Proceedings of the
Estonian Academy of Sciences
2025, **74**, 2, 149–154

https://doi.org/10.3176/proc.2025.2.12

www.eap.ee/proceedings
Estonian Academy Publishers

DIGITAL TWIN MODEL,
SMART MONITORING

RESEARCH ARTICLE

Received 3 February 2025
Accepted 26 February 2025
Available online 21 April 2025

Keywords:
boiler water walls, digital twin model, smart monitoring, power plants

Corresponding author:
David Bassir
david.bassir@utbm.fr

Citation:
Luo, L., Wang, W., Lei, Z., Bao, S., Bassir, D. and Chen, G. 2025. Smart monitoring of the expansion state of boiler water walls in coal-fired power plants using a digital twin model. *Proceedings of the Estonian Academy of Sciences*, **74**(2), 149–154. https://doi.org/10.3176/proc.2025.2.12

Smart monitoring of the expansion state of boiler water walls in coal-fired power plants using a digital twin model

Lijia Luo[a], Weida Wang[b], Zhenheng Lei[a], Shiyi Bao[a], David Bassir[c,d] and Gongfa Chen[c]

[a] College of Mechanical Engineering, Zhejiang University of Technology, China
[b] Zhejiang Rancon Turbine Machinery Co., Ltd., China
[c] Smart Structural Health Monitoring and Control Laboratory, Sino-French Institute, Dongguan University of Technology, China
[d] IRAMAT UMR-CNRS 7065, UTBM, Belfort CEDEX, France

ABSTRACT

This article presents an approach for monitoring the expansion state of water walls in coal-fired power plants using a digital twin (DT) model. The monitored boiler belongs to a 1000 MW ultra-supercritical power generating unit; it has been in service for more than 14 years and has accumulated more than 100 000 hours of operation. The fracture of the water wall has become a serious problem for safe operation. The size of the water wall is huge, the structure is complex, the stress state is changeable, and the fracture treatment is difficult. Existing online monitoring systems are mainly based on wall temperature, and it is difficult to evaluate the stress state of the water wall. However, there are few technical systems that can monitor the expansion displacement and local strain/stress of water walls online. To address this problem, a DT model is built to monitor the expansion state of boiler water walls. An optical non-contact strain monitoring system (based on digital image correlation (DIC) technologies) coupled with finite element analysis is developed to measure the actual strain/stress data and generate more simulation data for improving the accuracy of the DT model. This monitoring system provides an effective way to prevent the expansion fracture of the water wall.

1. Introduction

A boiler water wall accident may occur due to the frequent start-stop and the deep-load changing of coal-fired plants. Such accidents seriously threaten the safe and stable operation of coal-fired plants. Moreover, corrosion of boiler water walls leads to potential failures and downtime [1,2]. Therefore, monitoring the state of boiler water walls in coal-fired power plants is crucial for maintaining structural integrity and operational efficiency. Advancements in online monitoring technologies have enhanced the ability to assess and manage these systems in real time [3,4]. Hence, condition monitoring, such as the digital twin (DT) approach [5,6] for the water wall, is an important means to ensure the safety of the water wall. Existing online monitoring systems are mainly based on wall temperature [7], but evaluating the stress state of the water wall remains difficult.

Recently, General Electric introduced the Digital Power Plant for Steam [8], a suite of technologies designed to enhance efficiency and reduce emissions of coal-fired plants. By interpreting data from over 10 000 sensors, this system improves performance and increases efficiency by up to 1.5 percentage points. Such digital model solutions contribute to better monitoring and control of boiler components, including water walls. However, there is a lack of technical systems that can monitor the expansion displacement and local strain/stress of water walls online. In this article, we present a power plant of 1000 MW that has been in service for over 14 years. The fracture of the water wall has become a serious problem for safe operation (Fig. 1).

For the structural health monitoring of boiler water walls, we need to investigate mechanical properties such as strain/stress and expansion displacements of the water wall structure under different loading conditions. Knowing the values of the expansion and strain/stress will allow us to assess the water wall's state of health.

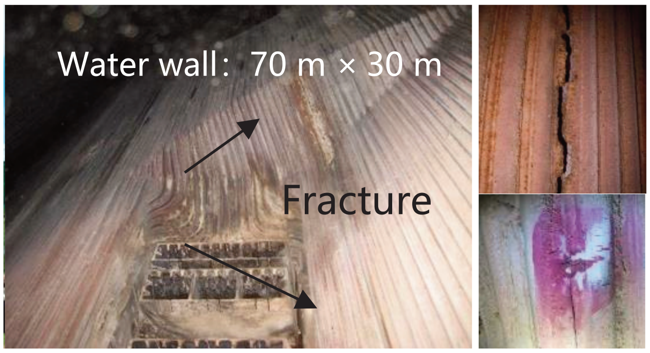

Fig. 1. Water wall with details of the fractures.

For this, we developed two systems for data acquisition: an online expansion monitoring system and an optical non-contact strain monitoring system. Based on these two systems, DT approaches are developed for smart monitoring of the expansion state of boiler water walls in coal-fired power plants.

2. Methodology

Laser-ranging technology is used to measure the expansion displacements of water walls online. A total of 40 laser sensors are installed at different positions on the water walls (Fig. 2). As shown in Fig. 3, the Internet of Things (IoT) technology is used to gather and transmit the data on expansion displacements. Firstly, the data of 40 laser sensors are gathered by 20 wireless gateways that have the data acquisition function. The time interval of data acquisition is set at 1 s. Then, the gathered data are transmitted via the 4G network to a database in the cloud. Finally, the data are analyzed on the monitoring platform to indicate the expansion state of water walls. A statistical analysis method is developed to perform the expansion state monitoring. The expansion data are analyzed using a statical value T^2, calculated as follows [9]:

$$T_t^2 = (x_t - \bar{x})\, S^{-1} (x_t - \bar{x})^T, \tag{1}$$

$$\bar{x} = \frac{1}{n} \sum_i x_i, \tag{2}$$

$$S = \frac{1}{n-1} \sum_i (x_i - \bar{x})^T (x - \bar{x}), \tag{3}$$

where $x_t = [x_{t-k-1}, x_{t-k-2}, \ldots, x_t]$ denotes the data vector of a sensor at time t that consists of k data points in a moving data window, x_i ($i = 1, \ldots, n$) are the n reference data vectors of this sensor. The T^2 statistic generally follows an F distribution, and thus its statical limit T_α at the significant level of α ($\alpha = 0.05$) is computed by [9]:

$$T_\alpha = \frac{k(n^2-1)}{n(n-k)} F_\alpha(k, n-k). \tag{4}$$

Based on the T^2 statistic, a decision is made regarding the anomaly warning and damage assessment. Once the computed T^2 value exceeds the statical limit T_α, i.e., $T_t^2 > T_\alpha$, the expansion state is considered to be abnormal. The out-of-limit T^2 values are accumulated to assess the damage degree at the location where the sensor is installed. The larger the accumulated T^2 value is, the higher the damage degree is. Figure 3b illustrates the algorithm for decision making regarding the anomaly and damage.

For strain evaluation, an optical non-contact monitoring system based on digital image correlation (DIC) technologies [10], coupled with the finite element analysis, was implemented (Fig. 4a). The design concept and installation of the strain monitoring system are described in Fig. 4b,c. The finite element model of the water wall structure is developed with the ANSYS software, which can compute the stress/strain field of the water wall in given conditions. A simple DT model was built to compute the stress using the expansion displacements measured by laser sensors and the strain measured by DIC. This DT model was validated by the simulation data of the finite element model. This combination of DIC and finite element analysis technologies allows us first to measure the actual strain/stress data and second to generate more simulation data for improving the accuracy of the DT model.

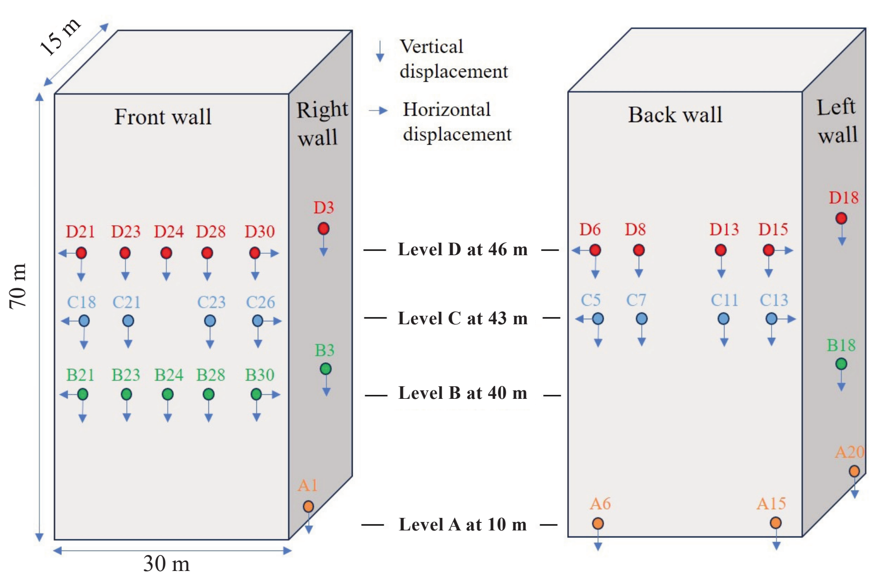

Fig. 2. Installation positions of laser sensors on the water wall.

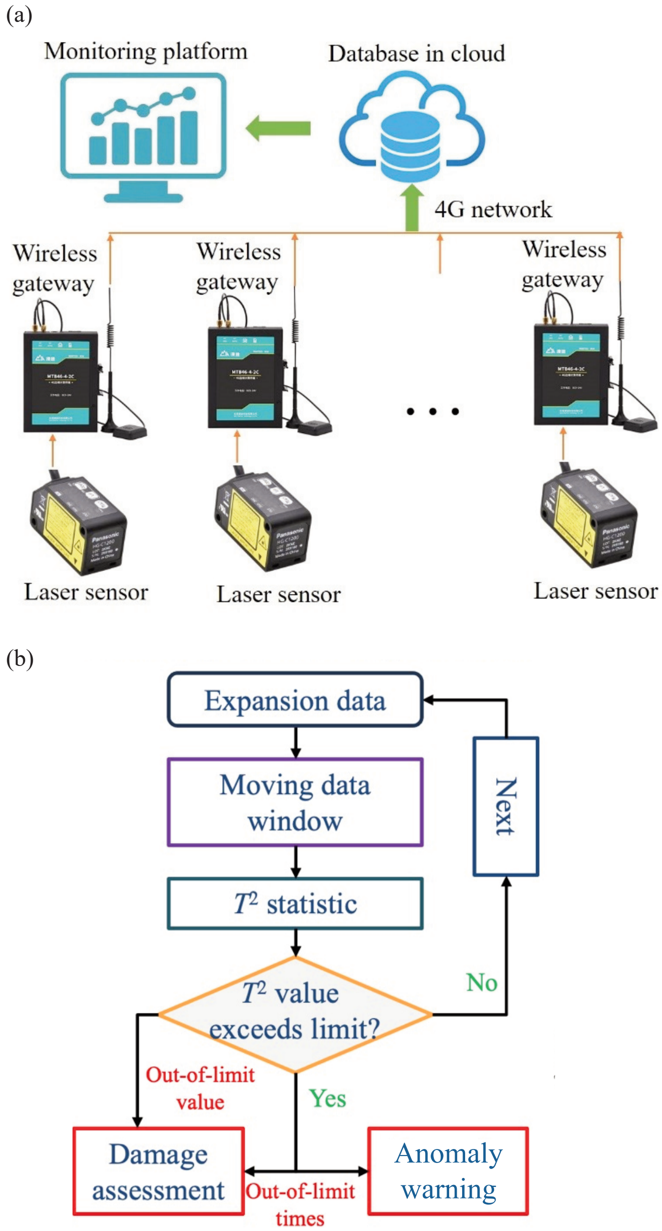

Fig. 3. Online expansion monitoring system: (a) IoT architecture for acquiring and transmitting expansion data, (b) algorithm for decision making regarding anomaly and damage.

This monitoring approach provides an effective way to prevent the expansion fracture of the water wall.

In the DT model, the stress caused by restricted thermal expansion is calculated as follows:

$$\sigma = E\frac{L - L^*}{L_0}, \tag{5}$$

where L^* is the theoretical thermal expansion displacement (mm), L is the actual expansion displacement (mm), and L_0 is the original length of the water wall pipe segment (mm). The local stress computed from the strain measured by DIC is

$$\sigma = E(\varepsilon - \varepsilon^*), \tag{6}$$

$$\varepsilon^* = \alpha(T_2 - T_1), \tag{7}$$

where σ is the stress (MPa), ε is the strain measured by DIC, ε^* is the strain due to thermal expansion, E is the elasticity modulus of the pipe material (MPa), α is the linear expansion

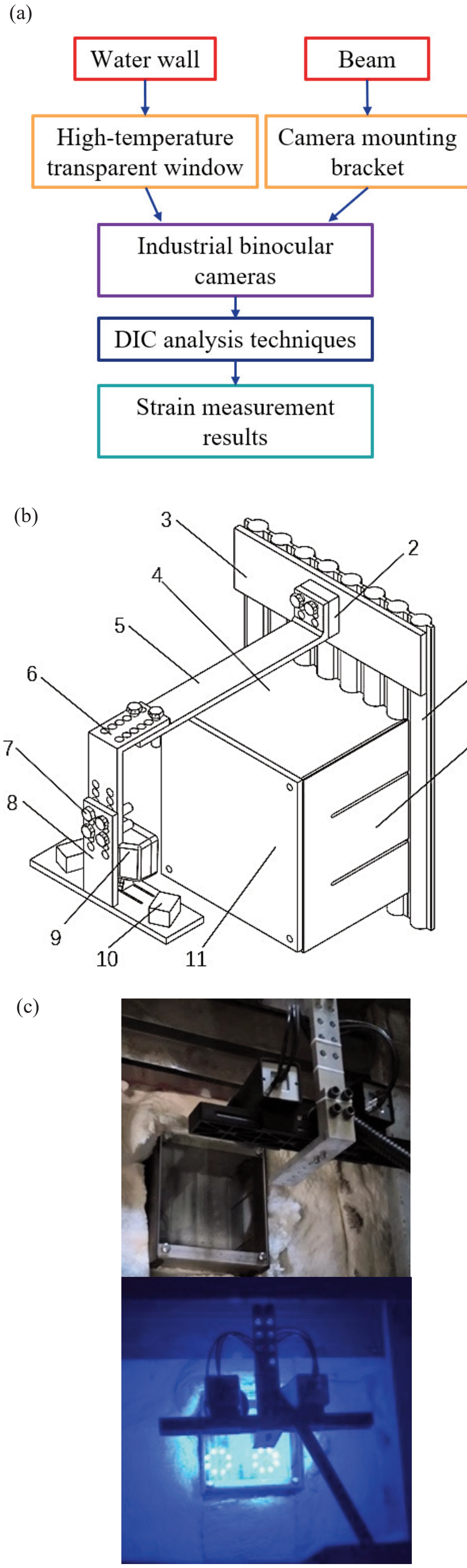

Fig. 4. Strain monitoring system: (a) algorithm, (b) computer-aided design (CAD) model of the system for DIC measurement, (c) implementation for the water wall. The notations in (b) are: 1 – water wall, 2 – welded fixed plate, 3 – steel frame, 4 – window bracket, 5 – horizontal bracket, 6 – vertical bracket, 7 – bolts, 8 – camera mount, 9 – blue light, 10 – binocular digital video camera, 11 – high temperature resistant glass window, 12 – window side panel.

coefficient of the pipe material (°C^{-1}), T_1 is the original wall temperature (°C), and T_2 is the current wall temperature (°C).

3. Results

As a result of the described methodology and correlation analysis, we observe that the expansion has a similar variation trend as the temperature and load (Fig. 5a–c). Based on the matrix representation, the correlation between the expansion, temperature, and load data is greater than 0.94 (Fig. 5d). This result demonstrates that it is feasible to monitor the state fluctuation of the water wall with the expansion displacement data.

Figure 5a,b shows that the temperatures and expansion displacements of the six measuring points all show a trend of first rising and then falling. The change trends of the measuring points located on the same perpendicular line are basically the same (e.g., D21, C18, and B21 have almost the same temperature change trends). However, there is a certain difference in temperatures at six measuring points, which may be caused by the uneven expansion of the water wall. The temperature of C21 at about 18:00 far exceeds the temperatures of other monitoring points, which causes the expansion displacement of this monitoring point to exceed the expansion displacements of other points (e.g., C18) on the same floor, resulting in the excessive local stress on layer C of the water wall.

Figure 6a,b shows the expansion monitoring results at the monitoring points D21 and D23. The T^2 values of the two monitoring points exceeded the corresponding control limits at multiple moments, indicating that the expansion anomaly occurred at these moments. Figure 6c shows the total number and the accumulated T^2 value of the out-of-limit expansion at the monitoring points on layers C and D. It can be observed that the number of out-of-limit expansions is higher at D21, B21, and B23, while the accumulated T^2 value of out-of-limit expansions is larger at D23. Considering that the accumulated T^2 value has a greater influence on the damage degree of the water wall than the total number of out-of-limit expansions, the damage degree at D23 is greater than that at other monitoring points.

Figure 7 shows the strain cloud images of the strain monitoring area at different times between 06:00 and 22:00. As indicated in Fig. 7, the overall strain in the monitored area shows a trend of increasing first (the strain contour changed from purple to green) and then decreasing (the strain contour changed from green to blue). At about 06:00, the strain in the whole monitoring area is relatively uniform, and there are only a few locations with high strain. Then, with the increase of wall temperature at 12:00, the degree of strain inhomogeneity in the monitoring area increases, and the area with high strain also increases. At about 22:00, even though the overall strain in the monitoring area falls back to a low level with the decrease in wall temperature, the degree of

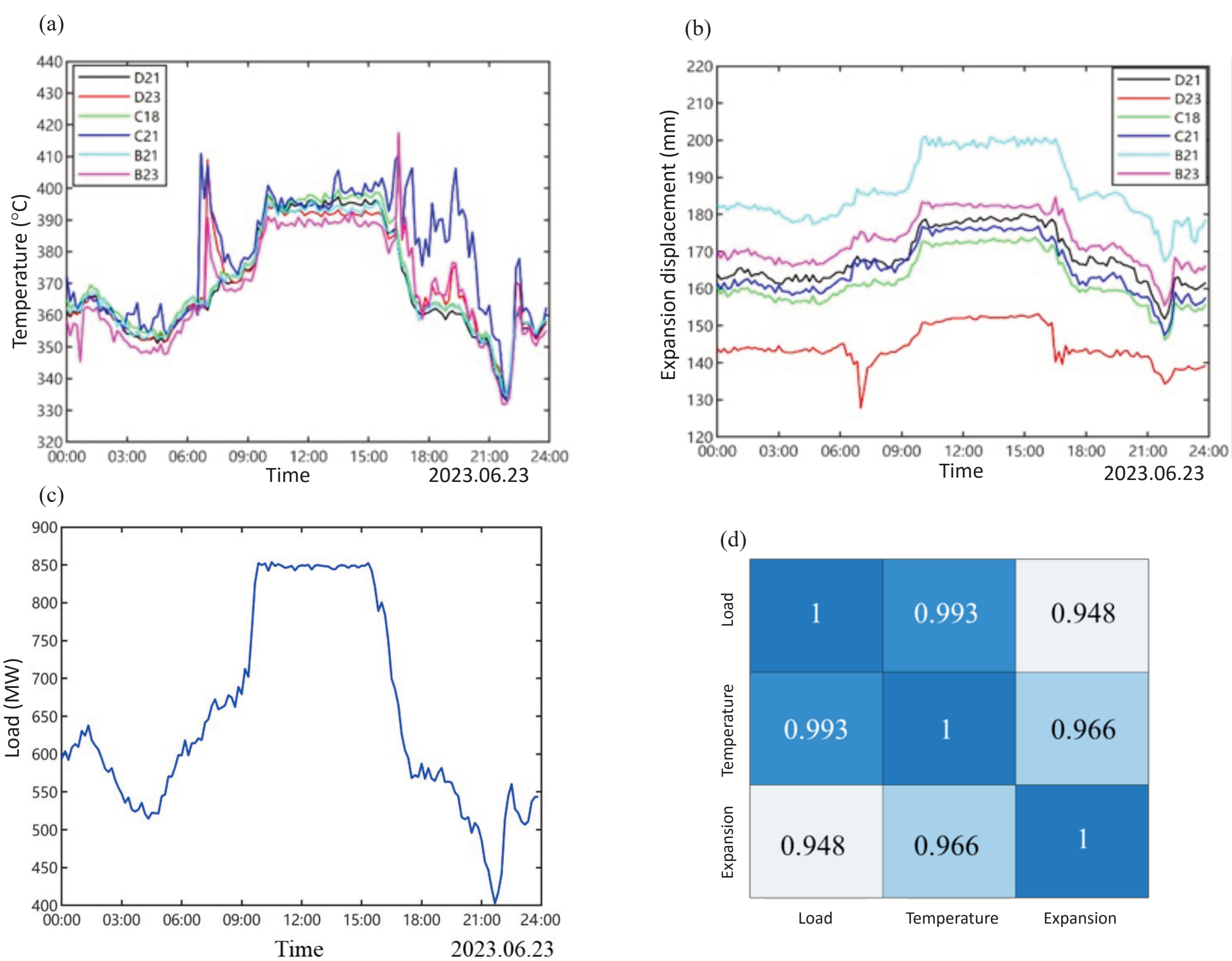

Fig. 5. Data of the water wall: (a) temperature, (b) expansion, (c) load, (d) correlation analysis.

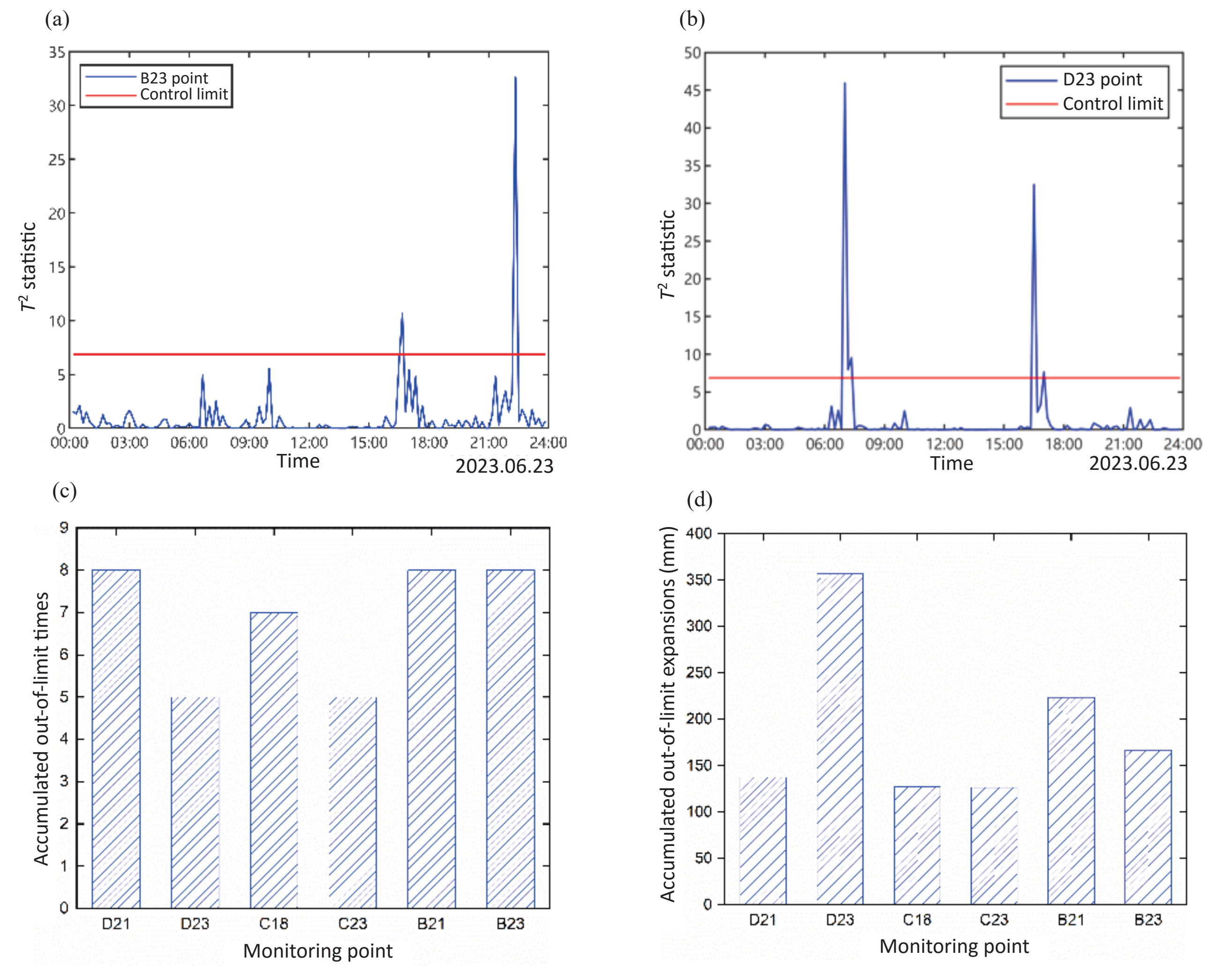

Fig. 6. Expansion monitoring results: (a) T^2 value at B23, (b) T^2 value at D23, (c) accumulated out-of-limit times, (d) accumulated out-of-limit expansions.

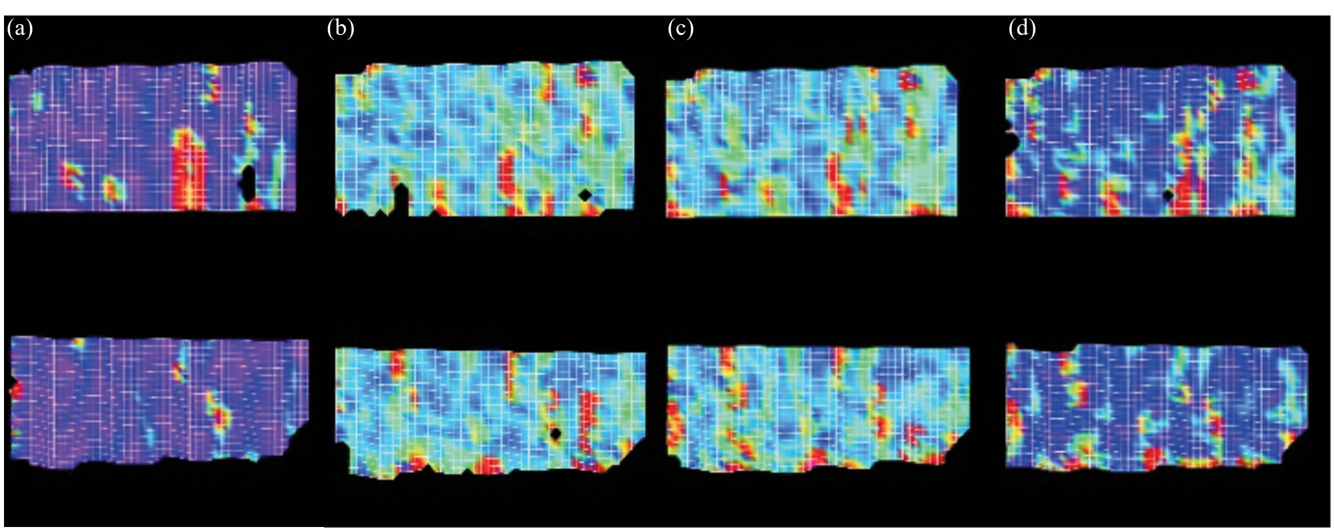

Fig. 7. Strain cloud images of the monitoring area at different times: (a) 06:00, (b) 12:00, (c) 17:00, (d) 22:00.

strain unevenness is still high, and the area of high strain is still larger. By comparing the strain contour diagram of the monitoring area with the water wall structure, we can infer that the high-strain area mainly appears at the fin as well as at the weld joint of the pipe and the fin. This is mainly due to stress concentration in these two regions. The stress area of the fin is much smaller than that of the pipe for the transverse load, and the temperature of the fin is generally higher than that of the pipe. Therefore, it is easy to create a high-strain region at the weld joint and the fin.

4. Conclusion

An online monitoring system was developed for the expansion displacements of boiler water walls, based on laser sensing and the Internet of Things technologies, which enabled the functions of real-time expansion measurement, abnormal expansion alarm, and expansion damage assessment. The monitoring system has the advantages of high scalability, good real-time performance, and high accuracy. An optical non-contact strain monitoring system was also developed for the water wall, based on binocular stereo vision and digital image correlation analysis technologies, which enabled the functions of dynamic strain/stress measurement and out-of-limit strain/stress warning. However, this strain monitoring system still has some shortcomings, such as the small monitoring range, slower dynamic response, and larger stress calculation errors (due to the use of a linear elastic material model). Future work may focus on the improvement of the strain monitoring system. Moreover, the digital twin model used for computing the stress of water walls is very simple. More complex and accurate digital twin models are required to improve the condition monitoring performance of boiler water walls.

Data availability statement

All research data are contained within the article and can be shared upon request from the authors.

Acknowledgment

The publication costs of this article were partially covered by the Estonian Academy of Sciences.

References

1. Davis, K. A., Linjewile, T. M., Valentine, J., Swensen, D., Shino, D., Letcavits, J. J. et al. A multi-point corrosion monitoring system applied in a 1,300 MW coal-fired boiler. *Anti-Corros. Methods Mater.*, 2004, **51**(5), 321–330. https://doi.org/10.1108/00035590410554883
2. Xiong, X., Liu, X., Tan, H. and Deng, S. Investigation on high temperature corrosion of water-cooled wall tubes at a 300MW boiler. *J. Energy Inst.*, 2020, **93**(1), 377–386. https://doi.org/10.1016/j.joei.2019.02.003
3. Li, P., Li, K., Zhou, Y., Li, Q., Shi, Z. and Zhong, W. An effective strategy for monitoring slagging location and severity on the waterwall surface in operation coal-fired boilers. *Energies*, 2023, **16**(24), 7925. https://doi.org/10.3390/en16247925
4. Salawu, E. Y., Akerekan, O. E., Afolalu, S. A., Kayode, J. F., Ongbali, S. O., Edun, B. M. et al. Condition monitoring and reliability assessment, an essential tool for boiler plant maintenance – a review. *E3S Web Conf.*, 2023, **430**, 01228. https://doi.org/10.1051/e3sconf/202343001228
5. Lin, M., Chen, G., Hu, B. and Bassir, D. Stability factor prediction of multilayer slope using three-dimensional convolutional neural network based on digital twin and prior knowledge data. *Environ. Earth Sci.*, 2024, **83**, 259. https://doi.org/10.1007/s12665-024-11562-w
6. Luo, W., Cai, S., Zeng, L., Chen, G. and Bassir, D. Cable force estimation method based on UAVs and EMD. *Int. J. Simul. Multidisci. Des. Optim.*, 2024, **15**, 14. https://doi.org/10.1051/smdo/2024012
7. Pang, L., Luo, Z., Zhang, K. and Song, J.-H. The development of the on-line monitoring system of the ultra-supercritical boiler heating surface's wall temperature. In *2012 Asia-Pacific Power and Energy Engineering Conference, Shanghai, China, 27–29 March 2012.* IEEE, 2012, 1–4. https://doi.org/10.1109/APPEEC.2012.6306903
8. General Electric. *GE introduces Digital Power Plant for Steam to enhance efficiency and reduce emissions of coal-fired plants*. https://www.ge.com/news/press-releases/ge-introduces-digital-power-plant-steam-enhance-efficiency-and-reduce-emissions-coal?utm_source (accessed 2025-01-15).
9. Mason, R. L. and Young, J. C. *Multivariate Statistical Process Control with Industrial Applications*. ASA/SIAM, Philadelphia, 2002. https://doi.org/10.1137/1.9780898718461
10. Bassir, D., Guessasma, S., Zheng, Y., Cai, Y. and Salzenstein, P. Composite characterization using digital image correlation (DIC) approach for stress-strain prediction. *AIP Conf. Proc.*, 2024, **3094**(1), 230003. https://doi.org/10.1063/5.0213202

Katlamaja veeseinte paisumise nutikas jälgimine söeküttel töötavates elektrijaamades digitaalsete kaksikute mudeli abil

Lijia Luo, Weida Wang, Zhenheng Lei, Shiyi Bao, David Bassir ja Gongfa Chen

Töös tutvustatakse metoodikat söeküttel töötavate elektrijaamade veeseinte paisumise oleku jälgimiseks digitaalsete kaksikute (DT) mudeli abil. Uuritav katel kuulub 1000 MW ultra-superkriitilise elektritootmisüksuse koosseisu ja on olnud kasutuses üle 14 aasta, töötades enam kui 100 000 töötundi. Veeseina pragunemine on muutunud tõsiseks probleemiks ohutu töö tagamisel. Kuna veesein on suur ja keeruka struktuuriga ning pingeseisundid muutuvad pidevalt, on pragude kõrvaldamine keeruline. Olemasolevad reaalaja jälgimissüsteemid põhinevad peamiselt seina temperatuuri andmetel, mistõttu on veeseina pingeseisundi hindamine komplitseeritud. Seni on olnud vähe tehnilisi süsteeme, mis suudaksid reaalajas jälgida veeseinte siiret ning lokaalset deformatsiooni ja pinget paisumise käigus. Katla veeseinte paisumise oleku modelleerimiseks on arendatud DT-mudel. Samuti on loodud optiline kontaktivaba deformatsiooni jälgimissüsteem, mis põhineb digitaalse pildikorrelatsiooni (DIC) tehnoloogial ning on ühendatud lõplike elementide analüüsiga, et mõõta tegelikke pinge-deformatsiooni seisundeid ja genereerida rohkem simulatsiooniandmeid DT-mudeli täpsuse parandamiseks. Väljatöötatud jälgimissüsteem pakub tõhusa lahenduse veeseina paisumispragude tekke ennetamiseks.