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空冷塔内外流场的数值分析

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摘　要: 采用数值模拟的方法, 研究了侧风条件下自然通风空冷塔的运行情况, 并参照内蒙丰镇电厂的海勒式空冷系统, 做了具体的算例分析。计算结果显示了空冷塔内外流场和热力性能在侧风条件下的变化规律和特点, 揭示了散热量下降的主要原因, 为改善空冷塔运行的后继研究工作提供了思路。

关　键　词: 空冷塔; 海勒式间接空冷系统; $k-\varepsilon$ 双方程模型; 数值模拟; 湍流流场

中图分类号: TM621.7^{+}3

文献标识码: A

1　引言

发电厂空冷技术的应用始于 30 年代末的德国, 在六七十年代应用增多。进入 80 年代以来, 由于节约水资源和环境保护的需要, 空冷技术在许多国家得到了进一步发展。我国的水资源相对贫乏, 发电厂空冷技术在我国, 特别是北方的富煤贫水地区, 展示了较好的发展前景。1987 年和 1988 年, 山西大同第二发电厂的两台 200 MW 机组相继引进了匈牙利的海勒式间接空冷系统。尔后, 内蒙丰镇电厂投运了国产相应系统, 太原第二发电厂的哈蒙式间接空冷系统也已投入运行。空冷系统的运行实践表明, 该系统的节水效果显著, 运行比较稳定, 但是冷却塔的冷却性能受环境的影响很大, 特别是受到环境侧风的影响, 导致汽轮机背压的变幅增大。因此, 研究不同运行状态和环境条件下, 空冷塔内外的流场, 特别是流场的变化与空冷塔运行性能变化之间的关系, 对于提高空冷塔的设计水平, 提出改善空冷塔运行的有关措施, 具有重大的现实意义。同时, 该问题是涉及换热的、具有复杂边界的湍流三维流动问题, 对此种流场的数值分析, 也具有一定的理论意义。目前, 应用数值方法研究侧风对冷却塔运行的影响, 在国外已有一定的研究成果, 而针对空冷塔内外流场的全面模拟, 国内外也已经起步。本文将以内蒙丰镇电厂的空冷塔(空冷散热器塔外竖直布置)做为研究对象的原型, 采用较为先进的计算模型, 对侧风中运行的空冷塔内外流场做较为系统和深入的研究。

2　流动与换热分析

空冷塔塔外的流场是近地层的大气湍流流动, 大气流动的不稳定性, 给实际测量工作带来了很大困难。计算中塔外流场的外部边界条件考虑了大气流动的统计规律, 即风速沿高度的变化循幂次律:

$$u/u_1 = (z/z_1)^b$$

式中 z 为垂直高度, z_1 为参照高度(本文中为 10 米), u 为水平风速, u_1 为参照高度处的水平风速, 指数 b 为经验常数。通常 b 的取值与风速大小、大气稳定程度、日照等因素有关。本文根据丰镇地区的气象统计资料和有关文献, 取 $b = 0.16$。计算中不考虑风向随高度的变化, 认为风向是稳定的。

空冷塔内的核心区是高雷诺数的湍流流动, 近壁区则是壁剪切湍流的形式, 出口以上是侧风中的自由射流。计算中塔内与塔外是连通的统一流场, 塔体固壁通过设置计算区域中网格界面堵塞系数(固壁即全堵塞)的方式给出, 并形成计算区域中的内边界。针对计算域中不同部位的流动形式的不同, 有关文献对冷却塔内外的流场作了分别处理, 即塔内湍流, 塔外层流, 采用了不同的数学模型[3]。由于目前湍流计算技术已经比较成熟, 同一模型可以处理多种不同形式的流动, 本文中对塔内外流场采用了单一的数学模型, 流动的特性在计算中体现, 减少了人为干预增加的不准确性。在空冷塔进风口处需设置流动阻力源项和加热源项, 塔内设备所带来的流动阻力以及空气和空冷散热器之间的换热计算, 采用了福哥型空冷散热器的经验公式(取百叶窗开度为 100%)[4]。对于换热计算, 当地换热量的大小主要和冷却水温度、空气温度以及当地进塔风量有关。

3　数值分析

对于塔内外的流场, 采用了不可压缩流体的湍

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流时均控制微分方程(连续性方程、动量方程和能量方程),湍流流动采用的数学模型是 $k-\varepsilon$ 双方程模型。计算区域的外边界除地面形成的壁面边界外,上部和周边的边界取在距离空冷塔较远的大气环境中,使该处的流场已基本不受空冷塔的影响,从而可以取环境参数作为外部边界条件。由于流场具有对称性,计算区域的选取是以空冷塔的中心线为轴心,高 315 米,半径 242 米的半圆柱体。塔体尺寸为高 115 米,出口直径 61.6 米,喉部直径 60 米,底部外围直径 97.2 米,进风口高 15 米。计算中采用了非正交贴体坐标网格系统(9× 25× 35),即在直角坐标网格的基础上,对网格系统进行扭曲和伸缩变形,使之具有计算域的几何外形,并在内部塔体壁的位置形成与塔型双曲线一致的网格界面。控制微分方程的离散化采用了有限差分法中的控制容积公式法,针对对流项的离散,采用了上风差分格式。动量方程的离散化采用了交错网格的方法。流场的计算则采用典型的 SIMPLE 算法。计算中压力取相对值,并且不考虑大气静压差的影响,压力场的变化只是表明速度头的变化,因此,浮升力的计算采用公式:

$$S_{buoy} = T_m \cdot (\rho - \rho_{amb})/\rho_{amb}$$

其中 ρ_{amb} 是环境密度,g 是当地的重力加速度,ρ 是当地密度,T_m 是网格内流体的质量。密度的计算按理想气体状态方程给出。所有固体壁面上的流动计算采用壁面函数法。数值计算应用了大型通用程序 PHOENICS*,计算的边界条件按通用程序推荐的方式处理,包括来流、出口、顶部、固壁和对称边界,其中 k 和 ε 的来流边界值依来流速度和塔体尺寸按经验公式计算给出。

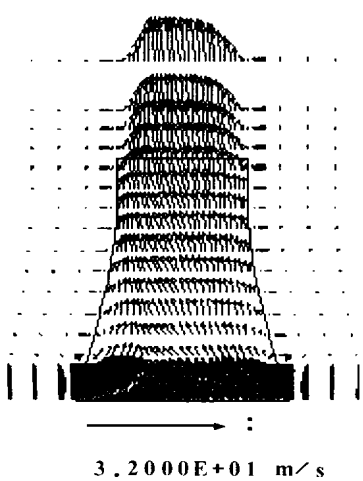
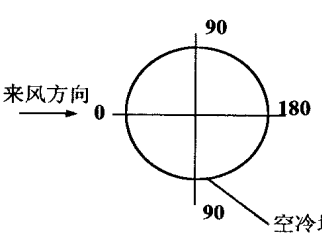


图 1　无风时的流场图



附图 1　来风方向与空冷塔周向角度标定

4　计算结果分析

本文在叙述中,空冷塔周向方位以角度标定,0 度为前驻点,0 ~ 45 度为迎风侧,45 ~ 135 度为切线侧,135 ~ 180 度为背风侧(附图 1)。

(1)自然通风空冷塔是利用塔内空气被加热后由于塔内空气的密度差而产生的浮升力驱动空气流动的。在无风时,塔外压力场保持为环境状态,塔内形成负压,分布比较平整,沿高度压力逐渐升高,至塔外后与环境压力平衡(图 2,压力分析是略去流体静压差并采用相对压力的计算结果)。塔体周围空气的流动很弱,塔内流场基本呈轴对称分布,进塔气流的速度指向轴心,上升气流的速度分布也比较平整,塔壁附近流速偏低。塔内塔体底部周边的气流转折处,形成较小的回流流动(图 1)。进塔气流速度周向分布均匀,纵向分布底部略高于顶部,风速值在 2.1 ~ 2.4 m/s,基本与现场实测相符。

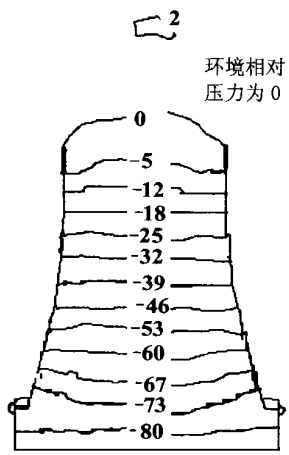


图 2　无风时的压力场

(2)当塔外有侧风流动时,塔外的压力场发生变化(图 3)。在塔外的迎风面上,空气流动受到塔的阻碍,压力略有升高,气流流向塔的两侧,塔两侧附近的区域风速加大,空冷散热器外侧压力降低(图中带 * 曲线)。在同一风速下,随着高度的增加,上述现象愈加明显。当侧风风速加大时,空冷塔两侧的压力降低加剧。背风侧的压力变化不大,部分绕塔气流在背风侧汇聚,流动减弱,压力稍有增高。在塔出口以上的区域,出塔气流受到侧风的吹动,流动向背风侧偏斜。由于水平流动与垂直流动相汇合,在塔出口以上的区域形成一个倾斜的压力升高

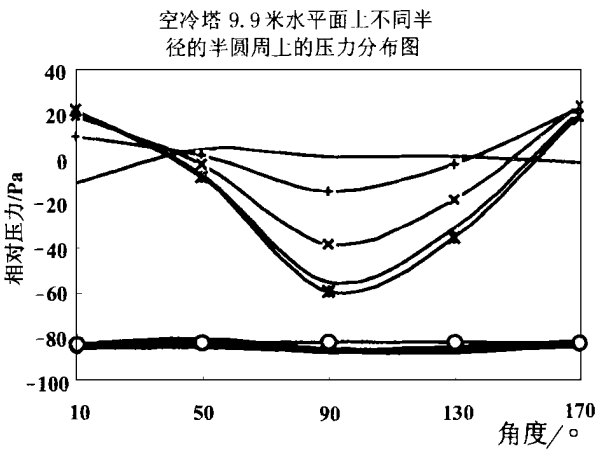


图 3　8.5 m/s 风速时塔内外压力变化曲线)(* 为散热器外侧压力,o 为散热器内侧压力)

* 1994　shareware EP 版

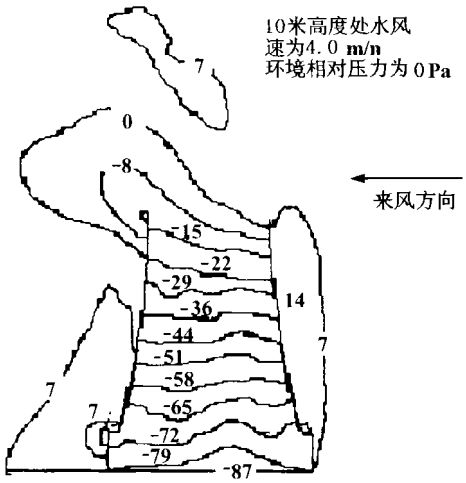


图 4 4.0 m/s 风速时的压力场图

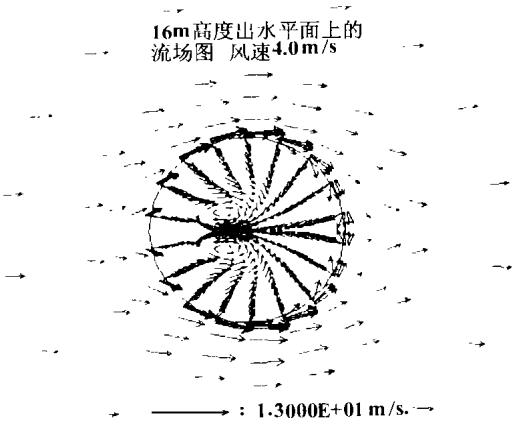


图 5 4.0 m/s 风速时的流场图

区(图 4)。出塔气流在出口的迎风侧减弱,而在背风侧流速加大,其效果相当于减小了塔出口的有效流通面积。

(3)在侧风的条件下,塔内的流动不再呈现轴对称特征,进塔气流的速度方向不再指向轴心,而是受到塔外圆柱绕流的影响,产生相应的偏斜,大致指向轴线两侧的两个圆柱面区域内。由进风口部位的水平截面流场图(图 5)可以看出,由于进塔气流速度的偏斜,塔内形成了两个对称的旋涡流,并一直上升影响到塔主体内的大部分区域,使大部分气流沿螺旋线上升,实际走行路线加长。计算发现,这种现象在中等风速时比较明显,但在风速加大时,并无增强趋势,而是略有减弱,因为风速加大时塔外迎风侧的压力升高加剧,使得塔内中心区域偏向迎风侧的流动受到抑制,而塔两侧的进气量又有所减少,故旋涡流动受到一定的削弱。在塔内周边进气气流转折区域所形成的回转流动中,当风速较大时,由于受到旋涡流动的影响,迎风侧的回转流动加强,使塔内有效流动受到影响。在侧后区,回转流动的变化不大。

(4)在侧风条件下,空冷塔的入口风速发生变化。在迎风侧和背风侧变化较小,风速略有增加。当侧风风速加大时,在迎风侧,空冷塔入口风速沿高度的差别减小,在切线侧特别是切线后侧区域,入口风速降低(图 6)。当侧风风速在 4.0 m/s 以下时,降低幅度较小,最小进塔风速在 1.8 m/s 左右;当侧风风速达到 8.5 m/s 时,降低幅度明显增大,最低风速只有 0.5 m/s 左右,相当于无风时进塔风速的 20%。当侧风风速达到 10 m/s 时,在切线后侧区域,塔内热空气外溢。空冷塔两侧进塔风速的降低,减少了空冷塔的进气量,致使局部区域入塔空气温度升高,散热器换热量减少。

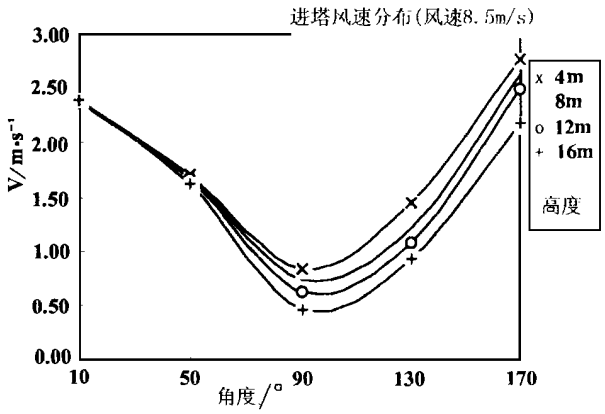


图 6 侧风风速 8.5 m/s 时进塔风速分布

5 结论

通过数值分析的方法研究了侧风对空冷塔内外流场及对空冷塔运行的影响,获得的计算结果与原型塔的实测资料基本吻合。结果分析表明,侧风对空冷塔的影响主要体现在如下几个方面:1. 出塔气流与来风汇合、相互挤压,在塔出口上方形成一个倾斜的压力升高区,影响了空冷塔出口的有效流通通道。2. 塔内气流形成旋涡,流程延长,回卷流动加强,削弱了塔内的通畅性。3. 侧后区进气口的入塔风速随着侧风的加强而显著降低,换热减少,是空冷塔散热量下降的直接原因。

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(何静芳 编辑)

continuous on-line soot blowing. It can reduce the flue gas resistance by 100 - 400 Pa and lower the exhaust gas temperature by 5 ~ 10 ℃. In addition to achieving significant economic benefits, the above unit enjoys a high potential for wide engineering applications. **Key words**: soot blowing, pulsed gas, air heater, computer-based monitoring

船用主锅炉的改进设计＝**Marine Main Boiler Improved Design**〔刊, 中〕/Chen Qinglong (Harbin No. 703 Research Institute) // Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —41 ~ 42

A brief description is given of the marine main boilers currently manufactured in the People's Republic of China. Based on the analysis of some difficult issues involved in an improved design the author has proposed a new design scheme for academic discussion. **Key words**: marine main boiler, improved design, scheme

在不同工况下 300 MW 锅炉过热器, 再热器的特性试验研究＝**Experimental Study of the Boiler Superheater and Reheater Characteristics of a 300 MW Unit under Various Operating Conditions**〔刊, 中〕/Xin Zhiming, Wu Luchen, Liu Hengyu (Harbin Boiler Co. Ltd.), et al // Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —43 ~ 46

Through the tests of a boiler under steady and dynamic operating conditions a comprehensive analysis is conducted of the wall temperature profiles of a superheater and reheater at various operating conditions. The suggestions given in the present paper can be helpful for solving overheating problems of the superheater and reheater. **Key words**: superheater, reheater, wall temperature characteristics

近流线数值计算方法在四角切圆燃烧炉膛中的应用＝**Application of Quasi-streamline Numerical Simulation Method for a Boiler Furnace with Tangential Firing**〔刊, 中〕/Zhang Ze, Wu Shaohua, Qin Yukun (Harbin Institute of Technology) // Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —47 ~ 49

A numerical simulation method incorporating a composite coordinates grid system, strong non-uniform staggered grid arrangement and a staggered calculation mode was described in this paper. This method has been employed for the first time to perform a detailed computation of the three-dimensional flow field characteristics of a large-sized boiler furnace. The latter features a tangential firing mode with the use of burner nozzles of a sophisticated construction. Because of this, the false diffusion problem in the calculation domain caused by a relatively large included angle between a resultant speed direction and grid line one has been solved relatively well. Furthermore, a comparison with industrial test results shows that the numerical simulation method can quite accurately reflect the flow field characteristics in a boiler furnace combustion zone. A quasi-streamline numerical simulation is thus effectively realized. **Key words**: numerical simulation, false diffusion, quasi-streamline method, tangential firing

链条炉排的分区模型＝**Zoned Model for a Chain Grate**〔刊, 中〕/Zhu Jinrong (Nanjing Electrical Power Institute) // Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —50 ~ 51

After the establishment of a mathematical zoned model for a chain grate some turbulence simulation tests were conducted. The test results were in full agreement with theoretical ones. The model can reflect the effect of air distribution on combustion results. **Key words**: boiler, chain grate, air distribution on a zone-by-zone basis, mathematical model

空冷塔内外流场的数值分析＝**Numerical Analysis of the Inner and Outer Flow Field of an Air-cooling Tower**〔刊, 中〕/Zhang Xiaodong, Zheng Yonggang, Wang Qingzhao (North China Electrical Power University) // Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —52 ~ 54

With the use of a numerical simulation method the performance of a natural draft air-cooling tower working in a cross-wind has been investigated. By consulting the Heller type air-cooling system employed at Fengzhen Power Plant in Inner Mongolia an analysis was conducted of a specific calculation example. The analytical calculation results bring forth a perfor-

mance variation relationship and the specific features of the air-cooling tower inner and outer flow fields under cross-wind operating conditions. By revealing the major cause of the drop in heat dissipation the above work is helpful in providing some new ideas for further improving the cooling-air tower performance. **Key words**: air-cooling tower, Heller type indirect air-cooling system, k -ε dual equation model, numerical simulation, turbulent flow field

燃机 Mark V 遥控监控系统=**Mark V Remote-controlled Monitoring System for Gas Turbines**〔刊, 中〕/Wang Jingyi, Shen Qingwen, Yun Ruitian (Harbin No. 703 Research Institute), et al //Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —55 ~ 58

The application of an industrial control PC is described. Through the preparation of a pertinent software the use of GE Co. Mark V gas turbine control system as a remote-controlled monitoring system was successfully realized. Furthermore, a detailed account of the software design process is also given. **Key words**: gas turbine control system, remote-controlled monitoring, software design

工业锅炉热力计算软件编制=**Preparation of a Thermodynamic Calculation Software for Industrial Boilers**〔刊, 中〕/Han Muxin, Fan Wei (Harbin No. 703 Research Institute), Lu Hengyu (Harbin Boiler Works), et al //Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —59 ~ 61

By the use of a target-oriented programming language the authors have developed a Windows 95-based industrial boiler thermodynamic calculation software. Described in this paper are the specific features of the above development process. A proper approach for solving some key technical issues has also been expounded. **Key words**: industrial boiler, thermodynamic calculation, OOP

用 VB 编制 AutoCAD 阀门绘制程序=**Application Program of AutoCAD Plotting of Valves with the Help of a Visual Basic Language**〔刊, 中〕/Lin Xiangdong (Harbin No. 703 Research Institute) //Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —62 ~ 64

The preparation of an application program for AutoCAD plotting of valves with the aid of a visual basic language is briefly described in this paper for use in a thermodynamic system. This results in a significant enhancement of the AutoCad plotting efficiency. **Key words**: AutoCAD, VB language, plotting of valves

利用冷却塔排放湿法脱硫锅炉净烟气的技术=**New Technology Featuring the Discharge of Desulfurized Gas via a Cooling Tower for Boilers with a Flue Gas Wet Desulfurization System**〔刊, 中〕/Luo Chuankui Nong Youxing, Ying Chunhua (Zhejiang Provincial Electric Power Design Institute) //Journal of Engineering for Thermal Energy & Power, 2000, 15(1). —65 ~ 66

With the development and gradual sophistication of flue gas desulphurization technology, especially flue gas wet desulphurization, there emerged in succession various versions of this new technology. The discharge via a cooling tower of desulphurized flue gas represents one of the typical methods currently widely employed in some developed countries with high effectiveness. By contrast, the use of such technology in China is still in its infancy. Nevertheless, its rapid popularization can be readily expected in view of its varied technical merits. After a brief description and economic evaluation of the above technology the present paper proposes some original approaches for stepping up its engineering applications in China. **Key words**: cooling tower, discharge of flue gas, desulphrization

锅炉制造业几种简易设备的研制=**Development and Fabrication of Some Simple Machines Used in Boiler Manufacturing Industry**〔刊, 中〕/Zhao Yan (Heilongjiang Provincial Machine Manufacturing Technicum), Dong Dachang (Harbin Boiler Inspection Research Institute), Song Wei (Hegang Municipal Water, Electricity and Thermal Power Co.) //Journal of Engineering for Thermal Energy &Power, 2000, 15(1). —67 ~ 68, 74