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不同热天平煤粉燃烧特性试验差异的原因分析

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摘　要: 从热天平结构及试验条件等影响因素出发, 分析了不同热天平煤粉燃烧特性试验结果间产生差异的原因, 提出了改善不同热天平煤粉燃烧特性试验结果间可比性的建议。

关　键　词: 热天平; 煤粉燃烧试验

中图分类号: TQ038.1　　文献标识码: A

1　前言

采用热天平研究煤粉燃烧特性时, 能同时记录试样温度(*T*)曲线、重量变化(*TG*)曲线及重量变化率(*DTG*)曲线等, 具有试验简单, 试验结果重现性好等优点, 因此得到了广泛的应用。但不同热天平煤粉燃烧特性试验结果间的差异较大, 可比性较差。本文较详细地分析了由于热天平本身结构差异等因素对试验结果的影响, 以期更广泛地考虑有关影响因素, 提出了改善不同热天平试验结果间可比性的建议。

2　目前国内使用热天平的概况

目前国内使用热天平进行煤粉燃烧特性研究的一些主要单位及相应的热天平名称如下:

北京煤化所采用英国 Stanton Rodcroft 公司生产的 STA－780 型热天平, 如图 1。天平为立式结构, 气体从炉子底部进入, 经坩埚后再从炉底排出。坩埚直径为 0.6 cm, 高为 0.4 cm。

清华大学采用美国 Du Pont 公司生产的热天平, 如图 2。天平和炉体均为卧式结构, 气体轴向流过坩埚。

西安热工所采用美国 PE 公司制造的 TGS－2 型热天平, 如图 3。天平置于上部容器中, 试样坩埚与平衡坩埚悬吊在天平的两端, 吹扫气由天平下部进气口进入容器中, 氧气由反应气进口进入。坩埚直径为 0.6 cm; 高为 0.12 cm。

哈尔滨发电设备成套设计研究所(以下简称哈成套所)采用 Netizh 公司生产的 STA－429 型热天平, 如图 4。氮气和氧气从炉膛下部进入, 经坩埚后流出炉膛。坩埚上部为圆柱形, 下部近似为圆锥形, 外径为 0.55 cm, 内径约 0.5 cm, 坩埚总高度约为 1.2 cm, 其中圆柱形区域高为 0.9 cm。

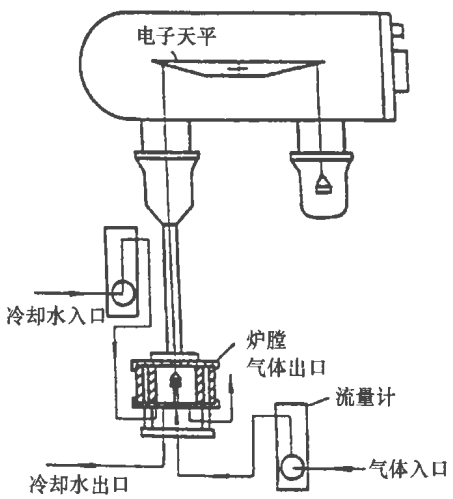

图 1　STA－780 型热天平简图

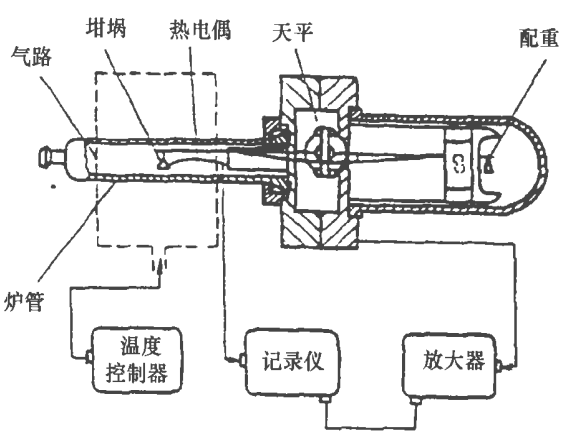

图 2　Du Pont 热天平简图

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哈尔滨工业大学采用日本 RIKAGU8150 型热天平,如图 5。天平为立式结构,气体从炉子底部进入,经坩埚后从炉顶排出。坩埚直径为 1.0 cm,高为 0.2 cm 及 0.8 cm。

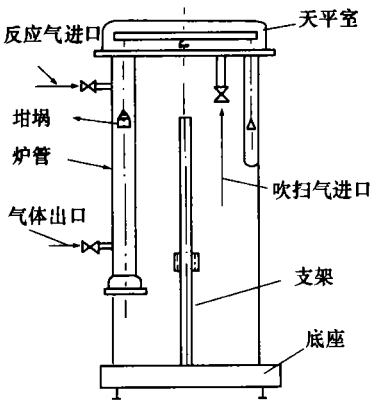

图 3 TGS—2 型热天平简图

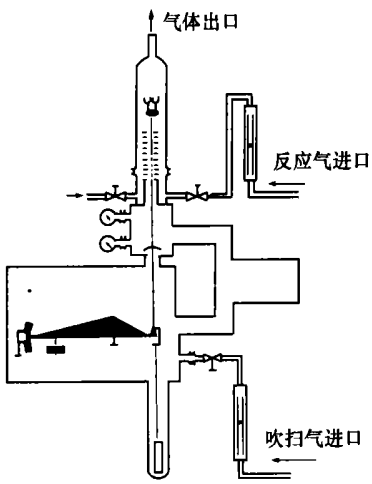

图 4 STA—429 型热天平简图

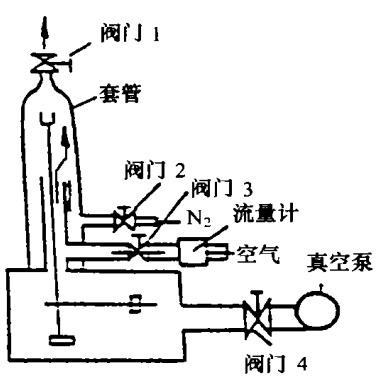

图 5 RIKAGU8150 型热天平简图

其它一些单位,如上海发电设备成套设计研究所,中国矿业大学等,所用的热天平都各有特点。

3 不同热天平试验结果间差异的原因分析

3.1 热解试验结果间差异的原因分析

3.1.1 热解试验结果

以北京煤化所及清华大学为例。

两家试验条件除气体流量外,其余均相同。样品粒度为 200 ~ 360 目;样品量,可燃质约 5 mg;气氛,高纯氮;流量,北京煤化所为 100 ml/min,清华大学为 650 ml/min;升温速度,20 ℃/min;终温,900 ℃。

图 6 ~ 图 8 为清华大学和北京煤化所部分煤种的热解试验结果[1]。煤种的工业分析如表 1。

表 1 煤样的工业分析

		V_{ad}	FC_{ad}	M_{ad}	A_{ad}
1 号	甘肃阿干煤	25.61	56.27	2.72	15.40
2 号	大同永定煤	29.84	60.93	1.61	7.62
3 号	潍坊煤	18.75	49.03	1.22	31
4 号	辽源泰信煤	33.67	41.29	2.47	22.57
5 号	织金煤	7.24	78.77	1.02	12.97

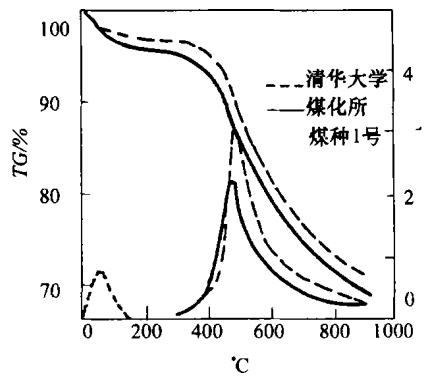

图 6 热解试验结果

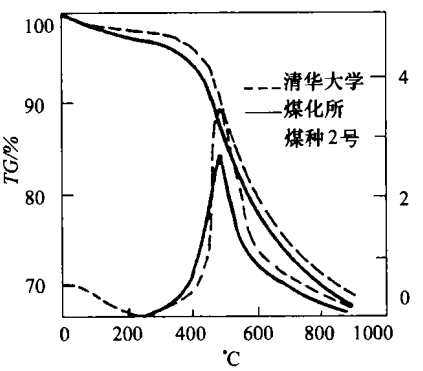

图 7 热解试验结果

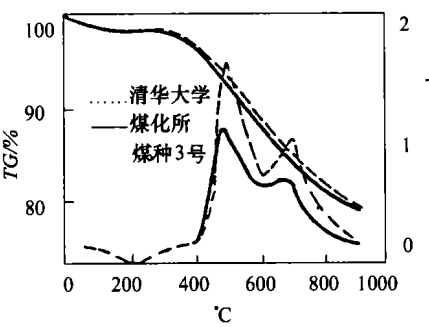

图 8 热解试验结果

由图 6 ~ 图 8 可见,图中 *TG*、*DTG* 曲线均有一定的差异。两家试验结果有以下一些特点。

(1) 900 ℃时试样析出的挥发分 V_{900} 与 V_{ad} 的比值 $V_{900}/V_{ad} > 1.0$,其比值偏大。

(2) 对 *DTG* 曲线,变化趋势基本相同。清华大学所得的最大失重率、最大失重率对应的温度及初始热解温度均大于北京煤化所的试验值。

3.1.2 结果间差异的原因分析

(1) 两家热解试验前天平系统没有抽真空,热解过程中由于残留的空气,试样可能产生氧化。

(2) 氮气纯度对热解试验结果有很大影响,尤其当升温速度较低时,影响更大。

(3) 未仔细分析坩埚空载时,随着炉膛温度升

高，气体密度变化而引起的支持器的空气浮力及炉内气体流速等一些因素的综合作用所导致的试样重量变化，即虚假失重或增重。

（4）虽然统一了某些试验条件，但对仪器本身某些参数的设置也应仔细考虑，如时间常数 t_s。在其它试验条件相同时，改变 t_s 值，*TG*、*DTG* 曲线也会发生相应的变化。

本文采用 RIKAGU8150 型热天平，对上述几个影响热解试验结果的因素进行了一些试验分析。

图 9 为采用 RIKAGU8150 型热天平时，抽真空与否对热解试验结果的影响，可见影响较大。

有些热天平不设抽真空装置，则在试验前可先用氮气吹扫，以除去天平室及套管中的空气。图 10 为采用 RIKAGU8150 型热天平在不同的吹扫时间下的热解特性曲线。吹扫气流量为 100 ml/min。可见，当吹扫时间为 30 min 时，试验结果与抽真空条件下的试验结果相近。

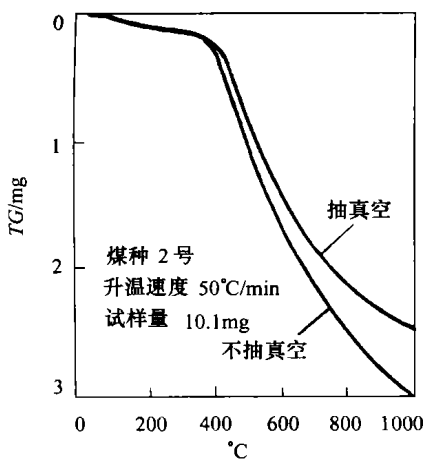

图 9　抽真空对热解的影响

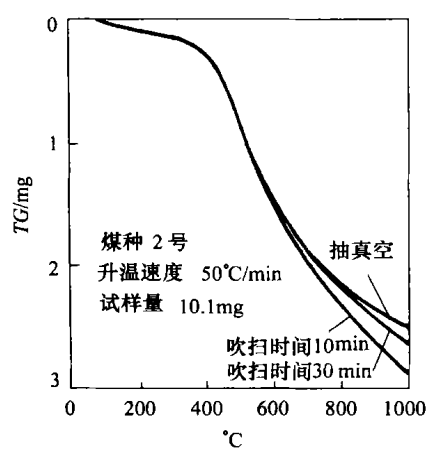

图 10　吹扫时间对热解的影响

试验发现，即使采用高纯氮，有时氮气纯度也难以保证，本文作者采用 RIKAGU8150 型热天平进行了氮气纯度考核试验。在符合热解试验条件下，将煤样升温至 900 ℃，并恒温 7 min，此时已基本完成热解，而后将温度降至 600 ℃，继续恒温 30 min，发现试样仍以某一失重率缓慢失重，且该失重率随氮气纯度降低而加大（分别采用普氮、纯氮及高纯氮），因此，在进行热解试验时，应对氮气纯度会对试验结果带来的误差大小进行分析。

吹扫气流量对虚假失重的影响较大。以 RIKAGU8150 型热天平为例，当吹扫气流量为 100 ml/min，TG 支架，升速为 100 ℃/min，终温为 1 000 ℃时，虚假失重达 0.4 mg，如当试样失重为 5 mg 时，由虚假失重产生的误差就高达 8%。吹扫气流量越大，由于虚假重量变化引起的试验误差随之增加。

另外，在其它试验条件相同时，改变时间常数 t_s，*TG*、*DTG* 曲线也会发生相应的变化。

3.2　煤粉燃烧特性试验结果间差异的原因分析

3.2.1　煤粉燃烧特性试验结果

以西安热工所及哈成套所为例。

两家试验条件除气体流量外，其余均相同。样品粒度为 200～360 目；样品量，可燃质约 10 mg；气体流量，哈成套所的氧气流量为 100 ml/min，保护气体氮气流量为 50 ml/min；西安热工所的氧气流量为 47 ml/min，保护气氮气流量为 186 ml/min；升温速度，40 ℃/min；终温 900 ℃。

图 11～图 12 为两家部分煤种的燃烧特性试验结果，由图可见试验结果有以下一些特点。

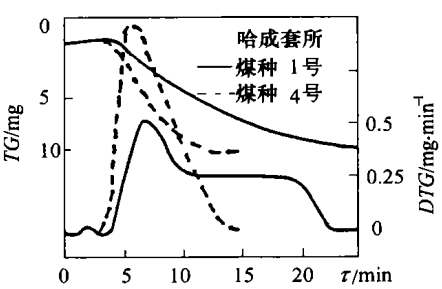

图 11　煤粉燃烧试验结果

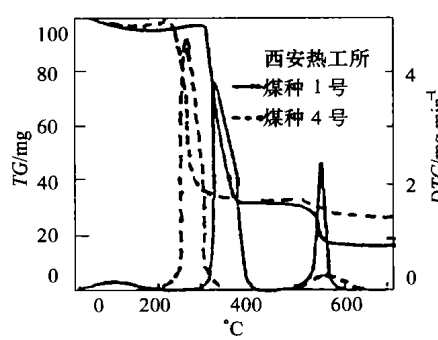

图 12　煤粉燃烧试验结果

（1）在着火点（失重率迅速增加点）均有一微量增重。

（2）西安热工所的 *DTG* 曲线上一般均有两个峰值，最大失重率较大；哈成套所的 *DTG* 曲线上有一个峰值，最大失重率较小，紧接峰值后出现一个平台区，只有少数高挥发分煤种的 *DTG* 曲线无平台区。

(3) 燃烧 98%可燃质所需时间相差很大。

3.2.2 结果间差异的原因分析

哈成套所采用深坩埚, 气体由下往上流经坩埚(相对于坩埚), 因此通过坩埚出口截面的氧通量可采用文献[2] 中有关公式计算。在煤粉燃烧前期试样失重包括两部分, 一是挥发分快速析出, 二是坩埚中煤粉的燃烧, 对应于 *DTG* 曲线表现为失重率较大。随着挥发分不断析出, 此时试样失重取决于坩埚中焦碳的燃烧速度, 由于坩埚较高, 经坩埚出口截面的氧通量较小, 燃烧速度取决于通过坩埚出口截面的氧通量, 燃烧过程为扩散控制区, 即对应于 *DTG* 曲线上的平台区。采用文献[2] 中的有关公式, 计算得通过坩埚出口截面氧通量与 *DTG* 曲线上平台区的燃烧速率相对应。对于一些高挥发分煤种, 随着挥发分不断析出, 坩埚中可燃质的量较小, 通过坩埚出口截面的氧通量能满足坩埚中焦碳燃烧所需的氧量, 此时 *DTG* 曲线上的平台区消失。

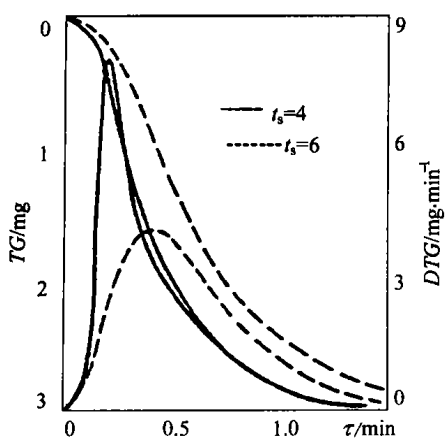

图 13 t_s 对燃尽时间的影响

西安热工所采用浅坩埚, 通过坩埚出口截面的氧量能满足燃烧的需要, 因此燃烧曲线无平台区。

时间常数 t_s 或仪器本身反应试样重量变化的迟延时间对燃尽时间也有影响, 图 13 为采用 RIKAGU8150 型热天平时织金煤焦的燃尽时间试验结果, 试验条件为: 氧气, 流量为 130 ml/ min, 燃烧温度为 980 K, 等温燃烧, 试验用煤焦量为 6.5 mg, *TG* 支架, 采用直径为 1.0 cm, 高为 0.2 cm 的坩埚, 可见 t_s 取为 6 时, 在相同的燃尽度下, 燃尽时间明显增加。

4 改善不同热天平试验结果间可比性的建议

4.1 对热解试验结果

(1) 试验前, 应对所用的氮气纯度进行简单测试, 以了解由于氮气不纯, 试样氧化对热解试验结果影响的大小。

(2) 尽量抽真空, 如不能抽真空时, 应在试验前先用氮气流吹扫; 对于不同的热天平, 在一定的吹扫气流量下, 可以找到一个合理的吹扫时间, 以控制由于天平室、套管中残存的空气对热解试验结果带来的误差。

(3) 应仔细考虑虚假重量的变化对热解试验结果的影响。

(4) 在热天平允许的条件下, 尽量提高升温速度, 一般控制在 50 ℃/min ~ 300 ℃/min 较为合适, 此时可大大减小由于试样氧化而带来的误差。

(5) 适当增加试样量, 以减小某些误差对试验结果的影响。

(6) 考虑仪器本身某些可调参数, 如时间常数 t_s。

4.2 对煤粉燃烧特性试验结果

(1) 尽量保证具有相近的坩埚形状及相同的坩埚尺寸, 此时可保证试样层厚度基本相同, 氧气在试样层内的扩散规律相同。

(2) 应仔细分析坩埚周围氧浓度的变化, 选择合适的进气、排气方式, 以便能估算试验中坩埚周围氧浓度的变化。

(3) 应考虑仪器本身某些可调参数, 如 t_s。

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(渠 源 编辑)

喜庆《热能动力工程》创刊百期

action mechanism of wet calcium base sorbent. The test results indicate that as compared with traditional single-level water spray the multi-level water spray can result in a more uniform temperature distribution in the fluidized bed, a relatively large reduction of the approach saturation temperatureΔT, a marked increase in desulfurization efficiency and a more stable and reliable operation of the system. A mass spectrographic analysis and an electronic microscope analysis have shown that after the reaction of SO_2 with $Ca(OH)_2$ a reaction product layer was formed on the surface of the desulfurizing agent, which alleviates the further reaction between SO_2 and the desulfurizing agent. **Key words**: circulating fluidized bed, flue gas desulfurization, multi-level water spray, approach saturation temperatureΔT, desulfurization efficiency, electronic microscope analysis

大型电站锅炉煤种适应性分析实例＝**Analysis of the Adaptability of Large-sized Power Plant Boilers to Various Kinds of Coals** [刊, 汉] / SUN Lu-shi, LU Ji-dong, ZENG Li, et al (State Key Laboratory for Coal Burning Research under the Huazhong University of Science &Technology, Wuhan, China, Post Code: 430074) // Journal of Engineering for Thermal Energy &Power. —2002, 17(4): 353 ~ 355

Combustion characteristics of 12 kinds of coal, intended for an existing 670 t/h boiler, have been analyzed. A correlation of these characteristics with the boiler construction features was conducted to evaluate the adaptability of these coals to the above-mentioned boiler. This evaluation aims at providing a basis for deciding on and exploring new sources of coal in order to ensure the safe and economical operation of the boiler. **Key words**: combustion characteristics, boiler constants, adaptability of various kinds of coal to boilers

垃圾焚烧灰渣的成分分析及其熔融特性＝**Component Analysis of Municipal Solid Waste Incineration (MSWI) Ash and Its Melting Characteristics** [刊, 汉] / YAN Chang-feng, LIN Bo-chuan, CHEN En-jian, CHEN Yong (Thermo-fluid Process Lab of Guangzhou Energy Conversion Research Institute under the Chinese Academy of Sciences, Guangzhou, China, Post Code: 510070) // Journal of Engineering for Thermal Energy &Power. —2002, 17(4): 356 ~ 358, 369

For a municipal solid-waste incineration (MSWI) boiler the ash melting characteristics of municipal solid waste (MSW) are one of the most important factors, which have a decisive influence on the harmful effect of ash deposited on heating surfaces. Through the measurement and determination of MSW ash components and the ash melting point a systematic analysis was performed of the relation between the MSW ash melting characteristics and ash components. Furthermore, the difference between MSW ash and coal ash of low-melting point in respect of melting characteristics and components is also identified. On the above basis some proposals are put forward to improve MSW combustion in general. **Key words**: municipal solid waste, ash burning, , component analysis, melting characteristics

径向分层旋流燃烧器燃烧可视化研究＝**Visualization Study of Coal Combustion in a Radially Stratified Swirl-type Burner** [刊, 汉] / HE Lei, FAN Wei-dong, ZHANG Ming-chuan, WU Jiang, et al (Department of Energy Engineering, Shanghai Jiaotong University, Shanghai, China, Post Code: 200240) // Journal of Engineering for Thermal Energy &Power. —2002, 17(4): 359 ~ 362, 374

With the help of an image acquisition and processing system a visualization study was conducted of the coal gas flame of a radially stratified swirl-type burner. The quantitative analysis of a separated flame front was then performed through the use of a fractal theory. The results of analysis indicate that it is possible to truthfully describe the spatial and geometric characteristics of the flame front by using a fractal dimension, thus providing an effective means for an in-depth study of the effect of flame structural shape on the mixing of fuel and air. **Key words**: image processing, swirl-type burner, fractal dimension, visualization

不同热天平煤粉燃烧特性试验差异的原因分析＝**An Analysis of the Factors Causing Differences in the Test Results of Pulverized coal Combustion Obtained from Using Different Thermobalances** [刊, 汉] / ZHU Qun-yi, QIN Yu-kun, WU Shao-hua (School of energy Science &Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001), XU Yan (Heilongjiang Provincial Electric Power School, Harbin, China, Post Code: 150020) //

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From the perspective of influencing factors of thermobalance construction and test conditions, etc., analyzed are the causes leading to differences in the test results of pulverized coal combustion characteristics obtained from different thermobalances. Meanwhile, some proposals are put forward to improve the comparability of test results of pulverized coal combustion characteristics obtained from different thermobalances. **Key words**: thermobalance, pulverized coal combustion test

水平管内油气水三相分层流截面含气率的研究=**A Study of the Void Fraction of Oil-gas-water Three-phase Stratified Flows in a Horizontal Tube** [刊, 汉] / ZHOU Yun-long, SUN Bin, CAI Hui, et al (Power Engineering Department, Northeast Electric Power Institute, Jilin, China, Post Code: 132012) // Journal of Engineering for Thermal Energy & Power. —2002, 17(4): 367 ~ 369

With an oil-gas-water three-phase mixture serving as a working medium a theoretical and experimental study was performed of the average-section void fraction of stratified flows in a horizontal tube. Through a simplified dynamic analysis of the stratified flows a theoretical model was obtained of the section void fraction. The calculated values agree well with experimental ones. It has been found that the factors having an influence on the section void fraction of the stratified flows include not only the reduced gas speed and liquid speed, but also the oil fraction of the oil-water mixture. **Key words**: horizontal tube, section void-fraction, oil-gas-water three-phase flow, stratified flow

竖直细小管内水—空气环状流蒸发换热特性研究=**A Study of the Evaporation Heat Exchange Characteristics of Water-air Annular Two-phase Flows in a Vertical Slender Tube** [刊, 汉] / YI Jie, LIU Zhen-hua, WANG Jing (Power and Energy Engineering Institute under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for TheOrmal Energy & Power. —2002, 17(4): 370 ~ 374

Through a theoretical analysis a study has been carried out concerning the evaporation heat exchange characteristics of water-air annular two-phase flows in a vertical slender tube. The study results indicate that in a slender tube the influence of gravitational force and gas-liquid surface tension force can be neglected. The evaporation heat exchange characteristics under a constant heat-flux density very approximate to those under a constant wall temperature. The results of calculation have also shown that the evaporation heat exchange of water-air two-phase annular flows in a vertical slender tube represents a very effective means of intensified heat exchange. **Key words**: annular two-phase flow, evaporation, intensified heat exchange, phase change

正倾斜叶片压气机叶栅二次流的数值研究=**Numerical Investigation of Secondary Flows in a Compressor Cascade with Positively leaned Blades** [刊, 汉] / WANG Hui-she, ZHONG Jing-jun, WANG Zhong-qi (Energy Engineering College under the Harbin Institute of Technology, Harbin, China, Post Code: 150001), ZHAO Gang (No.1 Engineering Division of Heilongjiang Thermal Power Co., Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. —2002, 17(4): 375 ~ 378

With the help of Beam-Warming's approximate and implicit factorization scheme and a MML algebraic turbulence model and by using the method of quasi-compressibility for the solution of a Reynolds-average quasi-compressibility N-S equation a numerical investigation was performed of the three-dimensional viscid flow field of a compressor cascade with positively leaned blades. The results of the investigation were compared with those of a linear cascade. It has been found that the generation and development process of the upper and lower channel vortex of the positively leaned cascade is distinctly different from that of the linear cascade. This has led to a weakening of the secondary flow at the positively leaned side, an expansion of the secondary-flow high loss zone at the negatively leaned side and a deterioration of the flow conditions. The separation of the boundary layer at the cascade top region has developed into a greater zone expanding to the cascade middle portion. The calculated results agree relatively well with the experimental ones. **Key words**: leaned blade, compressor cascade, secondary flow, quasi-compressibility N-S equation

带粒透平中叶片冲蚀的数值计算及振频变化预估=**The Numerical Calculation of Blade Erosion in a Particle-**