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直接空冷凝汽器单元样机流动和传热性能研究

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摘　要: 直接空冷凝汽器由一个个直接空冷单元组成。对直接空冷凝汽器单元的研究具有重要的意义。依托实际工程项目, 对某 135 MW 直接空冷凝汽器单元样机进行流动和传热的性能研究。利用计算传热学(NHT)软件 Fluent, 对空冷单元样机的设计和实验工况进行数值模拟。分析了模拟结果与设计和试验数据存在一定偏差的原因。对直接空冷凝汽器外部空气的速度场、温度场的模拟、分析和研究, 为直接空冷系统的优化设计提供帮助。

关　键　词: 直接空冷凝汽器; 单元样机; 数值模拟; 优化设计

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引　言

空冷是"富煤缺水"地区火电厂的主要冷却方式, 它改变了原来"以水定电"的被动局面, 在水资源日益紧张的今天, 具有重要的意义。山西格瑞特实业有限公司煤矸石综合利用发电项目规划容量为 2×135 MW, 采用机械通风直接空冷系统冷却汽轮机排汽。上海电气集团提供 NZK135-13.24/535/535 直接空冷超高压中间再热凝汽式汽轮机。江苏双良空调股份有限公司提供双排管直接空冷凝汽器。

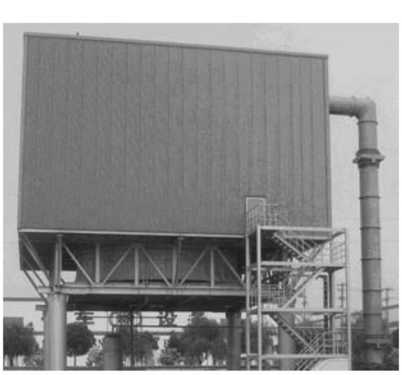

图 1　双良 直接空冷单元样机

直接空冷系统关键技术和设计国产化面临很多技术难题。火电厂直接空冷系统和空冷凝汽器(ACC)设计的优劣直接关系到投产后电厂的安全和经济效益。目前, 国内对于空冷凝汽器单元内部流场及相应条件下管束的传热特性了解不够。为此, 江苏双良空调股份有限公司专门建立了该项目的单个空冷单元的样机, 如图 1 所示。利用数值传热学软件 Fluent, 对单元样机设计和试验工况下流动和传热特性进行数值模拟、分析和研究。

1　计算条件[1]

表 1　直接空冷单元样机设计和试验参数[3]

	A. 设计	B. 试验	C. 试验
大气压力/kPa	89.29	100.3	100.3
环境温度/℃	28	33.68	34.44
空气密度/$kg·m^{-3}$	1.024	1.14	1.14
环境风速/$m·s^{-1}$	3.0	2.1	1.1
饱和蒸汽温度/℃	72.7	73.29	75.04
出口空气温度/℃	64.00	63.98	64.01
传热系数/$W·m^{-2}·℃^{-1}$	28.27	31.16	33.20
进风量/$m^3·s^{-1}$	400.30	404.34	479.62
迎面风速 $m·s^{-1}$	2.16	2.18	2.59
散热量/MW	13.43	14.08	16.27

山西朔州多年平均大气压 89.29 kPa, 多年平均风速为 2.2 m/s, 空气密度约 1.024 kg/m^3。朔州地区全年主导风向为静风(C), 次主导风向为西南西(WSW); 夏季各朝向平均风速均低于 2.5 m/s。根据技术协议, 直接空冷系统的主要性能考核点为: 在夏季空气干球温度为 28 ℃, 外界环境风速≤3.0 m/s(测量位置按德国 VGB-R131Me[2]), 每台汽轮机的排汽量为 335.97 t/h, 排汽焓为 2 606.1 kJ/kg, 排热

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量为 243.2 MW(其中，空冷凝汽器散热量为 214.82 MW)的条件下，应保证汽轮机排汽口处背压不大于 35 kPa，满足汽轮机满发条件。空冷单元样机的设计参数与现场试验结果，如表 1 所示。由表可见，两种试验工况下，空冷凝汽器的实际平均传热系数略大于设计值。

2 直接单元样机模型

根据设计图纸，空冷凝汽器紧靠汽机房 A 列柱外侧布置，单台机组的空冷凝汽器由 4 行 4 列共 16 个空冷换热单元组成。每个空冷换热单元的尺寸为 10.79 m×10.64 m×12.0 m。钢筋混凝土支撑柱高 28 m，空冷平台下部钢桁架高 3.7 m，桁架内风机挡风圈高度为 1.7 m，挡风墙高度为 12 m。空冷平台底标高为 31.7 m，顶标高为 43.7 m。据此，江苏双良空调股份有限公司在厂区内建立了直接空冷凝汽器的一个单元样机，蒸汽分配管直径为 2 m。

直接空冷凝汽器的基本换热元件一般为多排、双排或单排翅片管。由多个换热元件组成的换热器管束，如图 2 阴影部分所示，与钢结构支撑构成“A”形架。“A”形架与设置在下部的大直径轴流风机和挡风墙组成一个直接空冷凝汽器单元。多个直接空冷凝汽器单元组成空冷凝汽器。空冷单元的几何结构十分复杂。若按照实际情况建模，必将导致计算工作量巨大，计算机资源不足，难以进行精确计算。因此，有必要对空冷换热单元进行合理的简化处理，建立如图 2 所示的空冷单元模型。

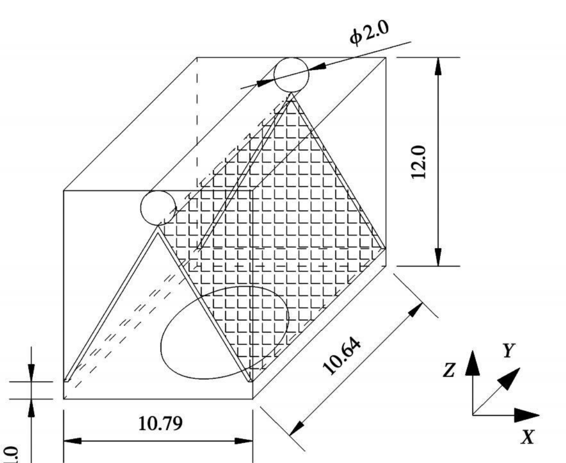

图 2 直接空冷单元样机模型

空冷凝汽器的阻力及传热系数随迎面风速的变化曲线参见文献[4~5]。空冷风机选用保定惠阳航空螺旋桨制造厂生产的直径为 7.925 m 电站空冷低噪声风机。该风机叶片安装角为 18.5°，叶片数为 6 片。风机转速为 95.0 r/min，风量为 407.0 m^3/s 时，风机静压为 113.1 Pa，叶尖速度为 39.4 m/s。根据风机试验数据拟合出风机性能曲线，如图 3 所示。风机静压 P 和风速 v 之间具有如下关系：

$$P=164.96+6.4774v-1.3697v^2 \quad (1)$$

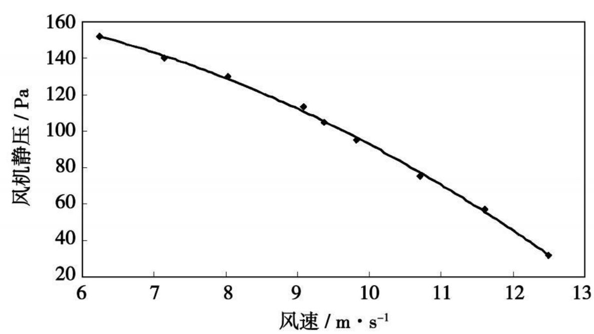

图 3 空冷风机性能曲线

3 数学模型

直接空冷单元空气的流动和换热满足以下控制方程。

3.1 质量守恒(连续性)方程

$$\partial u_i/\partial x_i=0 \quad (2)$$

3.2 动量守恒方程

对于牛顿流体，时均形式的纳维-斯托克斯(Navier-Stokes)方程，即雷诺(Reynolds)方程：

$$\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\frac{\partial u_i}{\partial x_j}-\rho\overline{u_i' u_j'}\right) \quad (3)$$

采用 Boussinesq 假设(hypothesis)，结合流体应力与应变率的本构方程，湍流脉动所造成的应力可以表示为：

$$-\rho\overline{u_i' u_j'}=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\left(\rho k+\mu_t\frac{\partial u_i}{\partial x_i}\right)\delta_{ij} \quad (4)$$

式中：ρ—空气的密度；u—流速，$i, j=1, 2, 3$；P—压力；μ—空气的动力粘性系数；μ_t—湍流动力粘性系数；k—单位质量流体的湍流脉动能。

湍动能方程：

$$\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon+S_k \quad (5)$$

耗散方程：

$$\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\mu_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+G_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \quad (6)$$

式中: G_k—由层流速度梯度而产生的湍流动能; G_b—由浮力产生的湍流动能; $C_{1\varepsilon}$、$C_{2\varepsilon}$、$C_{3\varepsilon}$—常数; σ_k、σ_ε—k 方程和 ε 方程的湍流 Prandtl 数; S_k、S_ε—源项。

湍流粘度:

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \quad (7)$$

式中: $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$, $C_\mu=0.09$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.3$ 为常数。

$$G_k=-\rho\overline{u_i'u_j'}\frac{\partial u_j}{\partial x_i} \quad (8)$$

Boussinesq 假设下:

$$G_k=\mu_t S^2 \quad (9)$$

式中: S—平均应变率张量系数, $S\equiv\sqrt{2S_{ij}S_{ij}}$

$$G_b=\beta g_i\frac{\mu_t}{Pr_t}\frac{\partial T}{\partial x_i} \quad (10)$$

式中: Pr_t—能量湍流普朗特数, $Pr_t=0.85$; g_i—重力在 i 方向上的分量。

β 为热膨胀系数:

$$\beta=-\frac{1}{\rho}\left(\frac{\partial\rho}{\partial T}\right)_p \quad (11)$$

由于温度变化所引起的空气密度变化, 采用 Boussinesq 近似(approximation):

$$(\rho_0-\rho)\approx\rho\beta(T-T_0) \quad (12)$$

式中: ρ_0—参考温度 T_0 下的参考密度。

3.3　能量守恒方程

以温度为变量的能量守恒方程:

$$div(\rho\vec{u}T)=div\left(\frac{h}{c_p}gradT\right)+S_T \quad (13)$$

式中: c_p—比热容; T—温度; h—流体的传热系数; S_T—粘性耗散项, 流体内热源及由于粘性作用流体机械能转换为热能的部分。

3.4　源项

对于空冷凝汽器翅片管束, 通过在标准流动方程中增加动量源项的方法, 引入多孔介质(porous media)的概念进行模拟。源项 S_i 由两个部分组成, 一部分是粘性损失项; 另一部分是惯性损失项。对于简单均匀多孔介质:

$$S_i=-\left(\frac{\mu}{\alpha}u_i+C_2\frac{1}{2}\rho|u_i|u_i\right) \quad (14)$$

式中: α—渗透率; C_2—惯性阻力系数。

通过修改多孔区域中的导热热流和瞬态项来求解标准能量方程。在多孔介质中, 导热热流使用有效导热系数, 瞬态项包括固体区域的热惰性。多孔介质的有效导热系数, 为流体导热系数和固体导热系数的体积平均:

$$\lambda_{eff}=\gamma\lambda_f+(1-\gamma)\lambda_s \quad (15)$$

式中: γ—介质的多孔率; λ_f—流体的导热系数; λ_s—固体导热系数。

4　结果及分析

建立空冷单元样机的稳态数值模型, 并考虑由于温度变化而导致的空气密度变化和浮升力。整个计算区域为(−100, −100, 0)到(100, 100, 100)米。上部和四周边界距离空冷单元较远, 该处的流场已基本不受空冷岛的影响, 取为环境参数。地面和空冷单元四周的挡风墙, 采用固体壁面边界条件。模拟中, 风向沿 Y 轴负方向(炉后来风方向)。气象站风速仪的高度一般为 10 m, 编写入口边界条件的用户自定义函数(UDF)。数值模拟计算机为 HP 工作站 XW8200, 3.6 GHz 主频, 4 G 内存。

对表 1 设计和试验工况的数值模拟结果, 如表 2 所示。对设计工况的模拟结果显示: 风机风量为 426.60 m^3/s, 空冷单元散热量为 14.25 MW。即当模拟风量高于设计风量 6.57% 时, 模拟散热量高于设计值 6.11%。数值模拟结果与设计点基本吻合。

表 2　直接空冷单元样机模拟结果

	模拟 A	模拟 B	模拟 C
进风量/$m^3 \cdot s^{-1}$	426.60	473.75	479.68
散热量/MW	14.25	13.62	14.03

数值模拟模型是正确、可信的。而模拟试验工况的结果与实测数据有一定的差异: 当模拟风量高于试验风量 17.1% 时, 模拟散热量小于试验散热量约 3.38%。而在相同的风量下, 模拟散热量比试验散热量小约 16%。模拟与试验结果之间存在差异的原因为:

(1) 数值模拟是在来流稳定, 稳态传热情况下的结果, 与实际情况有一定出入。自然状态下, 一定的环境风速范围内, 风向具有随机性的特点。某方向上的来流状态参数难以持续和稳定;

(2) 未考虑空冷凝汽器传热系数随迎面风速的变化, 用空冷凝汽器的平均传热系数代替实际传热系数所带来的误差;

(3) 风机风量依赖于风机性能和流场的阻力特

性;其数值在迭代中确定,难以调到设计或试验点;

(4) 实际测试中,也可能出现的误差。

另外,还对单元样机在朔州地区的静风状态进行了研究。模拟结果显示:当风量为 443.38 m^3/s,空冷单元散热量为 14.68 MW。单元样机在 $Y=0$ 处的速度场和温度场,如图 4 和图 5 所示。空冷单元的出口速度分布规律与理论解基本吻合[6]。模拟结果还显示:由于风机旋流的影响,空冷单元样机内部流场并不均匀,但空冷凝汽器出口具有较均匀的出口风速。散热器下部区域存在流动死区和回流,空气温度较高。

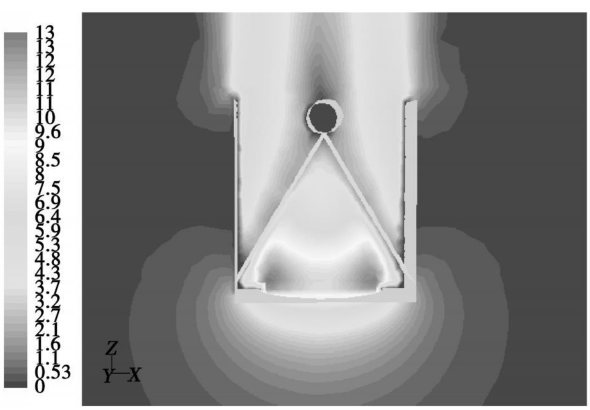

图 4 直接空冷单元样机速度云图(m/s)

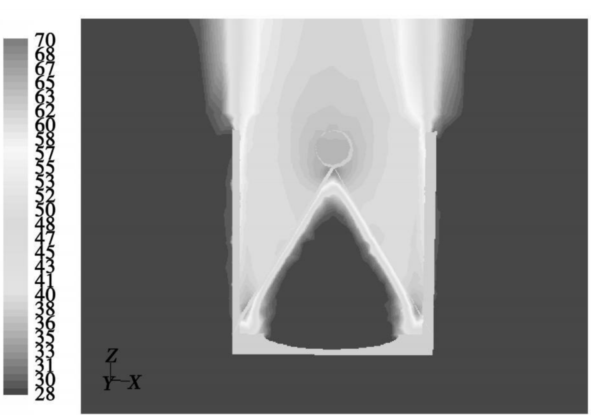

图 5 直接空冷单元样机温度云图(℃)

空冷单元样机四周均为挡风墙,与处于空冷岛中间的空冷单元边界条件略有不同。空冷单元样机模型只要稍做修改,即可进行空冷岛中间空冷单元的详细研究。同时,单元样机模型也为空冷岛及空冷电厂空气场的数值研究提供了理论基础。

5 结束语

在设计工况和试验工况下,对江苏双良空调股份有限公司格瑞特项目的空冷单元样机进行了流动和传热的数值模拟,并与实测数据进行对比分析。结果表明:数值模拟结果与设计工况基本吻合,但与试验点之间存在一定的偏差。分析了造成数值模拟与试验数据之间存在偏差的原因。空冷单元样机的数值模型可用于实际空冷单元及空冷岛的详细工程模拟分析和计算。

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was analyzed in a comprehensive way. On this basis, a study was conducted of the conversion of a high power simple-cycle marine gas turbine (MGT-33) to an intercooled cycle one. The precondition of the conversion is to keep the majority of the flow path and structure of the original engine gas generator unchanged to inherit the reliability of the prototype machine. The results of the study indicate that after the adoption of the IC cycle, under the precondition of minimum structure modification and retaining the compactness of the whole machine, the overall performance of the gas turbine still secures a conspicuous enhancement, with its power output being increased by about 34% and the efficiency, enhanced by approximately 4.1%, thus demonstrating the merits of the relevant engineering modifications. **Key words**: marine gas turbine, IC (Intercooled Cycle) cycle

汽轮机热力性能考核指标的通用方程 = **A General Equation of Indexes for Appraising the Thermodynamic Performance of a Steam Turbine**[刊,汉]/ YAN Shun-lin, GUO Jia-lei (College of Energy Source and Power Engineering, North China Electric Power University, Baoding, China, Post Code: 071003)// Journal of Engineering for Thermal Energy & Power. – 2009, 24(1). – 65 ~ 67

For the safe and cost-effective operation of a whole thermal power plant, it is of the utmost importance to grasp and know well the thermodynamic performance of steam turbine units. Currently, only a definition and basic calculation formulae of various indexes are given in the technical specification for thermodynamic performance tests of a steam turbine. If for different steam turbine units, calculation formulae are to be listed separately, a relatively poor generalization will result and this is not conducive to the development of general-purpose computer programs. On the basis of a long-time analysis and observation, a unified physical model of thermal power plants was established, and a general-purpose equation of indexes for appraising the thermodynamic performance of a steam turbine, proposed. This not only provides an underlying basis for preparing the calculation indexes of steam turbine thermodynamic tests, but also lays a foundation for a further refinement of the test specification. **Key words**: thermodynamic performance, indexes for appraisal, general equation

一种识别气液两相流流型的新方法 = **A New Approach for Identifying Gas-liquid Two-phase Flow Patterns** [刊,汉]/ ZHOU Yun-long, LI Hong-wei, YUAN Jun-wen (College of Energy Source and Mechanical Engineering, Northeast Dianli University, Jilin, China, Post Code: 132012)// Journal of Engineering for Thermal Energy & Power. – 2009, 24(1). – 68 ~ 72

In the light of the statistical characteristics of image grey-scale histograms, proposed was a new method for identifying gas-liquid two-phase flow patterns by combining an image processing with an ameliorated supportive vector machine. The method in question is to use a high-speed video camera to acquire an image of 7 typical flow patterns on a gas-liquid two-phase flow test rig. Through the image processing, the statistical characteristics of the image grey-scale histograms were extracted to form an eigenvector, which serves as a flow pattern specimen to perform a training for and identification of the ameliorated supportive vector machine. The test results show that the characteristics of the image grey-scale histograms can very well reflect the difference of various flow patterns. Compared with the original supportive vector machine, the ameliorated one provides a good classification performance, a short operation time and a network identification rate as high as 99.04%, thus providing a new effective approach for an on-line discrimination of flow patterns. **Key words**: flow pattern identification, image processing, statistical characteristics of grey-scale histograms, ameliorated supportive vector machine

直接空冷凝汽器单元样机流动和传热性能研究 = **A Study of the Flow and Heat Transfer Performance of a Direct Air-cooled Condenser Sample Unit**[刊,汉]/ SHI Lei (College of Civil Engineering, Beijing Jiaotong University, Beijing, China, Post Code: 100044), SHI Cheng (China Electric Power Engineering Consultant Group Corporation, Bei-

jing, China, Post Code: 100011), HUANG Xiang, XU Yan-qiang (China Huadian Engineering (Group) Co. Ltd., Beijing, China, Post Code: 100044)// Journal of Engineering for Thermal Energy & Power. – 2009, 24(1). – 73 ~ 76

A direct air-cooled condenser consists of several direct air-cooled elements. A study of its elements is of major importance. Based on a practical engineering project, the flow and heat transfer performance of a 135 MW direct air-cooled condenser sample unit has been studied. By using a numerical heat transfer (NHT) software Fluent, a numerical simulation has been performed of the air-cooled sample unit at its design and test operating conditions. The reason why the simulation results differ from the design and test data was analyzed. The simulation, analysis and study of the external air speed and temperature field of the direct air-cooled condenser can be helpful for the optimized design of the systems in question. **Key words**: direct air-cooled condenser, sample unit, numerical simulation, optimized design

常规工况下多弯头数脉动热管运行性能的实验研究 = **Experimental Study of the Operation Performance of Multi-elbow Pulsating Heat Pipes at Conventional Operating Conditions**[刊,汉]/ YANG Hong-hai, WAN Qing, HAN Hong-da (College of Environment Science and Engineering, Donghua University, Shanghai, China, 201620) // Journal of Engineering for Thermal Energy & Power. – 2009, 24(1). – 77 ~ 80

Two groups of pulsating heat pipes consisting of 40 thin copper tube elbows with an inner diameter of 1 and 2 mm respectively were designed. Two loop types, closed or open, can be made available by opening or closing a valve in the pipe. With R123, water and alcohol serving as working media respectively, liquid filling rate ranges from 15% to 95% and the installation angle can be regulated freely. Through tests, analyzed and compared was the influence of the inner diameter, working medium, liquid filling rate, heating angle and loop type of the multi-elbow pulsating heat pipe on its startup and heat transfer performance at conventional operating conditions. **Key words**: pulsating heat pipe, number of elbows, loop type, operation performance, influencing factor

超临界变压运行直流锅炉中间集箱分配特性的试验研究 = **Experimental Study of Intermediate Header Flow Distribution Characteristics of a Supercritical Once-through Boiler Operating at Variable Pressures**[刊,汉]/ ZHU Yu-qin (Technology Research Center of Petroleum Refinery Engineering, Xi'an Shiyou University, Xi'an, China, Post Code: 710065), BI Qin-cheng, CHEN Ting-kuan (National Key Laboratory on Multi-phase Flows in Power Engineering, Xi'an Jiaotong University, Xi'an, China, Post Code: 710049)//Journal of Engineering for Thermal Energy & Power. – 2009, 24(1). – 81 ~ 84

In the light of the structural and parameter features of an intermediate header serving as a transition connection between the spiral coil-tube water-wall at the lower part of the furnace and the vertical tube water-wall at the upper part of the furnace in a 600 MW supercritical boiler, the distribution characteristics of gas-liquid two-phase flows in the intermediate header of the supercritical boiler at a load of 35% ECR (Economical Continuous Rating), 50% ECR and 75% ECR were simulated by using an air-water test loop. Through observations and a high-speed photographic method, the flow pattern in parallel branch tubes of a distribution header was measured and analyzed. By using a quick-closing valve and friction resistance method, measured respectively were the phase and flow distribution among various branch tubes. The test results show that at three operating conditions and with inlet dryness ranging from $x = 0.7$ to 0.95, the flow distribution of the air-water two-phase flows passing through the parallel branch tubes of the distribution header is comparatively uniform, and in most cases, the flow rate deviation is less than 10%. **Key words**: supercritical once-through boiler, header, distribution characteristics, air-water two-phase flow

氧燃烧方式下煤粉锅炉辐射传热特性分析 = **Thermodynamic Calculation of Radiative Heat Transfer in a Coal-**