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小型增压锅炉过热器性能评估方法研究

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摘　要: 结合传热学和流体力学基本理论, 建立了增压锅炉过热器数学模型, 采用差分方法对数学模型进行离散, 并利用实验数据对仿真模型进行了验证, 进而编制了小型增压锅炉过热器性能仿真程序。得到蒸汽、烟气和管壁相关参数的空间分布, 为过热器的优化设计和安全运行提供了一种评估方法和手段。

关　键　词: 增压锅炉; 过热器; 评估方法
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引　言

过热器是船舶蒸汽动力装置中关键部件之一, 它利用高温烟气使饱和蒸汽过热, 进而提高动力装置热效率。由于其外壁受高温烟气冲刷, 受空间限制存在较大热力与水力不均匀性, 无法安装减温及吹灰装置等原因, 船舶过热器容易发生超温爆管, 降低了整个锅炉的安全可靠性, 且随着蒸汽参数的不断提高, 此问题尤为突出。因此建立一种快速、准确的过热器性能计算方法, 确定最高壁温位置及变化规律, 进而评估过热器的安全可靠性, 对于增压锅炉的合理设计、安全运行有重要的理论及实际意义。

目前, 过热器仿真研究主要有两种方法: (1) 采用CFD(计算流体力学)数值模拟软件对过热器进行三维数值计算, 揭示过热器内部参数分布规律[1-3]; (2) 根据过热器运行机理, 建立集总参数数学模型, 研究过热器出口参数的动态响应[4-5]。方法(1)难以满足过热器仿真实时性要求, 而方法(2)无法获得过热器内部参数分布规律。

为了同时兼顾仿真实时性以及掌握过热器内部参数分布规律的要求, 本研究以小型增压锅炉为研究对象, 依据传热学和流体力学基本原理建立过热器数学模型, 采用差分方法对数学模型进行离散处理, 得到便于程序编写的仿真模型, 并利用实验数据对模型进行了验证, 最后应用C语言编制了小型增压锅炉过热器稳态性能计算程序, 得到了一种适合船舶过热器性能评估的方法, 同时也为后续过热器动态性能仿真奠定了基础。

1　过热器数学模型

图1为某小型增压锅炉过热器示意图。该型过热器布置紧凑, 过热蒸汽被上、下集箱中的挡板分成3个流程, 蒸汽流速大。同时, 由于增压燃烧、烟气流速和比重都得到不同程度提高。这使得该过热器与常压锅炉过热器相比, 换热得到极大提高。

1.1　过热器数学模型建立

根据过热器实际工作特点, 假设: 烟气不发生横向混合, 烟气之间没有传热; 过热器上、下集箱尺寸较小, 忽略并联管束间的水力不均匀性; 忽略辐射换热和蒸汽、管壁的轴向导热, 管壁内外温度一致; 蒸汽沿流动方向横截面上参数分布均匀; 烟气入口处速度沿竖直方向按抛物线分布, 其余参数分布均匀。对图2所示的微元体, 可以得到以下方程。

1.1.1　质量方程

$$\frac{\partial(\rho V)}{\partial t} = -\frac{\partial(\rho u A)}{\partial \xi}\mathrm{d}\xi \tag{1}$$

式中: ρ—工质密度, kg/m^3; V—控制体体积, m^3; t—时间, s; u—工质速度, m/s; ξ—工质流动方向长度, m; A—工质流动方向截面面积, m^2。

对于蒸汽有: $V = \frac{\pi}{4}d_i^2\mathrm{d}x$, $A = \frac{\pi}{4}d_i^2$, 于是:

$$\frac{\partial\rho_{zq}}{\partial t} = -\frac{\partial(\rho_{zq}u_{zq})}{\partial x} \tag{2}$$

式中: 下标 zq—蒸气; x—蒸汽流动方向上长度, m。

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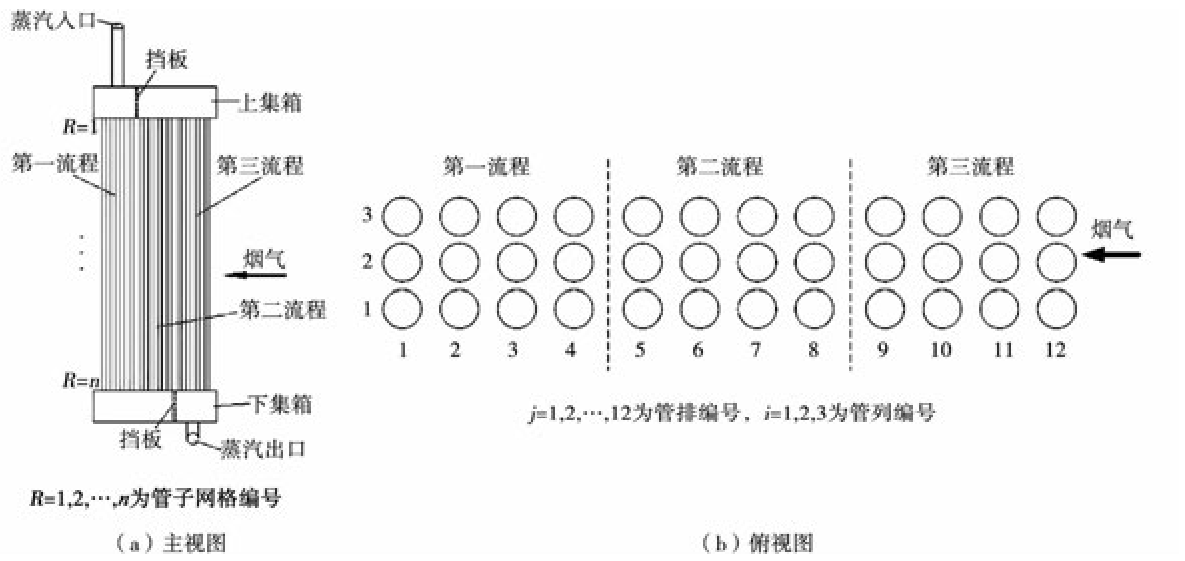


图 1　过热器示意图

Fig. 1 Schematic diagram of a superheater

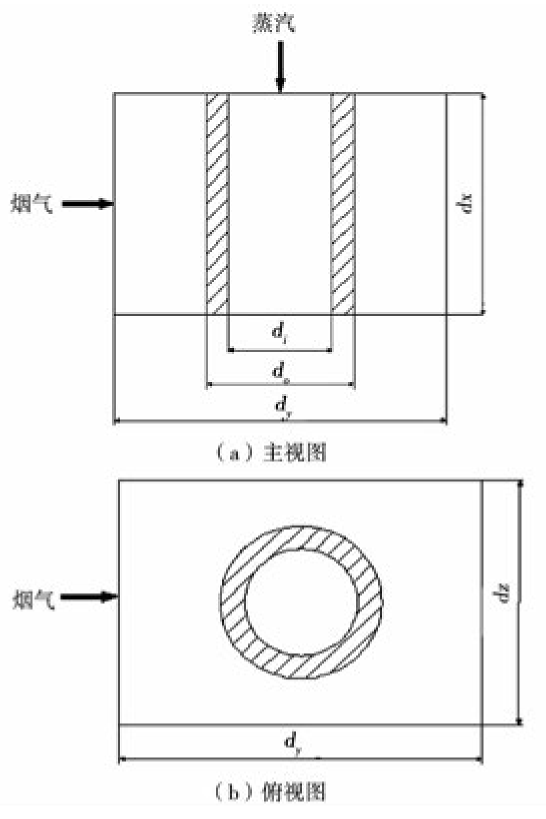


图 2　过热器微元体

Fig. 2 The infinitesimal body of superheater

对于烟气有: $V = \mathrm{d}x\mathrm{d}y\mathrm{d}z - \frac{\pi}{4}d_o^2\mathrm{d}x$, $A = \mathrm{d}x\mathrm{d}z$, 于是:

$$\frac{\partial \rho_{yq}}{\partial t} = -\frac{\partial(\rho_{yq}u_{yq})}{\partial x}\frac{\mathrm{d}y\mathrm{d}z}{\mathrm{d}y\mathrm{d}z - \pi d_o^2/4} \tag{3}$$

式中: 下标 yq—烟气; dy—控制体烟气流动方向长度,m; dz—控制体烟道宽度方向长度,m; d_o—管束外径,m。

1.1.2　能量方程

$$\frac{\partial(\rho Vh)}{\partial t} = -\frac{\partial(\rho uAh)}{\partial \xi}\mathrm{d}\xi + Q \tag{4}$$

式中: h—工质比焓,kJ/kg; Q—工质吸热量,kJ。

蒸汽侧传热方程:

$$Q_1 = K_{zq}\pi d_i \mathrm{d}x(T_W - T_{zq}) \tag{5}$$

烟气侧传热方程:

$$Q_2 = K_{yq}\pi d_o \mathrm{d}x(T_{yq} - T_W) \tag{6}$$

因此,得到蒸汽能量方程:

$$\frac{\partial T_{zq}}{\partial t} = -\frac{m_{zq}}{M_{zq}}\frac{\partial T_{zq}}{\partial x} + \frac{K_{zq}\pi d_i}{M_{zq}c_{pzq}}(T_W - T_{zq}) \tag{7}$$

式中: 下标 zq、W—蒸汽、管壁; K—表面传热系数,W/(m^2 · K) ; d_i—管束内径,m; T—温度,℃; M—沿蒸汽流动方向单位长度工质质量,kg/m; c_p—定压比热容,J/(kg · K) 。

管壁能量方程:

$$\frac{\partial T_W}{\partial t} = \frac{K_{yq}\pi d_o T_{yq} + K_{zq}\pi d_i T_{zq}}{M_W c_W} - \frac{K_{yq}\pi d_o + K_{zq}\pi d_i}{M_W c_W}T_W \tag{8}$$

烟气能量方程:

$$\frac{\partial T_{yq}}{\partial t}=\frac{m_{yq}\mathrm{d}y}{M_{yq}\mathrm{d}x}\frac{\partial T_{yq}}{\partial y}-\frac{K_{yq}\pi d_o}{M_{yq}c_{pyq}}(T_{yq}-T_W) \quad (9)$$

过热器稳态微分方程:

$$\left.\begin{aligned}0&=-\frac{m_{zq}}{M_{zq}}\frac{\partial T_{zq}}{\partial x}+\frac{K_{zq}\pi d_i}{M_{zq}c_{pzq}}(T_W-T_{zq})\\0&=\frac{K_{yq}\pi d_o T_{yq}+K_{zq}\pi d_i T_{zq}}{M_W c_W}-\frac{K_{yq}\pi d_o+K_{zq}\pi d_i}{M_W c_W}T_W\\0&=\frac{m_{yq}\mathrm{d}y}{M_{yq}\mathrm{d}x}\frac{\partial T_{yq}}{\partial y}-\frac{K_{yq}\pi d_o}{M_{yq}c_{pyq}}(T_{yq}-T_W)\end{aligned}\right\} \quad (10)$$

1.2 过热器数学模型离散

对方程组(10)直接求解是十分困难的,因此使用差分方法将方程组(10)离散为代数方程组。

过热器管束沿烟气流动方向分成12排,用 $j=1,2,3......,12$ 表示管排序号;沿烟道宽度方向分成3列,用 $i=1,2,3$ 表示管列序号;沿蒸汽流动方向均匀划分成 n 段,用 $R=1,2,3......,n$ 表示。至此,过热器在空间上已完全离散。过热器内部参数可表示为 $S[i,j,R]$。

对空间项采用向后差分:

$$\frac{\partial T_{zq}}{\partial x}=\frac{T_{zq}[i,j,R]-T_{zq}[i,j,R-1]}{\Delta x} \quad (11)$$

$$\frac{\partial T_{yq}}{\partial y}=\frac{T_{yq}[i,j,R]-T_{zq}[i,j-1,R]}{\Delta y} \quad (12)$$

将式(11)、式(12)代入方程组(10)中,得:

$$\begin{pmatrix}-\left(\frac{m_{zq}}{M_{zq}\Delta x}+\frac{K_{zq}\pi d_i}{M_{zq}c_{pzq}}\right) & \frac{K_{zq}\pi d_i}{M_{zq}c_{pzq}} & 0\\ \frac{K_{zq}\pi d_i}{M_W c_W} & -\frac{K_{yq}\pi d_o+K_{zq}\pi d_i}{M_W c_W} & \frac{K_{yq}\pi d_o}{M_W c_W}\\ 0 & \frac{K_{yq}\pi d_o}{M_{yq}c_{yq}} & -\left(\frac{m_{yq}}{M_{yq}\Delta x}+\frac{K_{yq}\pi d_o}{M_{yq}c_{pyq}}\right)\end{pmatrix}\cdot$$

$$\begin{pmatrix}T_{zq}[i,j,R]\\T_W[i,j,R]\\T_{yq}[i,j,R]\end{pmatrix}=\begin{pmatrix}-\frac{m_{zq}}{M_{zq}\Delta x}T_{zq}[i,j,R-1]\\0\\-\frac{m_{yq}}{M_{yq}\Delta x}T_{yq}[i,j-1,R]\end{pmatrix} \quad (13)$$

蒸汽压降计算参考文献[6],蒸汽的热物性计算根据IAPWS-IF97/IFC67标准计算,上、下集箱中的蒸汽温度、压力按各流程内蒸汽出口温度、压力的平均值计算。通过方程组(13)的求解,不仅得到过热器总体性能参数随负荷的变化规律,还可以计算过热器内部蒸汽、烟气及管壁温度等参数随空间变化趋势,最终得出了一种快速有效的过热器性能评估方法。

2 边界条件及仿真模型验证

边界条件包括过热蒸汽产量、过热蒸汽入口温度和压力、燃料消耗量和烟气入口温度和压力,其值由小型增压锅炉仿真试验平台运行数据给出,如表1所示。

表1 小型增压锅炉试验平台运行数据

Tab.1 The operating data of small supercharged boiler platform

工 质	参 数	工况3	工况4
0号柴油	油量/kg·h^{-1}	64.0	81.7
蒸汽	进口温度/℃	174.1	195.8
	进口压力/MPa	0.824	1.375
	流量/t·h^{-1}	0.66	0.81
烟气	进口温度/℃	491.2	535.4
	压力/MPa	0.163	0.197

进口截面烟气速度分布为:

$$v=[-2.4(x-0.5)^2+1.2]\times v_0 \quad (14)$$

式中: x—相对高度, $x\in[0,1]$; v_0—进口截面烟气平均速度,m/s。

表2为蒸汽和烟气出口温度的实验值和仿真值对比。从表中可以看出,该仿真模型能够较精确的反映过热器的实际工作过程。

表2 过热器仿真数据与实验值对比

Tab.2 Comparison of simulation results and experimental values

工况	参 数	实验值	仿真值	误差
工况4	蒸汽出口温度/℃	298.2	298.3	0.03%
	蒸汽出口压力/MPa	1.363	1.344	-1.39%
	烟气出口温度/℃	456.2	472.2	3.55%
工况3	蒸汽出口温度/℃	286.5	286.5	0.0%
	蒸汽出口压力/MPa	0.802	0.807	0.62%
	烟气出口温度/℃	405.0	426.5	5.31%

3 仿真计算结果及分析

图3为蒸汽与烟气出口温度随管子网格数量变

化曲线,较小网格数量对计算精度影响较大;随着网格数量的增加,蒸汽和烟气出口温度逐渐趋于定值,为了兼顾计算速度和仿真精度,本研究取单管网格数量为 $n=50$,总体网格数量为1 800。

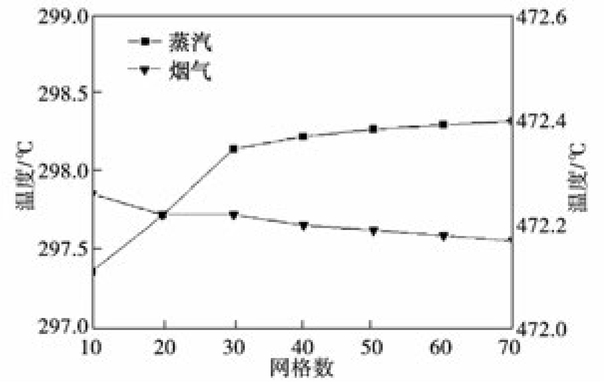


图3　出口参数随网格数变化曲线

Fig. 3 The change curve of outlet parameters varying with the mesh numbers

图4为每流程传热管在相同横截面处平均蒸汽温度沿蒸汽流动方向的分布规律。从图中可以看出,蒸汽温度在第三流程出口处最高;同一根传热管内,蒸汽温度增加速率在中间位置最大,往两端逐渐减小。

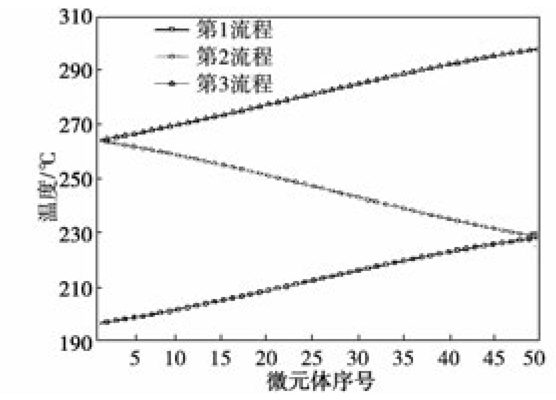
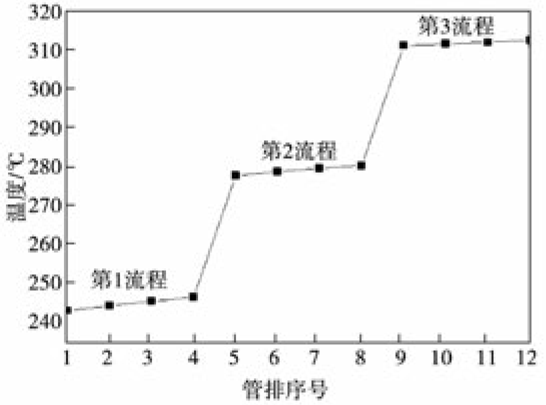


图4　蒸汽温度沿流动方向分布

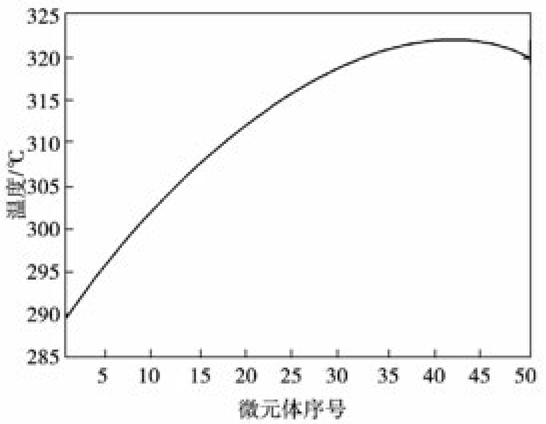
Fig. 4 The graph showing steam temperature varying with the flow direction

图5为管壁温度分布。

从图5(a)可知:管壁温度主要受蒸汽温度的影响,这是因为蒸汽侧换热强度比烟气侧大得多;管壁平均温度在同一个蒸汽流程内相差不大,而在不同流程内变化很大;从图5(b)可知:最高温度出现在第12排管距蒸汽出口处约1/5的位置处,为330 ℃左右,由于小型增压锅炉热负荷较低,此温度远低于材料允许温度。本研究方法通过与实船增压锅炉运行监控数据的交互,能够快速、准确地获得过热器的最高壁温位置和数值,进而评估和监测过热器的安全可靠性。



(a)管壁平均温度



(b)第12排第2列管壁温度

图5　管壁温度分布

Fig. 5 Tube wall temperature diatribution

4　结　论

(1) 通过数学离散方法,能够对过热器性能评估参数进行快速、详细的计算。

(2) 该方法不仅能计算过热器总体性能参数,还能得到内部蒸汽、烟气及管壁相关参数随空间分布规律。

(3) 该方法能够确定最高壁温位置和数值,为过热器的设计和运行真正提供了一种依据。

该评估方法不但具有比现有方法更全面、更准确的优点，而且为进一步研究过热器动态性能仿真奠定了基础。

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（姜雪梅 编辑）

新技术、新工艺

供暖系统计算的方法及其应用的可能性

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据《Электрические станции》2013 年 3 月刊报道，ВТИ(全俄热工研究所)的专家研究了供暖系统的计算方法及其应用的可能性。

得到了供暖系统广义的特性曲线方程，利用该方程可以确定给定的计算工况下室内、外的空气温度、供给管路内水的温度和来自热网的水的流量之间的相互关系。

在建筑物供暖系统内实施动力捉住措施要求预先完成一些计算，以便评定供暖系统条件的某一种变化的可能性和合理性以及所提议措施的效果。利用文章中提出的方法的基本规则，可以进行这些计算。

给出了供暖系统计算方法的要点及其应用的例子。

（吉桂明 摘译）

the stator blades and making the installation angle of the stator blades to change step by step with the load. On this basis, a simulation platform for steam-turbine-driven forced draft fans was set up based on the APROS software, being capable of accurately simulating changes of various parameters of a forced draft fan in its practical operation process and a simulation was performed of the control strategies optimized by using the APROS simulation platform. It has been found that the optimized control strategies can effectively avoid the surge problem of the forced draft fan and enhance the operation safety of the unit. **Key Words**: steam-turbine-driven forced draft fan, control strategy, APROS

燃煤电厂烟囱内烟气温度分布计算 = **Calculation of the Temperature Distribution of Flue Gases in a Smoke Stack in a Power Plant** [刊,汉] FANG Li-jun, YIN Rong-rong, GAO Jian-qiang (College of Energy Source, Power and Mechanical Engineering, North China University of Electric Power, Baoding, China, Post Code: 071003) //Journal of Engineering for Thermal Energy & Power. -2015, 30(3). -452-454

Smoke stacks are regarded as one of important equipment items in thermal power plants. When the temperature on the inner wall surface of the smoke stacks is lower than the dew point temperature of sulfuric acid, the sulfuric acid steam in the flue gases will dew on the wall surface to corrode it and shorten service life of the smoke stacks. Through calculating the temperature distribution of the flue gases inside a smoke stack, one can determine the dewing locations of flue gases inside the smoke stack and also finalize an on-the-spot corrosion and erosion version. By adopting the heat balance method, the authors established a general-purposed theoretical mathematical model for calculating the temperature of flue gases and the temperature on the wall surface inside the smoke stack. For a sleeve type smoke stack in a CFB power plant, the mathematical model in question was used to calculate the distribution of the temperature in the air interlayer of a sleeve type smoke stack in both winters and summers along the height of the smoke stack and that inside the wall surface of the smoke stack at various loads and analyze their variation regularities. The calculation results are in relatively good agreement with those calculated by using the semi-empirical calculation formulae and tested on the spot. **Key Words**: smoke stack, temperature distribution, mathematical model, sleeve type smoke stack, interlayer temperature

小型增压锅炉过热器性能评估方法研究 = **Study of the Method for Evaluating the Performance of a Small-sized Supercharged Boiler Superheater** [刊,汉] CHI Miao (International Exchange and Cooperation Division, Harbin Engineering University, Harbin, China, Post Code: 150001), ZHANG Hong-yan, XIE Hai-tao, LI Yan-jun, ZHANG Guo-lei (College of Power and Energy Source Engineering, Harbin Engineering University, Harbin, China,

Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. －2015,30(3). －455－459

In combination with the heat transfer and hydrodynamics fundamentals, established was a mathematical model for supercharged boiler superheaters and the differential method was used to discretize the model in question. On this basis, a simulation model was also verified by utilizing the test data. Afterwards, a performance simulation program for small-sized supercharged boiler superheaters was prepared. The distributions of relative parameters of steam, flue gases and tube walls in a space were obtained, therefore, offering a method and approach for evaluating the optimized design and safe operation of a superheater. **Key Words**: supercharged boiler, superheater, evaluation method

风力机桨叶气膜加热的数值研究 = **Numerical Study of the Air-film Heating of the Blades of a Wind Turbine**[刊,汉] YU Jing-mei, YU Yan-hong, LIU Pan-pan, FU Chun-tian (School of Mechanical Engineering, Liaoning Technical University, Fuxin, China, Post Code: 123000) //Journal of Engineering for Thermal Energy & Power. －2015,30(3). －460－465

On the basis of the currently available gas turbine air-film cooling achievements, proposed was an air-film heating ice-prevention theory. Based on the control volumetric method, for a NACA63(2)-215 airfoil and by using the Realizable k－ε turbulent flow model, a numerical simulation of the three-dimensional flow field in the blades of a wind turbine at an emergence angle of 90 degrees was performed. The fundamentals of the air-film heating was described and the flow characteristics, heat transfer characteristics and heating effective degree of the air film at the leading edge, lift and pressure surface of the aerofoil were summarized. It has been found that the air-film covering effectiveness achieved when the air film holes are in the staggered arrangement is relatively better than that when the air film holes are in the line arrangement. The attack angle is regarded as an important factor influencing the air-film flow and heat transfer characteristics. The peak value of the heat exchange on the wall surface of the aerofoil is located at places close to the air-film holes and with a change in the attack angle, the flow characteristics of the suction and pressure surface will assume a non-monotone change. When the emergence angle is set at 5 degrees, all the three zones nearing the jet flow holes can achieve relatively good heating air coverage effectiveness and the air-film heating effective degrees of the suction and pressure surface are basically identical, thus, the heating effectiveness is relatively good. When the simulation results are compared with those of the experimental study, both variation tendencies are basically in agreement. **Key Words**: air-film heating, numerical simulation, attack angle, air-film heating effective degree