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Development of high-temperature corrosion risk monitoring system in pulverized coal boilers based on reducing conditions identification and CFD simulations

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HIGHLIGHTS

- Corrosion risk monitoring system was demonstrated based on CO and O_2 measurements.
- Four global gas phase kinetic mechanisms were implemented into CFD.
- Global mechanisms were compared with detailed one in a perfectly stirred reactor.
- CFD predictions were compared with measurements received from the monitoring system.

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ABSTRACT

Low-emission combustion (for example the use of low-NO_x burners and air staging) contributes to formation of a reducing atmosphere in the furnace, that is accompanied by oxygen depletion and excess of CO in the vicinity (boundary layer) of waterwalls. Corrosion of boiler tubes is often caused by reducing atmosphere. O_2 and CO measurement in the boundary layer of evaporators can be a good indicator of corrosion risk assessment. System based on the on-line measurement of the O_2 and CO concentration in the boundary layer of the industrial scale boiler walls was described. To improve the functionality of the monitoring system Computational Fluid Dynamics may appear helpful. A validated CFD model capable of properly predicting the CO and O_2 concentration in the vicinity of the combustion chamber walls may help to adjust the monitoring system during variable boiler operating conditions or different fuel properties without the necessity to repeat the measurements for new conditions. The scientific part of the current research is concentrated on volatiles combustion simulation with the emphasis on CO burnout. Four popular global mechanisms have been implemented into CFD code and their CO and O_2 predictive capabilities are demonstrated. Additionally global mechanisms have been compared to detailed one in Perfectly Stirred Reactor model. It appears that the choice of global mechanism has significant influence on CO and O_2 prediction. The measurements of the CO and O_2 in the waterwalls boundary layer have been extracted from the monitoring system and compared to simulation results. One of the tested mechanisms demonstrated acceptable qualitative agreement with the measurement in terms of O_2 predictions. The quantitative accuracy of CFD-based oxygen prediction in the boundary layer was described as moderate. CFD-based CO prediction was less satisfactory.

1. Introduction

Deployment of renewables, need to improve coal plant efficiency and increase in natural gas utilization tends to decrease coal consumption in OECD (Organization for Economic Co-operation and Development) member countries. However according to International Energy Agency [1] coal will long remain a key energy fuel for electricity generation in a number of developed countries. Utility industry face the challenge of adopting their boilers to new requirements and conditions. One of the most crucial matters of the conventional coal energy sector are unprecedented environmental requirements for pollutant emissions. More restrictive environmental regulations are being enforced and power generation companies are forced to maintain the agreement between efficient and clean combustion.

The implementation of the low-emission combustion technologies for NO_x emission reduction often results in the intensification

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of high-temperature corrosion of the boiler heating surfaces. The corrosion of boiler tubes increases the operational costs and has strong negative effect on the reliability and availability of the whole power unit [2]. Low-emission combustion (for example the use of low-NO_x burners and air staging) contributes to formation of a reducing atmosphere in the furnace, that is accompanied by oxygen depletion and excess of CO in the vicinity of waterwalls. The process of high temperature corrosion is affected by many factors such as the fuel chemical composition (chlorine and alkali content), composition of the flue gas (O_2, CO, H_2S, HCl), deposition process, chemical composition of ash deposits formed on the surfaces, flue gas and tube surface temperature [3].

Most of the corrosion monitoring systems are based on off-line analysis. Ultrasonic tube thickness, electrical resistance and coupon weight measurement are usually carried out periodically and are labor intensive. Plant operator obtains historical corrosion data that has already occurred and may undertake only corrective actions. To prevent corrosion a monitoring system operating in on-line (real-time) manner is needed with the measurement data updated every few minutes. Ideally corrosion measurements should be integrated within the plant Distributed Control System. However on-line high-temperature corrosion monitoring is still a developing technology. Market review showed that there is no on-line monitoring solution widely applied in the industry.

The real-time corrosion monitoring system adapt either electrochemical approach or identify the reducing atmospheres were corrosion process usually occurs. The first one is often based on electrochemical noise (EN) measurements. The principal of operation of the instrument is associated with spontaneous fluctuation of the current and potential of a corroding electrode. This phenomena is commonly described as electrochemical noise. The fluctuations are converted to a digital signals and supplied to a computerized data acquisition unit. The EN based corrosion monitoring technique has been traditionally exploited in industry at low temperature. In the work of [4] researchers demonstrate attempt to continuously monitor both fouling and corrosion of a convective heat exchanger tube. The paper shows situations where EN variations correlate with changes in corrosion and fouling. This technology was applied recently in high temperature radiant sections of large scale utility boilers. In [5] the EN probe was installed in a 125 MW boiler. The probe operated in the temperature range 300–1000 °C. The corrosion rate results showed good agreement with previously measured rates using long-term single-coupon probes. Electrochemical corrosion sensors ability to respond to changing combustion conditions were conducted in a pilot-scale combustion test facility [6]. Large scale tests were arranged in the 600 MW, supercritical boiler. Two locations have been selected for probe installation. A good correlation was observed between boiler load and indicated corrosion rate. In general, as load increased, corrosion rate also increased. It was also discussed that testing of an electrochemical corrosion monitoring system difficult to identify with certainty because operating conditions other than firing rate also vary with load. Quantitative accuracy of on-line techniques by means of precision metrology. Satisfying results were presented. A multiple EN sensors were applied in a 1300 MW coal-fired boiler [7]. Six electrochemical sensors were prepared for installation on two walls. The probe locations were chosen on the basis of prior knowledge of plant corrosion behavior. The research also demonstrated good correlation between boiler load variation and corrosion rate. It was concluded that the local corrosion behavior also can be influenced by ash and slag deposition. The presence of molten slag might have facilitated corrosion by dissolution of iron into the slag melt. More recently the real-time electrochemical measurements were used to evaluate the impact of oxy-fuel combustion conditions on corrosion rate of three superheater materials and one boiler waterwall material [8]. Firing tests were conducted in a 1.5 MW furnace while firing bituminous, high-sulfur bituminous and subituminous coals. Waterwall corrosion rates decreased consistently when converting from air- to oxy-firing while superheater corrosion rates generally increased, although they were less than twice the air-fired rate under most conditions.

The electrochemical noise based monitoring system was validated in numerous research studies in pilot as well as large scale plants. It has proven both qualitative and quantitative reliability. Despite encouraging results this technology has not become a widely-applied solution for boiler waterwalls high-temperature monitoring system. Because EN requires monitoring of very small signal fluctuations, this approach to corrosion monitoring is also affected by extraneous sources of signal noise in the plant. One of its limitations is related to fact that electrochemical sensors provide only local information. The measurement are usually conducted in few furnace locations. The probes are located in sites determined from boiler corrosion experience. Change in boiler operating conditions or firing system modification might result in original probe location choice being inadequate.

The real-time corrosion monitoring system demonstrated in the current paper is based on the identification of reducing conditions zones. There is very limited literature [9] on this type of corrosion prevention technology applied in large scale furnaces. It is manifested that the more reducing the conditions, the higher is the corrosion rate. One of the dominant paths of corrosion is the attack of reduced sulfur species (e.g. H_2S) which are formed under reducing conditions ($O_2 < 0.5\%$ and $CO > 2\%$), especially for high chlorine coals [10]. The system detects atmospheres with low oxygen content and high levels of carbon monoxide. Knowing these components the corrosion hazard to the boiler wall can be identified based on assumed criteria and appropriate measures can be taken. The advantage of the system is that it generates two-dimensional maps covering most of the boiler wall and not just selected locations. Additionally it is less complicated in terms of instruments used and cost effective. It needs to be emphasized that reducing atmosphere monitoring system describes corrosion hazard while electrochemical based system monitors corrosion rate.

The practical part of the research resulted in the implementation of a corrosion risk monitoring system in industrial scale unit. The system was developed and tested in 160 MW tangentially fired boiler operating in Combined Heat and Power (CHP) plant in Wroclaw (Poland). Detailed description of the monitoring system and operational experience of its application to 380 MW tangentially fired boiler was presented in previous work [9].

Some researchers demonstrate development of CFD and field instrumentation as a complementary approach to corrosion management. In [4–7] expressions defining corrosion rate as a function of tube temperature, steel composition, and H_2S concentration were developed. Correlations were based on the published data and the experiments at a pilot-scale test furnace. These functions were implemented into CFD code and applied in utility boiler simulations. Model predictions show good overall agreement with furnace observations and field measurements (ultrasonic tube wall thickness analysis). It was suggested that this tool can be applied to a range of firing configurations, firing rates and fuel types.

A validated CFD model capable of properly predicting the CO and O_2 concentration in the vicinity of the combustion chamber walls may help to adjust the demonstrated monitoring system based on the identification of reducing atmospheres. The characteristic feature of presented system is the requirement of it to learn after introducing major changes affecting boiler operating conditions [9]. Reliable CFD model might substitute the expensive learning process.

Simulation of pulverized coal flow with combustion brings the necessity to employ three major sub-models: char burnout,