WEP Warwick Evans Publishing

International Journal of Mechanical and Electrical Engineering

ISSN: 3005-9615 (Print), ISSN: 3005-7132 (Online) | Volume 5, Number 2, Year 2025
DOI: https://doi.org/10.62051/ijmee.v5n2.08
Journal homepage: https://wepub.org/index.php/IJMEE/index

A Review on Boiler Modeling and Simulation Research for Supercritical Power Generation Units

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ABSTRACT

With the global energy structure undergoing a transition towards low-carbonization, supercritical coal-fired power generation technology, due to its high efficiency and low emission characteristics, has become one of the core paths for the clean-up transformation in the power generation sector. This paper mainly discusses and summarizes three types of methods for the mechanism modeling, data-driven modeling, and hybrid modeling of the DC boilers in supercritical power generation units. The hybrid modeling integrates the mechanism and data-driven methods, possessing both physical interpretability and data adaptability, and holds significant theoretical and application value.

KEYWORDS

Supercritical Power Generation Unit with Direct Current Boiler; Mechanism Modeling; Data-driven Modeling; Hybrid Modeling.

1. INTRODUCTION

Energy security is a comprehensive and strategic issue concerning the development of a country's economy and society. In the face of new changes in the energy supply and demand pattern and new trends in international energy development, ensuring national energy security requires promoting the revolution in energy production and consumption.[1] Although coal-fired energy is currently the dominant energy resource in China's power production, in the current situation of energy resource shortage, reducing pollutant emissions, strengthening environmental protection attributes, and utilizing comprehensive power generation technologies that are efficient, clean, energy-saving, and reliable are the main research directions at present.

As the global energy structure transitions towards low-carbonization, supercritical coal-fired power generation technology, due to its high efficiency and low emission characteristics, has become one of the core paths for the clean transformation of thermal power in the field. Considering the large scale and complex structure of supercritical units, conducting theoretical research on them is complex and difficult. Therefore, through mechanism analysis and process research, a reasonable mathematical model for boilers is established and studied.[2] However, in the pseudo-critical zone of supercritical boilers, the physical properties of the working medium undergo drastic changes, and the strong coupling characteristics of multiple physical fields such as combustion, heat transfer, and fluid dynamics lead to highly nonlinear and uncertain dynamic responses, which pose severe challenges to traditional mechanism modeling methods.

At present, supercritical units have strong demands for deep peak shaving and flexible application. These further highlight the importance of high-precision modeling and simulation. Mechanism models constructed based on traditional thermodynamic conservation laws have the advantage of clear physical meaning, but they are difficult to accurately depict the dynamic characteristics under variable load conditions. Data-driven models rely on a large amount of high-quality operating data and have limited generalization ability in complex conditions. In recent years, hybrid modeling methods that integrate mechanism and data-driven approaches, by embedding physical constraints or using reduced-order models to improve prediction efficiency, have gradually become a frontier direction for breaking through the bottleneck of supercritical system modeling.

2. STRUCTURAL CHARACTERISTICS OF SUPERCRITICAL DIRECT CURRENT BOILER

The characteristic of a direct current boiler is that water passes through the boiler once and completes the processes of heating, evaporation and superheating. The structure of a direct current boiler is relatively simple, with high thermal efficiency and fast startup speed. It is suitable for high-parameter and large-capacity power generating units. However, due to the absence of a drum, a direct current boiler has higher requirements for water quality and more complex control. As shown in Figure 1, it is a simplified schematic diagram of the structure of a supercritical direct current boiler.

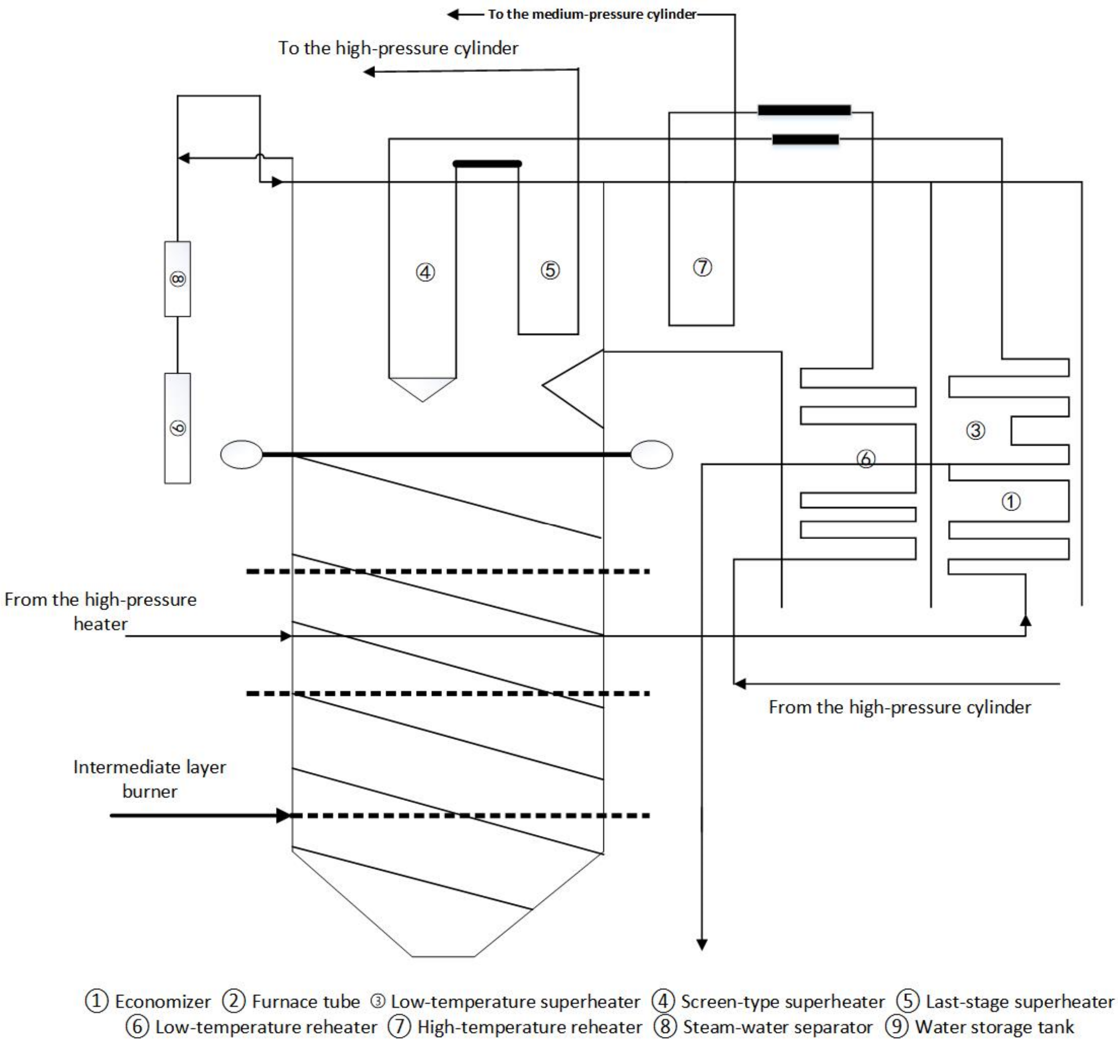

Figure 1. Simplified structural diagram of supercritical direct current boiler

The overall operation process of this direct current boiler: The feedwater first enters the economizer for preheating, then proceeds to the furnace, where it is heated and partially evaporated into steam under the high-temperature flame generated by the burner; the steam then passes through the low-temperature superheater, the screen superheater and the last-stage superheater successively, gradually increasing its temperature and pressure, forming high-temperature and high-pressure superheated steam; after doing work in the high-pressure cylinder of the steam turbine, the superheated steam is reheated again through the low-temperature reheater and the high-temperature reheater, and enters the intermediate-pressure cylinder and the low-pressure cylinder to continue doing work; the steam after doing work enters the condenser to condense into water, and is sent back to the economizer through the feed pump to complete the cycle. During this process, the steam-water separator and the water storage tank ensure the dryness of the steam and prevent moisture from entering the steam turbine. Through this efficient and continuous process, the direct current boiler converts water into high-temperature and high-pressure steam, driving the steam turbine to generate electricity.

3. BOILER MODELING METHOD

3.1. Mechanism Modeling Method

Mechanism modeling is a modeling method based on the fundamental laws of system physics, chemistry and thermodynamics. It quantitatively describes the intrinsic mechanism and dynamic behavior of the research object through mathematical equations. By using the laws of conservation of mass, energy and momentum, as well as constitutive relations, mathematical models with clear physical meanings are constructed. Currently, it has been widely applied in both pure scientific fields and practical engineering fields. With the advancement of science and technology, more and more scholars have published mechanism models with good performance.

The simulation model of the thermal system was established by Ray.R in the 1970s. Through linearization of the equations and estimation of the values of unknown parameters from the input-output operation records of the boiler, as well as the water and steam flow rates, including the forward and backward causal relationships, a dynamic mathematical model was established to improve the control system of the supercritical direct-flow boiler at that time.[3] RD Bell, KJ Astrom used the lumped parameter method in the modeling process and established a nonlinear dynamic model of the subcritical drum boiler.[4] This provided convenience for the establishment of a simplified nonlinear model of the supercritical direct-flow boiler later. De-Mello F.P. established a simplified model with a more concise representation of the nonlinear process characteristics by coordinating the pressure control and eliminating the errors in simulating the steady-state response of the boiler itself. A simplified boiler model with dynamic performance was established.[5] Based on this, Zeng Deliang et al. further improved the dynamic model of the boiler through statistical analysis of the parameter variation patterns and ranges of the dynamic model of a thermal power plant.[6] M.E. Flynn and M.J. O'Malley established the dynamic model of the unit in the event of an accident in the power system by evaluating the deviations of internal parameters such as steam pressure, drum water level, and steam temperature beyond the safety limits.[7]

Compared with traditional drum boilers, supercritical direct-flow boilers are more complex and challenging in terms of structure, operation, and control. Firstly, the direct-flow boilers do not have drum boilers, resulting in low thermal inertia, fast dynamic response, increased flow instability, and complete reliance on pump flow in the system, which increases the control difficulty. The lumped parameter model is suitable for qualitative simulation and training simulation, but it is insufficient in engineering analysis and quantitative research of control systems. Therefore, by increasing the number of segments of the model zone, a distributed parameter model is constructed to describe the dynamic characteristics of the thermal object more accurately.

Joao G.S, Fonseca Jr and Paulo S.Schneider modeled each component of the factory using the mass and energy balance equations and achieved the overall model of the thermal power plant through continuous substitution schemes.[8] Kau-Fui V.Wong simulated the boiler of a certain power plant in the boiler model, where the heat transfer in the combustion chamber was simulated using the area method, and the heat transfer in the secondary superheater, reheater, primary superheater and economizer was simulated using the lumped parameter method.[9] Liu Shuqing et al. established a simulation model of the supercritical direct-flow boiler evaporator, the combustion model of the furnace, the start-up separator model and the simulation model of superheated steam based on the specific characteristics of the "900MW boiler unit of Shanghai Waigaoqiao Power Plant". They analyzed the changes in the heat transfer coefficient of the evaporative heating surface, the influence of the structure of the burner on the flue gas temperature, the distribution scheme of radiant heat in the furnace, and the calculation methods of steam dryness and steam condensation in the economizer.[10] Yang Chen et al. followed the principle of module modeling and established dynamic mathematical models of the furnace, water-cooled wall, economizer, storage tank, and water level regulating valve of the storage tank based on the mathematical models of the working medium side, flue gas side and metal heat storage during the start-up process, providing a basis for the optimization design of the boiler start-up system and the operation personnel to master the start-up characteristics.[11] Wang Chao et al. divided the water-cooled wall into multiple modules, distinguished the uneven heat load along the height direction and the circumferential direction, and established a dynamic simulation model of the water-cooled wall area of a 660 MW supercritical boiler. They compared the response characteristics of the water-cooled wall under different boundary condition steps and investigated the water dynamics and wall temperature characteristics of the water-cooled wall during variable load processes.[12]

3.2. Data-driven Modeling

Data-driven modeling is a modeling method based on data rather than physical laws. It extracts features and patterns from system operation data to construct a mapping relationship between input and output. Its core idea is to utilize machine learning, statistics, and data mining technologies to discover hidden patterns from massive data, thereby achieving modeling and prediction for complex systems. In the modeling of supercritical boilers, data-driven methods have gradually become an important supplement to mechanistic modeling due to their strong adaptability to nonlinear and uncertain systems.

Kalogirou proposed the feasibility of using artificial neural network algorithms in the modeling of various subsystems of energy systems.[13] Dong Yan et al. based on the linear or nonlinear relationship between the outlet temperature of the decomposition furnace and its influencing factors, proposed a method based on wavelet extreme learning machine, and achieved modeling of the decomposition furnace temperature of the cement kiln by training and testing on a large amount of existing data.[14] Wei Liang analyzed the characteristics of power station operation data and the prediction of reheated steam temperature of the boiler in the power station as the research object, proposed the PLS-LSSVM modeling method, and used partial least squares (PLS) to extract feature vectors and least squares support vector machine (LSSVM) to improve the prediction accuracy of the model.[15] Ogilvie and Hogg established a power plant model under all working conditions based on the performance monitoring data of data mining.[16] Zhang Xiaotao et al. analyzed the dynamic modeling of thermal objects based on the identifiableness of on-site data, selected dynamic data of the unit load during variable working conditions for data modeling.[17] Yuan Shitong et al. analyzed the characteristics of the combustion system of ultra-supercritical boilers, mined the operating data of the unit, summarized the experience of data selection and data preprocessing methods, and used swarm intelligence optimization algorithms to identify transfer function parameters, thereby obtaining the linear transfer function model of the combustion system.[18] Fu Zhongguang et al. used a large amount of on-site operation data collected from Unit 1 of Huaneng Fuzhou Power Plant, selected the partial least squares algorithm, and attempted to establish a mathematical model of a local system using the reverse modeling idea.[19]

3.3. Hybrid Modeling

Hybrid modeling integrates the advantages of mechanistic models and data-driven models to construct a composite model that combines physical interpretability and data adaptability. Its core idea is to base on the mechanistic framework and use data-driven methods to compensate for unmodeled dynamics or uncertainties, thereby reducing data requirements while improving model accuracy and generalization ability. In the modeling of supercritical boilers, hybrid modeling is considered an effective approach to solve complex nonlinear and multi-physics field coupling problems.

Henryk Rusinowski et al. described a boiler hybrid model developed by applying analysis modeling and artificial intelligence. For large-scale energy boilers, the indirect method is usually used to determine energy efficiency. Flue gas losses and unburned combustible losses have a significant impact on the efficiency of the boiler.[20] Zeng Deliang et al. aimed to understand the operating characteristics of the pulverizing system and improve the accuracy of system output control, as well as reduce the fluctuation amplitude of main operating parameters of coal-fired units. They used genetic algorithms for parameter identification and established a nonlinear dynamic model of the direct-fired pulverizing system.[21] Cao Xia established a neural network model based on the mechanism model and obtained the hybrid model through weighted fusion of the two models. In the neural network model, immune clustering was used to determine the optimal center position of the RBF neural network hidden layer, and the particle swarm algorithm was used to optimize the neural network weights, thereby improving the accuracy of the model.[22] Li Bingnan et al. proposed a discrete-continuous modeling method and applied it to the model predictive control algorithm. By combining discrete models to obtain the overall model of the unit, the superiority of the improved algorithm in the coordinated control of the unit system was improved.[23] Jia Zuozi et al. established a supercritical thermal power unit model through the combination of mechanism and data, and carried out parameter identification and verification based on actual operating data to verify the accuracy of the model, laying the foundation for the subsequent control system optimization of thermal power units.[24] Li Maoyuan established a mathematical model of the boiler through mechanism analysis and studied it using on-site data and neural networks for self-correction. The established model was used for dynamic characteristic research and analysis of the boiler system.[25] Zhang Ning used on-site data to verify the model and adopted the integrated modeling idea of combining the mechanism model and neural network model to study the dynamic characteristics of the boiler system.[26] Qin Zhiming proposed a soft measurement method based on sparse kernel partial least squares and used it for soft measurement of the thermal state parameters of the working medium based on the inherent characteristics of water and water vapor within a certain range. This method was applied to the mechanism modeling of the direct-fired boiler, establishing the dynamic models of the evaporation heating surface and superheater of the direct-fired boiler.[27]

4. SUMMARY

In conclusion, actual thermal processes often exhibit high uncertainty, external disturbances, and nonlinear characteristics, making it difficult to directly apply mechanistic models. Moreover, mechanistic models are usually based on simplified assumptions and ideal conditions, and their theoretical analysis is insufficient, making it impossible to fully reflect the complexity of real industrial systems. As a result, there is a deviation between the models and actual production. Although data-driven modeling methods have effectively reduced the complexity of mechanistic modeling and the workload of modeling calculations, they require a large amount of data and information. The high-temperature and high-pressure environment of supercritical boilers leads to high data acquisition costs. Other environmental variables and data preprocessing factors also need to be considered. Additionally, data-driven models perform well within the data training range but may lose effectiveness or even fail when new operating conditions arise. Based on these two approaches, hybrid modeling, as a combination of the two, can reveal the intrinsic dynamic characteristics of the system through physical mechanisms and dynamically respond to external disturbances through the data-driven module. At the same time, it can deeply explore the potential value of historical data. It shows broad prospects in both theoretical research and industrial applications.

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