

充气热管空气预热器的设计分析及应用

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摘 要: 对充气热管空气预热器的结构进行分析和应用介绍, 采用平界面模型, 确定充气热管冷却段的有效长度。在原始参数相同的条件下, 对充气和不充气的热管换热器进行试验, 分析热管最低控制工作温度、排烟温度和换热面积之间的差异。工业试验和实际应用结果表明: 在变工况和高硫煤(5%—7%)的条件下采用充气热管空气预热器具有十分优良的防腐蚀和防积灰的性能。

关 键 词: 充气热管; 空气预热器; 防腐蚀; 防积灰

中图分类号: TK172.4 文献标识码: A

1 前 言

采用热管作为换热元件实现了烟气换热在管外表面进行, 且其加热段与冷却段的换热面是分开布置的, 热端和冷端可以通过选用不同的肋化系数改变其两端的热阻比例, 使换热面温度在一定程度上实现调节, 可使壁温处于烟气酸露点腐蚀的相对安全区, 避免或减轻低温烟气对金属壁的腐蚀。壁温较高, 换热面干燥, 积灰现象大大减少。再者, 热管换热器可以做到不泄漏, 冷热流体不渗混。但是, 工业锅炉起停炉频繁, 负荷变化很大, 进入热管空预器烟气的温度和流量也在变化。一般热管换热器是通过改变热管两端肋化系数来达到调节壁温, 在设计工况和燃用低硫燃料下可有效地防止腐蚀和积灰, 但在变动工况或燃用高硫煤时就难尽人意。因此, 采用了充气热管可提高其在低温运行状况下防积灰和抗腐蚀的能力。笔者曾在重庆某厂 35 t/h 锅炉上采用较低充气压力的热管, 从热管运行 20 个月来看, 达到了防止因结水露而积灰的效果, 但该换热器最末几排热管仍有较严重的因酸露而积硬灰的现象, 该灰 1% 的水溶液 pH 值达到 1。由此看来, 要使空预器既不结水露又不结酸露, 必须使热管的壁温(既在设计工况又在变动工况下)高于烟气的酸露点, 采用较高的充气压力用较多的受热面换取较高

的热管工作温度, 是解决工业锅炉尾部受热面积灰和腐蚀等问题的一种有效方法。热管采用充气压力较高后, 其传热性能将如何变化, 是否真正行之有效地起到防腐蚀和防积灰是本文所关注的问题。

2 充气热管的冷凝段的有效长度

文献[1]报导的充气热管即变导热性热管(VCHP)达到平衡状态的情况, 如图 1 所示。并对充气热管作如下假设: (1) 不凝结气体服从理想气体定律; (2) 热管处于稳定状态工作; (3) 不凝结气体和工质蒸汽存在明显的分界面。由理想气体定律知, 充入气体应满足:

$$P_1 V_1 / T_1 = P_2 V_2 / T_2 \quad (1)$$

式中: P_1 —充气压力;

P_2 —热管工作时的压力;

V_1 —充入气体时的容积;

V_2 —热管工作时充入气体的容积;

T_1 —充入气体时的气体的温度;

T_2 —热管工作时充入气体的温度。

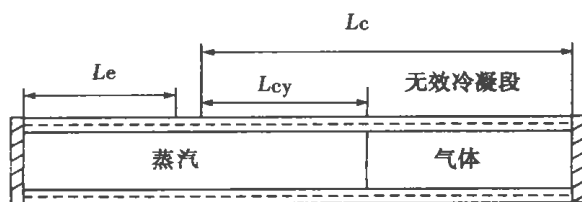


图 1 充气热管平衡状态

一般热管是等直径的, 由此可得出所充入气体在工作时所占据的热管长度 L_q 为:

$$L_q = L \frac{P_1 T_2}{P_2 T_1} \quad (2)$$

式中: L —充气时所充气体占据的热管长度。式中的

L 、 T_1 、 P_1 可认为是已知的, P_2 可以通过假定冷却段的有效换热长度迭代计算, 只要确定了 T_2 、 L_q 则为已知, 由此可得到热管冷却段的有效换热长度 L_q 为^[2]:

$$L_{cy} = L_c - L_q \tag{3}$$

式中: L_{cy} —热管冷却段的有效长度; L_c —热管冷却长度。由于各排热管工作压力 P_2 和温度 T_2 及冷却段的有效换热长度 L_q 不同, 所以 P_2 、 T_2 和 L_q 需反复迭代方可确定。在确定了热管冷却段的有效长度后, 只需将不充气热管计算中的 L_c 替换为 L_{cy} , 即可进行充气热管的分排设计计算。

3 充气热管换热器的传热性能

3.1 试验结果

文献[3]报道了充气热管性能的实验结果。在稳定状况下充气热管沿长度方向的壁温分布中得出结论, 热管在低温状态下能够自动关闭部分冷凝段, 而在热管工作温度升高后又会自动投入工作。图 2 是在工业试验现场实测的充气和不充气热管在实际换热器中(最末排)壁温随入口烟温的变化^[4]。显然充气热管比不充气热管有较高的壁温。设计得当可使热管的最低工作温度高于烟气的酸露点温度(保护温度), 所以能起到低温自动保护的作用。

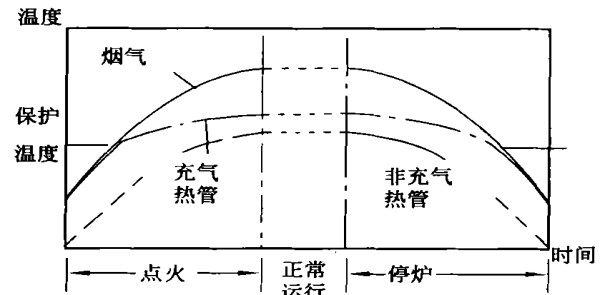


图 2 两种热管末排壁温随烟温的变化

3.2 设计分析

为了了解充气热管的传热性能, 以一台 20 t/h 工业锅炉为例, 对充气和不充气的热管换热器进行设计和对比分析热管最低控制工作温度 T_v 、排烟温度 T_{gi} 和换热面积 N 之间的差异。两种换热器的烟气和空气流量相同。烟气进口温度 T_{giw} 为 250 °C、空气进口温度 T_{ai} 为 20 °C。烟气和空气迎面流速分别为 3 m/s 和 2.8 m/s; 采用相同几何参数的热管, 高温区 12 排为一种肋片间距组合, 低温区为另

一种肋片间距组合^[2]。

图 3 是充气热管的最低工作温度 T_v 控制在 130 °C, 排烟温度 T_{go} 为 150 °C 和 170 °C 时, 各管排充气压力沿管排的变化和烟气出口温度为 150 °C 时的工作温度 T_v 沿管排的变化。由图看出, 充气热管的排烟温度 T_{go} 仅低 20 °C, 所需的管排数多 11 排。这一方面是排烟温度 T_{go} 为 150 °C 与热管介质的传热温差仅 20 °C, 导致后几排热管的传热量大幅度降低; 另一方面, 充气热管的有效长度由较大幅度的减少所致。因此, 在最低控制工作温度较高时, 不宜选取太低的排烟温度。

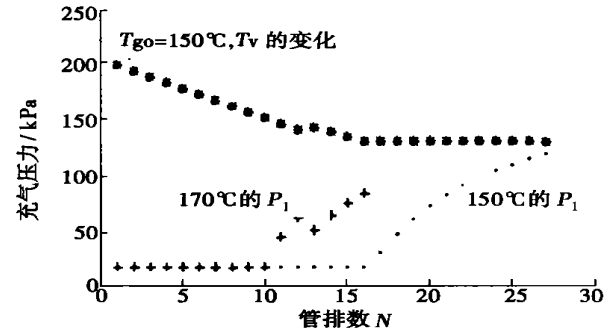


图 3 充气压力 P_1 、 T_v 随管排数 N 的变化

图 4 是充气热管冷却段有效长度随热管管排数的变化, 图中平直实线为不充气时的冷却段长度 L_c 。平直实线与曲线之间所围成的区域代表了所充气体关闭的冷凝段。为了确保不腐蚀, 随着管排数增加, 充气压力增加, 冷凝段的有效长度逐排减少。

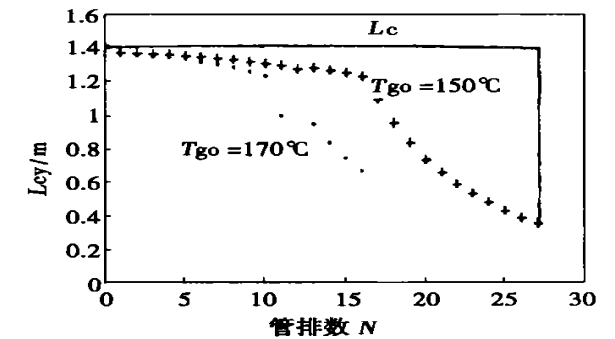


图 4 有效冷凝段 L_{cy} 随管排数 N 的变化

图 5 是设计排烟温度为 160 °C, 充气热管最低工作温度 $T_v=130$ °C, 不充气热管 $T_v=100$ °C 时换热器在变动工况下, 实际排烟温度 T_{go} 和最低工作温度 T_v 随来流烟温 T_{gi} 的变化。由图看出, 充气热管的 T_{go} 、 T_v 曲线的斜率小, 尤其是充气热管 T_v 曲

线较不充气热管 T_v 曲线平直得多,这对工作状况不稳定的锅炉来说是极有利的。如在来流烟温为 $200\text{ }^{\circ}\text{C}$ 时,不充气热管的工作温度 T_v 低到 $82\text{ }^{\circ}\text{C}$,而充气热管的最低工作温度 T_v 仍达到 $122\text{ }^{\circ}\text{C}$,高出 $40\text{ }^{\circ}\text{C}$,充分显示了充气热管换热器对低烟温的适应能力较强的特点。

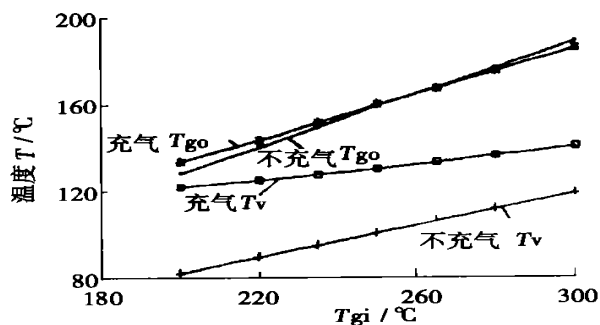


图5 T_{go} 、最低热管工作温度 T_v 随 T_{gi} 的变化

4 应用

某厂1996年11月投运的3台20 t/h 锅炉的热管空气预热器,该锅炉燃煤含硫量为3%,设计排烟温度为 $160\text{ }^{\circ}\text{C}$,比采用管式空气预热器低 $20\text{ }^{\circ}\text{C}$,有节能效果。该新装锅炉前一年负荷很不稳定,起停炉很频繁,产汽量在 $4\sim 16\text{ t/h}$ 之间,运行5年半后检查积灰很轻,期间一直未清过灰。图6所示的照片于1999年11月拍摄,其中积满灰的是没充气的热管。图7所示的是于1996年2月投运的两台35 t/h 锅炉(BG-35/54-M₃)的热管空气预热器。该锅炉空预器烟气是由下向上流动的,燃用煤的含硫量为3.34%,该充气热管空气预热器的设计排烟温度为 $155\text{ }^{\circ}\text{C}$ 。从照片可看到其中有一支成了光管,那正是一支没有充气的热管,从该图对比可得出,充气热管确实有防积灰和防腐蚀的功能。以上几台热管空预器至今仍在运行。目前,还有多台这种换热器用于煤的含硫量高达5%(有时高达7%)的链条和循环流化床锅炉,这些热管空预器运行2年多了,还一直未清过灰,也没有发现漏风。以前采用管式空预器运行不到三个月就因腐蚀漏风而拆除。可见这种充气热管空气预热器对燃用高硫煤也确有防积灰、漏风和腐蚀的作用。在工业锅炉中应用有很好的经济效益。

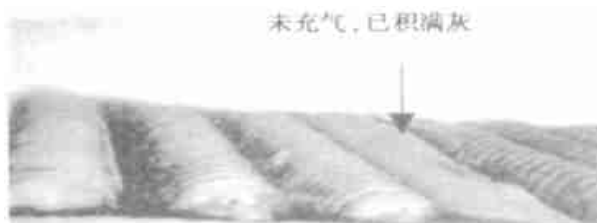


图6 后第四排热管的积灰情况

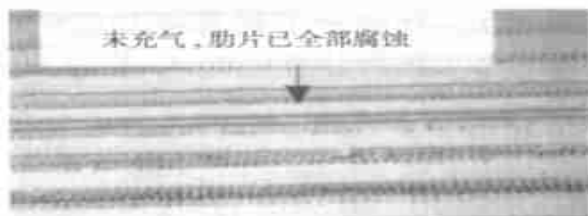


图7 最末排充气、不充气热管腐蚀情况

5 结 论

(1) 在计算条件范围内,采用充气热管换热器的排数要增大(换热面积大),如图3所示,阻力也要增大。要使热管具有强的防腐蚀、防积灰的能力,需增加对换热器的初投资。

(2) 在变工况下,充气热管的排烟温度和热管最低工作温度是随来流烟气温度而变化,有较明显的低温保护功能,较适用于起停炉频繁,负荷变化大的锅炉的空气预热器可达5%~7%。

(3) 通过多年多台多煤种高含硫量的实际应用表明:充气热管换热器确实具有优良的防腐蚀、防积灰性能,该结果可供工程应用参考。

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design, information integration, general assembly drawing integration.

基于谐波小波变换的4-73风机压力侧失速特性分析= **An Analysis of Pressure-side Stalling Characteristics of a 4-73 Air Fan Based on Harmonic Small-wave Transformation** [刊, 汉] / WANG Song-ling, HOU Jun-hu, AN Lian-suo (Power Engineering Department, North China Electric Power University, Baoding, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 295 ~ 298, 315

Based on a qualitative analysis of the pressure-side stalling formation mechanism of a centrifugal fan, the authors have through an experimental study of 4-73 air fan discovered the pressure-side stalling phenomenon of the latter. The time-frequency characteristics of the pressure-side stalling are analyzed by using a harmonic small-wave transformation. During the analysis the orthogonal harmonic small waves, which have a relatively poor time-domain locating ability, underwent a frequency-domain smoothing processing. In the analysis of the rotating stall introduced was a non-orthogonal harmonic small-wave transformation. The results of the analysis have demonstrated the effectiveness of harmonic small-wave transformation for analyzing the rotating stall characteristics of centrifugal fans. **Key words:** centrifugal fan, harmonic small wave, rotating stall, characteristics analysis

船用锅炉方形翅片管经济器的试验与应用= **Experimental and Applied Research of the Square Finned-tube Economizer of a Marine Boiler** [刊, 汉] / LIU Xiang-yuan, LI Yu-hong, WU Xiao-bing (Thermal Energy Engineering Department, Tsinghua University, Beijing, China, Post Code: 100084), JIANG Xiao-yan (Naval Materiel Research and Demonstrative Center, Beijing, China, Post Code: 100073) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 299 ~ 301

A discussion is conducted regarding the necessity to upgrade a marine main boiler economizer along with the analysis of the application circumstances and merits of square finned tubes. On a heat-transfer wind tunnel test rig an experimental research of the air-side flow resistance and heat transfer was performed of square finned tube banks. The results of the research indicate that in case of air speed greater than 25 m/s it is necessary to revise heat transfer factors through tests. Finally, a rational design scheme was decided for the economizer with square finned tubes on the basis of the test results. **Key words:** marine boiler, economizer, square finned tube

火电厂单元制循环水系统离散优化模型及应用= **A Discrete Optimized Model for the Monobloc Configured Circulating Water System of a Thermal Power Plant and Its applications** [刊, 汉] / HUANG Xin-yuan, ZHAO Li, AN Yue-li (College of Energy and Power Engineering under the Shandong University, Jinan, China, Post Code: 250061), CHANG Jia-xing (Huangtai Power Station, Jinan, China, Post Code: 250100) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 302 ~ 305

A discrete optimized model was proposed for a monobloc configured circulating water system featuring non-continuous change of water flow rate. By conducting iterative calculations of equivalent profit points the model can determine the critical operating conditions at the juncture of switch-over of circulating-water pumps. With the power unit No. 7 of the Huangtai Power Station serving as an example the present model was used to study operation optimization in order to determine the most economical grouping-mode of operation for the circulating water pumps at different seasons and at various loads of the power unit. A profit analysis indicates that for a 300 MW power unit through the introduction of discrete optimization for a circulating water system it is possible to achieve a reduction of coal consumption by 0.5 - 0.7 g/(kWh). On the basis of thermodynamic test data an empiric formula is determined for the heat transfer factor of a steam condenser, which can serve as a guide for other similar units. **Key words:** circulating water system, discrete optimization, economic operation

充气热管空气预热器的设计分析及应用= **Design Analysis and Application of a Gas-filled Heat-pipe Air Preheater** [刊, 汉] / SHI Cheng-ming, HU Hui-li, LI Ling-bo (College of Power Engineering under the Chongqing University, Chongqing, China, Post Code: 400044) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 306 ~ 308

The structure of a gas-filled heat-pipe air preheater is analyzed along with a description of its applications. By using a flat interface model it is possible to determine the effective length of a gas-filled heat pipe cooling section. Under the condition of identical initial parameters the gas-filled heat-pipe heat exchangers and those not being gas-filled are tested and the difference among the heat-pipe minimum operating-control temperature, exhaust gas temperature and heat exchange area is analyzed. The results of industrial tests and practical use indicate that under off-design operating conditions and when firing coal of high sulfur content (5% - 7%) the gas-filled heat-pipe air preheaters excel in corrosion-prevention and ash-fouling resistance performance. **Key words:** gas-filled heat pipe, air preheater, corrosion prevention, ash fouling resistance

2.8 MW 热水链条锅炉改烧水煤浆燃烧试验分析 = The Combustion Test and Analysis of a 2.8MW Hot-water Traveling-grate Boiler Retrofitted for Firing Coal-water Slurry [刊, 汉] / XIE Yong-gang, ZHAO Xiang (Institute of Thermal Power Engineering under the Zhejiang University, Hangzhou, China, Post Code: 310027), ZHANG Chuan-ming, WANG Feng-yin (Xinwen Mining Group Corporation, Xinwen, Shandong Province, China, Post Code: 271219) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 309 ~ 311

Coal-water slurry is a new type of clean fuel, which enjoys very good usage prospects. Its use on a retrofitted 2.8MW hot-water boiler in the central hospital of Xinwen Mining Group Corp. is credited with a stable combustion even at low loads. The combustion process of coal-water slurry in the above-mentioned boiler is described along with an analysis of the flame center and length as well as slag-forming characteristics etc. After its retrofitting the boiler has attained a thermal efficiency of 80.04% and a combustion efficiency of 99.36%. It is noted that the secondary-air swirl intensity, atomization air pressure, slurry pressure, air feed rate and boiler load, etc have a significant impact on the combustion of the coal-water slurry, and, hence, combustion efficiency. The retrofitting of this hot-water boiler can serve as a fine example for the retrofitting of other analogous boilers. **Key words:** coal water slurry, combustion process, boiler modification and upgrading

鳞片式锅炉链条起拱问题及预紧力分析 = An Analysis of the Humping of Fish Scale-shaped Boiler Chains and the Application of a Pretension Force [刊, 汉] / ZHANG Yao-wen (Yantai Bing Lun Boiler Co. Ltd., Yantai, China, Post Code: 264002), WANG Xu-dong (College of Mechanical Engineering under the Xi'an University of Electronic Science & Technology, Xi'an, China, Post Code: 710071) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 312 ~ 315

Through the solution for a catenary equation and the clarification of the rigidity relationship between the upper and lower chains the mechanics problem of humping of boiler grate chains was analyzed and discussed. On this basis a critical pretension force along with its simple assessment and control has been proposed, which can be used as a target index for the design and safe operation of front-drive boiler chains. A comparison of the two drive modes, namely, the front and rear shaft drives, has led to the conclusion that a front shaft drive is more rational for use on industrial boiler chain grates. **Key words:** fish scale-shaped chain, chain rigidity, chain pretension, catenary

一种新的流量管标定方法 = A New Method for Calibrating Air Flow-rate Measuring Tubes [刊, 汉] / LI Dian-xi, WANG Hong (Harbin No.703 Research Institute, Harbin, China, Post Code: 150036), WANG Shi-an, YOU Ke-quan (Naval Representative Office Resident at No.703 Research Institute) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 316 ~ 317

Key words: aerodynamic test rig, air flow-rate measuring tube, calibration, equipment

工业锅炉给水泵选型的方法 = Type Selection Method for the Feedwater Pumps of Industrial Boilers [刊, 汉] / LIU Xue-hai, YAN Feng-zhen (Equipment Engineering Department, Wondersun Milk Products Industrial Co. Ltd., Harbin, China, Post Code: 150090) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(3). — 318 ~ 319

Key words: industrial boiler, feedwater pump, type selection