应用技术

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基于氟塑料换热器的新型烟气余热深度回收技术研究

胡 清,孙少鹏,蒋 文,朱文中
(1. 杭州华电能源工程有限公司,浙江 杭州 310030)

摘 要: 本文介绍了一种基于氟塑料换热器的新型烟气余热深度回收技术,阐述了该技术的原理及其主要特点,并以某1 000 MW机组为例,对该技术的经济性进行了计算分析。分析表明: 新型烟气余热深度回收系统具有适用性强、调节性好、高效性和可操作性强等特点; 该新型烟气余热深度回收系统经济效益显著,工程投入运行后,锅炉排烟温度由130 ℃降至85 ℃,机组年平均标煤耗降低2.58 g/(kW·h),年节水量443 100 t,系统年节约标煤净收益695.3万元,且环境效益显著,系统投资回收期约5.61年。

关 键 词: 氟塑料换热器; 烟气余热深度回收; 经济性; 标煤耗; 年收益

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引 言

对燃煤火力发电机组而言,锅炉效率是衡量机组经济性运行的重要指标。而排烟损失则是锅炉效率的重大影响因素,锅炉排烟热损失约占锅炉总体热损失的70% ~80%。研究结果表明[1],锅炉排烟温度每上升20 ℃,锅炉效率将下降1%,机组的年平均标煤耗将随之上升3 g/(kW·h)以上。锅炉排烟温度偏高在导致机组年平均标煤耗上升的同时,还将造成粉尘、SO_2、NO_x等污染物排放量的增加,从而影响机组整体的经济性运行及污染物排放指标。2014年新推出的煤电节能减排升级与改造行动计划指出,到2020年,新建燃煤火电机组大气污染物排放基本达到燃气机组排放标准,即粉尘、SO_2、NO_x排放标准分别不高于10、35、50 mg/m^3。因此,为降低燃煤机组煤耗,提高机组经济性,减少污染物的排放量,对锅炉尾部烟气余热进行回收利用具有重大意义。

针对如何有效地回收利用锅炉尾部烟气余热,国内外的专家学者开展了大量的研究工作[2~5]。目前,最为常用的方式有两种: 一是利用回收的烟气余热加热凝结水; 二是利用回收的烟气余热加热供热热网水。但由于金属换热器低温酸腐蚀问题的存在,烟气余热回收利用的深度有限; 虽然目前已经开发了耐低温酸腐蚀的特种钢材,但其价格昂贵导致改造投资费用很高、投资回收期较长,而且特种钢材低温酸腐蚀环境下的运行效果还有待考证。基于以上问题,本文提出了一种基于氟塑料换热器的新型烟气余热深度回收技术,并以某1 000 MW机组为例,计算分析了该技术的运行效果及经济性。

1 氟塑料换热器

近年来,一种氟塑料材质的换热器以其耐腐蚀性强、摩擦系数小、耐250 ℃以下高温等特点受到广泛关注[6~7]。用于氟塑料换热器的材料主要有PTFE(聚四氟乙烯)、PFA(四氟乙烯与全氟代烷基乙烯基醚共聚物)和FEP(聚全氟代乙丙烯)等高分子材料。

与金属换热器相比,氟塑料换热器具有以下显著优点[8]:

(1) 比金属换热器传热面积与体积比高,高出一到几个数量级,且氟塑料换热管的密度很小。同时,由于采用管径小、管壁薄的氟塑料管,其综合传热系数比金属换热器高,可达到120 ~220 W/(m^2·K)。因此,在相同的换热负荷下,氟塑料换热器的重量远小于金属换热器;

(2) 耐腐蚀性强,适用于各种强酸、强碱类强腐蚀条件,换热器在使用过程中无需考虑腐蚀问题;

(3) 氟塑料管摩擦系数小、流动阻力小、不易发生堵塞;

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作者简介: 胡 清(1987 -),男,湖南衡阳人,杭州华电能源工程有限公司工程师.

(4) 氟塑料换热器可在 250 ℃以下的环境内长期使用,且换热器的使用寿命长,在 15 年以上。且氟塑料换热器为模块式安装,安装检修方便。

2　新型烟气余热深度回收技术

2.1　技术原理

新型烟气余热深度回收系统如图 1 所示,该系统包括两级换热器,两级换热器为串联布置,并通过管路系统与机组的低温加热回热系统并联连接。第一级为传统的金属材质低压省煤器,布置在空预器和除尘器之间; 第二级为氟塑料换热器,布置在除尘器后脱硫塔前。两级换热器采用串联的连接方式。热媒水为取自 JD8(8 号低温加热器) 入口和 JD7(7 号低温加热器) 出口的凝结水,汇合后依次进入氟塑料换热器换热、低压省煤器换热,换热完成后回到 JD6(6 号低温加热器) 入口。

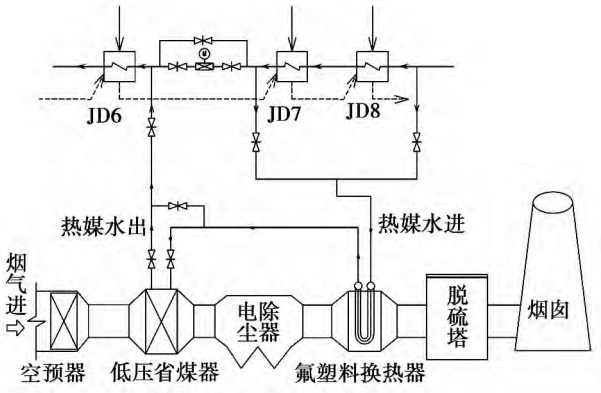

图 1　新型烟气余热深度回收系统

Fig. 1 New flue gas deep heat recovery system

该系统包含以下两个保证参数: (1) 金属材质低压省煤器出口烟温保证在烟气酸露点温度 15 ℃以上,保证低压省煤器及电除尘器不存在低温酸腐蚀问题; (2) 经过第二级氟塑料换热器换热后,烟气温度降低至较低水平,保证脱硫塔的运行效果,减少脱硫系统的减温水补水量。以上两个保证参数均通过管道系统上设置的调节阀门进行调节。

2.2　系统优点

相比其它烟气余热回收系统,该新型烟气余热深度回收系统具有以下显著优点:

(1) 适用性强。系统通过阀门调节,保证低压省煤器出口烟温保证在烟气酸露点温度以上 15 ℃,确保低压省煤器无低温酸腐蚀问题; 系统第二级换热器为氟塑料材质,不存在换热器的低温酸腐蚀问题、积灰问题;

(2) 调节性好。通过调节阀门调节进入换热器的凝结水量,控制换热器出口烟温,从而可适应各种锅炉燃煤和传热负荷的变化;

(3) 高效性。该系统可将排烟温度降低至较低水平,实现烟气余热的深度回收利用。采用氟塑料换热器,换热器总的传热系数高于金属换热器,在换热量相同时需要的传热面积更小,换热器的重量更轻;

(4) 可操作性强。在低负荷工况下,若空预器出口烟气温度很低,可开启增设在低压省煤器旁路的调节阀门、关闭低压省煤器热媒水侧进出口阀门,隔离低压省煤器系统,使氟塑料换热器单级运行,保证低压省煤器和电除尘器不存在低温酸腐蚀问题。

3　工程应用效果分析

针对某 1 000 MW 机组,应用该新型烟气余热深度回收技术,回收锅炉尾部烟气余热加热机组回热系统的凝结水,根据等效焓降法原则及原则性热力系统计算分析[9-10],以机组的额定运行工况为例,分析比较了系统投运后的经济性。

3.1　系统主要参数

该新型烟气余热深度回收技术第一级金属材质低压省煤器采用 H 型鳍片管结构,第二级换热器为氟塑料光管换热器,两级换热器主要的结构及设计参数如表 1 所示。表 1 中的烟气酸露点温度根据冯俊凯等主编的锅炉原理及计算得到[11],为保证脱硫系统的水平衡,氟塑料换热器出口烟温为 85 ℃。

表 1　主要设计参数

Tab. 1 Main design parameters

参　数	1 000 MW 机组
烟气量/$Nm^3 \cdot h^{-1}$	3 251 000
低压省煤器进口烟温/℃	130
低压省煤器出口烟温/℃	108
烟气酸露点温度/℃	92
氟塑料换热器进口烟温/℃	108
氟塑料换热器出口烟温/℃	85
低压省煤器重量/t	380
氟塑料换热器重量/t	42
换热器总阻力/Pa	650

3.2 经济性分析

根据机组及烟气余热深度回收系统运行参数，依据等效焓降法原则，对该系统投运后的经济性进行了计算分析，计算结果如表 2 所示。

表 2 经济性分析

Tab. 2 Economical analysis

参 数	1 000 MW 机组
机组热耗率/kJ·(kW·h)$^{-1}$	7 297
机组汽耗率/kg·(kW·h)$^{-1}$	2.815
汽轮机进汽量/t·h^{-1}	2 815
汽轮机机电效率/%	98
锅炉效率/%	94
管道效率/%	98
机组热耗率减少量/kJ·(kW·h)$^{-1}$	100.8
节约标煤量/g·(kW·h)$^{-1}$	3.53
真空降低多耗标煤量/g·(kW·h)$^{-1}$	0.54
凝泵阻力增加多耗煤/g·(kW·h)$^{-1}$	0.07
烟气阻力增加多耗煤/g·(kW·h)$^{-1}$	0.22
总节煤量/g·(kW·h)$^{-1}$	2.7

由表 2 可知，根据等效焓降法原则，系统投运后，总节约标煤量 2.7 g/(kW·h)。根据单元机组原则性热力系统计算方法，校核机组发电功率增加 0.845%，机组发电标煤耗约降低 2.58 g/(kW·h)。

按年运行小时数 7 000 h、负荷率 0.7 计算，1 000 MW机组年节约标煤量 12 642 吨，按标煤价格 550 元/吨计算，年节约标煤净收益 695.3 万元。

3.3 环境效益分析

(1) 研究结果表明[12]，烟气温度在 100 ~ 140 ℃的区间范围内，随着烟气温度的降低，粉尘的比电阻显著降低。因此，在系统投运后，由于电除尘器入口烟温的降低，电除尘器的除尘效率可得到显著提高；

(2) 对湿法脱硫水平衡的研究表明[13~14]，脱硫系统耗水量主要和脱硫系统蒸发水量有关。脱硫塔入口烟气温度的降低减少了脱硫系统减温水的补水量。原烟气携带的水量及净烟气携带的饱和水蒸气量按式(1)、式(2)计算，二者的差值即为脱硫系统的蒸发水量。

$$M_1 = 18 \times \frac{Q_2 - Q_1}{22.4} \times 10^{-3} \tag{1}$$

$$M_2 = Q_2 \times \rho \times d = Q_2 \times \rho \times 622 \times \frac{p_w}{0.11 - p_w} \times 10^{-3} \tag{2}$$

式中：M_1 —原烟气携带的水量，t/h；Q_1 —脱硫塔入口烟气量，Nm^3/h；Q_2 —脱硫塔出口烟气量，Nm^3/h；M_2 —净烟气携带的饱和水蒸气量，t/h；ρ —标态下烟气密度，kg/Nm^3；d —烟气湿度，%；p_w —烟气中水蒸气分压力，MPa。

烟气余热深度回收系统投运后，烟气温度由 130 ℃降低至 85 ℃，脱硫系统蒸发水量降低 90.4 t/h。按年运行 7 000 h、负荷率 0.7 计算，机组年节约脱硫系统补水量443 100 t。

(3) 烟气余热回收降低了机组的供电煤耗，从而间接减少了二氧化碳、二氧化硫以及氮氧化物的排放。系统年节约标煤量13 570 t，则每年可以减少排放二氧化碳 35 560 t，二氧化硫 115 t，氮氧化物 100 t。

3.4 投资回收期分析

根据烟气余热深度回收系统，依据系统的经济性计算分析，对该系统的投资回收期进行了估算分析，计算结果如表 3 所示。

表 3 投资回收期分析

Tab. 3 Analysis of the payback period of investment

参 数	1 000 MW 机组
低压省煤器设备投资/万元	610
氟塑料换热器设备投资/万元	1 890
附属设备及控制系统投资/万元	520
施工及设备安装投资/万元	320
系统总投资/万元	3 340
系统年收益/万元	695.3
投资回收期/年	5.61

4 结 论

本文介绍了一种基于氟塑料换热器的新型烟气余热深度回收技术，并以国内某 1 000 MW 机组为例，计算分析了该系统的经济性，得出以下结论：

(1) 新型烟气余热深度回收技术系统具有适用性强、调节性好、高效性等特点；

(2) 该新型烟气余热深度回收系统经济效益显

著,工程投入运行后,锅炉排烟温度由 130 ℃降至 85 ℃,机组年平均标煤耗降低 2.58 g/(kW·h),年节水量 443 100 t,系统年节约标煤净收益 695.3 万元,且环境效益显著,投资回收期约 5.61 年。

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(陈　滨　编辑)

In the process of building LNG ship, the welding residual stress not only can induce the cracks of LNG Tanks, but also can change the loading capacity of LNG Tanks when superimposed upon applied pressure. In order to obtaining mechanical behavior of welding process, it is necessary to analyze the welding residual stresses of LNG Tanks with finite element method. Using axisymmetric model and Live-dead Element, this study aims to investigate the distributions of the welding residual stresses in a LNG Tanks Used in LNG Carrier. According to the national standard, the effect of the LNG tank groove size on residual stress distribution was studied, and the effect of heat treatment to welding residual Mises stress was also discussed. The results indicate that with the increase of the groove depth, the welding residual Mises stress first decreases and then increases, and reaches the minimum when the groove depth is 6mm. Compared to the V and U type groove angles, groove depth has more significant influence on welding residual Mises stress. In order to reduce the welding residual Mises stress, it is suggested to choose a small groove depth and groove angle according to the actual structure and technology. The heat treatment can also reduce the residual Mises stress by 21%. These results provide a theoretical reference regarding the control of the welding residual stresses in the LNG tanks. **Key words:** LNG Tanks, 9Ni Steel, Residual Stress, Design of Weld Grooves, Live-dead Element

太阳能辅助供热电站变工况特性研究 = Off-design Performance of Solar Hybrid Heating Power Plant [刊, 汉] LI Shao-hua, WANG Di, CHE De-yong, GAO Long (Northeast Dianli University, Jilin, China, Post Code: 132012) //Journal of Engineering for Thermal Energy & Power. -2016, 31(8). -99 ~ 105

Upgrading the heating power plant by using of a complementary way of solar and coal can solve urban heating shortage and other issues caused by eliminating small units. Based on the design prototype of 12MW coal fired units, the coal and solar complementary system model was established by using numerical simulation. The influence of solar radiation intensity and heat conduction oil temperature on the performance of the system was analyzed. A new solar energy complementary way was put forward, and compared to the typical complementary way of replacing high pressure heater. The results showed that these two complementary ways can both increase generating capacity and heat supply quantity of units with the increase of the intensity of radiation. In the case of constant heat supply, the total thermal efficiency gap of these two complementary ways can reach 10%. When the heat conduction oil temperature is higher than 350 ℃, the thermal efficiency of the solar energy direct heating system is higher. **Key words:** solar and coal complementary heating power plant, radiation intensity, heat conduction oil temperature, coal saving rate, total thermal efficiency

基于氟塑料换热器的新型烟气余热深度回收技术研究 = A New Technology for Deeply Flue Gas Heat Recovery based on the Fluorine Plastic Heat Exchanger [刊, 汉] HU Qing, SUN Shao-peng, JIANG Wen, ZHU Wen-zhong (Hangzhou Huadian Energy Engineering Institute, Hangzhou, Zhejiang, China, Post Code: 310030) //Journal of Engineering for Thermal Energy & Power. -2016, 31(8). -106 ~ 109

This article introduced a new technology for deeply flue gas heat recovery based on the fluorine plastic heat exchanger, elaborated the principle and main characteristics of this technology, and analyzed the economic performance

of this technology in a 1 000 MW Unit. The results showed that the new technology has the wide adaptability, well adjustment ability, high efficiency, and strong operability. The new technology has significant economic benefits in a 1 000 MW Unit; the exhaust gas temperature reduces from 130 ℃ to 85 ℃, the consumption of standard coal decreases by up to 2.58 g/(kW·h), that is, 6.953 million Yuan revenues per year, and 443 100 tons water is saved in a year. Furthermore, this technology has significant environmental benefits, and the payback period of investment is about 5.61 years. **Key words:** fluorine plastic heat exchanger, deeply flue gas heat recovery, economic performance, the consumption of standard coal, revenues

75TCFB **锅炉出力下降原因分析及改造措施** = **Root Cause of the Reduced Output Capacity of 75T CFB Boiler and its Countermeasures** [刊, 汉] CHAI Jian-zhong (Lu'an Mining Group, Wu Yang Thermal Power Plant, Changzhi, China, Post Code: 046205), WANG Jun (The North University of china, Taiyuan, China, Post Code: 030051) //Journal of Engineering for Thermal Energy & Power. -2016, 31(8). -110 ~ 114

To identify the root cause of the reduced output capacity of 4 sets of 75tCFB boilers in WU Yang power plant, the burning coal quality was analyzed and it was found that the volatile fraction of coal decreases, calorific value increases, and the coal ash lowers and the fluidization velocity of dense zone slightly declines. To determine the countermeasures, the dense-phase zone size of 4 sets of 75t CFB boilers was calculated and the primary air and secondary air were compared. It was found that the boilers encounter difficulty in load carrying capacity. By changing the primary air rate and secondary air rate of CFB boilers and the cross-sectional area of dense zone, the combustion fraction of the boiler's dense-phase zone was reduced and the temperature difference between the dense zone and the dilute-phase zone decreased. These results indicate that the CFB boiler's output capacity can be improved by reforming the structure of the CFB's dense-phase zone. **Key words:** dense-phase zone, primary air and secondary air, output capacity, fluidization velocity

超临界锅炉奥氏体钢管氧化层研究与预防 = **Investigation and Prevention of Supercritical Boiler Austenitic Steel Pipe Oxide Layer** [刊, 汉] SONG Quan-xuan (The Boiler & Pressure Vessel Safety Inspection Institute of Henan Province, Zhengzhou, Henan, China, Post Code: 450016) //Journal of Engineering for Thermal Energy & Power. -2016, 31(8). -115 ~ 119

SA-213TP347H (Cr19Ni11Nb) steel tube with excellent high temperature lasting and high temperature antioxidation is widely used in high temperature superheater and reheater as the power boiler is marching to the ultra supercritical parameters. As the operation time increases, the abnormal shutoff of the power boiler happens more and more frequently due to oxidation skin peeling and accumulating. In this article, the causes of the TP347H oxidation skin formation, growth, pealing and accumulation in ultra-supercritical power generation boiler were investigated by the long-term sampling of TP347H steel pipe inner surface oxide skin and sample analysis. And a countermeasure of preventing and delaying the growth of spalling was put forward. **Key words:** supercritical boiler, austenitic steel, scale, spalling damage