}{M_{g\,b}^2\,\eta_b\,\gamma_g} +$$

$$\left(1 + \sigma_a\frac{x}{1-x}\right)\tilde{u}_{g,a} \qquad (22)$$

　　　　　　,　、　　　　　　　　:

$$m_g\left(c_{p,g}T_{g\,b} + \frac{u_{g\,b}^2}{2}\right) + m_p\left(c_{v,p}T_{p,b} + \frac{u_{p,b}^2}{2} + p_b v_{p\,b}\right) =$$

$$m_g\left(c_{p,g}T_{g\,a} + \frac{u_{g\,a}^2}{2}\right) + m_p\left(c_{v,p}T_{p,a} + \frac{u_{p\,a}^2}{2} + p_a v_{p\,a}\right) \qquad (23)$$

　　　　　　　　　,　　　　　,

　　　:

$$(1-x)\left(c_{p\,g}T_{g,b} + \frac{u_{g\,b}^2}{2}\right) + x\left(c_{v,p}T_{p,b} + \sigma_b^2\frac{u_{g\,b}^2}{2}\right) =$$

$$(1-x)\left(c_{p\,g}T_{g,a} + \frac{u_{g\,a}^2}{2}\right) + x\left(c_{v,p}T_{p,a} + \sigma_a^2\frac{u_{g\,a}^2}{2}\right) \qquad (24)$$

　　　　　,　　　　$C_{v,p} = C_{p,p}$,

　　　:

$$H_i = T_{p\,i}/T_{g\,i} \qquad (25)$$

　　(24)　　　　　:

$$(1-x)\left(c_{p\,g}T_{g,b} + \frac{u_{g,b}^2}{2}\right) + x\left(c_{p,p}H_b T_{g,b} + \sigma_b^2\frac{u_{g\,b}^2}{2}\right) =$$

$$(1-x)\left(c_{p\,g}T_{g,a} + \frac{u_{g,b}^2}{2}\right) + x\left(c_{p,p}H_a T_{g,a} + \sigma_a^2\frac{u_{g\,a}^2}{2}\right) \qquad (26)$$

$$a_{g,b} = \sqrt{k_g R_g T_{g\,b}}$$

(21)　　　$T_{g\,b}$:

$$T_{g\,b} = \frac{u_{g,b}^2}{M_{g\,b}^2\,\eta_b\,\kappa_g R_g} \qquad (27)$$

　　　　,　　　　　　　　C_r　　: $C_r = c_{p,p}/c_{p,g}$,　　　　　:

$$\frac{c_{p,g}}{R_g} = \frac{\kappa_g}{\kappa_g - 1} \qquad (28)$$

　: $\kappa_g = c_{p,g}/c_{v,g}$。

　　(26)　　　　　　　($R_g T_{g,b}$),　　　:

$$(1-x)\left(\frac{\kappa_g}{\kappa_g - 1} + \frac{M_{g\,b}^2\,\eta_b\,\kappa_g}{2}\right) +$$

$$x\left(\frac{C_r H_b\,\kappa_g}{\kappa_g - 1} + \frac{\sigma_b^2 M_{g\,b}^2\,\eta_b\,\kappa_g}{2}\right) = (1-x)\times$$

$$\left(\frac{\kappa_g}{\kappa_g - 1}\frac{T_{g,a}}{T_{g,b}} + \frac{M_{g\,b}^2\,\eta_b\,\kappa_g}{2}\left(\frac{u_{g\,a}}{u_{g,b}}\right)^2\right) +$$

$$x\left(\frac{C_r H_a\,\kappa_g}{\kappa_g - 1}\frac{T_{g,a}}{T_{g,b}} + \frac{\sigma_a^2 M_{g\,b}^2\,\eta_b\,\kappa_g}{2}\left(\frac{u_{g\,a}}{u_{g\,b}}\right)^2\right) \qquad (29)$$

　　　　　　　　,　:

$$(1-x)\left(\frac{\kappa_g}{\kappa_g - 1} + \frac{M_{g,b}^2\,\eta_b\,\kappa_g}{2}\right) +$$

$$x\left(\frac{C_r H_b\,\kappa_g}{\kappa_g - 1} + \frac{\sigma_b^2 M_{g\,b}^2\,\eta_b\,\kappa_g}{2}\right) = (1-x)\times$$

$$\left(\frac{\kappa_g}{\kappa_g - 1}T_{g,a} + M_{g,b}^2\,\eta_b\,\kappa_g\,\frac{\tilde{u}_{g,a}^2}{2}\right) +$$

$$x\left(\frac{C_r H_a\,\kappa_g}{\kappa_g - 1}T_{g,a} + \sigma_a^2 M_{g,b}^2\,\eta_b\,\kappa_g\,\frac{\tilde{u}_{g,a}^2}{2}\right) \qquad (30)$$

　　　　　　　　:

$$M_{g\,a} = \frac{u_{g,a}}{a_a} = \frac{\tilde{u}_{g,a}\,u_{g,b}}{\sqrt{\kappa_g R_g T_{g,a}T_{g,b}\,\eta_a}}$$

$$= \frac{\tilde{u}_{g,a}}{\sqrt{T_{g\,a}}}\frac{\eta_b}{\eta_a}M_{g\,b} \qquad (31)$$
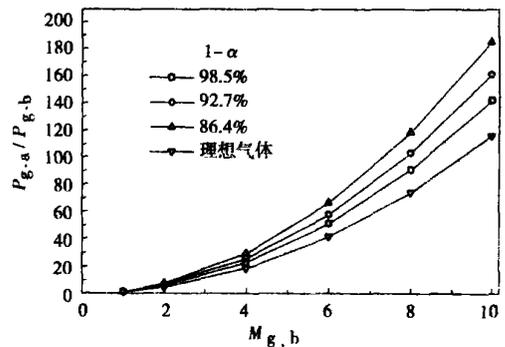
　　　　(13)、　　(14)、　(22)、　(30)　　(31),　　　　　　　$\tilde{p}_{g,a}$、$P_{g\,a}$、$\tilde{u}_{g,a}$、$T_{g,a}$　　$M_{g\,b}$　　　　。

图 3　激波升压比与波前马赫数的关系

4

　　　　　　　　　　　　　　　　　　,　　　　　　　　　　,　　　　　　1,　　　$\sigma_a = \sigma_b = 1.0$, $H_a = H_b = 1.0$,　　　　　30℃,　　　0.1 MPa。

　　　　,　　3~6　　　　　3　　　　　,　　　　　　　　,　　　　　　　　,　　　　　。　　　4~6　　,　　　　　　　,
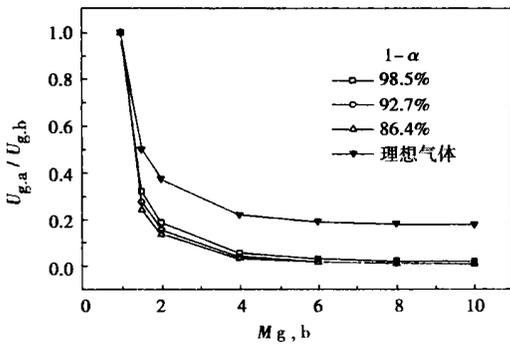
图 4 波后无量纲速度与波前马赫数的关系
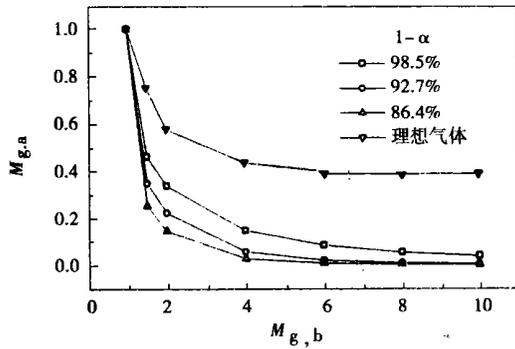
图 5 波后马赫数与波前马赫数的关系
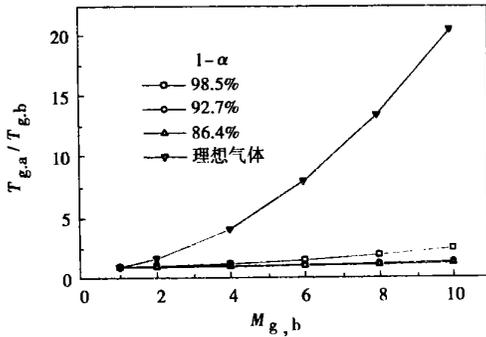
图 6 波后无量纲温度与波前马赫数的关系

330. 86 m/s,

7

(92.7%) ,

348. 73 m/s,

37. 52 m/s,

8

, Jackson

,

, $M_{g,b}=4$, $p_{g a}/p_{g b}=2\ 235$,
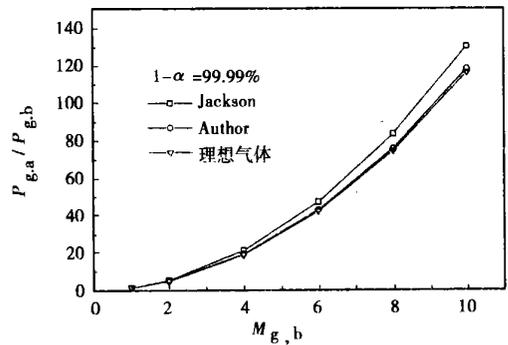
图 7 高气相体积比时两种模型的激波比较

图 8 较低气相体积比时两种模型的激波比较

,

, Jackson

,

5

Jackson

,

,

30 ℃, 0.1

MPa, 7 8 6

。 (99.99%) ,

, 348.73 m/s,

$$\overline{SPAN} = \sum_i Q_i (SPAN)_i / \sum_i Q_i \qquad (3)$$

$\overline{SPAN}$ 11

图 11 平均径跨随出口直径变化曲线图

（1）

（2）

（3）　　　　　　60 mm ，

（4）

（5）　　　　　　$\overline{SPAN}$ ，

参考文献：

[1] ， ． [M] ． ： ，2002．

[2] K． [M] ． ， ， ． ： ，1983．

[3] ， ， ． 、 [M] ． ： ，1997．

[4] ． Y [J] ． ，1992，**13**(4)：425—430．

（何静芳 编辑）

Jackson

（1）　　　50%

（2）

参考文献：

[1] ALKIMOV A P, KOSAREV V F, PAPYRIN A N. A method of cold gas dynamic deposition[J] . **Dokl Akad Nauk SSSR**, 1990, **315**(5)：1062—1065．

[2] VAN STEENKISTE T H, SMITH J R, TEETS R E, et al. Kinetic spray coatings[J] . **Surface and Coatings Technology**, 1999, **111**：62—71．

[3] VAN STEENKISTE T H, SMITH J R, TEETS R E. Aluminum coatings via kinetic spray with relatively large powder particles[J] . **Surface and Coatings Technology**, 2002, **154**：237—252．

[4] L． [M] ． ： ，1984．

[5] ． 、 [D] ． ： ，2001．

[6] JACKSON C R, LEAR W E, SHERIF S A. Generalized wave analysis of two-phase flow[J] . **Mechanics Research Communications**, 1998, **25**(6)：613—622．

[7] ZENG DANLING, ZHAO LIANGJU. Sound velocity in vapor-liquid two-phase fluid system[A] . **Proceedings of ICECA[C]** . Wuhan, Huazhong University of Science and Technology Press, 2001. 50—55．

[8] ， ． [J] ． ，1994，**28**(5)：73—81．

[9] ． [J] ． ，1990，**22**(6)：660—669．

（何静芳 编辑）

CFB   = **An Investigation of the Impact of Fly-ash Reburning on the Operation of an Anthracite-firing CFB（Circulating Fluidized Bed）Boiler**［　，　］/HE Hong-zhou（Institute of Energy and Power Engineering under the Jimei University，Xiamen，China，Post Code：361021）//Journal of Engineering for Thermal Energy ＆Power．— 2006，21（1）．—53～57

The reactivity of fly-ash carbon and that of other coals fed into a boiler was investigated and compared through experiments with the help of a thermobalance. A theoretical analysis was conducted of the impact of fly-ash reburning on the combustion efficiency of a CFB（circulating fluidized bed）boiler. Moreover，by way of industrial tests investigated and measured was the impact of the fly-ash quantity recycled for reburning on the following items：the operating temperature of a recycle-to-boiler device，fly-ash particle distribution and its carbon content，boiler combustion efficiency and other operating parameters．The results of the investigation indicate that the reactivity of fly-ash carbon of the CFB boiler burning Fujian anthracite is higher than that of other corresponding coals fed into the boiler. In addition，other parameters，such as carbon content of the reburnt fly ash，the ratio of the reburnt fly ash amount to other coals fed into the boiler，have a major influence on the combustion efficiency of the boiler. The use of fly-ash reburning technology will be conducive to reducing the carbon content of the fly ash and the operating temperature of recycle-for reburning device as well as enhancing the combustion efficiency of the boiler. However，a relatively large amount of fly ash assigned for reburning will affect the stable operation of the boiler．**Key words**：Fujian anthracite，circulating fluidized bed boiler，fly ash，reburning

= **Experimental Study of the Volt-ampere Characteristics of Fly Ash Resulting from Coal Firing**［　，　］/YUAN Yong-tao，QI Li-qiang（Institute of Environmental Science ＆Engineering under the North China University of Electric Power，Baoding，China，Post Code：071003）//Journal of Engineering for Thermal Energy ＆Power．— 2006，21（1）．—58～61

The dielectric character of fly ash is a major factor having an impact on the efficiency of electrostatic precipitators. By employing a self-developed direct-current high voltage test system the current leakage and specific resistance of the fly ash of various kinds of coal being fired were measured and analyzed，and a series of volt-ampere characteristic curves obtained．It has been found that the relation among the following three items，i．e．，the voltage applied to the ash layer，the current leakage through the ash layer and fly-ash specific resistance，does not always conform to the classic Ohm's law，namely，$V/I \neq$ constant. At the three segments of high，middle and low voltage the volt-ampere characteristic curves of the fly ash have different configuration features. With an increase in voltage the specific resistance of the fly ash assumes a descending tendency with the range of descending amount being within one order of magnitude（$10^1 \Omega \cdot cm$）．The cause leading to the occurrence of this phenomenon consists in the high-resistance feature of the fly ash. Meanwhile，this is also closely related with the physical-chemical properties of the coal rank and fly ash．**Key words**：fly ash of coal fired，dielectric properties，specific resistance，electrostatic precipitator

= **A Study of Two-phase Shock Waves with a Two-phase Flow Sonic Velocity being Taken into Account**［　，　］/ZHAO Liang-ju，GAO Li-juan，YUAN Yue-xiang，et al（Institute of Power Engineering under the Chongqing University，Chongqing，China，Post Code：400044）//Journal of Engineering for Thermal Energy ＆Power．— 2006，21（1）．—62～65，69

On the basis of a two-phase flow sonic velocity a gas-solid two-phase flow shock-wave model was set up，and calculations and analyses were performed．When compared with the calculation results of a shock wave model based on a single-phase flow sonic velocity it has been found that in the case of a relatively large gas-phase volume the sonic velocity difference as calculated by using the above two kinds of models is relatively small and the shock wave results for the two models are in good agreement. When the gas phase volume is relatively small，the sonic velocity value calculated through the use of the two-phase sonic velocity model is in better correspondence with the actual value，resulting in more rational shock wave re-

sults. In view of the above, the shock wave analysis based on the two-phase flow sonic velocity model is more suited for general applications. **Key words**: gas-solid two phase flow, sonic velocity, shock wave

=**A Study of the Atomization Characteristics of Swirl Spray Nozzles Used in a Wet-process Flue-gas Desulfurization Unit** [,] / LI Zhao-dong, WANG Shi-he (Department of Municipal Construction Engineering, Southeastern University, Nanjing, China, Post Code: 210096), WANG Xiao-ming (Guodian Environmental Protection Research Institute, Nanjing, China, Post Code: 210031) //Journal of Engineering for Thermal Energy &Power. — 2006, 21(1). —66~69

Atomization spray nozzles are key components in a wet-process flue-gas desulfurization sprinkling tower. The quality of atomization can directly affect desulfurization efficiency and the utilization rate of a desulfurization agent. Tests were conducted with the hollow cone-shaped and eccentric swirl nozzle often used in wet-process flue-gas desulfurization technology serving as an object of investigation. Developed were a series of geometrically similar spray nozzles and also those with a change only in outlet diameters. A systematic study was performed of the above-mentioned nozzle as regards the following characteristics: volumetric flow rate, atomization particle diameter, atomization angle, and atomization particle distribution, etc. From the tests a set of rules or laws governing the following factors were obtained: the variation of volumetric flow rate with a change in pressure and spray nozzle structure, the variation of atomization particle diameter with a change in pressure, flow rate and spray nozzle structure, the variation of atomization angle with a change in pressure, etc. Average-diameter span was used to indicate the dispersion degree for judging the distribution of atomization particles. Identified was a variation law governing a decrease in average diameter span with an increase in outlet diameter. **Key words**: wet-process flue gas desulfurization, swirl nozzle, atomization characteristics

=**Numerical Simulation of the Flow Field and Performance of an Innovative Cyclone Separator with a Downward Discharge of Gases** [,] / HUANG Sheng-zhu (Department of Thermal Energy &Power Engineering, Harbin Institute of Technology, Weihai, Shandong Province, China, Post Code: 264209), ZHU Lin (Weihai Boiler Works, Weihai, Shandong Province, China, Post Code: 264200), MA Chun-yuan (Institute of Energy and Power Engineering under the Shandong University, Jinan, China, Post Code: 250061), WU Shao-hua (Department of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001)Journal of Engineering for Thermal Energy &Power. — 2006, 21(1). —70~74

By employing a RNG (Renomalization Group) k-ϵ turbulent flow model, RSM (Reynolds Stress model) turbulent flow model and a Lagrangian model in a CFD (computational fluid dynamics) software - Fluent a numerical simulation was carried out for the gas-phase flow field and separation efficiency of an innovative cyclone separator with a downward discharge of gases. The cyclone separator features an improved construction with its two sides cut at the inside and outside. An analysis of its specific features and separation performance shows that the gas flow of the cyclone separator has generated three branch flows, namely, an apex vortex ring flow, a flow characterized by a direct entry into an exhaust pipe, and a flow, which after rotating at the outer wall makes its way downward to come to a conic surface, and then turns back to flow upward. The composite vortex structure of a tangential velocity distribution appears to be not distinct. The graded efficiency and pressure losses at different outlet velocities, obtained by simulations, can be used as a practical reference during the engineering design and type selection of cyclone separators. **Key words**: cyclone separator, flow field, RNG (renomalization group) k-ϵ turbulent flow model, RSM (Reynolds stress model) turbulent model, numerical simulation

PEMFC   =**Dynamic Simulation of Coordinated Control of PEMFC (Proton Exchange Membrane Fuel Cell) Distributed Power Generation System** [,] / ZHANG Ying-ying, CAO Guang-yi, ZHU Xin-jian (Automation Department of Fuel Cell Research Institute under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) //Journal of Engineering for Thermal Energy &Power. — 2006, 21(1). —75~79, 95