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Muszynska 模型经验系数对转子系统稳定性的影响

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摘 要: 基于 Muszynska 模型, 推导建立密封流体激振力作用下的转子 - 密封系统非线性动力学方程。对运动微分方程进行数值分析, 研究了该系统的分岔特性以及 Muszynska 模型中经验系数对系统稳定性的影响规律。分析结果表明, 密封流体激振力导致的转子非线性动力学行为具有非常复杂的演化过程, 其中平均周向速比常数及描述平均周向速比与转子涡动之间关系的经验系数是影响转子系统稳定性的关键因素, 而其它经验系数影响均在 5% 以内, 该结果为降低相关的实验费用提供了理论依据。

关 键 词: 转子-密封系统; Muszynska 模型; 稳定性; 密封流体激振

中图分类号: O322; TH133 **文献标识码**: A

引 言

随着蒸汽轮机装置介质压力不断提高, 转子柔性不断增加, 密封流体激振力导致的机组自激振动问题日益突出, 严重时会引起机组轴系的失稳破坏[1]。Muszynska 密封流体激振力模型由于把握住了 Alford 力的主要力学特征[2], 具有较强概括性, 能够较好地反映密封力的非线性特性, 因此目前密封流体激振力作用下的转子稳定性问题研究大多基于该模型[3~7]。

Muszynska 流体激振力模型中涉及的参数大致可以分为两类。第一类为密封结构及介质参数, 包括密封直径、密封长度、密封半径间隙以及密封轴向压降等。研究这一类参数对转子系统稳定性的影响能够指导密封系统的设计, 为解决密封流体激振故障提供理论依据; 第二类是与损失或者流体 - 壁面摩擦相关的经验系数, 包括平均周向速比常数、密封气流进口损失系数、流体 - 壁面摩擦系数等。目前, 这些经验系数往往是通过实验来获得, 而且实验费用较高, 虽然文献[8]给出了基于定常流场三维 CFD 模拟的经验系数确定方法, 但是该方法的准确性还有待实验验证。因此, 本研究是在研究密封流体激振力作用下转子系统非线性分岔特性的基础上, 通过分析第二类经验参数对转子系统稳定性的影响规律, 找出影响转子系统稳定性的关键经验参数, 为降低相关的实验费用提供理论依据。

1 Muszynska 密封流体激振力模型

Muszynska 密封流体激振力模型是 Muszynska 和 Bently 在大量实验的基础上提出来的[2], 其特点是: 密封激振力对转子的扰动反力以平均角速度 $\tau\omega$ 绕轴颈旋转, 其中 τ 为流体平均周向速比, 该激振力在固定坐标中可描述为:

$$-\begin{bmatrix} F_X \\ F_Y \end{bmatrix} = \begin{bmatrix} K - m_f\tau^2\omega^2 & \tau\omega D \\ -\tau\omega D & K - m_f\tau^2\omega^2 \end{bmatrix}\begin{bmatrix} X \\ Y \end{bmatrix} + \begin{bmatrix} D & 2\tau m_f\omega \\ -2\tau m_f\omega & D \end{bmatrix}\begin{bmatrix} \dot{X} \\ \dot{Y} \end{bmatrix} + \begin{bmatrix} m_f & 0 \\ 0 & m_f \end{bmatrix}\begin{bmatrix} \ddot{X} \\ \ddot{Y} \end{bmatrix} \quad (1)$$

式中: K、D、m_f—流体对转子扰动运动的刚度、阻尼和惯性效应。实验和数值研究结果显示 τ、K、D 为扰动位移 X, Y 的非线性函数, 即:

$$K = K_0(1 - e^2)^{-n}, D = D_0(1 - e^2)^{-n},$$
$$\tau = \tau_0(1 - e)^b$$

其中, $e = \sqrt{X^2 + Y^2}/c$ 为转子相对偏心位移, c 为密封间隙。K_0、D_0 以及 m_f 可以用 Childs 的环压密封动力系数公式计算[9]:

$$K_0 = \mu_3\mu_0, D_0 = \mu_1\mu_3 T, m_f = \mu_2\mu_3 T$$

$$\mu_0 = \frac{2\sigma^2}{1 + \xi + 2\sigma}E(1 - m_0)$$

$$\mu_1 = \frac{2\sigma^2}{1 + \xi + 2\sigma}\left[\frac{E}{\sigma} + \frac{B}{2}\left(\frac{1}{6} + E\right)\right]$$

$$E = \frac{1 + \xi}{2(1 + \xi + 2\sigma)}$$

$$\mu_2 = \frac{\sigma}{1 + \xi + 2\sigma}\left(\frac{1}{6} + E\right)$$

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$$\lambda = n_0 R_a^{m_0}[1 + (R_v/R_a)^2]^{(1+m_0)/2},$$

$$B = 2 - \frac{(R_v/R_a)^2 - m_0}{(R_v/R_a)^2 + 1}$$

$$\sigma = \lambda l/\delta, T = l/\nu, R_v = R\omega\delta/\upsilon, R_a = 2\nu\delta/\upsilon$$

其中,平均周向速比常数 τ_0、密封气流进口损失系数 ξ、m_0、n_0、n 及 b 等系数,目前往往都是通过实验获得,实验费用较高,因此有必要通过分析这些经验参数对转子系统稳定性的影响,找出其中影响转子稳定性的主要经验参数,减少非关键因素造成的不必要实验费用支出。

2　单盘转子 – 密封系统动力学模型

图 1 为单盘转子 – 密封系统,转子为两端简支的单圆盘系统,密封力等效作用在圆盘处,转子存在不平衡量,圆盘几何中心为 O',质量偏心为 O_1,偏心距为 r,圆盘质量为 m_R,转子阻尼为 D_R,转子刚度为 K_R,转子转速 ω,密封力为 F_X、F_Y,系统动力学方程可写为:

$$\begin{bmatrix} m_R & \\ & m_R \end{bmatrix}\begin{bmatrix} \ddot{X} \\ \ddot{Y} \end{bmatrix} + \begin{bmatrix} D_R & \\ & D_R \end{bmatrix}\begin{bmatrix} \dot{X} \\ \dot{Y} \end{bmatrix} + \begin{bmatrix} K_R & \\ & K_R \end{bmatrix}\begin{bmatrix} X \\ Y \end{bmatrix}$$

$$= \begin{bmatrix} F_X \\ F_Y \end{bmatrix} + \begin{bmatrix} 0 \\ -m_R g \end{bmatrix} + \begin{bmatrix} m_R r\omega^2\cos(\omega t) \\ m_R r\omega^2\sin(\omega t) \end{bmatrix} \quad (2)$$

引入无量纲变换 $x = X/c, y = Y/c, \tau = \omega t$,则式(2)变为:

$$\begin{cases} \ddot{x} = -D_{a1}\dot{x} - D_{a2}\dot{y} - K_{a1}x - K_{a2}y + \rho\cos(\tau) \\ \ddot{y} = D_{a2}\dot{x} - D_{a1}\dot{y} + K_{a2}x - K_{a1}y + G + \rho\sin(\tau) \end{cases} \quad (3)$$

其中,$K_{a1} = \dfrac{K_R + K - m_f\tau^2\omega^2}{M\omega^2}, K_{a2} = \dfrac{\tau D}{M\omega}, G = -\dfrac{m_R g}{Mc\omega^2}$

$$D_{a1} = \frac{D_R + D}{M\omega}, D_{a1} = \frac{2m_f\tau}{M}, \rho = \frac{m_R r}{Mc}, M = m_R + m_f$$

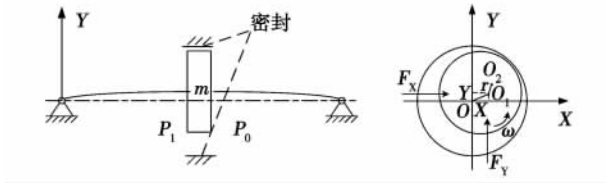

图 1　单盘 – 转子密封系统动力学模型

3　单盘转子 – 密封系统分岔特性分析

采用 Runge-Kutta 法对式(3)进行时程分析,计算时 Muszynska 模型中的相关经验参数参考文献[8],如表 1 所示,转子、密封结构及蒸汽参数如表 2 所示,计算结果如图 2 和图 3 所示。

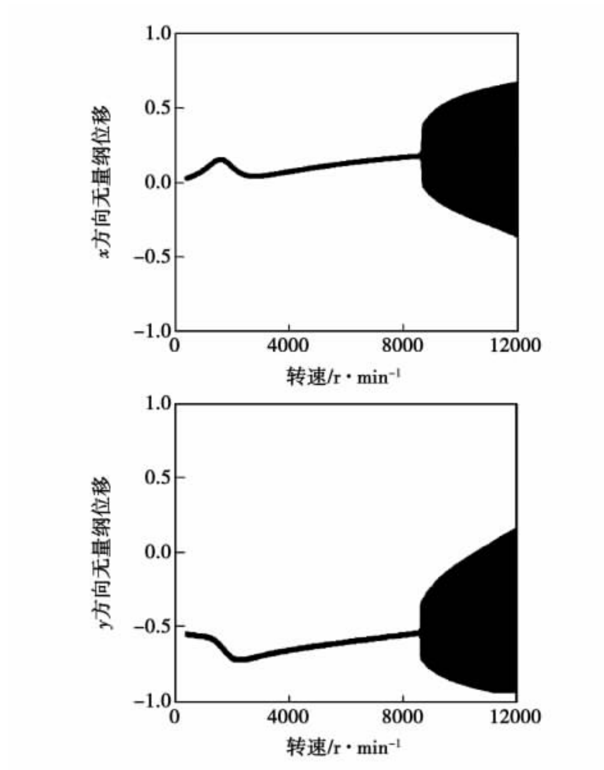

图 2　单盘转子–密封系统分岔图

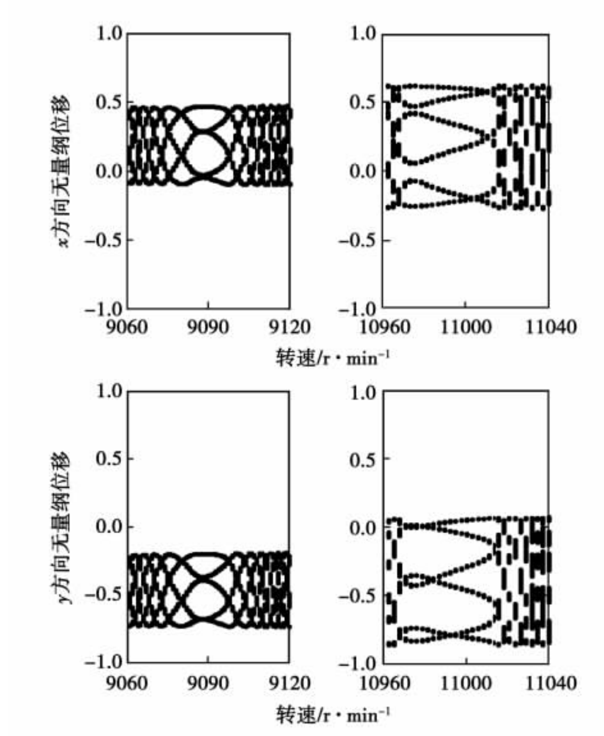

图 3　单盘转子–密封系统分岔图局部放大图

表 1　Muszynska 模型中涉及的与损失相关的参数

ξ	m_0	n_0	τ_0	n	b
0.093	-0.24	0.079	0.28	2.11	0.30

表 2　转子、密封结构及蒸汽参数

	数　值
转子质量 m_R/kg	125
转子刚度 K_R/N · m^{-1}	4.2×10^6
密封半径间隙 c/mm	0.5
密封半径 R/mm	200
转子结构阻尼 D_R/N · s · m^{-1}	5 000
偏心距 r/mm	0.05
密封长度 l/mm	80
密封两端压差 ΔP/Pa	0.5×10^5

图 2 为单盘转子-密封系统的分岔图，图 3 为分岔图的局部放大图，从中可以看出，该转子转速上升到 8 370 r/min 后，转子系统的振动突然增大，转子失稳。整个转速域可以分为若干区域，转子振动特性在这些区域中完全不同，整个演化过程复杂。转速低于 8 370 r/min 时，转子为稳定的周期运动；转速在 9 075 ~ 9 098 r/min 范围内，转子发生 5 倍周期运动；转速在 10 970 ~ 11 015 r/min 范围内，转子发生 6 倍周期运动；其它转速区域内转子发生 Hopf 分岔运动。由此可知，转子-迷宫密封系统失稳后，其分岔特性非常复杂，在绝大部分转速范围内都处于概周期运动状态，在某些狭窄的转速域内系统会出现各种亚谐运动，倍周期分岔和 Hopf 分岔随着转速的升高交替出现。

4　经验系数对单盘转子-密封系统稳定性的影响

在密封流体激振力作用下单盘转子-密封系统分岔特性分析的基础上，在可能的变化范围内，分别改变 τ_0、ξ、m_0、n_0、n 及 b 的值，对不同经验系数下单盘转子密封系统的稳定性进行研究，结合 Floquet 理论，采用文献[6]的快速 Galerkin 法和同伦算法得到不同经验系数下单盘转子 - 密封系统的失稳转速，并将失稳转速随各经验参数的变化规律绘于图 4。

从图 4 中可以看出，平均周向速比常数及描述平均周向速比与转子涡动之间关系的经验系数 b 是转子 - 密封系统稳定性的主要经验参数。随着平均周向速比常数的增大，转子系统的失稳转速降低，平均周向速比常数越小，失稳转速变化越剧烈；经验系数 b 是对平均周向转速在不同偏置情况下的修正，也是直接影响密封内流场的脉动频率主要因素，随着经验参数 b 的增大，转子系统的失稳转速升高，经验系数和失稳转速近似成正比关系。因此，在应用 Muszynska 模型分析转子系统稳定性时，对平均周向速比常数及经验系数 b 的精度要求比较高，需要提高这两个参数实验测定的准确性。

随着当量刚度、阻尼修正系数 n 的增大，转子系统的失稳转速降低，修正系数 n 越小，失稳转速变化越剧烈，但在整个修正系数 n 变化范围内，其失稳转速最大变化小于 5%；随着入口损失系数 ξ 的增大，转子系统的失稳转速升高，但是入口损失系数 ξ 的变化范围内，失稳转速的变化非常小，其最大变化量小于 1%；随着与流体 - 壁面摩擦相关的系数 m_0 和 n_0 的增大，转子系统的失稳转速降低，系数 m_0、n_0 和失稳转速近似成反比关系，且在整个参数的变化范围内，其失稳转速变化均小于 4%。相对于平均周向速比常数及描述平均周向速比与转子涡动之间关系的经验系数 b 而言，当量刚度、阻尼修正系数 n、入口损失系数 ξ 以及与流体 - 壁面摩擦相关的系数 m_0 和 n_0 对转子系统的失稳转速影响较小，因此实验测定时无需花费太大的代价来测定这 4 个参数。

5　结　论

（1）转子-迷宫密封系统失稳后，分岔特性非常复杂，在某些狭窄的转速域内系统会出现各种亚谐运动，倍周期分岔和 Hopf 分岔随着转速的升高交替出现。

（2）平均周向速比常数及描述平均周向速比与转子涡动之间关系的经验系数 b 是转子 - 密封系统稳定性的主要经验参数，实验测定时需要提高这两个参数的准确性。

（3）入口损失系数对转子的失稳转速几乎没有影响，当量刚度、阻尼修正系数 n 以及与流体 - 壁面摩擦相关的系数 m_0 和 n_0 对转子-密封系统稳定性的影响都不大，在参数变化范围内失稳转速的变化均小于 5%，无需花费太大的代价来提高这 4 个参数实验测定的准确性。

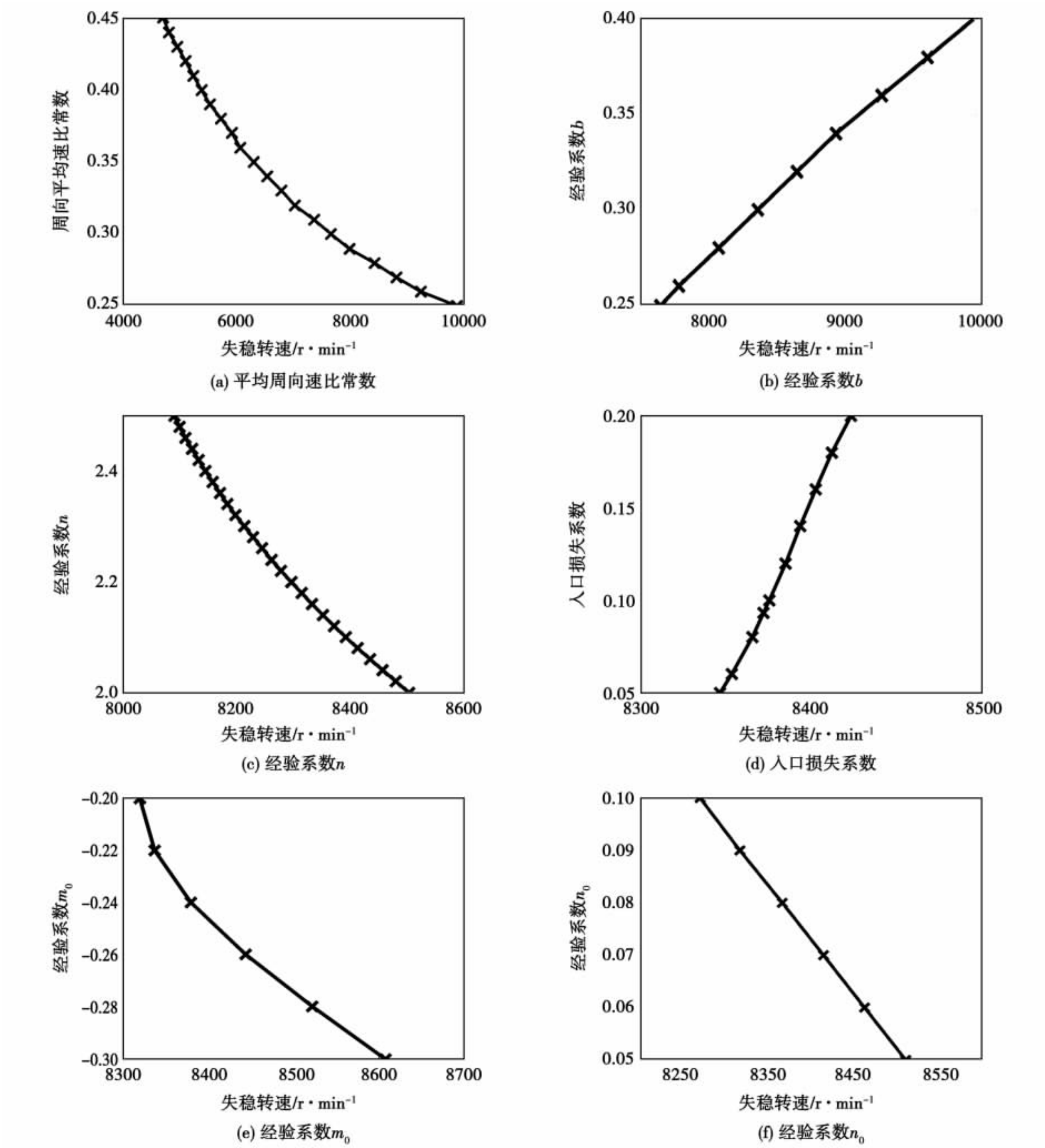

图 4 经验系数对单盘转子-密封系统稳定性的影响规律

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Studied was the influence of the flow path arrangement and number of branch lines in a finned tube heat exchanger on the performance of its air-source gas engine heat-pump system. The research results show that when a reverse cross flow path arrangement mode is adopted, the air-source gas engine heat pump will obtain the best performance, while that adopting a positive flow path arrangement mode will result in the worst. Compared with the direct flow path arrangement mode, the above-mentioned performance can increase by about 10% when the reverse cross flow path arrangement mode is adopted. The foregoing performance adopting 14 branch lines for a finned tube heat exchanger will increase by about 7% when compared with that adopting 7 branch lines. Therefore, the design of a finned tube heat exchange has a relatively big influence on the performance in question and a rational design of the finned tube heat exchange can play a definite role in enhancing the performance under discussion. **Key words**: air-source gas turbine heat pump, flow path arrangement, number of branch lines, system performance

不同叶轮高速部分流泵非定常压力场数值分析 = **Numerical Analysis of Unsteady Pressure Fields of a High-speed Portion Flow Division Pump in Various Impellers** [刊,汉] CHAI Li-ping, PAN Bing-hui, DING Ya-na (Research Center for Fluid Mechanical Engineering Technology, Jiangsu University, Zhenjiang, China, Post Code: 212013), SHI Hai-xia (Hefei Institute of Technology, Hefei, China, Post Code: 230009) // Journal of Engineering for Thermal Energy & Power. - 2011, 26(1). - 20~22

To study the pressure pulsation caused by the interference between the rotating and static portion, i. e. an impeller and a volute in a high speed portion flow division pump by using the S-A turbulent flow equation and sliding grid technology in software Fluent 6.3, a straight impeller and a complex one were chosen respectively. An unsteady numerical simulation was performed at the design operating point to analyze the total pressure and static pressure distribution chart in the middle section. It has been found that the total pressure of the complex straight impeller is higher than that of the straight impeller but their static pressures are close. 4 monitoring points were arranged at the circumferential locations of 0°, 90°, 180° and 270° of the inner volute wall at the outlet. A comparison of the total pressure pulsations shows that the peak values of the complex impeller are conspicuously higher than those of the straight one and the fluctuation amplitude between the peaks, however, is smaller than that of the straight one. **Key words**: Impeller, high-speed flow division pump, unsteady pressure field, pressure pulsation

Muszynska 模型经验系数对转子系统稳定性的影响 = **Influence of Muszynska Model Empirical Coefficient on the Stability of a Rotor System** [刊,汉] LI Yong, DONG Hong-yun (College of Energy Source and Mechanical Engineering, Northeast University of Electric Power, Jilin, China, Post Code: 132012) // Journal of Engineering for Thermal Energy & Power. - 2011, 26(1). -23~26

Based on Muszynska model, derived and established was a non-linear dynamic equation for a rotor-gland seal system under the action of a seal fluid excitation force. A numerical analysis was performed of the movement differential equation and a law governing the influence of the bifurcation characteristics of the system under discussion and the empirical coefficient in Muszynska model on the system stability was studied. The analytic results show that the nonlinear kinetic behavior of the rotor caused by the seal fluid excitation force features a very complicated evolution process. During this process, the average circumferential speed ratio constant and the empirical coefficient depicting the relationship between the average circumferential speed ratio and the rotor swirling constitute the key factors influencing the stability of the rotor system. The influence of other empirical coefficients, however, is invariably within 5%. This result can provide a theoretical basis for lowering relevant experiment costs. **Key words**: rotor-gland seal system, Muszynska model, stability, seal fluid excitation

泡沫陶瓷填料湿化器加湿性能实验研究 = **Experimental Study of the Humidifying Performance of a Foam Ceramic Packing Humidifier** [刊,汉] LIU Jian-jian, XU Zhen, XIAO Yun-han (Key Laboratory on Advanced Energy and Power, Engineering Thermophysics Research Institute, Chinese Academy of Sciences, Beijing, China, Post Code: 100190) // Journal of Engineering for Thermal Energy & Power. -2011, 26(1). -27~30

A humidifier constitutes a key component in a humid air turbine cycle and its performance has an important influence over the cycle performance. The humidifying performance of a humidifier under a pressurization condition using a new-type SiC foam ceramic packing was experimentally studied and the influence of the water/air ratio, inlet water temperature, operating pressure and inlet air temperature on the humidifying process, analyzed. The research results show that to increase the water/air ratio or inlet water temperature can increase accordingly the inlet and outlet air temperature difference and moisture content difference as well as the node temperature difference of the humidifier. To increase the operating pressure can increase the inlet and outlet air temperature difference and decrease the moisture content difference. To increase the air temperature can increase the outlet water temperature but exercise no big influence on the outlet air temperature and moisture content. **Key words**: HAT (humid air turbine) cycle, humidifier, foam ceramic packing, node temperature difference

竖直矩形细通道内水沸腾换热的数值模拟 = **Numerical Simulation of Water Boiling Heat Exchange Inside a Vertical Rectangular Slim Passage** [刊,汉] GUO Lei, ZHANG Shu-sheng, CHENG Lin (Research Center for Thermal Sciences and Engineering, Shandong University, Jinan, China, Post Code: 250061) //Journal of Engineering for Thermal Energy & Power. -2011, 26(1). -31~35

Studied was the boiling heat exchange inside a vertical rectangular slim passage of 1 and 0.1 mm width. Through the adoption of a numerical simulation method, the bubble formation, growth and separation process were investigated. The influence of the phase interface movement and change on the pressure difference inside the system and average surface heat exchange coefficient was obtained by using a geometrical reconstruction and interface tracing method. During the calculation, the actions of gravity, surface tension and wall surface adhesion were taken into account. It has been found that the difference in the width of the passage produces a very big influence on the bubble growth mode and morphology and thereby leads to a change in the critical heat flux density. The action of the surface tension is far bigger than that of the gravity in the boiling heat exchange process inside the slim passage. With a decrease of the passage size, the boiling heat exchange coefficient will increase conspicuously, proving that the slim passage plays a role of intensifying the heat exchange. As idealization assumptions were made in the numerical calculation, they may result in a boiling heat exchange coefficient obtained by the numerical simulation calculation mostly higher than the test one currently available for boiling heat exchange inside a slim passage. **Key words**: slim passage, boiling heat exchange, numerical simulation, intensified heat exchange