

600MW 锅炉机组膜式水冷壁壁温的试验研究及理论分析

(武汉水利电力大学) 余艳芝 唐必光 刘勇
(平圩电厂) 薛文元 李树雷

摘要: 在 600MW 锅炉机组水冷壁热力试验的基础上, 为找到使壁温发生波动的根本原因, 利用有限元分析的方法对低倍率锅炉膜式水冷壁管壁温度分布随传热工况的动态变化进行了分析。分析表明: 导致水冷壁管壁温度波动最根本的原因是管内传热恶化; 单面受热水冷壁在管内发生传热恶化时其向火侧管内外壁温差随时间的波动较小, 而水冷壁周向温差则随向火侧外壁的壁温波动而剧烈波动。

关键词: 水冷壁; 温度场; 有限元

中图分类号: TK223.31

1 前言

电站锅炉炉管爆漏已成为影响大型机组安全、稳定运行的最主要原因之一, 近年来国内电厂水冷壁泄露事故频繁发生。安徽平圩电厂 1 号炉系哈尔滨锅炉厂引进美国 CE 公司技术生产的配 600MW 汽轮发电机组, 出力为 2008 t/h 的亚临界、控制循环、低倍率、燃煤锅炉, 于 1989 年投入运行。自 1994 年 10 月开始频繁发生横向裂纹泄漏, 造成机组多次非计划停机, 带来重大经济损失。为查明该炉水冷壁泄漏原因, 我们与平圩电厂合作, 于 1997 年 4 月对 1 号炉水冷壁进行了现场热力试验, 试验结果表明, 水冷壁壁温在一部分工况下发生严重波动, 波幅大的可达 $60^{\circ}\text{C} \sim 80^{\circ}\text{C}$ ^[1]。水冷壁向火侧壁温主要取决于炉内热负荷分布、水冷壁管内侧沸腾传热工况及蒸发受热面的污染。究竟什么原因导致水冷壁管有如此大的壁温波动, 膜式水冷壁内的温度分布随管内传热工况恶化变化的情况, 此温度变化对水冷壁内热应力的影

响, 本文对此做了进一步的探讨。

2 炉内壁面热负荷的确定

将炉膛沿高度分成若干段, 分别计算各段的热负荷。炉内最大放热区段在燃烧器区域, 根据不同锅炉负荷时所投入的燃烧器层次的情况, 最大放热区段略有差别。在热负荷的计算时, 炉膛沿高度方向分成大致相等的七个区段, 各区段的热负荷按炉内辐射传热公式计算, 结果见表 1。

表 1 不同锅炉负荷下, 炉膛各区段的热负荷计算结果

平均热负荷(kW/m ²)	负荷(MW)			
	380	450	550	600
第一区段(13.38~18.81)	92.56	102.74	115.90	120.29
第二区段(18.81~24.00)	154.19	170.37	191.36	198.83
第三区段(24.00~32.00)	273.41	284.17	300.32	306.85
第四区段(32.00~38.00)	229.56	241.98	260.34	269.39
第五区段(38.00~44.00)	163.93	178.01	198.98	210.68
第六区段(44.00~50.00)	125.96	139.55	159.61	170.92
第七区段(50.00~53.50)	80.89	91.05	103.69	108.65

3 水冷壁管内沸腾放热系数的确定

平圩电厂 1 号炉出现裂纹的区域位于炉膛标高 30~50m 的范围内, 热力试验测点布置在炉膛标高的 30m、40m、50m 处。在此高度处对应炉膛壁面热负荷的值取表 1 中的计算结果。利用热力试验测得的不同负荷工况下的平均最高外壁温度及平均最低外壁温度由公式(2)得到水冷壁管内沸腾放热系数,

收稿日期: 1998-11-27

作者简介: 余艳芝(1966-), 女, 河南人, 武汉水利电力大学动力系讲师。邮编 430072

计算结果见表 2。

$$\alpha = \frac{\mu\beta q}{t_{wb} - t_s - 2\mu\beta \frac{q\delta}{(\beta+1)\lambda}} \quad (2)$$

式中： μ 热量均流系数 β 管子内外径之比
 t_{wb} 实测管子外壁温度 t_s 管内工质的饱和温度
 δ 管壁厚度 λ 金属管壁的导热系数

表 2 放热系数的计算结果

负荷(MW)	标高(m)	对应平均最高壁温下的	对应平均最低壁温下的
		对流放热系数 α (W/m ²)	对流放热系数 α (W/m ²)
380	30.0	8389.00	22603.00
	40.0	5667.00	9728.00
	30.0	9997.00	30079.00
450	40.0	9298.00	29162.00
	50.0	3761.00	6631.00
	30.0	10269.00	29211.00
550	40.0	10109.00	30909.00
	50.0	2868.00	3592.00
	30.0	9139.00	27849.00
600	40.0	10606.00	44463.00
	50.0	3009.00	4963.00

4 温度场数学模型的建立

水冷壁外壁向火侧受炉膛高温火焰热辐射作用,背火侧外壁有一定的散热率;内壁与汽水两相强制流动换热。随着辐射热强度及水冷壁管内的传热工况的变化,水冷壁管壁内为非稳态二维温度分布,可用如下定解方程表示:

$$\begin{cases} \lambda \left[\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} \right] = \rho C_p \frac{\partial t}{\partial \tau} \\ \lambda \frac{\partial t}{\partial n} \Big|_{\Gamma_2} = q(x, y) \\ \lambda \left[\frac{\partial t}{\partial n} \right] \Big|_{\Gamma_3} = \alpha(t - t_f) \end{cases} \quad (1)$$

式中： λ 为导热系数； q 表示热流量； t_f ， α 表示工质温度及管内沸腾换热系数； Γ_2 表示给定热流的第二类边界条件； Γ_3 表示给定边界放热系数、介质温度的第三类里边界条件。

方程(1)可采用有限元分析的方法,利用计算机编程进行求解,方法及程序的编制见[2]。对膜式水冷壁温度场计算而言,关键是炉内热负荷分布的确定及管内沸腾放热系数的确定。在以往的水冷壁的沸腾传热计算中,水冷壁管内的放热系数作一平均

值处理,这与实际情况有一定的差别。由向火侧对管内工质的加热超过背火侧,蒸汽的蒸发大部分在向火侧完成,如果管内发生传热工况的恶化,局部的膜态沸腾出现在向火侧管内壁的可能性较大,此时管内向火侧与背火侧放热系数有较大的差别。若只计算向火侧正面外壁温度,误差不会太大,但对于膜式水冷壁整个温度场分布而言,应该考虑到这种差别。本文的计算将管内沸腾传热分成两个部分,向火侧和背火侧分别用不同的管内对流传热系数计算整个膜式水冷壁的温度分布。

5 膜式水冷壁温度分布计算

选择膜式水冷壁管的 1/2 作为计算模型进行有限元分析,采用四边形八节点等参数单元,共分 132 个单元、487 个节点。

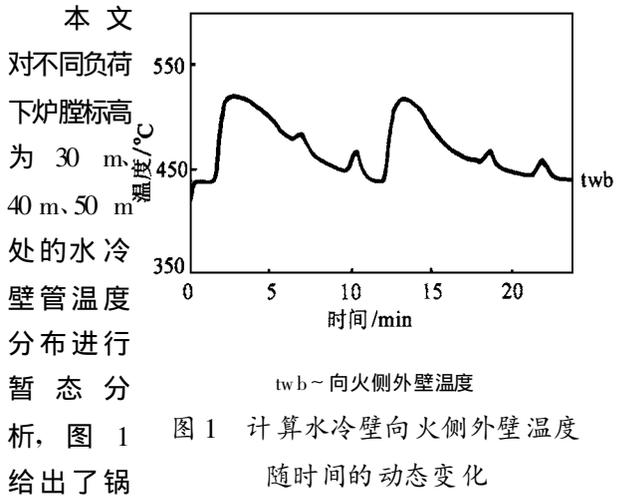


图 1 计算水冷壁向火侧外壁温度随时间的动态变化

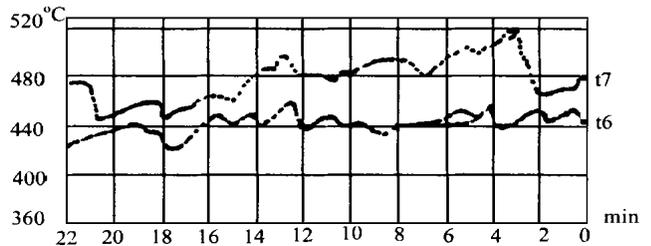


图 2 热力试验时水冷壁向火侧外壁温度随时间的动态变化

炉在 600MW 负荷时炉膛标高 30 m 处水冷壁管外壁温度随时间的动态变化,与图 2 热力试验结果相比符合得较好,由此可以确定水冷壁管壁温波动是

由水冷壁管内的传热恶化造成。壁温波动幅度随水冷壁管内沸腾放热系数的变化及炉内的热负荷的大小而变化。典型的水冷壁管壁温度分布如图4所示。在锅炉负荷为600MW水冷壁管内发生膜态沸腾2分钟时管壁温度分布表明,水冷壁管内不仅沿半径方向有较大的温度梯度,沿周向也有较大的温度梯度。此温度分布较为合理^[3]。随着传热工况的变化,水冷壁径向温差及周向温差均发生变化,径向温差的变化较小,周向温差的变化较大。图3给出了径向温差及周向温差随传热工况变化时动态变化过程。

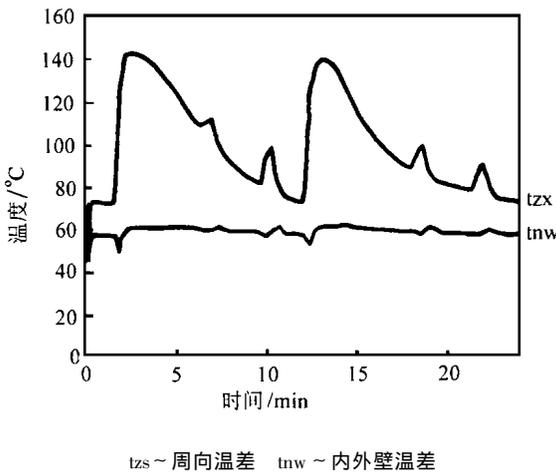


图3 计算水冷壁向火侧内外壁温差及周向温差随时间的动态变化情况

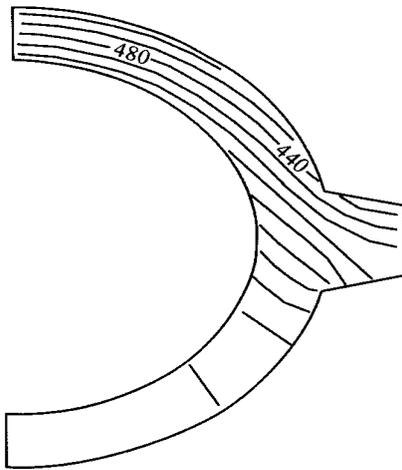


图4 膜式水冷壁内典型的温度分布(对应600MW膜态沸腾发生后第2分钟时)

从图3可以看出,水冷壁向火侧内外壁温差随传热工况的变化波动很小,而周向温差的变化却很大。对一般的承压管壁而言,径向温差所产生的应力以周向为最大,而周向温差可使管壁内产生较大的轴向应力^[4]。从计算结果看出,水

的轴向应力及轴向应力的波动。可以肯定,变化的轴向热应力,加之内螺纹引起的应力集中,水冷壁管内产生横向裂纹在所难免。水冷壁管内除热应力外,还承受内压引起的机械应力,此应力的大小及其变化与运行方式和运行工况有关。水冷壁管壁内应力状况如何及其对水冷壁管材的寿命损伤的影响有待进一步的研究。

6 结论

通过水冷壁壁温分布的暂态分析可得出以下结论:

(1)水冷壁壁温波动是由管内传热工况的恶化造成,在热负荷较高的区域水冷壁管内发生局部的膜态沸腾现象。

(2)随炉内热负荷的脉动,水冷壁传热工况发生变化。水冷壁管传热工况恶化时,管内侧的放热系数突然变小,维持较短时间后再缓慢增大,增大的过程中仍有小范围的汽膜产生,水冷壁管壁温度随此过程而发生波动。

(3)水冷壁的内外壁温差随传热工况变化时的波动较小,而周向温差随传热工况变化的波动很剧烈,最大周向温差达140°C,波动幅度也高达70°C。

(4)水冷壁管壁内周向温差及周向温差的变化将产生的波动较大的轴向应力,加之水冷壁管内压力的变化及内螺纹结构的应力集中,水冷壁管壁产生横向裂纹是不可避免的。

参考文献

[1] Tang B, Yu Y, Liu Y, Xiang J. A Research on the root cause of the water walls circumferential cracking. International Conference on Power Engineering—97, Tokyo; ICOPE—97, Volume 2.
 [2] 余艳芝. 200MW 锅炉汽包暂态温度场和应力场的有限元计算及疲劳寿命分析. 热力发电, 1994, 4.
 [3] 范谨. 膜式水冷壁温度场解析. 热力发电, 1996, 3.
 [4] Timoshenko S P and Goodier J N. Theory of elasticity, 3th. ed. New York; McGraw-Hill, 1980.

(渠源 编辑)

水冷壁管内的周向温差及周向温差的变化将导致较大

ICR 进展及关键技术 = **New Developments in ICR Engines and Related Key Techniques** [刊, 中] / Liu Yongbao, Zhang Renxing (Naval Engineering Academy) // Journal of Engineering for Thermal Energy & Power. — 1999, 14(6). — 415 ~ 418

In addition to a series of advantages specific to a simple cycle gas turbine ICR engines feature an excellent off-design performance with Model WR-21 engine being ranked as the most advanced. This paper gives a brief description of some new developments in WR-21 gas turbines. The key techniques relating to such major components as intercoolers, regenerators, engine enclosures and digital control systems are also analyzed. **Key words:** ICR gas turbine, intercooler, regenerator, enclosure, control system

气体燃料再燃对 NO_x 还原的影响 = **Effects of Gaseous Fuel Reburning on NO_x Reduction** [刊, 中] / Zhong Beijing, Fu Weibiao (Qinghua University) // Journal of Engineering for Thermal Energy & Power. — 1999, 14(6). — 419 ~ 423

Gaseous fuel reburning pertains to one of the most effective methods being extensively studied for the reduction of NO_x content in flue gases. With the gases in a typical primary combustion zone serving as simulation gases the authors have studied the influence of different gaseous fuels (CH₄, C₂H₂ and C₂H₄) and the reburning zone combustion conditions (excess air coefficient and reburning temperature) on NO_x reburning process and its reduction. Through calculations it is found that different compositions of gaseous fuels, the excess air coefficient and firing temperature in the reburning zone exercise a significant influence on the NO_x reburning process and NO_x reduction rate. **Key words:** fuel reburning, gaseous fuel, NO_x reduction

煤粉锅炉炉膛燃烧、传热一维数学模型的研究 = **A Study of the Combustion and Heat Transfer One-dimensional Mathematical Model for a Pulverized Coal-fired Boiler Furnace** [刊, 中] / Dong Peng, Hong Mei, Qin Yukun et al (Harbin Institute of Technology) // Journal of Engineering for Thermal Energy & Power. — 1999, 14(6). — 424 ~ 427

A combustion and heat transfer one-dimensional mathematical model has been set up for the analytical computation of one-dimensional distribution magnitudes of such thermodynamic parameters as furnace gas temperatures, water wall absorption heat flux density, heat release rate, etc. under various operating conditions. The calculation and analysis of three different models of boilers and a comparison of the calculated results with original design data have validated the rationality of the adopted mathematical model. **Key words:** furnace internal process, in-furnace heat transfer, mathematical model, pulverized coal combustion

折焰角结构对上部炉膛流场影响的数值研究 = **Numerical Simulation of the Effect of Arch Nose Structure on Furnace Upper Section Flow Field** [刊, 中] / Li Yanpeng, Xu Jinyuan (Xi'an Jiaotong University) // Journal of Engineering for Thermal Energy & Power. — 1999, 14(6). — 428 ~ 430

Based on a porosity conception conducted is a numerical simulation of the flow field in a boiler furnace under various arch nose structures. The effects of such structures on the residual swirl at the furnace outlet and the velocity distribution at the inlet of horizontal gas-pass were studied. The study results have been verified by way of a cold-state simulation test. They can serve as useful reference data during the design and retrofitting of utility boilers. **Key words:** arch nose, residual swirl, thermal excursion, numerical simulation

椭圆锥急燃器对煤粉火焰的稳燃作用 = **The Combustion Stabilizing Role Played by an Ellipsoidal Cone Combustion Stabilizer** [刊, 中] / Jing Youyin, Wang Baosheng (North China Electrical Power University) // Journal of Engineering for Thermal Energy & Power. — 1999, 14(6). — 431 ~ 433

By introducing the characteristics parameters of a gas-solid two-phase flow and proceeding from the structure of a pulverized-coal flow an analysis is performed of the combustion stabilizing action of an ellipsoidal cone combustion stabilizer on a pulverized-coal flame. **Key words:** ellipsoidal cone combustion stabilizer, characteristics parameter, pulverized-coal flame, ignition and steady combustion

600MW 锅炉机组膜式水冷壁壁温的试验研究及理论分析 = **Experimental Investigation and Theoretical Analysis of Membrane Water Wall Temperature in a 600 MW Boiler Unit** [刊, 中] / Yu Yanzhi, Tang Biguang, Liu Yong, et al (Wuhan University of Water Resources and Electrical Power) // Journal of Engineering for Thermal Energy & Power. — 1999, 14(6). — 434 ~ 436

On the basis of the water wall thermodynamic test of a 600 MW boiler unit and through the use of a finite-element analytical method an analysis was conducted of the dynamic variation with heat transfer conditions of membrane water wall tube wall temperature distribution of a low-circulation ratio boiler. The analysis aims at identifying the underlying basic cause of water wall tube wall temperature fluctuations. The results of the analysis show that the basic cause leading to the fluctuations of the water wall tube wall temperature lies in the deterioration of in-tube heat transfer. In the course of a heat transfer deterioration taking place inside the tubes of a single-side heated water wall the temperature difference between the fire-facing tube inner and outer tube wall surface has a relatively small time-dependent fluctuation. However, the water wall peripheral temperature difference suffers a drastic fluctuation triggered by the wall temperature fluctuations of the fire-facing outer wall. **Key words:** water wall, temperature field, finite element

换热器性能的火用经济评价 = **Exergy-economic Evaluation of a Heat Exchanger Performance** [刊, 中] / Wu Shuangying (Chongqing University) // Journal of Engineering for Thermal Energy & Power. — 1999, 14(6). — 437 ~ 440

Based on the exergy-economic analysis of heat exchanger heat transfer and flow process the author has come up with a heat exchanger performance evaluation index, the so-called η criterion, defined as the total cost per unit quantity of heat transferred. Furthermore, conducted was the exergy-economic analysis and optimization of three types of heat exchangers i. e., down-flow, cross-flow and counter-flow. The methods employed and results presented in this paper can serve as a guide during the performance evaluation of heat exchangers. **Key words:** heat exchanger, exergy-economic analysis, performance evaluation

三维温度场计算机可视化系统的研制与开发 = **Development and Fabrication of a Computer-based Visual System for Three-dimensional Temperature Fields** [刊, 中] / Zhang Shishuai, Luo Jun, Zhu Maoshu, et al (Central University of Science & Technology) // Journal of Engineering for Thermal Energy & Power. — 1999, 14(6). — 441 ~ 442

Described in this paper is a computer-based visual system for the visualization treatment of a three-dimensional temperature field encountered in engineering thermophysics by the use of computer graphic and image techniques. The above-cited system includes a variety of modules, which are used for performing such functions as the model building of the three-dimensional temperature field, color mapping, setting-up of a visual model, extraction of a sectional plane, the setting of visual angle, etc. The system is developed and realized on a Windows 95 platform with the help of Visual C. **Key words:** three-dimensional temperature field, visual system, model building

大型亚临界无烟煤电站锅炉的开发设计 = **The Design and Development of a Large-sized Anthracite-fired Subcritical-pressure Utility Boiler with a Tangential firing System** [刊, 中] / Chen Jirong, Gao Feng (Harbin Boiler Co. Ltd.) // Journal of Engineering for Thermal Energy & Power. — 1999, 14(6). — 443 ~ 446

The present paper describes the technical features and operational achievements of a 300 MW subcritical-pressure, natural-circulation and anthracite-fired boiler developed and designed by Harbin Boiler Co. Ltd (HBC). It focuses on some effective technical measures taken to ensure a good ignition, stable combustion and thorough burn-off, a stable combustion without relying on oil support even at low loads and complete combustion of low volatile coal as well as a slag-free operation and a reduction in NO_x emissions. With respect to the burner design a "self-stabilizing combustion technology incorporating double primary air channel" developed jointly by HBC and Qinghua University has been adopted. This item of technology was awarded a China National Golden Prize for outstanding creative and inventive patents. The marked flame stability at low loads and excellent overall performance provided by the above-cited technology have advanced the design of high-capacity anthracite-fired boilers to a new level. Such boilers with a tangential firing system enjoy the advantages of low steel consumption, low NO_x emission, etc. Their successful development has blazed a new trail for the utilization of low volatile coals, an abundant resource in China. **Key words:** anthracite, sub-critical, natural circulation, boiler design, burner

煤粉锅炉液化气点火装置的理论与实践 = **Theory and Practice of a Liquefied Petroleum Gas-based Ignition**