W火焰锅炉多次引射分级燃烧机理及技术研究

李争起*, 张鑫, 陈智超, 曾令艳, 谭紫莹, 朱群益, 秦裕琨

哈尔滨工业大学能源科学与工程学院, 燃煤污染物减排国家工程实验室, 哈尔滨 150001

* E-mail: green@hit.edu.cn

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摘要 引进国外技术制造的W火焰锅炉实际运行中普遍存在飞灰可燃物含量高、 NO_x 排放量高及结渣严重等问题. 我们对不同技术流派W火焰锅炉的炉内流动、燃烧及 NO_x 生成特性, 开展了气固两相、数值模拟及工业试验研究, 在消化吸收国外技术的同时, 找出了问题的原因. 提出了W火焰锅炉多次引射分级燃烧技术, 该技术已被用于4台600-MW和350-MW机组新炉设计, 5台600-MW和300-MW机组锅炉燃烧系统改造, 解决了国外W火焰煤粉燃烧技术存在的问题, 实现了锅炉的经济、安全运行.

关键词 W火焰锅炉, 多次引射分级, 燃烧, NO_x 排放, 飞灰可燃物含量

1 引言

煤炭清洁高效开发利用是我国能源发展战略行动计划之一. 低挥发分(贫煤、无烟煤)、高灰分、低发热量煤为难燃煤, 难燃煤占我国动力用煤的2/5以上^[1,2]. W火焰锅炉下炉膛空间较大, 且温度较高、火焰行程长, 火焰先下后上返有利于着火, 是一种适合于难燃煤的炉型^[3-5]. 我国W火焰锅炉技术为引进国外技术或在国外技术基础上的改进技术, 锅炉数量在130台左右. 但是, 采用国外技术制造的W火焰锅炉一般燃烧效率较低、易于结渣, 特别是氮氧化物排放普遍较高, 不能满足环保标准要求^[6,7]. NO_x 是产生雾霾的主要前驱物之一. 为了满足环保要求, 现有的锅炉需要首先进行低 NO_x 燃烧技术改造, 使炉膛出口 NO_x

排放浓度大幅降低后, 再进行尾部烟气脱硝技术改造, 以大幅度降低 NO_x 减排的投资和运行成本. 同时, 迫切需要开发具有我国自主知识产权的W火焰燃烧技术.

为了解决W火焰锅炉存在的 NO_x 排放量高^[8-14]、飞灰可燃物含量高^[15,16]、燃烧不稳^[17,18]、结渣严重^[19,20]、炉内偏烧^[21-23]等问题, 我们通过冷态单相、气固两相试验、数值模拟以及在300-MW和600-MW机组锅炉上的工业试验研究, 消化吸收了英国三井巴布科克(简称英巴)^[24,25]、美国巴布科克·威尔科克斯(简称美巴)^[26,27]、美国福斯特惠勒(简称美国FW)^[28,29]燃烧技术, 找出了存在这些问题的原因, 提出了W火焰锅炉多次引射分级燃烧技术^[30-34]. 该技术已被用于4台600-MW和350-MW超临界机组新炉设计, 5台600-MW超临界、300-MW亚临界机组英巴、美巴锅炉燃

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烧系统改造,取得了较好的运行性能.本文总结了本团队近20年对W火焰锅炉燃烧技术的研究(图1).

2 国外W火焰锅炉燃烧技术锅炉炉内流动、燃烧及 NO_x 生成的特性研究

2.1 国外W火焰锅炉燃烧技术

国外的W火焰锅炉燃烧技术主要包括英巴、美巴及美国FW W火焰锅炉燃烧技术.图2为英巴W火焰锅炉炉膛结构及燃烧装置布置^[35].燃烧器成组布置在拱部,一、二次风喷口相间布置,乏气布置在靠近炉膛中心区域或靠近前、后水冷壁侧,在前、后墙下部设有成组布置的三次风喷口,与拱部各组燃烧器一一对应.拱部风占据主导,总一次风率15%~20%,二次风率约70%,三次风率不高于15%.锅炉下炉膛空间特别大而上炉膛短小.美巴、美国FW W火焰锅炉分别采用旋流、直流煤粉燃烧器^[36-38].

2.2 单相流动特性

单相试验速度测量截面如图3所示,其中坐标系原点位于炉膛中心线上, x 和 y 分别指水平方向(水平向右为正方向)和竖直方向(竖直向下为正方向), X_0 为下炉膛前、后墙之间的距离, X 为各列测点到炉膛中心的水平距离, H_0 为浓煤粉气流喷口的出口处中心到冷灰斗下沿的垂直距离, H 为浓煤粉气流喷口的出口处中心到各排测点的垂直距离, H/H_0 代表下炉膛不同的横截面.图中 $H/H_0=0.341, 0.375, 0.370$ 分别代表了英巴600-、350-MW机组锅炉和FW 300-MW机组锅炉的三次风喷口中心横截面.我们设定 V_x 和 V_y 分别为水平方向和竖直方向速度分量, V_0 代表浓煤粉气流喷口沿 y 方向的出口风速, $(V_y)_{\max}$ 表示前、后墙侧每排测点处最大竖直速度分量.

(1) 流场偏斜

图4为英巴600-MW W火焰锅炉额定负荷模化工

图1 (网络版彩图) W火焰锅炉燃烧机理及技术研究

Figure 1 (Color online) Research on combustion mechanism and technology of down-fired boiler.

况下不同三次风率无量纲竖直速度分量沿横截面 $H/H_0=0.341$ 的分布^[35]. 三个工况下该截面上前墙侧的

图2 英巴W火焰锅炉炉膛结构及燃烧装置布置. (a) 炉膛结构; (b) 炉拱上一组燃烧器喷口(见(a)中的A向)

Figure 2 Furnace configuration and combustion device layout of MBEL down-fired boiler. (a) Furnace configuration; (b) a group of burner nozzles on furnace arch (Direction A in (a)).

图3 速度测量截面

Figure 3 Section of velocity measurement.

V_y/V_0 值明显高于后墙侧, 前、后墙侧竖直速度对称性均较差, 炉内均形成偏斜流场.

(2) 浓煤粉气流下冲深度小

英巴W火焰锅炉由于炉内流场偏斜, 后墙侧煤粉气流下冲深度较小. 图5为美国FW 300-MW W火焰锅炉额定负荷模化工况下不同二次风配比浓煤粉气流竖直速度的衰减^[39]. 在FW W火焰锅炉中, E层、F层二次风布置于拱下前、后墙, E层二次风位于F层二次风正上方. E层、F层二次风速的初始设计值分别为2.14和20 m/s. 三个工况下浓煤粉气流到达的无量纲深度 H/H_0 均小于0.370, 不能穿透F层气流区域($H/H_0=0.370$), 煤粉气流下冲深度较小. 美巴W火焰锅炉的旋

图4 英巴600-MW W火焰锅炉不同三次风率下横截面 $H/H_0=0.341$ 上竖直速度分量^[35]

Figure 4 Vertical-velocity components along cross-section $H/H_0=0.341$ at different tertiary air ratios for the MBEL 600-MW down-fired boiler [35].

图5 美国FW 300-MW W火焰锅炉不同二次风配比浓煤粉气流竖直速度的衰减^[39]

Figure 5 Decay of the vertical-velocity components of fuel rich flow under different secondary air distribution for the FW 300-MW down-fired boiler [39].

流燃烧器内、外二次风角度较大时,煤粉气流的下冲深度也较小^[10].

(3) 二次风引射浓煤粉气流,浓煤粉气流入炉后速度大幅度升高

图6为英巴350-MW W火焰锅炉额定负荷模化工况下不同三次风率前墙侧下行气流的最大竖直速度衰减曲线^[40].拱部下行气流自离开喷口后, $(V_y)_{\max}/V_0$ 值大于1,之后 $(V_y)_{\max}/V_0$ 先迅速上升,在 $H/H_0=0.1\sim 0.15$ 处达到峰值后再迅速下降,这是因为浓煤粉气流喷口和二次喷口相间布置,且二次风速远高于浓煤粉气流风速,浓煤粉气流在离开喷口后很快与高速二次风混合,浓煤粉气流入炉后速度大幅度升高.工业锅炉运行中,浓煤粉气流风速大幅度提升,煤粉气流着火晚,火焰稳定性差,并引起飞灰可燃物含量升高^[38,41],煤粉在氧化性气氛下燃烧, NO_x 生成量大^[42].

对于国外的W火焰锅炉燃烧技术,“浓煤粉气流入炉后速度大幅度升高”和“浓煤粉气流下冲深度小”两种现象并存.原因:浓煤粉气流由炉拱向下进入下炉膛后,高速的二次风很快混入低速的浓煤粉气流,引起浓煤粉气流速度大幅度升高.从冷态流场方面来讲,浓煤粉气流入炉后速度大幅度升高,之后,两股气流充分混合,速度开始下降,而刚性强的水平三次风布置于下炉膛前、后墙,浓煤粉气流被三次风截断,开始折转上行,浓煤粉气流下冲深度小.特别是对于炉内存在流场偏斜的英巴W火焰锅炉,后墙侧煤粉气流下冲深

度更小.从热态燃烧方面来讲,煤粉气流着火后,火焰温度迅速升高至 1600°C 左右,二次风及烟气体积迅速膨胀、黏度增加,浓煤粉气流难以下冲,同时下行的浓煤粉气流被温度低、刚性强的水平三次风截断,折转向上.以上冷态流场和热态燃烧两方面的原因均说明了对于国外的W火焰锅炉燃烧技术,虽然浓煤粉气流入炉后速度大幅度升高,但是整体的浓煤粉气流下冲深度依然较小.

2.3 气固两相流动特性

试验测量截面及符号如图3所示.

(1) 竖直速度分布不对称,浓煤粉气流入炉后速度升高

图7为英巴600-MW W火焰锅炉额定负荷模化工况下,不同三次风率下3个横截面上气固两相流的竖直速度分布^[43].在3个截面上,从前、后墙侧至炉膛中心,气相和颗粒的无量纲竖直速度分量 V_y/V_0 均先快速上升,说明浓煤粉气流入炉后速度升高.之后在前墙侧 $X/X_0=-0.4$ 处和后墙侧 $X/X_0=0.3\sim 0.4$ 处分别达到峰值后再迅速下降, V_y/V_0 均呈双峰分布特征.相比于前墙侧,后墙侧的峰值衰减更快且峰值对应的位置(即 X/X_0)偏向炉膛中心($X/X_0=0$)要迅速得多.炉内气、固相的竖直速度沿炉膛中心均呈严重不对称分布特征.

(2) 颗粒体积流量及颗粒数浓度分布不对称

图8为英巴600-MW W火焰锅炉额定负荷模化工况下,不同三次风率下3个横截面上颗粒体积流量分布^[43].3个截面上颗粒体积流量均呈双峰分布特征,伴随气固两相流下行(即 H/H_0 值增大)和颗粒物不断扩散至周围稀相区,相比于前墙侧,后墙侧颗粒体积流量衰减更快且峰值位置(即 X/X_0)偏向炉膛中心的程度更强.对于截面 $H/H_0=0.224$ 和 0.341 ,在后墙侧的近壁区域处颗粒体积流量为负值,这是由于后墙侧下行气固两相流很快偏向炉膛中心并提早折转上行,使得其近壁区域为上行气流所占据.炉内颗粒体积流量沿炉膛中心呈严重不对称分布.

(3) 气固两相气流轨迹偏斜

如图9所示^[44],英巴W火焰锅炉炉内形成严重偏斜的气固两相流场,前墙侧下行气固两相流在下冲至冷灰斗下部后折转偏向冷灰斗右侧上行,后墙侧下行气固两相流离开喷口倾向炉膛中心侧下行,仅到达三次风区域就折转向上.

图6 (网络版彩图)英巴350-MW W火焰锅炉不同三次风率前墙侧下行气流衰减曲线^[40]

Figure 6 (Color online) Decay curves of the down-ward airflows at different tertiary air ratios for the MBEL 350-MW down-fired boiler^[40].

图 7 英巴600-MW W火焰锅炉不同三次风率3个截面上气相流(a)和固相流(b)竖直速度分布^[43]

Figure 7 Gas (a)/particle (b) vertical-velocity component distribution along the three cross-sections at different tertiary air ratios for the MBEL 600-MW down-fired boiler [43].

图 8 (网络版彩图)英巴600-MW W火焰锅炉不同三次风率3个横截面上颗粒体积流量分布^[43]

Figure 8 (Color online) Particle volume flux distribution along the three cross-sections at different tertiary air ratios for the MBEL 600-MW down-fired boiler [43].

图 9 (网络版彩图)英巴技术和多次引射分级技术下炉内气固两相流轨迹^[44]

Figure 9 (Color online) Downward gas/particle flow trajectories within the furnace with respect to MBEL technology and multi-injection multi-staging combustion technology [44].

(4) 靠近炉膛中心侧形成了低煤粉浓度区域
英巴W火焰锅炉的淡煤粉气流靠近炉膛中心布

置, 靠近炉膛中心侧形成了低煤粉浓度区域. 图10为美国FW 300-MW W火焰锅炉额定负荷模化工况下不同

图 10 美国FW 300-MW W火焰锅炉不同二次风配比炉内固相的竖直速度分布^[2]

Figure 10 Particle vertical-velocity component distribution within the furnace at different secondary air ratios for the FW 300-MW down-fired boiler [2].

二次风配比炉内固相的竖直速度分布, 曲线在截面 $H/H_0=0.08$ 和 0.137 时分别有两个峰值, 在 $X/X_0=0.50$ 附近的高峰值区域为浓煤粉气流区域, 在 $X/X_0=0.45$ 附近的低峰值区域为淡煤粉气流区域, 淡煤粉气流区域在靠近炉膛中心侧($X/X_0=0$). 靠近炉膛中心侧形成了低煤粉浓度区域^[2], 这是因为美国FW技术淡煤粉气流也是靠近炉膛中心布置.

2.4 燃烧及 NO_x 排放特性的工业试验研究

工业试验测点布置如图11^[35]所示.

(1) 煤粉气流着火晚

图12为英巴350-MW W火焰锅炉额定负荷下燃用

图 12 (网络版彩图)英巴350-MW W火焰锅炉不同三次风挡板开度燃烧器区域烟气温分布^[35]

Figure 12 (Color online) Gas temperatures in the burner region at different tertiary air damper openings for the MBEL 350-MW down-fired boiler [35].

图 11 工业实验测点布置^[35]

Figure 11 Monitoring points in industrial experiments [35].

无烟煤时不同三次风挡板开度燃烧器区域烟气温分布^[35], 三次风挡板开度增大, 三次风率相应增大. 选取 900°C 为浓煤粉气流着火温度, 前墙侧浓煤粉气流着火距离为 $2\sim 2.4\text{ m}$, 后墙侧浓煤粉气流着火距离为 $2.1\sim 3.1\text{ m}$, 煤粉气流着火晚. 美巴、美国FW W火焰锅炉浓煤粉气流着火距离一般大于 2 m ^[24-26].

(2) 火焰不对称及下炉膛水冷壁壁温超温

由图12可见, 英巴W火焰锅炉前墙侧煤粉气流着火距离均大于后墙侧, 下炉膛火焰偏斜. 另外, 英巴超临界机组W火焰锅炉通常凸现出水冷壁壁温偏差过大和壁温超过允许值的问题.

(3) 煤粉燃尽差

英巴600-MW、美巴300-MW、美国FW 300-MW

W火焰锅炉额定负荷下燃用无烟煤时飞灰可燃物含量分别为8.5%^[35]、11.5%^[33]、7.84%^[39], 煤粉燃尽差。

(4) NO_x排放浓度高

英巴600-MW、美巴300-MW、美国FW 300-MW W火焰锅炉额定负荷下燃用无烟煤时NO_x排放浓度分别为1467 mg/m³ (O₂=6%)^[19,35,45,46]、超过1400 mg/m³ (O₂=6%)^[27,33,36]、2101 mg/m³ (O₂=6%)^[5,8,39,47], NO_x排放浓度高。

(5) 下炉膛水冷壁结渣严重

英巴W火焰锅炉在翼墙、侧墙敷设卫燃带区域、在拱部位于乏气喷口周围以及后墙上三次风喷口周围结渣严重, 导致锅炉限负荷运行, 更甚者需要停炉整修。美巴、美国FW W火焰锅炉也存在炉膛结渣严重的问题。

2.5 国外W火焰锅炉燃烧技术存在问题的原因

(1) 下炉膛流场偏斜, 颗粒浓度分布不对称

英巴锅炉的拱上风率约占入炉总风量的88%, 拱上风动量较大, 拱上燃烧器喷口总跨度大(喷口跨度占炉拱深度的约2/3), 前、后拱上两股动量大、跨度大的气流下冲进入炉内, 在下炉膛中部区域折转向上时相互碰撞、挤压。同时, 三次风水平进入炉内, 对下行气流的横向推动作用较强, 加剧了两股气流间的相互挤压作用。由于锅炉结构设计、运行偏差等多种因素的影响, 前、后墙拱上气流风量、速度很难相同, 从而导致炉内形成偏斜流场, 颗粒浓度分布不对称。

(2) NO_x排放高

拱上、拱下配风不合理, 炉内空气分级水平低, NO_x排放量高。浓煤粉气流着火前与二次风、淡煤粉气流过早混合, 导致煤粉在富氧气氛下燃烧, 易生成NO_x。

(3) 煤粉燃尽差, 飞灰可燃物含量高

煤粉气流着火晚, 煤粉燃烧的时间并未保证, 导致煤粉燃尽差, 飞灰可燃物含量高。火焰偏斜, 下冲深度较小的一侧煤粉燃尽差。

(4) 火焰不对称及水冷壁壁温偏差大

炉内流场偏斜, 前、后墙两侧煤粉气流着火距离不同, 火焰不对称燃烧, 前、后墙水冷壁壁温偏差大。同时, 浓煤粉气流靠近前、后墙布置, 一次风煤粉气流要着火, 额外需要将混入的二次风、淡煤粉气流加热至着火温度, 但炉膛宽度方向的二次风分布又很难保

证均匀一致, 使得前墙和后墙侧沿炉膛宽度方向布置的燃烧器着火点位置不同, 燃烧器火焰下冲深度不同, 前、后墙沿炉膛宽度方向的水冷壁壁温偏差较大。

(5) 易发生结渣

煤粉颗粒流动易冲刷水冷壁, 引起结渣。

3 多次引射分级燃烧技术炉内流动、燃烧及NO_x生成特性研究

3.1 多次引射分级燃烧技术原理

多次引射分级燃烧技术的燃烧组织方式如图13所示。上、下炉膛的分界称为喉口, 在拱上(或上炉膛)靠近喉口处布置燃尽风; 从炉膛中心侧到前(后)墙侧依次布置浓煤粉气流、内二次风、淡煤粉气流和外二次风。拱下前(后)墙下部、冷灰斗上部布置有下倾的三次风。靠近喉口处布置下倾式燃尽风喷口。浓煤粉气

图13 W火焰锅炉多次引射分级燃烧组织方式。(a) 燃烧装置布置及炉内颗粒流动;(b) 炉拱上一组燃烧器喷口(见(a)中的A向)

Figure 13 Combustion organization mode of the down-fired boiler with multi-injection multi-staging combustion technology. (a) Combustion device layout and particle flow in furnace; (b) a group of burner nozzles on furnace arch (Direction A in (a)).

流布置在向火侧, 有利于煤粉着火; 多次引射下行, 保证了拱上气流的下冲深度, 且符合随燃烧的进行逐级供风的煤粉燃烧配风原理, 有利于煤粉燃尽; 拱上靠近喉口布置的燃尽风以一定角度向下炉膛喷射, 与下炉膛烟气充分混合后再反转向向上运动, 延长了燃尽风与煤粉充分混合后在炉内的停留距离及时间, 在保证分级燃烧降低 NO_x 的同时, 提高了煤粉燃尽率。

对于采用旋流燃烧器的美巴W火焰锅炉, 为了减小已有锅炉改造工作量, 提出了适于旋流燃烧器的多次引射分级燃烧技术(图14)。在燃烧器的内、外二次风喷嘴口处向火侧安装半圆环形挡块。旋流燃烧器向火

侧为浓煤粉气流, 背火侧依次布置弱旋的内二次风和外二次风(内、外二次风叶片角度为 10° 左右); 在下炉膛布置下倾的淡煤粉气流和下倾的三次风, 淡煤粉气流下倾角度设置为 $40^\circ\sim 50^\circ$ ^[48]; 在靠近喉口位置布置直流燃尽风。

3.2 单相流动特性

试验测量截面及符号如图3所示。

(1) 拱上气流对浓煤粉气流的引射过程

图15为采用直流燃烧器的600-MW W火焰锅炉额定负荷模化工况下各气流引射浓煤粉气流过程单相模

图14 锅炉燃烧装置布置及旋流燃烧器结构。(a) 炉膛结构; (b) 旋流燃烧器(见(a)中 I 放大); (c) 燃烧器喷嘴(见(b)中的 A 向)
Figure 14 Boiler combustion device layout and swirl burner configuration. (a) Furnace configuration; (b) swirl burner (enlarged view of I in (a)); (c) burner nozzle (Direction A in (b)).

图15 (网络版彩图) 600-MW W火焰锅炉各气流引射浓煤粉气流过程单相模化烟雾示踪实验照片^[35]。(a) 内二次风引射起始位置; (b) 淡煤粉气流引射起始位置; (c) 外二次风引射起始位置

Figure 15 (Color online) Photos of single-phase modeling smoke tracing experiment in the process of fuel-rich flow injected by various airflow for the 600-MW down-fired boiler [35]. (a) The starting position of inner secondary air injection; (b) the starting position of fuel-lean flow injection; (c) the starting position of outer secondary air injection.

化烟雾示踪实验照片^[35]。着火后的浓煤粉气流由临近的速度高、温度低的内二次风(在 $H/H_0=0.103$ 处)首先引射下行,内二次风逐渐混入浓煤粉气流,引射下行的同时,并参与燃烧;在内二次风参与燃烧后温度升高、速度衰减至一定程度后,再由速度高、温度低的淡煤粉气流、外二次风依次引射(分别在 $H/H_0=0.145$ 和 0.321 处)下行;之后,速度高、温度低的三次风从冷灰斗上方以一定角度喷入炉内进一步引射拱上气流下行,下炉膛形成了多次引射分级燃烧。

(2) 流场对称性

图16为600-MW W火焰锅炉额定负荷模化工况下不同燃烧器间距的炉内流场^[49],各工况流场对称性良好,拱上气流出喷口后,偏向前、后墙下射,到达三次风区域后,受下倾三次风向下的进一步引射,整体气流沿着冷灰斗倾斜水冷壁高速下行,并在冷灰斗中部区域相遇后折转向下,同时在前、后拱下形成两处对称

回流区。采用多次引射分级燃烧技术的W火焰锅炉炉内流场对称分布^[50]。

3.3 气固两相流动特性

试验测量截面及符号如图3所示。

(1) 竖直速度分布对称

图17为采用直流燃烧器的600-MW W火焰锅炉额定负荷模化工况下不同三次风率炉内气固相竖直速度分布^[43],各工况气、固相竖直速度沿炉膛中心($X/X_0=0$)均呈对称分布。2个截面上,靠近前、后墙水冷壁区域的气相速度较高,说明多次引射分级燃烧技术下外二次风布置在拱上靠近前、后墙侧,有利于防止煤粉气流冲刷前、后墙水冷壁,有利于防止结渣。

(2) 颗粒体积流量分布对称,靠近炉膛中心侧形成了高煤粉浓度区域

图18为600-MW W火焰锅炉额定负荷模化工况下

图 16 600-MW W火焰锅炉不同燃烧器间距下的炉内流场^[49]. (a) $d=971$ mm; (b) $d=1329$ mm; (c) $d=1687$ mm

Figure 16 Flow fields at different burner distances for the 600-MW down-fired boiler [49]. (a) $d=971$ mm; (b) $d=1329$ mm; (c) $d=1687$ mm.

图 17 600-MW W火焰锅炉不同三次风率下炉内气相(a)和固相(b)竖直速度分布^[43]

Figure 17 Gas (a)/particle (b) vertical-velocity component distribution at different tertiary air ratios for the 600-MW down-fired boiler [43].

图 18 英巴600-MW W火焰锅炉炉内颗粒体积流量^[43]

Figure 18 Particle volume flux distribution within the furnace for the MBEL 600-MW down-fired boiler [43].

炉内颗粒体积流量^[43], 颗粒体积流量分布对称, 截面 $H/H_0=0.035$ 和 0.075 上的颗粒体积流量的分布曲线呈现明显的“四峰分布”, 在 $X/X_0=\pm 0.4$ 附近的高峰值区域为浓煤粉气流区域, 在 $X/X_0=\pm 0.45$ 附近的低峰值区域为淡煤粉气流区域, 靠近炉膛中心侧($X/X_0=0$)形成了高煤粉浓度区域. 采用多次引射分级燃烧技术的W火焰锅炉炉内颗粒体积流量也呈对称分布, 靠近炉膛中心侧也形成了高煤粉浓度区域^[51,52].

(3) 前、后墙侧下行气固两相流轨迹

多次引射分级燃烧技术下前、后墙侧下行气固两相流轨迹如图9所示. 多次引射分级技术下前、后墙侧下行气固两相流轨迹较为对称, 前、后墙侧下行气固两相流均在下冲至冷灰斗中部区域后折转上行并于炉膛中心区域交汇, 炉内形成对称W型流场.

3.4 燃烧及NO_x排放特性的数值模拟及工业试验研究

(1) 600-MW W火焰锅炉

某厂2台锅炉是采用多次引射分级燃烧技术进行设计制造的600-MW超临界机组直流W火焰锅炉. 炉膛结构及燃烧系统介绍见3.1节. 锅炉燃用无烟煤时, 额定负荷下, 浓煤粉气流着火距离为0.66~1.05 m (图19), 锅炉效率为91.42%, 炉膛出口NO_x排放浓度为602 mg/m³ (O₂=6%). 锅炉可以在300 MW负荷(50%电负荷)下不投油长期稳定运行, 锅炉结渣轻微. 借助数值计算的方法对锅炉进行数值预测, 锅炉燃用无烟煤, 额定负荷下, 当浓、淡煤粉气流流量比为9:1^[53]时, 浓煤粉气流着火距离为0.7 m, 飞灰可燃物含量为5.52%,

图 19 (网络版彩图)不同燃尽风(OFA)挡板开度下浓煤粉气流升温曲线^[32]

Figure 19 (Color online) Heating curves of fuel-rich flow at different over fire air (OFA) damper openings [32].

NO_x排放浓度为662 mg/m³ (O₂=6%), 冷灰斗内高温区域面积小且出现位置远离冷灰斗倾斜水冷壁.

另外, 采用多次引射分级燃烧技术对另一电厂的600-MW超临界机组W火焰锅炉的燃烧系统进行低氮改造, 改造后, 在燃用无烟煤时, 额定负荷下, NO_x排放浓度明显降低, 由改前的1400 mg/m³ (O₂=6%)降低到570 mg/m³ (O₂=6%), 飞灰可燃物含量由8%降低至3%, 炉渣可燃物含量由10%降低至1%. 锅炉可以在290 MW负荷下(48%电负荷), 不投油长期稳定运行, 锅炉结渣轻微.

(2) 350-MW W火焰锅炉

某厂1、2号锅炉是采用多次引射分级燃烧技术设计制造的350-MW超临界机组直流W火焰锅炉. 电厂所属的地方电网为孤网运行, 锅炉单机高负荷一般在230 MW左右. 锅炉燃用低热值、高硫分、超高灰分的无烟煤时, 可以在146~159 MW负荷下(42%~45%电负荷)长期不投油稳定运行, 锅炉稳燃能力强; 过热蒸汽、再热蒸汽温度达到设计值; 230 MW负荷下, 飞灰可燃物含量在5%以内, 炉渣可燃物含量6%以内, 炉膛出口NO_x排放浓度为630~690 mg/m³ (O₂=6%), 锅炉结渣轻微.

借助数值计算的方法研究了燃尽风位置对一台采用多次引射分级燃烧技术的350-MW亚临界机组W火焰锅炉的燃烧及NO_x排放特性的影响^[54]. 上炉膛布置燃尽风炉膛出口烟温、飞灰可燃物含量和NO_x排放量

均高于拱上靠近喉口处布置燃尽风, 拱上靠近喉口处为燃尽风的较佳布置位置。

(3) 300-MW W火焰锅炉

采用多次引射分级燃烧技术对某厂2台美巴300-MW亚临界W火焰锅炉的燃烧系统进行改造, 改造后的燃烧系统如图14所示。改造后, 燃用无烟煤时, 额定负荷下, 煤粉气流的着火距离由改造前的2.2 m减小到0.6~1.4 m, 煤粉气流着火早; NO_x 排放浓度由改造前的 1350 mg/m^3 ($\text{O}_2=6\%$)降低到 778 mg/m^3 ($\text{O}_2=6\%$); 飞灰可燃物含量下降2.31个百分点; 锅炉热效率升高2.15个百分点。锅炉最低不投油稳燃负荷为90 MW (30%电负荷), 锅炉结渣轻微。

3.5 未来研究工作展望

(1) 适用于灵活性改造的低负荷稳燃技术。规模化光伏、风电波动幅度大, 火电机组深度调峰将成为常态。要求机组具有更宽的负荷调节范围。对于燃用无烟煤和贫煤的W火焰锅炉, 无法满足调峰的要求。因此, 有必要开发适用于灵活性改造的低负荷稳燃技术。

(2) 适用于宽范围煤种的燃烧技术。随着煤炭市场供应的变化, W火焰锅炉开始掺烧烟煤等高挥发分煤。这有利于降低 NO_x 生成和飞灰可燃物含量。掺烧时, 易出现燃烧器喷口烧损、结渣、SCR入口烟温超温等问题。因此, 开发燃用宽范围煤种的燃烧技术也是研究方向之一。

(3) NO_x 排放量更低的燃烧技术。随着环保要求日

益严格, 有必要开发 NO_x 排放量更低的燃烧技术。

4 结论

通过对W火焰锅炉的炉内流动、燃烧及 NO_x 生成特性研究, 得出以下主要结论。

(1) 英巴、美巴和美国FW燃烧技术靠近炉膛中心侧形成了低煤粉浓度区域。二次风包裹浓煤粉气流一起下冲, 高速的二次风很快混入低速的浓煤粉气流, 浓煤粉气流入炉后速度大幅度升高。煤粉气流下冲深度小, 特别是英巴技术还存在炉内流场严重不对称的问题。在300-MW, 350-MW及600-MW机组锅炉上的工业试验表明, 燃用无烟煤时, 额定负荷下, 浓煤粉气流的着火距离一般大于2 m, 着火晚, 飞灰可燃物含量为8.5%~11.5%, NO_x 排放浓度高达 $1400\sim 2101 \text{ mg/m}^3$ ($\text{O}_2=6\%$), 炉膛结渣严重。

(2) 多次引射分级燃烧技术靠近炉膛中心侧形成了高煤粉浓度区域。拱上多级二次风、淡煤粉气流、拱下下倾三次风引射浓煤粉气流下冲, 煤粉气流下冲深度大, 下炉膛流场对称分布。在300-MW, 350-MW及600-MW机组锅炉上的工业试验表明, 燃用无烟煤时, 额定负荷下, 浓煤粉气流的着火距离一般为0.6~1.4 m, 着火早, 飞灰可燃物含量为3%~5.52%, NO_x 排放浓度为 $570\sim 778 \text{ mg/m}^3$ ($\text{O}_2=6\%$)。锅炉最低不投油稳燃负荷可达30%电负荷, 炉膛结渣轻微, 水冷壁温度分布较为均匀, 未出现水冷壁超温引起的爆管。

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Multi-injection multi-staging combustion mechanistic studies and down-fired boiler technology

LI ZhengQi, ZHANG Xin, CHEN ZhiChao, ZENG LingYan, TAN ZiYing, ZHU QunYi & QIN YuKun

National Engineering Laboratory for Reducing Emissions from Coal Combustion, School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

Actual operating results have revealed that imported down-fired boilers that use foreign technologies suffer from various problems, such as high carbon content in the fly ash, high NO_x emissions, and heavy slagging. Gas/solid two-phase experiments, numerical simulations, and industrial measurements were carried out to investigate the flow, combustion, and NO_x formation characteristics in a furnace of a down-fired boiler using different foreign technologies. The cause of these problems was found, and the foreign technologies were examined. Multi-injection multi-staging combustion technology for the down-fired boiler is proposed. This technology had been used in the design of four 600-MW and 350-MW new down-fired boilers and in the combustion system transformation of five 600-MW and 300-MW down-fired boilers. The problems originating from foreign down-fired pulverized coal combustion technologies have been solved, and economic and safe operation of a down-fired boiler has been realized.

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