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Development of Two-Dimensional Acoustic Temperature Measurement Technology for Blast Furnace

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For decades, blast furnace operators have used above-burden temperature probes to measure the hot air flow's temperature distribution and assess the furnace's thermal efficiency. However, the thermocouple obstruction by the dust accumulation increased the maintenance workload and the charging material flow trajectory dispersed by the probes also reduced the uniformity of hot air. An online acoustic measuring system with 12 sound wave transceivers and 66 temperature measurement paths was accomplished on the CSC #4 blast furnace in 2021. Compared with the temperature measurement of the thermocouples on the traditional above-burden probes at the top of a blast furnace, a two-dimensional acoustic gas temperature measurement technology with a higher resolution of 1% of the diameter and a faster response speed of updating every six seconds has been developed. The robustness of the design of the sound wave transceivers is proven after two years of online use. The design of a commercial truck air horn was adopted to integrate into the sound wave transceiver requiring only 4.0 bar to operate, which can be provided by the existing nitrogen pipeline on the blast furnace top. The improved resolution and response of the acoustic measurement system have increased the detection frequency of some minor channeling events in the blast furnace. Operators will be able to monitor furnace changes in a faster and higher-resolution way by using the developed non-contact acoustic gas temperature measurement technology to improve the uniformity of the hot air flow in the blast furnace, thereby increasing operational efficiency.

Keywords: Blast Furnace, Acoustic Gas Temperature Measurement

1. INTRODUCTION

The thermocouples on the above-burden temperature probes measure the temperature distribution of the hot air flow at the blast furnace top, which indicates its operating thermal efficiency. However, the dust-laden air flow within the blast furnace often obstructs the thermocouple and impedes the gas temperature measurement. The above-burden temperature probes, which weigh approximately 800 kilograms, require disassembly and cleaning or replacement of the obstructed thermocouples during most blast furnace shutdowns. This measurement inconvenience not only adds to the maintenance workload but also hinders the operators from fully monitoring the furnace condition variations. Furthermore, the burden material impacts the probes during charging, which disperses the material flow trajectory and creates a concave shape on the burden surface beneath the probes, as shown in Figure 1. This results in uneven distribution of hot airflow in the furnace and reduces its thermal efficiency.

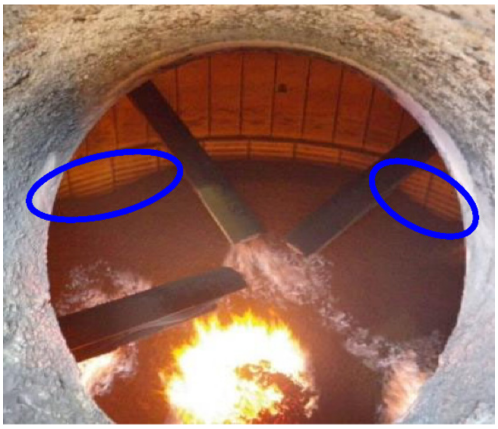

Fig.1. Concave shape on the burden surface beneath the probes

A two-dimensional gas temperature measurement system called t-matriX[1] provided by IMI Z&J is shown in Figure 2. The furnace top is surrounded by eight acoustic transceiver units. Each unit can transmit to the other seven units and receive signals from them, forming 28 measurement paths in total. The sound wave's time of flight at a fixed distance is used to calculate the average temperature along its path. The isothermal distribution of the gas field is then reconstructed using a 2D thermal model.

A two-dimensional top gas measurement system for the blast furnace, named SOMA[2] and supplied by TMT, was installed as depicted in Figure 3. The system consisted of ten acoustic wave transceivers and 45 temperature measurement paths. The system specification indicated a measurement accuracy of ±2.5% and a two-dimensional isothermal graph refresh rate of 4~6 seconds. The technical data also specified a temperature measuring range of 0 to 2000 degrees Celsius and an operating pressure of 6 to 8 bar. The tomography algorithm in SOMA can detect displacements of the central gas channel as small as 3% of the blast furnace diameter [3].

Figure 4 shows an acoustic gas temperature measurement system AGAM[4] for the combustion chamber, supplied by B&D. The system can measure temperatures of 200 paths in less than 15 seconds and update the tomographically determined 2D illustrations every second. The AGAM system utilizes acoustic signals within the 200 to 3000 hertz frequency range to monitor and optimize the fuel consumption and flue gas combustion in the boiler of the Rybnik power plant[5], since the temperature distribution in the combustion chamber is a key parameter affecting the boiler performance.

The BOILERWATCH from SEI is specifically designed for measuring gas temperature distribution in boilers[6]. Figure 5 shows its specifications, which include the support for 2 to 16 sensor sets, with up to 24 temperature measurement paths, and an update rate of about 5 seconds per path. Moreover, its accuracy is specified as 0.5%, and its temperature measurement resolution is indicated. A technical document from SEI in 2009

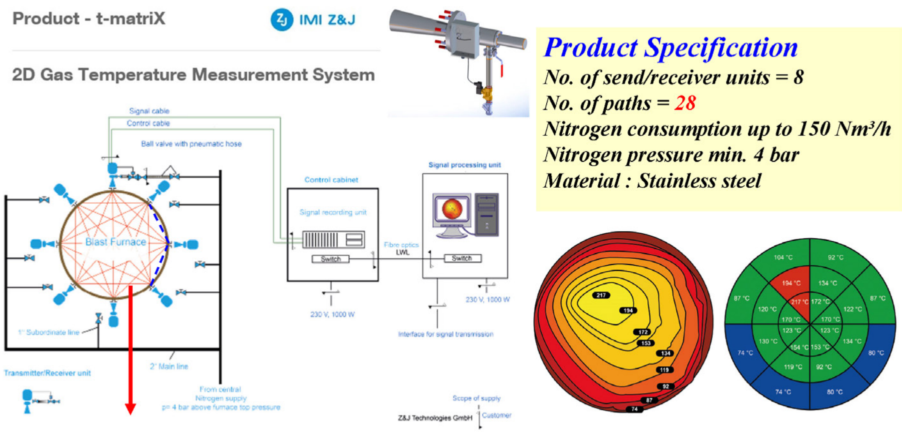

Fig.2. IMI Z&J's 2D gas temperature measurement system [1].

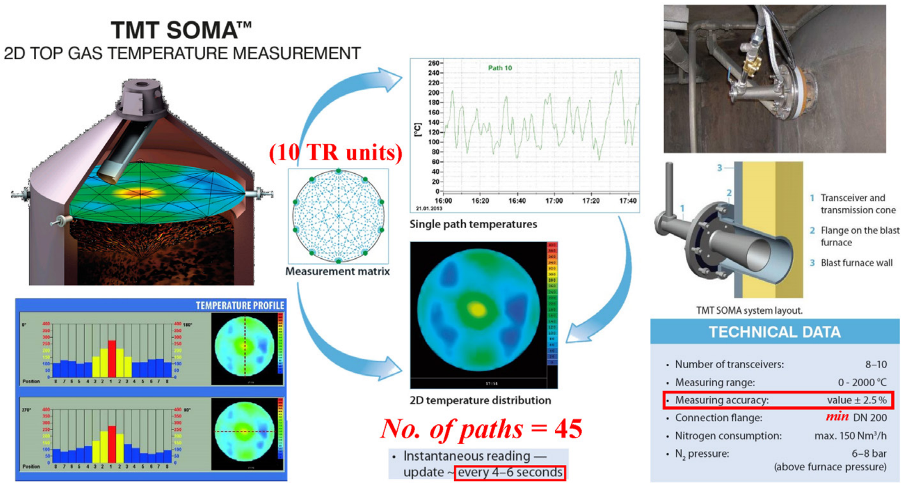

Fig.3. TMT's 2D top gas temperature measurement [2] .

reported the verification results of the acoustic temperature measurement at the ENEL Brindisi power plant in Italy using a 4-meter-long temperature probe[7]. The average temperature difference between the acoustic and thermocouple measurements was about 0.8%.

Enertechnix has developed a boiler gas temperature measurement system, PyroMetrix, with separate acoustic transmitter and receiver units rather than an integrated configuration, as shown in Figure 6[8]. The system offers instantaneous, repeatable, and spatially averaged temperature measurements with an error of less than 1%, according to its specifications. Despite the numerous and dispersed system components, its pipe diameter connecting the furnace body is only 1.5 inches, much lower than the 3 inches of SEI, and the 7.5 inches of TMT, which facilitates its online installation and increases the possibility of small space applications, such as exhaust boxes under sinter strand.

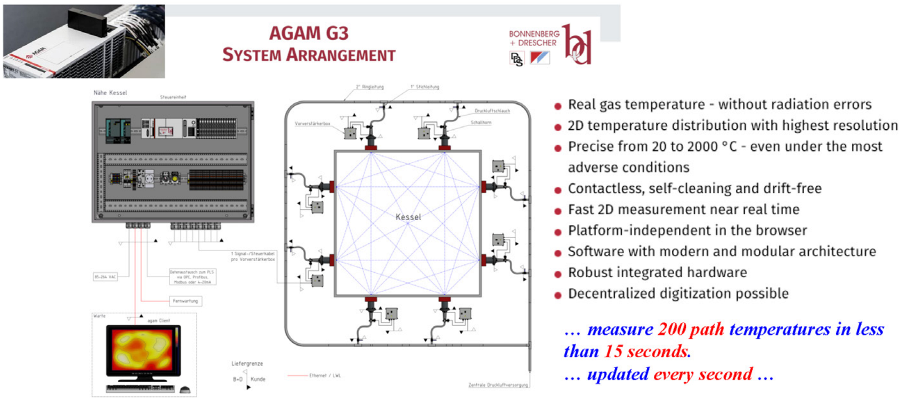

Fig.4. B&D's acoustic gas temperature measurement system [4] .

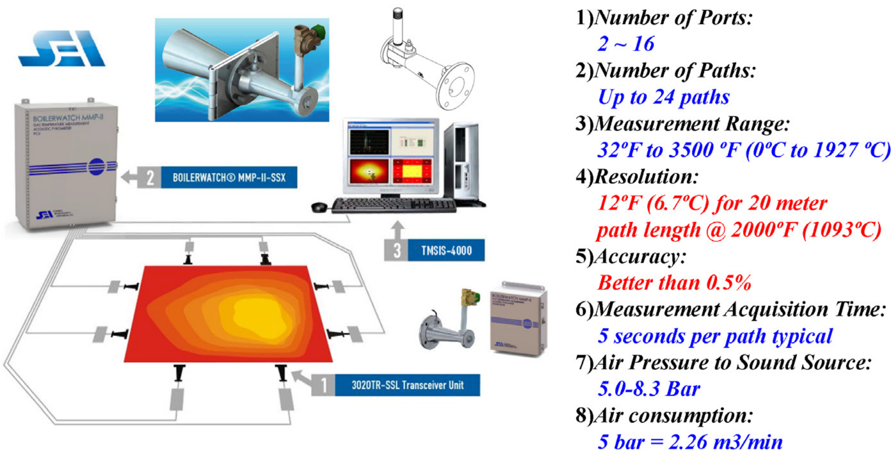

Fig.5. SEI's acoustic gas temperature measurement system [6] .

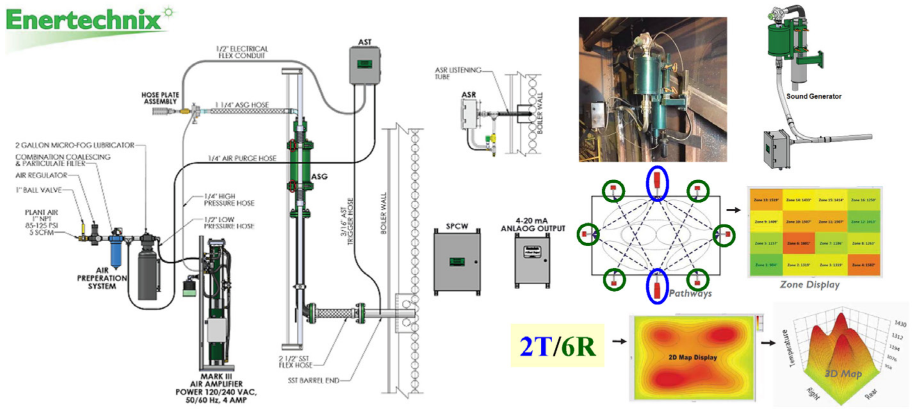

Fig.6. Enertechnix's boiler gas temperature measurement system [8] .

2. SYSTEM DEVELOPMENT

An acoustic gas temperature measurement system consists of two main components: the sound wave transceivers and a reconstruction model. The sound wave transceivers measure the propagation speed of sound waves in the gas, while the reconstruction model converts the average path temperature to a planar distribution. Meanwhile, system development is also divided into two parts: offline model development and online system verification. The off-line planar gas field temperature reconstruction model was developed using commercially available ultrasonic probes. An acoustic hotspot tracking algorithm with compatible reconstructed two-dimensional gas temperature map, acute sensitivity to hotspot shift for 1 % of region-of-interest's diameter, and 1.46% error in peak temperature, 5.89% root mean square error and 0.86% relative error on the point-to-point temperature was developed using a highly concentrated temperature distribution model, as shown in Figure 7[9].

An acoustic pyrometer platform for the study and analysis of the reconstruction algorithms dedicated to a highly concentrated temperature distribution field was proposed in Figure 8[10]. The necessity and the performance of an improved time-of-flight estimation based on the Schmitt trigger approach were confirmed. The details of the proposed platform were disclosed to facilitate the research about developing the reconstruction algorithm two-dimensional acoustic pyrometer. This open platform provided an affordable platform for researchers to test their algorithms in a practical environment.

A deep-learning-based method for reconstructing the gas temperature distribution is presented in Figure 9 [11]. The architecture of the neural network used mainly three up-sampling layers to enlarge the dimension and convolution layers to strengthen the relationship between each pixel. The deep-learning-based method reconstructed the gas temperature distribution without iteration, resulting in an average execution time of only 0.109 seconds. This was a 96% reduction compared to the spatial moving sampling method[9] with 1000 iterations.

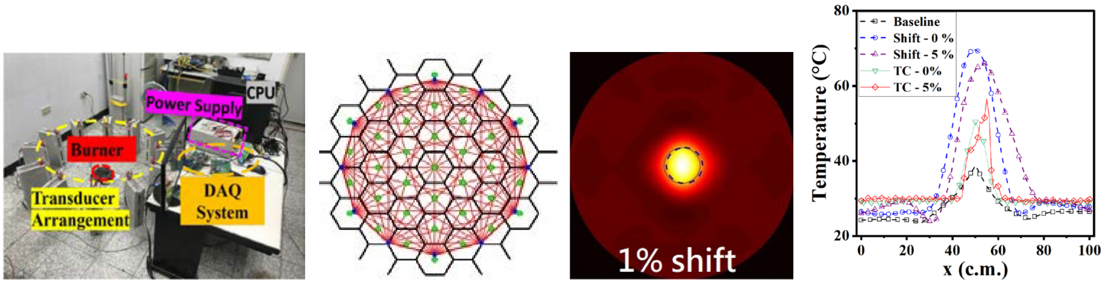

Fig.7. An off-line developed acoustic hotspot tracking algorithm [9] .

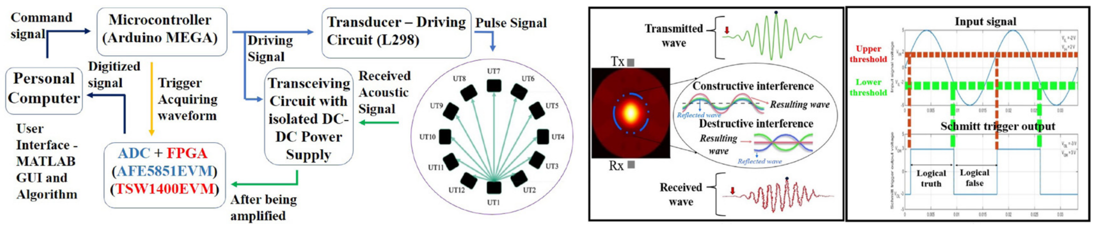

Fig.8. An acoustic pyrometer platform [10] .

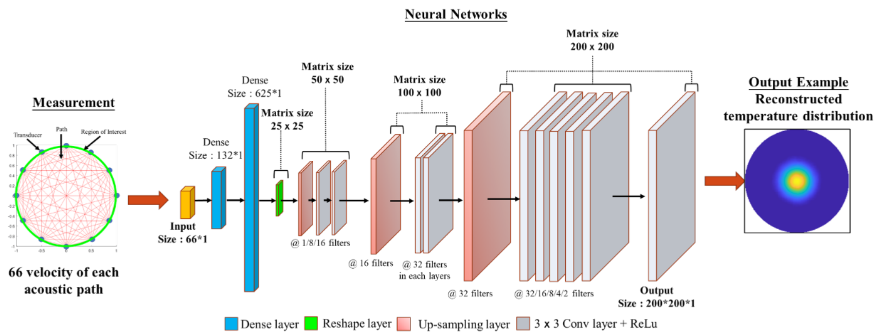

Fig.9. A deep-learning-based reconstructing method [11] .

An online test of the two-dimensional acoustic temperature measurement technology was implemented on the CSC #4 blast furnace in 2019, as shown in Figure 10. Two commercially available ultrasonic probes with a measuring range of 10 meters were installed on the opposite side of the blast furnace top. The signal strength was fine when the blast furnace was scheduled to shut down, but once the hot air was blown in, the strong airflow noise overwhelmed the emission signals. Moreover, the top of the blast furnace can reach temperatures above 100 degrees Celsius during operation, requiring additional cooling for the probes, which may further reduce their signal strength. The furnace dust accumulated on the probe surface can also attenuate the signal strength.

To overcome these problems, a sound wave transceiver is shown in Figure 11 regarding the design of a commercial truck air horn. A compact and high-precision pre-polarized microphone, commercially available, was adopted to integrate into the sound wave transceiver. Except for the horn, the transceiver components are located outside the blast furnace body to prevent the effects of high temperature and dust inside the furnace. Thus, no additional cooling and purging circuits are required for the transceiver. Moreover, the transceiver maintenance can be performed without shutting down the blast furnace. As shown in Figure 11, the online test results indicate that the received signals have relatively high strength at a low frequency of around 200 hertz.

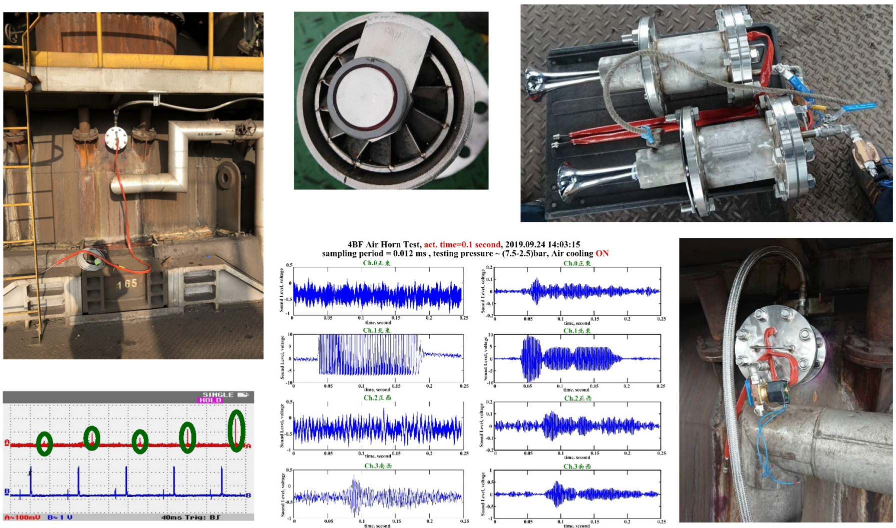

Fig.10. An online test on CSC #4 blast furnace.

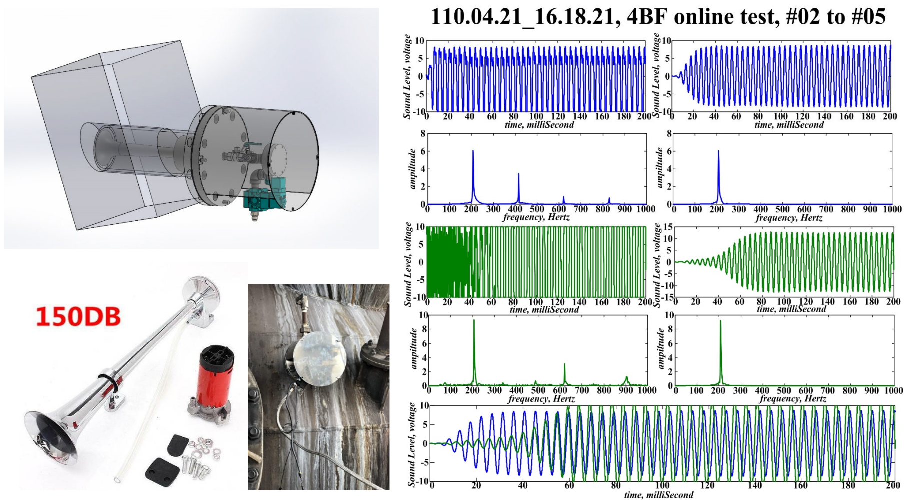

Fig.11. A sound wave transceiver designed and tested in the study.

Hence, the sound time-of-flight can be precisely determined from the phase difference between the wave peaks after filtering for a specific frequency window.

Following the online test, 12 sound wave transceivers were deployed and mounted on the top of CSC #4 BF in 2021, as shown in Figure 12. Since the presence of equipment and pipelines on the blast furnace top, the transceiver installation angles required flexible adjustment. The air horn of each transceiver was connected to the existing nitrogen pipeline on the blast furnace top, which supplied a pressure of approximately 4.0 bar. The air horn can still generate sound waves with adequate intensity to measure the path temperature at the furnace top, even under a blast furnace operating pressure of 1.5 bar. Furthermore, the planar gas temperature at the furnace top reconstructed from the 66 measured path temperatures had been integrated into the modern blast furnace AIoT platform and displayed on the website.

One of the two-dimensional acoustic gas temperature measurement results on the top of CSC #4 BF is shown in Figure 13. The temperature display range can be modified by the operator, the default was set to be 0 to 700 degrees Celsius and the planar position display was simplified to dimensionless coordinates. The web page of the acoustic temperature measurement results was refreshed every six seconds per the blast furnace

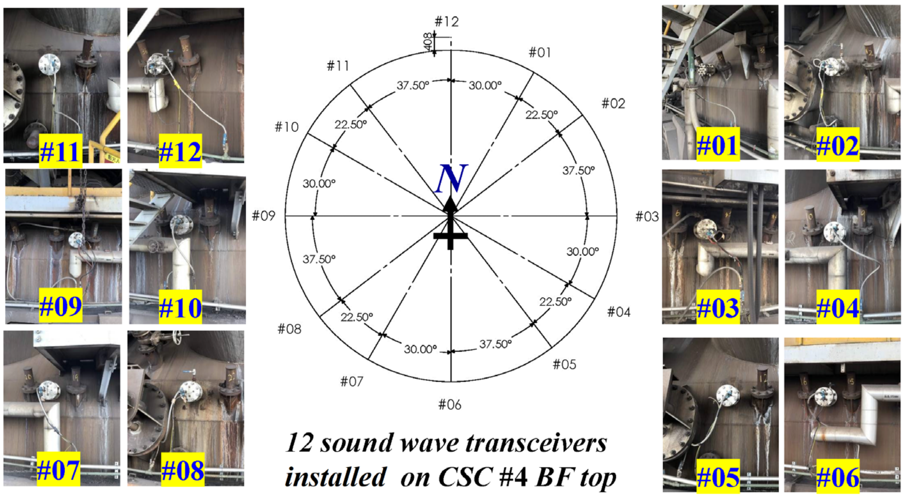

Fig.12. Arrangement of 12 sound wave transceivers on CSC #4 BF.

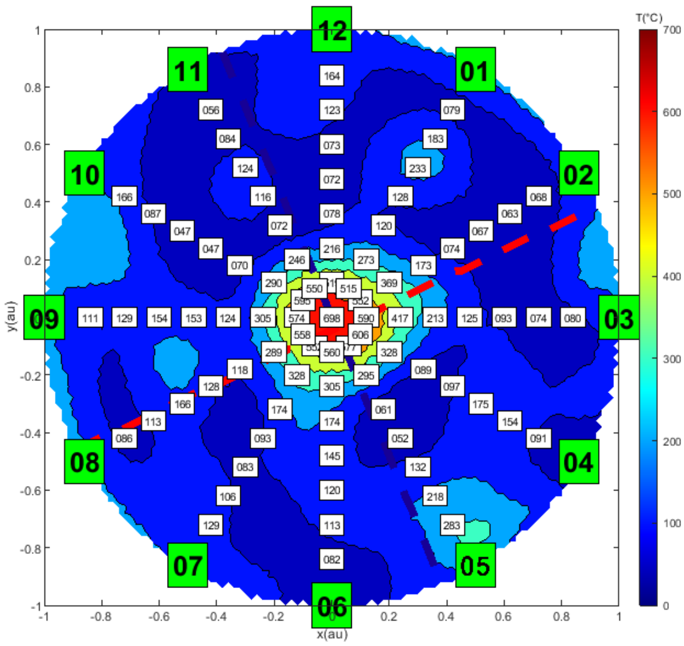

Fig.13. Gas temperature measurement result in CSC #4 BF.

production cycle and other detection equipment update rates. The diaphragm inside the air horn is a wear item that requires replacement after approximately 8-12 months of use, depending on the current update frequency setting, as it reaches the maximum number of effective vibrations. The sound wave transceiver features a fault self-diagnosis function. It displays a warning on the web page and alerts the maintenance personnel when the transmitted sound wave intensity falls below a threshold value.

The temperature data from the thermocouple on the above-burden probes was recorded at a low frequency of once per minute in the past, due to its long thermal response time. However, the acoustic gas temperature measurement results can be rapidly computed and displayed on the webpage. This enhances the detection frequency of some minor channeling events in the blast furnace. Figure 14 shows a transient channeling event near the furnace wall that was detected by the acoustic gas temperature measurement system for only 30 seconds. However, it still altered the profile along the measurement direction of an online blast furnace burden profile system[12]. Therefore, the acoustic temperature measurement, which is more sensitive to temperature changes, enables furnace operators to monitor the variation of furnace conditions more accurately.

Despite the slower temperature change response of the thermocouple compared to the acoustic temperature measurement, it can still provide a reliable reference for the long-term temperature trend analysis. Figure 15 shows the temperature trend chart of the central airflow with the highest temperature on the top of the blast furnace. The acoustic method showed significantly higher variability than the thermocouples. Moreover, because of the high resolution of the acoustic temperature measurement, its width at the center point of the

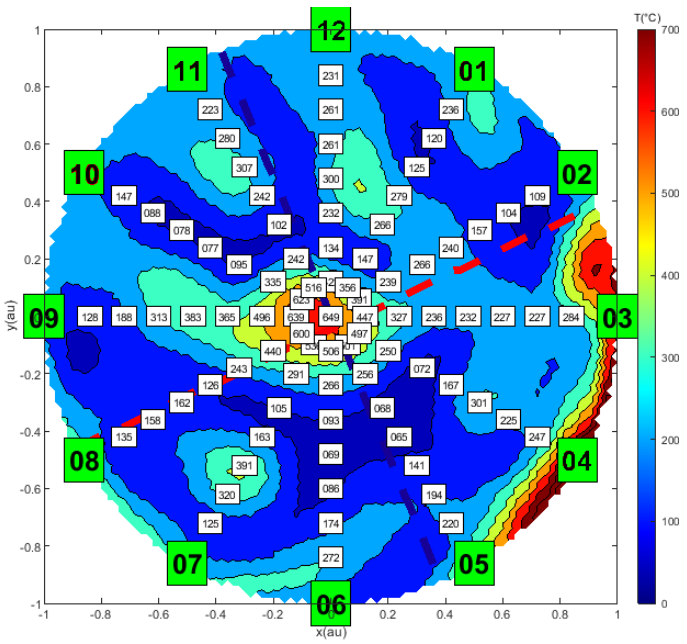

Fig.14. A channeling phenomenon observed on the acoustic gas temperature measurement system close to the furnace wall.

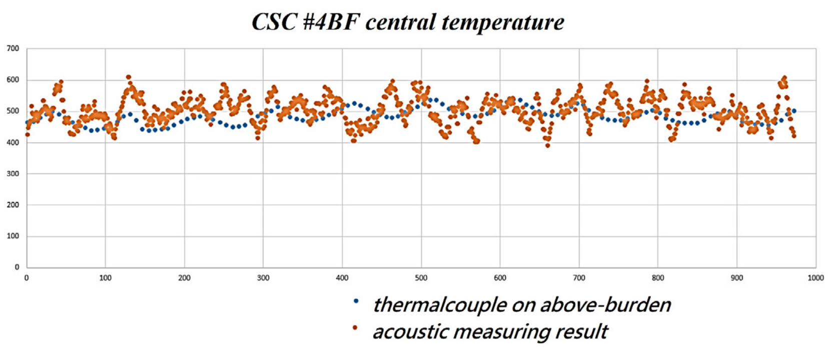

Fig.15. Trend chart of CSC #4BF central temperature.

furnace is only 1% of the furnace diameter. Therefore, when the airflow trajectory in the center of the furnace changes, the temperature at the center point varies accordingly. For practical blast furnace operation, dividing the acoustic temperature zone into 5% of the diameter and displaying the mean values within the zone would be closer to the trend of the traditional thermocouples on the above-burden probes.

3. CONCLUSIONS

Compared with the temperature measurement of the thermocouples on the traditional above-burden probes at the top of a blast furnace, a two-dimensional acoustic gas temperature measurement technology with a higher resolution of 1% of the diameter and a faster response speed of updating every six seconds has been developed. A reconstruction method using a highly concentrated temperature distribution model with 1.46% error in peak temperature, 5.89% root mean square error, and 0.86% relative error on the point-to-point temperature was verified in the offline static temperature test. An online acoustic measuring system with 12 sound wave transceivers and 66 temperature measurement paths was accomplished on the CSC #4 blast furnace in 2021. The robustness of the design of the sound wave transceivers is proven after two years of online use. The commercial truck air horn inside the sound wave transceiver requires only 4.0 bar to operate, which can be provided by the existing nitrogen pipeline on the blast furnace top. The diaphragm inside the air horn is a wear item that requires replacement after approximately 8-12 months of use. The improved resolution and response of the acoustic measurement system have increased the detection frequency of some minor channeling events in the blast furnace. The temperature trend chart of the central airflow with the highest temperature on the top of the blast furnace generated by thermocouple and acoustic temperature measurement respectively is compared and discussed. The traditional above-burden probes weigh nearly 800 kilograms, which not only makes it difficult to maintain but also disperses the material flow trajectory, thereby affecting the uniformity of the hot airflow in the furnace. Operators will be able to monitor furnace changes in a faster and higher-resolution way by using the developed non-contact acoustic gas temperature measurement technology to improve the uniformity of the hot air flow in the blast furnace, thereby increasing operational efficiency.

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