RESEARCH ON COMBUSTION VISUALIZATION OF COAL-FIRED BOILERS BASED ON THERMAL IMAGING TECHNOLOGY

Zi-Guo ZHANG[1*], Liang PAN[1], Hao WANG[1]

[1] Changchun Institute of Technology, Changchun, China

[*] Corresponding author; E-mail: nd_zzg@ccit.edu.cn

At present, there's a lack of combustion visualization in the combustion control of heating boilers. To understand the combustion of coal in the furnace, only experienced workers can observe it through visual inspection. Using infrared thermal imaging technology to monitor the combustion can realize combustion visualization. This paper analyzed and solved two problems: the installation position and number of infrared cameras, and the infeasible of using infrared cameras observing the combustion condition in the furnace through heat-resistant glass. Monitored parameters such as oxygen content, furnace temperature and smoke exhaust temperature, and monitored the concentration of PM, NO_X, and SO_2 in the main atmospheric pollutants in the flue gas. After calculation, the air leakage coefficient when the inspection doors are opened for observation is 0.04. This value still includes the sum of air leakage from coal hopper, furnace door, grate side seal, peep holes and other parts. The monitored average emission concentration of PM decreased by 16.28%, from which we can concluded that the use of thermal imaging technology to monitor the combustion in the furnace is conducive to emission reduction. The application of thermal imaging technology implementation of coal-fired boiler combustion visualization is feasible.

Key words: *Thermal imaging technology, Coal-fired boiler, Combustion visualization, oxygen content, furnace temperature, exhaust gas temperature, emission reduction*

1. Introduction

In addition to power plant, coal-fired systems are also widely used in other industrial boilers, and heating boilers are a common one. The combustion in a normal and stable state can make the boiler run efficiently, which is conducive to reducing pollutant emissions and energy consumption[1,2]. The geometry, color, brightness, flicker, temperature, etc. of the flame reflect the state of fuel combustion[3-6], Using digital visualization technology to monitor the characteristics of the flame in the boiler furnace, predict the combustion status of the boiler, and make corresponding adjustments to make the boiler in a good running status is the main direction of boiler combustion control[7-10]. Power plant boilers generally adopt circulating fluidized bed combustion mode with high combustion intensity, while common heating boilers such as chain furnaces and reciprocating furnaces adopt layer combustion mode, and the combustion intensity is relatively low. Therefore, infrared thermal cameras can be used to monitor the combustion in the boiler furnace[11,12].

At present, infrared thermal imaging technology has been applied to boilers such as power station boilers[13], and coal and biomass composite combustion boilers[14]; it has been applied to thermal equipment, pressure vessels and pipelines[15], and power equipment troubleshooting[16,17]; even thermal engineering of building exterior walls Defect and energy-saving detection have applications[18]. Due to the higher furnace temperature of the boiler, expensive cooling cameras are used to prevent lens damage to the power plant boiler, and the troubleshooting of thermal equipment and other faults can be completed by using ordinary infrared thermal cameras. Compared with power plant boilers, the investment in heating boilers is much less, so the investment in its subsidiary facilities is not expected to be much. How to get good results with less investment in the process of combustion visualization is the difficulty of this research.

In the past decade, the use of infrared thermal imaging technology in coal-fired boilers has mainly focused on the visual measurement of the flame temperature and emissivity of utility boilers[19-21]. The two-color pyrometry method for measuring the combustion characteristics of single-particle coal has also been reported[22]. SUN et al. proposed a visualization method for quantitatively calculating carbon combustion energy in a packed bed[23]. However, there are few related studies for monitoring the combustion situation of heating boilers and realizing the visualization of combustion. By using infrared thermal imaging technology, the combustion of coal in the furnace is transmitted in the form of thermal images to the computer screen in the control room, allowing management personnel to observe the combustion situation in the furnace at any time and make timely adjustments. It can not only improve the efficiency of boilers, but also reduce coal consumption. It is also possible to observe the operation of other facilities in the furnace through thermal imaging, which facilitates timely detection of hidden dangers and corresponding countermeasures.

This paper focuses on the design, constructing and verification of the combustion visualization system. The novelty of the research lies in the cost-effectiveness of the system, using ordinary infrared thermal cameras instead of expensive high-speed cameras. Firstly, a hand-held infrared imager is used to photograph the thermal images before, during and after the boiler furnace to determine the installation position and number of infrared thermal cameras. Then according to the number and location determined in the previous step, the infrared thermal cameras are installed and connected with the computer in monitoring room to monitor the combustion in the furnace. Oxygen content, furnace temperature, smoke exhaust temperature and emission concentration of major pollutants such as particulate matter, NO_X, SO_2 are monitored to verify the effect of the experimental system. The goal of the research is to determine whether it is feasible to apply infrared thermal imaging technology implementation of heating boiler combustion visualization, and to make it possible to realize full automation of heating boiler combustion control in the future.

2. Experimental system construction

At present, the combustion control of heating boilers mainly measures parameters such as furnace temperature, supply and return water temperature and pressure, exhaust gas temperature, furnace pressure, oxygen content, etc. Through the measured parameters and experienced workers to observe the flame state, and then manually adjust the drum, air diversion, and fuel filling[24,25]. The missing link in the boiler combustion control process is to visualize the actual state of the fuel combustion. The furnace temperature of coal-fired boilers for heating is generally above 1000℃. The contact temperature measuring elements are easily damaged, and can only measure the temperature at a single point, which cannot directly observe the combustion of fuel in the furnace. Using infrared thermal imaging technology to monitor the combustion inside the furnace not only can monitor the combustion of fuel in real time, but also the temperature distribution inside the furnace can be observed through thermal imaging. From which can adjust the boiler load, air and fuel supply, so that to solve the important link missing in the visualization of combustion conditions and realize the visualization of boiler combustion control.

2.1. Problems that the system needs to solve

The system needs to solve two problems: the installation location and quantity of infrared thermal cameras; It's not feasible to observe the combustion situation inside the furnace through heat-resistant glass.

2.1.1 The installation position and number of infrared thermal cameras

The combustion conditions of the front, middle and back parts of the boiler furnace were observed with a thermal imager. Fig. 1 is an infrared thermal image of combustion at the front of the furnace of the boiler. In this imaging, the coal is burning vigorously, the flame is high, and the whole image is very bright. Fig. 2 is an infrared thermal image of coal burning on the grate in the middle of the furnace. In which, the combustion is not as intense as the front, and the flame height is also lower, but the fire bed is still bright. Generally, coal burns well in the front and middle of the furnace. Because we are most concerned about whether the coal is completely burned, we also have observed the rear of the furnace, which is the tail of the grate. where we can see clearly whether the coal is completely burnt. Fig. 3 is an infrared thermal image of coal burning on the grate at the back of the boiler furnace. The bright part in the figure is the burning coal, and the blue-black part is the burnt coal. From the figure, we can see the combustion condition of the boiler No, there is burning coal falling off the grate. The cinders falling from the grate of the completely burned coal are blue-black, and no red flame can be seen. On the contrary, the combustion is incomplete. As a result of the above analyses, an infrared camera installed at the back of the furnace can effectively monitor whether the coal is burning adequately.

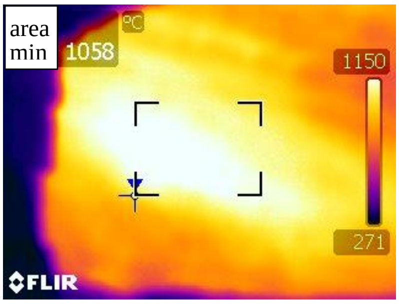

Fig. 1. Thermal image of the furnace front

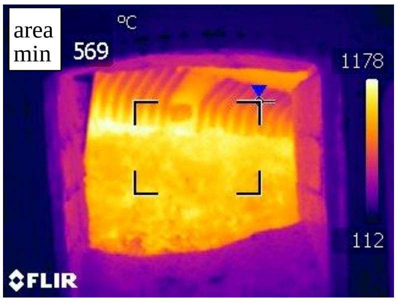

Fig. 2. Thermal image of the furnace middle.

Fig. 3. Thermal image of the furnace rear.

Install one or two? Fig. 4 and fig. 5 are infrared thermal images taken from both sides of the boiler respectively. From fig. 4, you can see that the coal near the shooting position has burned out, and the flame opposite the shooting position is bright and the coal is burning. Looking at the opposite side from fig. 5, it is not clear that the coal has burned out. Similarly, the burning situation near the shooting position in fig. 5 is not the same as that seen in fig. 4. If there is coal being burned in the middle of the grate width direction as in fig. 3, the combustion on the opposite side of the grate cannot be seen. It has been concluded from extensive practical observation that it is necessary to install one on each side of the boiler to give a complete view of the combustion throughout the rear of the furnace.

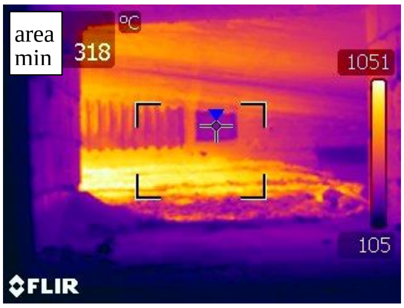

Fig. 4. Thermal image

taken from the right side of the furnace

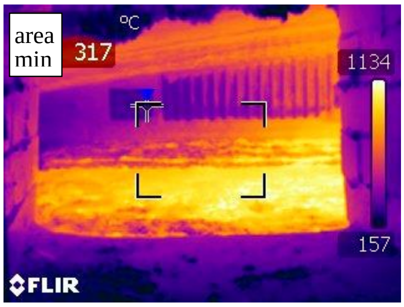

Fig. 5. Thermal image

taken from the left side of the furnace

2.1.2 It is not feasible to use an infrared camera to observe fuel combustion in the furnace through heat-resistant glass

If an infrared thermal camera is used to observe the combustion of coal in the furnace through the heat-resistant glass, it will not affect the air volume in the furnace. However, the radiation inside the furnace must pass through the glass and then to the surface. During this process, when the radiation passes through the inner surface of the glass, some of it is bounced back into the boiler furnace, and part of the radiation is absorbed; when it reaches the outer surface of the glass, part of the radiation is also bounced back to the interior, and part of it reaches the glass outer surface and escape, while part of the radiation is reflected again. Although this progressive reflection process gradually weakens, it has a very large impact to observe the combustion in the furnace. Fig. 6 is a thermal image of the infrared camera observing the combustion in the furnace through the heat-resistant glass, and the effect is very poor. The image observed through the glass is very unclear! Therefore, observation through glass cannot be performed. The temperature of the boiler furnace is relatively high, if the infrared thermal camera is directly embedded in the boiler wall for installation, it needs to adopt a cooling type, and in order to prevent lens ash accumulation, it must be equipped with air purge lens components. This equipment is expensive and complicated in operation and maintenance, and is mostly used for large power station boilers[1,4,5,26]. Therefore, the heating boiler can choose an uncooled infrared thermal camera to observe through the inspection door on the boiler to reduce investment and operation and maintenance costs. Fig. 7 is a thermal image observed when the inspection door is opened using an infrared camera, and the image is very clear. If the location of the boiler inspection door is not suitable for observation, a hole can be made in the boiler wall and a special observation door can be installed at a suitable location.

Fig. 6. Thermal image observed through heat-resistant glass.

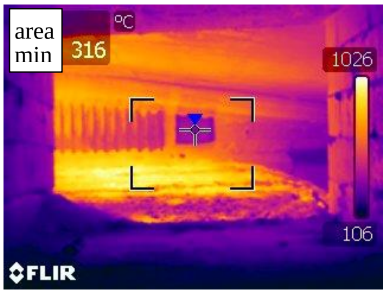

Fig. 7. Thermal image observed by opening the inspection door.

2.2. Experimental system construction

The infrared thermography system consists of five components: (1) Infrared lens: receives and gathers the infrared radiation emitted by the object to be measured; (2) Infrared detector assembly: converts thermal radiation models into electrical signals; (3) Electronic components: Processes electrical signals; (4) Display component: Converts electrical signals into a visible image; (5) Software: Processes collected temperature data and converts it into temperature readings and images. The infrared thermography system, computer and air supply adjustment mechanism constitute a coal-fired boiler combustion control visualization system based on infrared thermal imaging technology. The experimental system installation is shown in Fig. 8[27].

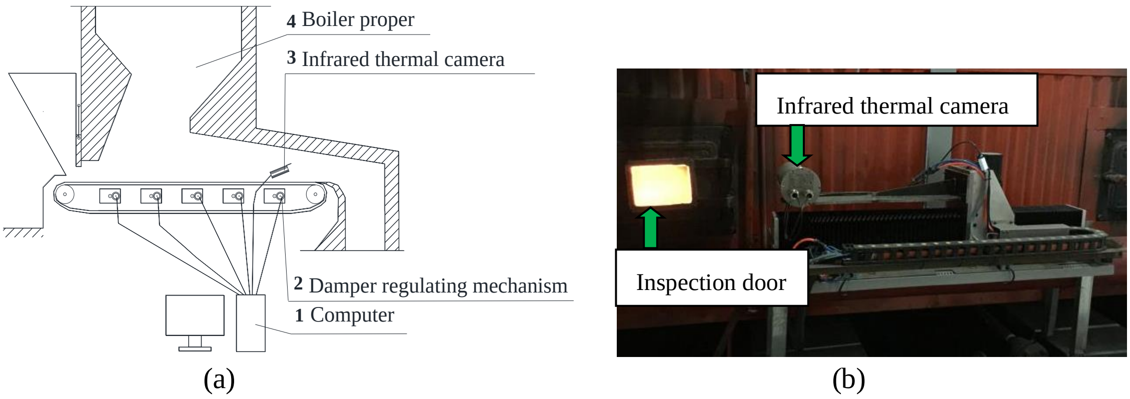

Fig. 8. Experimental system installation diagram: (a) System schematic, (b)Infrared thermal camera in place.

The equipment used in the experiment: (1) testo350 flue gas analyzer measures flue gas concentrations of PM, SO_2, NO_X and flue gas temperature. (2) FLIR T200 infrared camera, the temperature measurement range is -20-1200 ℃, which is used to observe the combustion in the furnace in the early stage of experiment. (3) Customized uncooled infrared thermal cameras, maximum measurement temperature of 1600℃ are installed at the tail of the boiler for combustion visualization monitoring. (4) Platinum-rhodium thermocouple, measuring temperature range 0-1300℃, measuring furnace temperature.

3. Results discussion

The information in the thermal image can guide the adjustment of air distribution and coal supply. As can be seen from Fig. 7, most of the grate is bright in color. The combustion situation in the furnace is not good, and most of the coal on the grate is not burned out. At this time, the height of the coal gate can be lowered to reduce the supply of coal. In addition, the color of the grate near the inspection door is darker, indicating that the air distribution volume here is relatively large and the coal burns faster than other parts. At this time, the opening of the air gate on this side should be reduced from less air distribution.

Because the furnace is under negative pressure when the boiler is working. The observation is carried out when the boiler inspection door is opened, which will inevitably change the air volume in the boiler furnace, and the air volume change will affect the boiler operation. Therefore, it is necessary to study the influence on the operation of the boiler when the inspection door is opened for observation.

The air volume in the boiler can be measured by monitoring the oxygen content in the boiler furnace. The amount of air required for complete combustion of coal without excess oxygen is called the theoretical amount of air. During the operation of the boiler, due to the imperfect combustion equipment of the boiler and the limitation of combustion technical conditions, the amount of air fed in cannot be ideally mixed with the fuel. In order to make the fuel burn as completely as possible, the airflow into the furnace is always greater than the theoretical amount of air. The portion of the actual air supply that is greater than the theoretical air volume is called excess air. The ratio of the actual air volume delivered to the theoretical air volume is called the excess air factor. The optimum value of the excess air factor is related to the type of fuel, the mode of combustion and the degree of refinement in the construction of the combustion equipment. Grate fired furnaces commonly used in heating boilers generally have an excess air factor between 1.3 and 1.6. It takes some time for the coal to burn completely in the furnace. Taking the chain furnace as an example, the running speed of the grate is generally 2-20 m/h depending on the coal type and load, and the movement is slow[28-30]. It is therefore not necessary to observe the combustion in the furnace all times, but it can be monitored by intermittently opening the inspection door and then taking a thermal image by an infrared thermal camera. The size of the inspection door is small compared to the boiler, and the shooting process takes less time. Generally, one shooting can be completed within 2 minutes, so that the amount of air entering the furnace through the inspection door is not much. Since the boiler needs a certain amount of excess air, intermittently opens the inspection door during observation, and closes the inspection door immediately after shooting, so that it will not have too much influence on the air volume of the boiler. Based on the above analysis, the intermittent observation method can be used to monitor the combustion in the furnace.

As the amount of air fed into the furnace increases, oxygen content in the flue gas will increase, and the furnace temperature will decrease accordingly. Due to the increase in the amount of air, the heat transfer from the heated surface of the tail will decrease, and finally the exhaust gas temperature will increase. Therefore, under different working conditions, the three parameters of boiler oxygen content, furnace temperature and exhaust gas temperature were monitored respectively to evaluate the impact of the use of infrared thermal cameras on the operation of the boiler when opening the inspection door to observe the combustion.

Monitor the change of the oxygen content of the boiler to analyze the influence of the excess air during the operation of the boiler due to the opening of the boiler inspection door to monitor the combustion in furnace. At the rear of the furnace, we monitored the oxygen content of the boiler without opening the inspection door, and opening the inspection door on both sides at the same time. The actual situation is shown in Fig. 9. It shows the changes in the oxygen content of the boiler under two conditions within 24 hours: the boiler is in normal operation, and using the infrared thermal camera to intermittently open the inspection doors on both sides to observe the combustion in the furnace. Through the monitored oxygen content data, the air leakage coefficient of the boiler can be calculated according to formula (1):

$$n_f = \frac{O_2' - O_2}{21 - O_2'} \tag{1}$$

where n_f is air leakage coefficient, O_2' is volume percentage of oxygen when opening the inspection door for observation, O_2 is volume percentage of oxygen at normal operation. From there, we can determine the effect on boiler operation when opening the inspection door and observing the combustion in the furnace with an infrared thermal camera. As can be seen from the monitoring data, the average oxygen content in the furnace was 10.52% when the inspection door was opened for observation, and the average oxygen content in the boiler during normal operation is 10.05%. The air leakage coefficient calculated from formula (1) can be obtained when opening the inspection door for observation is 0.04， Which still includes the sum of air leakage in the coal hopper, furnace door, grate side seal, peephole and other parts. It can be seen from the air leakage coefficient, compared with the normal operation of the boiler, the intermittent opening of the inspection door has little effect on the boiler air distribution and can be ignored.

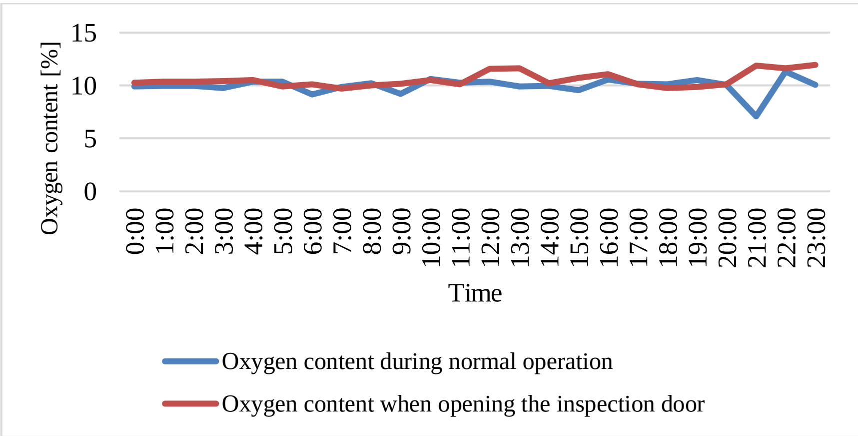

Fig. 9. Comparison of oxygen content.

While monitoring the oxygen content, the boiler furnace temperature was also monitored. Fig. 10 shows the boiler furnace temperature monitored in 24 hours when the boiler is in normal operation and the inspection doors are intermittently opened by infrared thermal camera to observe the combustion in the furnace. As can be seen from the data in Fig. 10 that the temperature curve of boiler furnace is basically consistent with that when the inspection doors were opened. The average temperature of the furnace during normal operation of the boiler is 1060.76 ℃, and the average temperature of the furnace is 1050.18 ℃ when the inspection doors were opened and the infrared thermal camera is used for observation. The difference between the two is very small. So that intermittent opening of the inspection doors and the use of infrared thermal cameras to monitor the combustion in the furnace have no significant effect on furnace temperature.

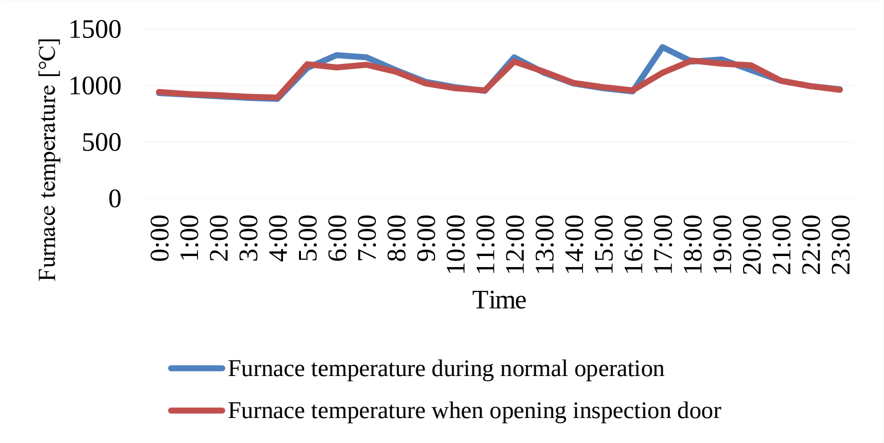

Fig. 10. Comparison of furnace temperature.

At the same time of monitoring the oxygen content, the exhaust temperature of the boiler was also monitored. Fig. 11 shows the boiler exhaust temperature monitored in 24 hours when the boiler is in normal operation and the inspection doors are intermittently opened to observe the combustion condition in the furnace. As can be seen from the data in Fig. 11 that the temperature curve of boiler furnace is basically consistent with that when the inspection doors were opened. The average smoke exhaust temperature during normal operation of the boiler is 178.86 ℃, and the average smoke exhaust temperature when the inspection doors were opened and observed by the infrared thermal cameras is 188.13 ℃, which is not much different. Therefore, when the inspection doors were opened intermittently and infrared cameras were used to monitor combustion in the furnace it has little effect on the exhaust temperature.

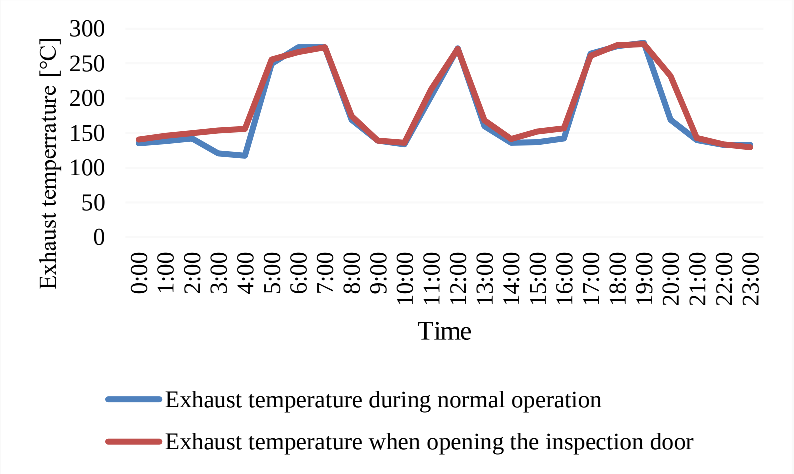

Fig. 11. Comparison of exhaust temperature.

From the above analysis of the oxygen content, furnace temperature and exhaust gas temperature monitoring data, the method of using infrared thermal cameras to intermittently open the inspection doors on both sides of the boiler tail to observe the coal combustion in the furnace will not adversely affect the normal operation of the boiler.

Along with the above parameters, the emissions of major air pollutants such as PM, SO_2 and NO_X were monitored to assess the impact of the experimental system on the atmospheric environment. The heating station of the laboratory has two identical boilers, one of which is equipped with the experimental system and the two boilers are running in parallel. In a month's time, the emission of the main air pollution of the two boilers was monitored at the same time, and the specific data are shown in Fig. 12-14.

From the measured data in Fig. 12, it can be concluded that the boiler with this experimental system installed has an average daily emission concentration of 16.30mg/Nm^3, while the boiler without the experimental system has an average daily emission concentration of 19.46mg/Nm^3. The average emission concentration was reduced by 16.28%. Since the boilers installed with this experimental system use infrared thermal cameras to monitor combustion in the furnace during operation, the combustion status is adjusted in a timely manner and the PM emissions are reduced.

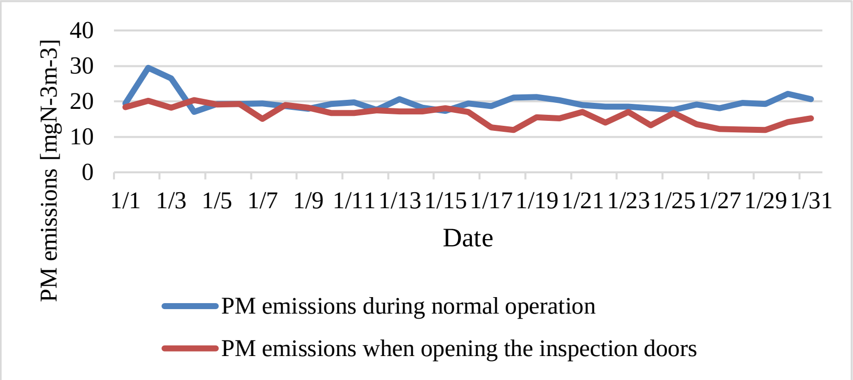

Fig. 12. Comparison of PM emissions.

From the measured data in Fig. 13, it can be concluded that the daily average emission concentration of SO_2 from the boiler installed with this experimental system is 147.20mg/Nm^3, while the daily average emission concentration from the boiler without the experimental system is 146.60mg/Nm^3. The average emission concentration increased by 0.4%, and the change was very small, because the emission concentration of SO_2 is mainly related to coal quality, and the amount of sulfur contained in coal determines the amount of SO_2 emission.

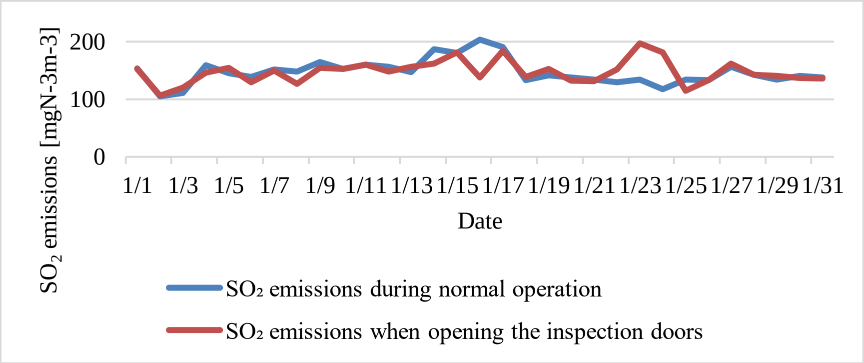

Fig. 13. Comparison of SO_2 emissions.

From the measured data in Figure 14, it can be concluded that the boiler NO_X installed with this experimental system has an average daily emission concentration of 266.92mg / Nm^3, while the boiler without the experimental system has an average daily emission concentration of 277.97mg / Nm^3. The average emission concentration is reduced by 4%, and the change is also very small. This is because NO_X in the heating boiler is mainly of thermal type and fuel type[31-33], and the thermal type furnace temperature is related. In this experiment, the furnace temperature changes little, and the fuel type is directly related to the nitrogen content in the coal.

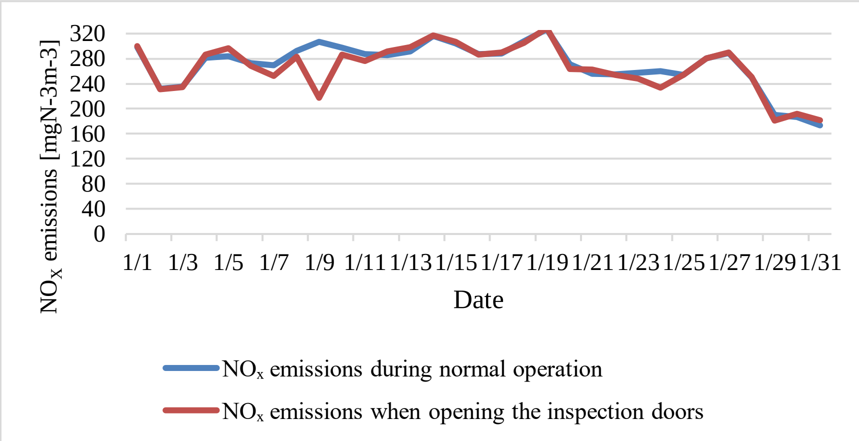

Fig. 14. Comparison of NO_X emissions.

From the monitoring data analysis of PM, SO_2, NO_X emissions, that this experimental system has a good effect on reducing PM emissions and is conducive to reducing air pollutant emissions.

4. Conclusion

Visualization of boiler combustion can be achieved by observing the boiler furnace combustion conditions using infrared thermal cameras. Visualizing the combustion process in coal-fired boilers by using infrared thermography not only allows you to visualize the thermal image in the furnace, but also to keep track of the temperature distribution in the furnace. From the analysis of the monitoring data of oxygen content, furnace temperature and exhaust temperature, intermittent opening of the inspection doors to observe the combustion of coal in furnace will not adversely affect the normal operation of the boiler. From the monitoring data analysis of PM, SO_2, NO_X emissions, that this experimental system has a good effect on reducing PM emissions and is conducive to reducing air pollutant emissions. It is feasible to apply infrared thermal imaging technology implementation of heating boiler combustion visualization, and to make it possible to realize full automation of heating boiler combustion control in the future.

References

[1] Han, Z., *et al.*, Prediction of Combustion State Through a Semi-supervised Learning Model and Flame Imaging, *Fuel, 289* (2021), pp. 119745

[2] Han, Z., *et al.*, Combustion Stability Monitoring Through Flame Imaging and Stacked Sparse Autoencoder Based Deep Neural Network, *Applied Energy, 259* (2020), pp. 114159

[3] Hernández, R., Ballester, J., Flame Imaging as a Diagnostic Tool for Industrial Combustion, Combustion and Flame, 155 (2008), 3, pp. 509-528

[4] Yana, Y., Colechinb, M., A Digital Imaging Based Multi-Functional Flame Monitqring System, IMTC 2003-Instrumentation and Measurement Technology Conference, Vail, CO, USA, 20-22 May 2003, pp. 94-99

[5] Gang Lu, *et al.*, Monitoring of Oscillatory Characteristics of Pulverised Coal Flames Through Image Processing and Spectral Analysis, Proceedings, *Proceedings* of the 21st IEEE Instrumentation and Measurement Technology Conference (IEEE Cat. No.04CH37510), Como, Italy, 2004, pp. 1801-1805

[6] Abdurakipov, S.S., *et al.*, Combustion Regime Monitoring by Flame Imaging and Machine Learning, Optoelectron. *Instrument. Proc., 54* (2018), 5, pp. 513-519

[7] Ballester, J., García-Armingol, T., Diagnostic Techniques for The Monitoring and Control of Practical Flames, *Progress in Energy and Combustion Science, 36* (2010), 4, pp. 375-411

[8] Han, Z., *et al*., A Hybrid Deep Neural Network Based Prediction of 300 MW Coal-fired Boiler Combustion Operation Condition, *Sci. China Technol. Sci.*, 64 (2021), 10, pp. 2300-2311

[9] Lu, G., *et al.*, Vision Based Monitoring and Characterisation of Combustion Flames, *J. Phys.: Conf. Ser.,* 15 (2005), pp. 194-200

[10] González-Cencerrado, A., *et al*., Characterization of PF Flames Under Different Swirl Conditions Based on Visualization Systems, *Fuel, 113* (2013), pp. 798-809

[11] Chin Chongshuang, *et al.*, A New Real-Time Fire Detection Method Based on Infrared Image, *Proceedings* of IEEE 7th International Conference on Computer Science and Network Technology, CCSNT 2019, pp. 476-479

[12] Ch. Kranz, A New Flame Detection Method for Two Channels Infrared Flame Detectors, *Proceedings* The Institute of Electrical and Electronics Engineers, 29th Annual 1995 International Carnahan Conference on Security Technology, Sanderstead, UK, 18-20 October 1995, PP. 209-213

[13] Hyeon Bae, *et al.*, Flame Detection for The Steam Boiler Using Neural Networks and Image Information in The Ulsan Steam Power Generation Plant, *IEEE Transactions on Industrial Electronics, 53* (1), PP. 338-348

[14] Juan Riaza, *et al*., Ignition and Combustion of Coal and Biomass, *Fuel*, *202* (2017), pp. 650-655

[15] Huang Guan, *et al.*, Automatic Fault Diagnosis Algorithm for Hot Water Pipes Based on Infrared Thermal Images, *Building and Environment, 218* (2022), pp. 109111

[16] Lu Zhu-Mao, *et al*., Research on Thermal Fault Detection Technology of Power Equipment Based on Infrared Image Analysis, 2018 IEEE 3rd Advanced Information Technology, Electronic and Automation Control Conference (IAEAC), Chongqing, China, 2018, pp. 2567-2571

[17] Ring, E.F.J., Beyond Human Vision: The Development and Applications of Infrared Thermal Imaging, *The Imaging Science Journal, 58* (2010), 5, pp. 254-260

[18] Fei Liu, Stefan Seipel, Infrared-visible Image Registration for Augmented Reality-Based Thermographic Building Diagnostics, *Visualization in Engineering,* (2015) 3:16

[19] Huaiping Mu, *et al.*, Visualization Measurement of The Flame Temperature in a Power Station Using The Colorimetric Method, *Energy Procedia, 66*(2015), pp. 133-136

[20] Teri Snow Draper, *et al.*, Two-Dimensional Flame Temperature And Emissivity Measurements Of Pulverized Oxy-coal Flames, *Applied Energy, 95*(2012), pp. 38-44

[21] Zhi-Wei Jiang, *et al*., A simple Measurement Method of Temperature and Emissivity of Coal-fired Flames from Visible Radiation Image and Its Application in a CFB Boiler Furnace, *Fuel 88* (2009) pp. 980-987

[22] Lin Li, *et al*., Pressurized Oxy-Fule Combustion Characteristics of Single Coal Particle in a Visualized Fluidized Bed Combustor, *Combustion and Flame, 211* (2020) 218-228

[23] Chengfeng SUN, *et al*., A Visualization Method of Quantifying Carbon Combustion Energy in the Sintering Packed Bed, *ISIJ International 61* (2021) pp. 1801-1807

[24] Lin, B., Jørgensen, S.B., Soft Sensor Design By Multivariate Fusion Of Image Features and Process Measurements, *Journal of Process Control, 21* (2011), 4, pp. 547-553

[25] Chen, H., *et al.*, Burning Condition Recognition Of Rotary Kiln Based On Spatiotemporal Features Of Flame Video, *Energy, 211* (2020), pp. 118656

[26] Bai, X., *et al.*, Multi-Mode Combustion Process Monitoring on a Pulverised Fuel Combustion Test Facility Based on Flame Imaging and Random Weight Network Techniques, *Fuel, 202* (2017), pp. 656-664

[27] Zhang, Z.-G., Preliminary Study on Application of Infrared Thermal Imaging Technology in Combustion Control of Coal-Fired Boilers, J. Phys.: Conf. Ser., 2009 (2021), 1, pp. 012055

[28] Wang Dunen, *et al., Design Calculation Method of Industrial Boiler*, Standards Press of China, Beijing, China, 2005

[29] Shi Peifu, *et al*., *Application Technology of Energy Saving and Emission Reduction in Industrial Boilers, 2nd Ed*. Chemical Industry Press, Beijing, China, 2016

[30] Wu Weilong, *et al*., *Boiler and Boiler Room Equipment, 5th Ed*. China Architecture and Building Press, Beijing, China, 2014

[31] Iman Rahimipetroudi, *et al*., Development of Environment-Friendly Dual Fuel Pulverized Coal-Natural Gas Combustion Technology for the Co-Firing Power Plant boiler: Experimental and Numerical Analysis, *Energy, 228* (2021), pp. 120550

[32] Xiangru JIA, *et al.*, Investigation of the Pollutant Emission Characteristics of Blends of Biomass and Coal Gangue in a Fluidized Bed, *Thermal Science 26* (2022), 5B, pp 4333-4343

[33] Chao CHEN, *et al*., Modelling and Combustion Optimization of Coal-Fired Heating Boiler Based on Thermal Network, *Thermal Science 25* (2021), 4B, pp 3133-3140

Submitted: 27.06.2023.
Revised: 11.07.2023.
Accepted: 18.09.2023.