文章编号:1001－2060(2004)02－0124－04

低流速净蒸汽产生点模型预测过冷沸腾空泡率

孙　奇[1,2], 杨瑞昌[2]

(1. 中国核动力研究设计院 空泡物理和自然循环重点实验室, 四川 成都 610041;
2. 清华大学 热能工程系, 北京 100084)

摘　要:空泡率是汽液两相流动的基本参数之一,而已有过冷沸腾空泡率计算方法研究以高质量流速为主,且大量文献报道现有空泡率模型难以适用于低流速过冷沸腾工况。本文基于低流速过冷沸腾净蒸汽产生点(NVG)理论模型,进一步建立了计算过冷沸腾空泡率的分布拟合模型。在较宽广的压力、质量流速、热流密度和流道尺寸范围内将模型计算结果与现有空泡率实验数据进行了比较,低流速工况下该模型与实验数据符合良好,表明该模型可适用于低流速过冷沸腾工况。

关　键　词:两相流;　空泡率;　过冷沸腾;　NVG

中图分类号:TK123; O359　　　文献标识码:A

1　引　言

沸腾传热及两相流动现象在石油、化工、冶金、动力以及原子能等工业中普遍存在。过冷沸腾由于同时存在着汽泡热力学与动力学不平衡,到目前为止仍有许多现象、规律未被人们充分认识,是沸腾传热及两相流动研究中的难点。过冷沸腾空泡率代表着过冷沸腾工况下两相流动的相分布情况,是决定过冷沸腾两相流内部结构的基本参数。当知道空泡率后便可求得过冷沸腾两相混合物的平均密度、计算压降、分析流道内流动及传热特性等。

目前,过冷沸腾空泡率的计算方法主要有机理模型法和分布拟合法,前者根据一定的传热机理推算真实含汽率及空泡率,后者多半是以净蒸汽产生点(NVG)及饱和沸腾起始点(OSB)为基准进行某种方便的数学拟合。分布拟合模型在工程上具有重要的意义,如目前应用非常广泛的Levy模型以及Saha模型等。对于分布拟合模型,NVG点的确定是模型建立的关键,而现有过冷沸腾空泡率分布拟合模型的差异也主要在于NVG点的确定方法上。

然而,现有研究主要以高质量流速为主,而低质量流速(包括自然循环)已成为热能动力系统重要的发展趋势之一,已有的高流速条件下过冷沸腾NVG点及空泡率计算方法难以可靠地用于低流速工况。在文献[1]中,本文作者曾指出如下:

Kroeger与Zuber研究表明低流速工况用Levy模型及Staub模型计算的结果不能得出满意的结果。Lin－wen与Chin的分析也表明Levy模型无法用于低流速工况。Levy在其文献中也提到Levy模型与Rouhani低流速下的实验数据比较显示该模型有过高估算空泡率的趋势。Saha指出,Ahmad根据汽泡搅动和一个假定的传热系数提出的模型虽在高流速工况可得出很好的计算结果,但对Dix和Rouhani的低流速数据来说却不能令人满意。Lee等人曾对有关过冷沸腾NVG点的研究报道进行过评述,认为Saha模型是已有模型中最精确的一个计算模型,但是Chang等人用水为工质,在低流速强迫循环条件下模拟研究自然循环过冷沸腾NVG点的实验结果表明,Saha模型预测的NVG点过冷度要比实验实测值低得多。杨瑞昌以氟里昂12为工质对自然循环过冷沸腾NVG点及空泡率的研究也表明Saha模型预测的NVG点过冷度偏低,无法直接用于低流速过冷沸腾空泡率的计算;而levy模型在低空泡率工况偏差较大,较高空泡率工况偏差较小(30%以内);Rouhani模型虽在过冷沸腾低空泡率工况计算结果较好,但随着空泡率的增加有明显偏低的趋势。

因此,就现有研究情况来看,对于低流速工况到目前还难以有一个普遍认同的过冷沸腾NVG点及空泡率计算模型。为此,本文作者曾提出了低流速过冷沸腾NVG点理论模型[1]。本文基于该NVG点模型,进一步建立了计算低流速过冷沸腾空泡率的分布拟合模型。

收稿日期:2003－08－11;　修订日期:2003－10－09

基金项目:国家自然科学基金资助项目(59995460－1);核工业科学基金资助项目(Y7100E5101)

作者简介:孙　奇(1975－),男,四川大竹人,中国核动力研究设计院助理研究员,清华大学博士研究生.

2 低流速过冷沸腾 NVG 点模型

在文献[1]中, 作者通过加热壁面汽相蒸发与汽液界面冷凝传热的分析, 同时考虑汽泡脱离的动力学特性, 建立了低流速 NVG 点理论模型:

$$X_{eq,NVG}=\frac{1-\sqrt{1+1.6\left(\frac{\rho_f}{\rho_g}\right)\frac{qc_{pf}}{h'_i i_{fg}}}}{2(\rho_f/\rho_g)} \tag{1}$$

$$h'_i=\frac{k_f}{D'_B}(Re'_{fg})^{0.5}Pr_f^{-1.2}(\rho_g/\rho_f)^{0.41} \tag{2}$$

$$Re'_{fg}=\frac{\rho_f u_{gj}D'_B}{\mu_f} \tag{3}$$

$$D'_B=\sqrt{\frac{\sigma}{(\rho_f-\rho_g)g+\frac{3}{4}\frac{G^2}{D_e\rho_f}}} \tag{4}$$

$$u_{gj}=1.41\left[\frac{\sigma g(\rho_f-\rho_g)}{\rho_f^2}\right]^{0.25} \tag{5}$$

式中: $X_{eq,NVG}$ 为 NVG 点热平衡含汽率; ρ_f 与 ρ_g 分别为液、汽相密度, kg/m^3; q 为热流密度, kW/m^2; , c_{pf} 为液相定压比热, kJ/(kg · K); i_{fg} 为汽化潜热, kJ/kg; k_f 为液相热传导率, kW/(m · K); Pr_f 为液相普朗特数; u_{gj} 为漂移速度, m/s; μ_f 为液相粘度, kg/(m · s); σ 为表面张力, N/m; g 为重力加速度, m/s^2; G 为质量流速, kg/(m^2 · s); D_e 为水力学当量直径, m; D'_B 为公式(4)确定的一个与汽泡脱离直径成正比的物理量, m。模型中物性建议取对应饱和温度下的值。

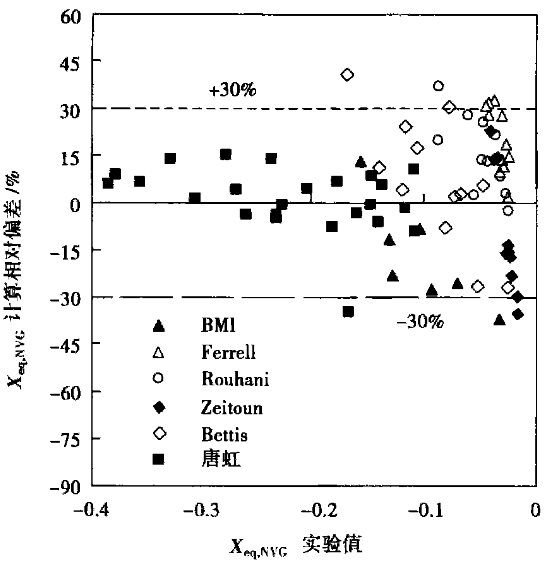


图 1 NVG 点模型与实验数据的比较

模型计算结果与唐虹 Freon12 自然循环实验数据, Zeitoun 常压低流速实验数据以及 Levy 报道的 Bettis、BMI、Ferrell、Rouhani 实验数据的比较如图 1 所示[1]。实验数据参数范围如下:

流动工质	Freon12、蒸汽-水
循环方式	自然循环、强迫循环
流道几何结构	环形、板型、圆管
压力	0.117 ~ 13.8 MPa
热流密度	12.7 ~ 1912 kW/m^2
质量流速	152.5 ~ 1 318 kg/(m^2 · s)

由图可见, 在较广的范围内模型计算结果与现有的低流速 NVG 点实验数据符合程度良好。

3 低流速过冷沸腾空泡率分布拟合模型

由本文净蒸汽产生点模型式(1) ~ 式(5)获得 NVG 点热平衡含汽率 $X_{eq,NVG}$ 后, 下游不同热平衡含汽率工况真实含汽率 X_α 可由下式表示:

$$X_\alpha=\frac{X_{eq}-X_{eq,NVG}\exp\left(\frac{X_{eq}}{X_{eq,NVG}}-1\right)}{1-X_{eq,NVG}\exp\left(\frac{X_{eq}}{X_{ep,NVG}}-1\right)} \tag{6}$$

由上式得出真实含汽率后, 根据相关空泡率计算式便可得出轴向空泡率分布。Friedel、Diener-Friedel 和 Vijayan 等人都曾对多个不同空泡率计算关系式进行过准确性评价[2]。Friedel 等人推荐 Rouhani 关系式。Diener-Friedel 利用截面平均空泡率对 26 个空泡率计算模型作了比较, 推荐 Rouhani 及 HTFS-Alpha 等模型。最近, Vijayan 等评价结果是 Chexal et al. 关系式与实验数据符合最好, 紧接着是 Rouhani、Mochizuki-Ishii 和 Hughmark 关系式。虽然 Chexal et al. 关系式非常复杂, 但该公式已在非常宽广的工况范围内得到验证, 并可实用于蒸汽-水、空气-水、制冷剂等工质的两相流动, 该公式已被著名的热工水力计算程序 RELAP5 以及 RETRAN 采用。综上所述本文采用 Chexal et al. 关系式进行空泡率 α 计算。对于本文研究的垂直上升蒸汽-水两相流 Chexal et al 关系式表示如下:

$$\alpha=X_a/\{C_{0v}\cdot[X_a+\rho_g/\rho_f(1-X_a)]+\rho_g u_{gjv}/G\} \tag{7}$$

$$C_{0v}=\frac{L(\alpha,p)}{K_0+(1-K_0)\alpha^r} \tag{8}$$

$$u_{gjv}=1.41\left[\frac{(\rho_f-\rho_g)\sigma g}{\rho_f^2}\right]^{0.25}C_2C_3C_4C_9 \tag{9}$$

式(8)中 C_{0v} 为垂直上升两相流分布参数，其中：

$$L(\alpha, P)=\frac{1-\exp(-C_1\alpha)}{1-\exp(-C_1)},\ C_1=\frac{4P_{crit}^2}{P(P_{crit}-P)},$$

$$K_0=B_1+(1-B_1)\left(\frac{\rho_g}{\rho_f}\right)^{1/4},$$

$$r=\left(1+1.57\frac{\rho_g}{\rho_f}\right)/(1-B_1),$$

$$B_1=\min(0.8, A_1),\ A_1=\frac{1}{[1+\exp(-Re/60,000)]},$$

$$Re=\begin{cases}Re_g=\dfrac{X_a G D_e}{\mu_g}\ldots IF\ldots Re_g>Re_f\ or\ Re_g<0\\ Re_f=\dfrac{(1-X_a)G D_e}{\mu_f}\ldots IF\ldots Re_g\le Re_f\end{cases}$$

式(9)中 u_{gjv} 为垂直上升两相流漂移速度，其中：

$$For\left(\frac{\rho_f}{\rho_g}\right)\le 18:\ C_2=0.4757\left[\ln\left(\frac{\rho_f}{\rho_g}\right)\right]^{0.7}$$

$$For\left(\frac{\rho_f}{\rho_g}\right)>18:\ C_2=\begin{cases}1\ldots IF\ldots C_5\ge 1\\ \dfrac{1}{1-\exp\left(\dfrac{-C_5}{1-C_5}\right)}\ldots IF\ldots C_5<1,\end{cases}$$

$$C_3=\max\begin{cases}0.5\\ 2\exp(-|Re_f|/300\,000),\end{cases}$$

$$C_4=\begin{cases}1\ldots IF\ldots C_7\ge 1\\ \dfrac{1}{1-\exp(-C_8)}\ldots IF\ldots C_7<1,\end{cases}$$

$$C_5=\sqrt{\frac{150}{\rho_f/\rho_g}},\ C_7=(0.09144/D_e)^{0.6},$$

$$C_8=C_7/(1-C_7),\ C_9=(1-\alpha)^{B_1}$$

由上得出本文低流速过冷沸腾空泡率分布拟合模型计算步骤如下：

(1)采用本文式(1)~式(5)计算过冷沸腾 NVG 点；

(2)采用式(6)计算 NVG 点下游不同热平衡含汽率工况真实含汽率 X_α；

(3)采用 Chexal et al 关系式计算空泡率 α。

4 分布拟合模型与实验数据的比较

将低流速过冷沸腾空泡率分布拟合模型与已有空泡率实验数据进行比较，比较的实验数据包括 Rouhani[3]、Levy[4] 以及 Maroti[5] 报道的实验数据。数据参数范围如下：

压力 2.92~13.8 MPa

热流密度 189~1 095 kW/m²

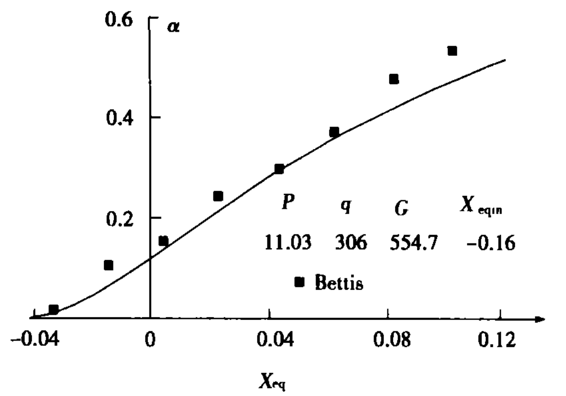
质量流速 130.5~1607 kg/(m²·s)

所比较的研究者(或研究机构)实验段几何尺寸如表 1 所示。

表 1 实验段几何结构

	Rouhani	Eklund	Bettis	BMI	Nylund	Christensen
流道/mm	环形	6 棒束	—	2.61~25.4 板型	36 棒束	11.1~44.4 矩形
D_e/mm	17.032	22.23	5.6	4.75	26.9	17.766
D_h/mm	40.106	46.56	5.6	4.75	36.6	17.766

图 2 给出了较低流速工况(G<900 kg/(m²·s))模型计算得出的轴向空泡率分布与 2 组实验数据的比较情况。图中“■”为实验点，曲线为模型预测结果，压力 P、热流密度 q、质量流速 G 量纲单位分别为 MPa、kW/m²、kg/(m²·s)。



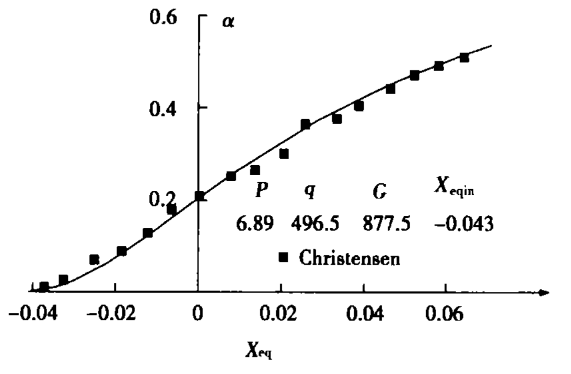


图 2 分布拟合模型预测空泡率轴向分布

本文分布拟合模型与表 1 中所有较低流速实验数据(G<900 kg/(m²·s))的比较如图 3 所示。由图 2，图 3 可见，较低流速工况下空泡率预测结果与实验数据符合非常好。图 2，图 3 所示结果进一步证实了低流速净蒸汽产生点模型对于低流速工况可得出满意的预测结果。

(下转第 174 页)

4 结 论

通过采用无量纲分析法对多股流板翅式换热器优化设计的研究,得出如下结论:

(1) 体积、重量与阻力有制约关系,要优化设计只能找出一个综合各种制约参数的最佳区域;

(2) 对多股流板翅式换热器的设计来说,无量纲分析法是一个非常有效的方法;

(3) *syn* 线真实地反应了体积、重量、阻力的变化情况。计算后,工程设计人员可直接从 *syn* 线入手,找出翅片的最佳参数。若对体积、重量、阻力的侧重点不同,根据所取权重可分别作出各自的线,找出最佳设计区域。

参考文献:

[1] 王松汉. 板翅式换热器[M]. 北京:化学工业出版社,1984.

[2] 陈长青,沈裕浩. 低温换热器[M]. 北京:机械工业出版社,1993.

[3] PRASAD B S V, GURUKUL S M K A. Differential methods for the performance prediction of multi-stream plate-fin heat exchangers[J]. **ASME J Heat Transfer**, 1992, **114** (1)41—49.

[4] 卢洪波,崔国民,李美玲. 多股流板翅式换热器温度交叉的数值分析[J]. 热能动力工程, 2002, **17**(6), 611—613.

(渠 源 编辑)

(上接第 126 页)

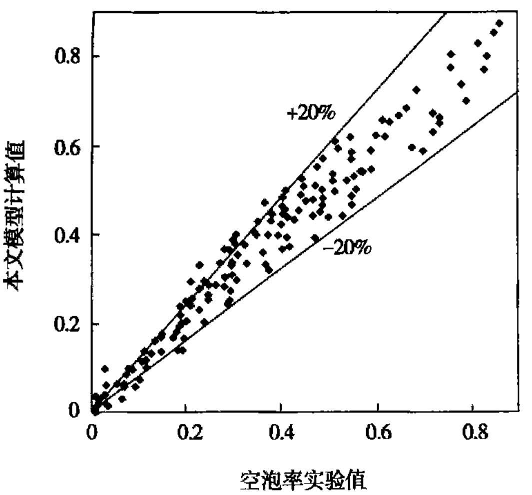


图 3 分布拟合模型与较低流速数据比较

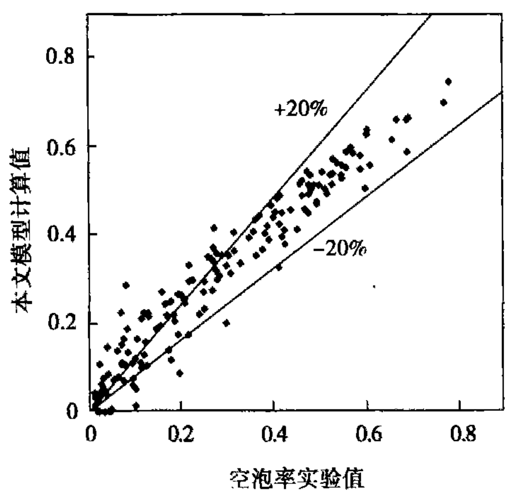


图 4 分布拟合模型与较高流速数据比较

分布拟合模型与表 1 中所有较高流速实验数据($G>900$ kg/(m^2◦s))的比较如图 4 所示,可见对于较高流速工况(G> 900 kg/(m^2◦s)),本文模型虽然仍可得出比较满意的预测结果,但其预测精度较低流速工况明显降低。

5 结 语

基于本文作者于文献[1] 提出的低流速过冷沸腾 NVG 点理论模型,进一步建立了计算低流速过冷沸腾空泡率的分布拟合模型。通过与现有实验数据的比较表明,该模型在低流速过冷沸腾工况可得出非常满意的空泡率计算结果。

参考文献:

[1] SUN QI, YANG RUICHANG, ZHAO HUA. Predictive study of the incipient point of net vapor generation in low—flow subcooled boiling [J]. **Nucl Engrg Des**, 2003, **225**(2—3): 249—256.

[2] VIJAYAN P K, MARUTHI RAMESH N, PILKHWAL D S, et al. An assessment of void fraction correlations for vertical upward steam—water flow[R]. India: Bhabha Atomic Research Center, 1997. 1—12.

[3] ROUHANI S Z, AXELSSON E. Calculation of void volume fraction in the subcooled and quality boiling region[J]. **Int J Heat Mass transfer**, 1970, 13(2): 383—393.

[4] LEVY S. Forced convection subcooled boiling prediction of vapor volumetric fraction[J]. **Int J Heat Mass transfer**, 1967, **10**(4): 951—965.

[5] MAROTI L. Axial distribution of void fraction in suncooled boiling [J]. **Nuclear Technology**, 1977, **34**(1): 8—17.

(渠 源 编辑)

燃气轮机装置湿压缩技术的研究发展状况＝**Present Status of the Research and Development of Wet Compression Technology for Gas Turbine Power Plants** [刊，汉] / WANG Yong-qing，LI Bing-xi (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(2). — 111～115

Wet compression technology represents a cost-effective and simple approach for the enhancement of gas turbine efficiency and power output as well as for the reduction of turbine exhaust pollution. The authors have briefly described the theoretical basis of wet compression，its specific features and types，the present status of its research and development both at home and abroad. In addition，its usage prospects are also predicted. **Key words**：wet compression，gas turbine power plant，present status of research and development

锅炉燃煤方式对痕量元素分布的影响＝**The Impact of Coal Combustion Modes of a Boiler on the Distribution of Trace Elements** [刊，汉] / YU Liang-ying，LU Ji-dong，ZHANG Juan，et al (State Key Laboratory on Coal Combustion under the Huazhong University of Science & Technology，Wuhan，China，Post Code：430074) // Journal of Engineering for Thermal Energy & Power. — 2004，19(2). —116～118，123

A broad overview is given of the impact of boiler combustion modes introduced both at home and abroad on the distribution of trace elements. Measurements were taken of the distribution of trace elements in bottom ash and fly ash for five Chinese industrial boilers of different models and power ratings. The results of the measurements indicate that fluidized bed combustion can lead to an enhancement of evaporation of volatile trace elements and the distribution of trace elements not tending to volatile will not be affected by the specific type of boilers. With the increase in power capacity of industrial boilers an enrichment of trace elements can be observed in fine particles. The smaller the fly ash particle size，the higher will be the enrichment of the trace elements. **Key words**：fluidized bed，stoker，trace element，enrichment factor

千瓦级质子交换膜燃料电池电堆的实验研究＝**Experimental Study of a PEM (Proton Exchange Membrane) Fuel Cell Stack of 1 kW Class** [刊，汉] / HU Ming-ying，ZHU Xin-jian，CAO Guang-yi (Fuel Cell Research Institute under the Shanghai Jiaotong University，Shanghai，China，Post Code：200030)，GU An-zhong (Institute of Refrigeration and Cryogenics Engineering under the Shanghai Jiaotong University，Shanghai，China，Post Code：200030) // Journal of Engineering for Thermal Energy & Power. — 2004，19(2). —119～123

A large-capacity PEM (proton exchange membrane) fuel cell stack of 1 kW class has been developed by the authors. During experiments hydrophilic membrane electrode assemblies were prepared. By making use of membranes of Nafion 115 and Nafion 1135 and with the Pt content of cathode and anode both being assessed at 0.5mg/cm2 the maximum power density of a single cell can respectively attain 0.19 w/cm2 and 0.24 w/cm2. Through an enlargement test and a stability test of a single cell verified were the feasibility of a bipolar-plate flow field of the cell stack and the stable performance of the cell proper. By way of assembling a cell stack of 100watt class the feasibility of sealing technology in a cell stack of 1 kW class and the ability of a gas manifold to achieve gas uniform distribution on a bipolar plate have been verified. Finally，it is shown that the maximum output power of the PEM cell stack composed of 30 single cells each with a reaction area of 235 cm2 may attain 1160w. **Key words**：fuel cell of proton exchange membrane，cell stack，membrane electrode assembly

低流速净蒸汽产生点模型预测过冷沸腾空泡率＝**Prediction of Subcooled-boiling Void Fraction by Means of a Model Based on a Low Flow-rate Net Vapor Generation (NVG) Point** [刊，汉] / SUN Qi (National Key Laboratory

of Bubble Physics &Natural Circulation under the Chinese Research and Design Institute of Nuclear Power Engineering, Chengdu, China, Post Code: 610041), SUN Qi, YANG Rui-chang (Thermal Power Engineering Department, Tsinghua University, Beijing, China, Post Code: 100084) //Journal of Engineering for Thermal Energy &Power. — 2004, 19 (2). —124~126, 174

Void fraction is one of the basic parameters in steam-liquid two-phase flows. To date, the study of methods for calculating subcooled-boiling void fraction mainly focused on high-mass flow rates. Moreover, a huge amount of technical literature now available on void fraction models is hardly suitable for low flow-rate subcooled- boiling operating conditions. Based on a theoretical model of NVG (net vapor generation) point in low flow-rate subcooled boiling the authors have developed a fitting model for calculating the distribution of subcooled-boiling void fraction. Within a relatively wide range of pressures, mass flow rates, heat flux density and flow path dimensions the results of model calculations are compared with the at present available void-fraction experimental data. Under low flow-rate operating conditions the data obtained from the model are in fairly good agreement with those of experiments. This shows that the model is well suited for low flow-rate subcooled-boiling operating conditions. **Key words**: two-phase flow, void fraction, subcooled boiling, net vapor generation

不同煤种挥发氮析出过程的数值模拟与试验研究=**Numerical Simulation and Experimental Study of the Separation-release Process of Volatile Nitrogen from Various Sorts of Coal** [刊, 汉] / ZHOU Hao, WENG An-xin, CEN Ke-fa, FAN Jian-ren (Education Ministry Key Laboratory of Clean Utilization of Coal and Environmental Engineering under the Zhejiang University, Hangzhou, China, Post Code: 310027) //Journal of Engineering for Thermal Energy &Power. — 2004, 19(2). —127~130

With the help of a numerical model a study was carried out regarding the following items. They include the separation-release of volatile nitrogen, the generation of intermediate nitrogen-containing product HCN and the process of the latter's transformation into NO. All the above took place in the course of pyrolysis and combustion of various types of coal, such as bituminous coal, lean coal and anthracite, etc. A finite volume method was utilized to perform a discrete solution for the equations of mass, chemical components, momentum and heat energy conservation. Through calculations a whole variety of data were obtained, such as the coal particle ignition time of various ranks of coal, pyrolysis process, porosity factor, HCN and NO formation rate, etc. In addition, the above data were also compared with the test results of a subsidence furnace followed by a pertinent analysis. **Key words**: pulverized coal, nitrogen fuel, numerical simulation

流化床密相区流动特性的数值模拟=**Numerical Simulation of Flow Characteristics in the Dense-phase Zone of a Fluidized Bed** [刊, 汉] / XU Xiang, XIANG Wen-guo, QIN Chen-hu (Education Ministry Key Laboratory of Clean Coal Power Generation and Combustion Technology under the Southeastern University, Nanjing, China, Post Code: 210096) //Journal of Engineering for Thermal Energy &Power. — 2004, 19(2). —131~133

Gas-solid two-phase flows in a fluidized bed have always been a focused objective of experimental research and numerical simulation. Based on an Eulerian two-fluid model, the authors have set up a model for the gas-solid two-phase flow in a fluidized bed. By making use of FLUENT software a numerical simulation was conducted of the two-phase flow characteristics in the dense-phase zone of the fluidized bed, and the characteristic features of the generation, movement and explosion/cracking of in-bed gas bubbles. In the model a particle-phase is treated as continuous media. A mathematical model identical in form to the gas phase was established. By utilizing the dynamic theory of discrete media the concept of granular temperature was introduced to describe the viscous stress of a solid phase. Moreover, a gas-solid two-phase coupling