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Study on Dynamic Characteristics and Energy Consumption Characteristics of Ultra-supercritical Units Operating at Wide-Load

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With the increasing integration of renewable energy generation into the power grid, coal-fired power plants are compelled to engage in deep load regulation. The dynamic characteristics and energy consumption of coal-fired units operating at ultra-low loads have emerged as significant concerns. In this study, a dynamic simulation model for the wide-load operation of a 1,000 MW ultra-supercritical coal-fired unit was established using GSE software. The model can simulate the operational process of the unit within the load range of 150-1,000 MW. This study initially analyses the dynamic characteristics of the unit load-up process, taking the intervals of 150-320 MW and 830-1,000 MW as examples. Subsequently, a comparative analysis is conducted on the energy consumption levels under different intervals and load-up rates. The results indicate that during the load-up process, 260 MW is the turning point at which the water wall operation state transitions from wet to dry. Under a load-up rate of 5 MW/min, as the load interval gradually increases, the total coal supply during the load-up process increases from 66.08 t to 195.83 t. Within the range of 830-1,000 MW, when the load-up rate rises from 5 MW/min to 15 MW/min, the total coal supply throughout this process decreases from 195.83 t to 67.86 t. This established model holds significance for optimizing energy consumption levels during wide-load operation processes of units by providing insights into their dynamic behaviour under varying loads.

1. Introduction

The global climate is facing major challenges due to the massive emission of greenhouse gases (Jia et al., 2022). Renewable energy power plants have emerged as a promising green energy source, offering potential solutions to global climate challenges (Mustafa et al., 2024). However, the inherent uncertainty in their output due to climate factors such as rainfall, wind speed, and sunlight poses significant obstacles to seamless integration into the grid (Fan et al., 2022). Since coal-fired generating units occupy a large proportion of the current energy mix (Abdul Manaf Norhuda and Abbas Ali, 2021), enhancing flexibility in coal-fired power units presents an effective approach towards integrating renewable energy sources into the grid seamlessly (Wang et al., 2020). It becomes imperative to thoroughly comprehend the operational characteristics and energy consumption characteristics exhibited by coal-fired power units across a wide-load range.

The investigation of the dynamic characteristics of coal-fired power units is crucial. Due to the high cost associated with on-site experiments, modeling and simulation have emerged as effective approaches for studying these dynamic properties (Alobaid et al., 2017). Numerous scholars have conducted modeling analyses to better understand this complex system. Liu et al. (2023) utilized the Dymola software to construct a comprehensive dynamic model of a supercritical coal-fired boiler, and developed necessary control models to analyze the dynamic characteristics under single-parameter and dual-parameter disturbances. However, the models proposed by Liu et al. (2023) solely focused on the dynamic characteristics of the boiler section, neglecting to establish a dynamic model for the turbine section.

For the modeling and analysis of the whole power plant, many scholars have also carried out a lot of research. Hou et al. (2021) applied a novel fuzzy neural network structure to the system modeling of a 1,000 MW ultra-

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supercritical coal-fired unit, specifically for analyzing its dynamic characteristics. The proposed approach demonstrates high accuracy. However, the simulation study in this paper only focuses on intervals above 50 % THA (Turbine Heat-acceptance) and does not investigate the dynamic characteristics of the unit in low-load conditions. Niu et al. (2019) developed a dynamic model for coal-fired once-through boiler-turbine unit. This model has a simple structure and demonstrates good accuracy, making it suitable for designing and implementing advanced control algorithms. However, this model only considers the operation of units at low-load conditions.

In current research on modeling coal-fired units, many scholars' models lack comprehensive consideration of the wide-load range operation of ultra-supercritical units, which encompasses ultra-low load to full load conditions. These models can only be separately applied for either low or high loads. It is crucial to adequately account for the distinct operational states of ultra-supercritical units, wet state with water wall at ultra-low load and dry state at high load. This study presents a dynamic simulation model for the wide-load operation of a 1,000 MW ultra-supercritical unit using GSE software. The simulation encompasses the load range from 150 MW to 1,000 MW, allowing for a comprehensive analysis of the unit's dynamic characteristics during low-load dry-wet transition and high-load operation. The main contributions of this paper are as follows:

- The unified dynamic model of the ultra-supercritical unit from ultra-low load to rated load is established.
- Based on the model, the dynamic characteristics and energy consumption characteristics of the unit under different load intervals and load-up rates are analyzed.
- The obtained simulation results lay a foundation for the unit to formulate an efficient and intelligent operation strategy, facilitating further enhancements in energy efficiency within the wide-load operating range of the similar unit.

2. Modelling

Accurate dynamic model is the basis of thermodynamic system analysis. In this section, a dynamic simulation model of a 1,000 MW ultra-supercritical unit is established using GSE software.

2.1 Dynamic model of the unit

This study focuses on the modeling and research of a typical 1,000 MW ultra-supercritical unit. The thermal system model primarily encompasses the boiler subsystem and the turbine subsystem. Regarding the water-steam flow direction, the modeling of the boiler subsystem includes various components such as economizer, water wall, separator, boiler circulation pump, low-temperature superheater, screen-type superheater, high-temperature superheater, low-temperature reheat system, and high-temperature reheat system.

The turbine system comprises a high-pressure (HP) cylinder, an intermediate-pressure (IP) cylinder, and low-pressure (LP) cylinders along with a condensing system. Additionally, this unit incorporates eight levels of reheating extraction heaters consisting of three high-pressure heaters, four low-pressure heaters, and one deaerator. The model also accounts for auxiliary systems like air preheaters.

Table 1 presents key parameters in the BMCR (Boiler Maximum Continuous Rating) conditions, and Table 2 provides information regarding the coal used in the model.

Table 1: Key parameters at BMCR condition.

Main thermal parameters	Value	Main thermal parameters	Value
Live steam flow rate	3,033 t/h	Reheater Inlet steam pressure	5.1 MPa
Superheater outlet steam pressure	26.25 MPa	Reheater outlet steam pressure	4.9 MPa
Superheater outlet steam temperature	605.0 °C	Reheater inlet steam temperature	354.2 °C
Reheat steam flow rate	2,469.7 t/h	Reheater outlet steam temperature	603.0 °C

Table 2: Coal information

$Q_{ar,net}$ (kJ/kg)	M_{war} (%)	V_{daf} (%)	C_{ar} (%)	H_{ar} (%)	O_{ar} (%)	N_{ar} (%)	A_{ar} (%)	S_{ar} (%)
20220	5.5	31.38	52.67	3.22	8.43	0.75	28.19	1.34

In this study, the GSE software was utilized to model the reference case. The GSE software is a widely employed simulation tool in the coal-fired power plants for modeling purposes (Zhang et al., 2014). Its two-phase calculations are based on a six-equation model, wherein separate mass, momentum, and energy conservation equations are established for gas and liquid phases. This facilitates convenient simulation research on dynamic characteristics of two-phase flow and heat transfer processes. The key components within the software encompass nodes, streamlines, slabs, valves, water tanks, and pumps. By combining these components according to the thermal system's configuration and equipment sequence, a comprehensive thermal system can be constructed (Wang et al., 2017). The thermal system of a power plant developed using GSE software is shown in Figure 1. In this model, nodes represent real power plant pipes, slabs represent metal walls, flow lines describe the flow direction and velocity, and cylinders represent the steam turbines.

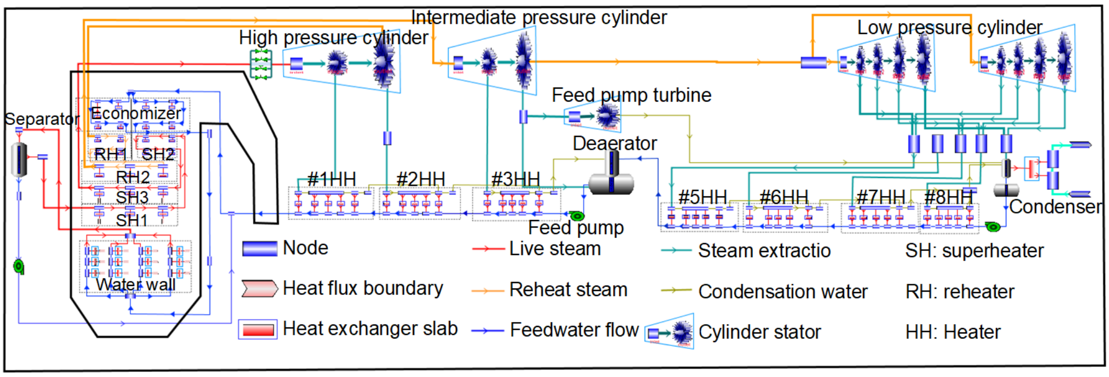

Figure 1: Dynamic simulation model on GSE

2.2 Model verification

In order to validate the steady-state performance, a comparison was made between the simulation results and the design values under steady-state conditions at 100 % THA, 70 % THA, 50 % THA, and 40 % THA. The relative errors are presented in Figure 2a. The findings indicate that the simulation results align with the design values for various operating conditions. This adherence to ISA-77.20.01-2012 standard requirements underscore the reliability of the simulation model established in this research study.
In order to validate the simulation model dynamically, historical operational data from a specific period were selected for a 1,000 MW unit. Figure 2b presents the comparison results between the simulated and measured power output, demonstrating a strong agreement between the two sets of values. Consequently, it can be concluded that the established model accurately represents the dynamic process.

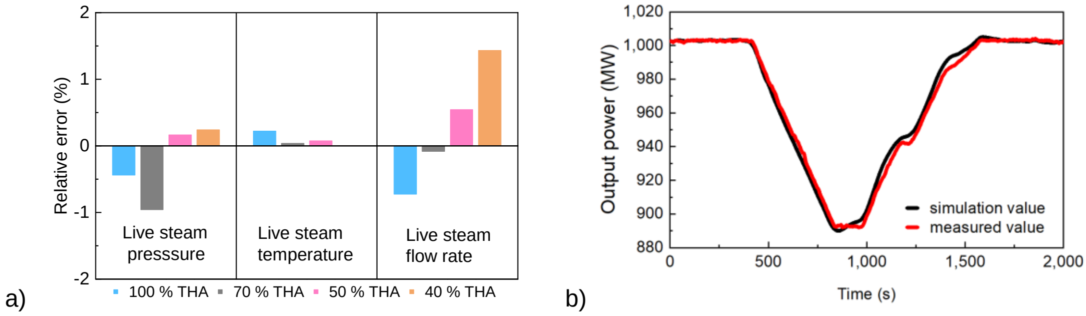

Figure 2: a) Relative error between simulation and set point. b) Validation of the established model during the variable load process

3. Results and Discussion

This section simulated five load-up intervals: 150-320 MW, 320-490 MW, 490-660 MW, 660-830 MW, and 830-1,000 MW. The ramp-up rates for load were set at 5, 10, and 15 MW/min. Firstly, this section analyzed the dynamic characteristics of load-up processes within the interval of 150-320 MW and 830-1,000 MW, and then the energy consumption characteristics in different load intervals and at different load-up rates are compared.

3.1 Dynamic characteristic

Dynamic characteristics of main operating parameters of the unit

The dynamic characteristics of the live steam pressure variation during the load-up process are illustrated in Figure 3a, while the maximum deviation between simulation values and set values is presented in Figure 3b. Within the range of 830-1,000 MW, the unit operates under sliding pressure mode, with a gradual increase in live steam pressure from 21.66 MPa to 25 MPa. In the range of 150-320 MW, the unit operates under constant pressure mode, maintaining a steady pressure of 9.1 MPa. During the load-up process, with the increase of load-up rate, there is an observable amplification in the maximum deviation of live steam pressure. Compared with the research of other scholars, such as Huang and Sheng (2020), they established a dynamic model of a 1,000 MW ultra-supercritical unit using a data-driven approach, but only operated in the high-load range. This study complements the low-load operation of the unit.

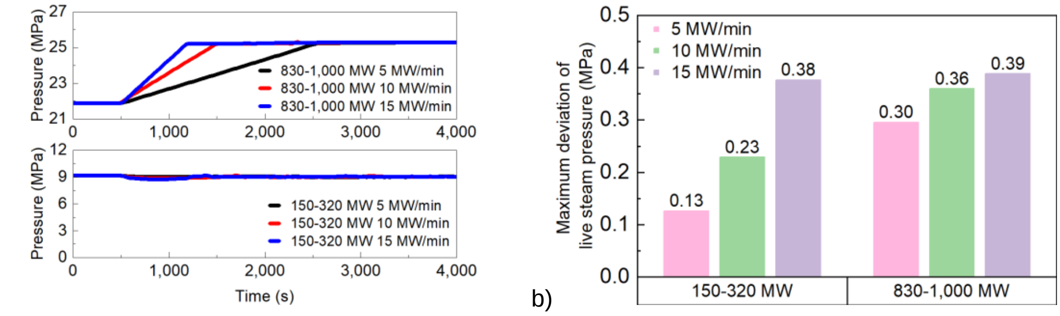

Figure 3: a) Dynamic characteristics of the live steam pressure during the load-up process. b) Maximum deviation of the live steam pressure of the load-up process

Dynamic characteristics of boiler water wall in ultra-low load operation

The dynamic characteristics of the mass flow rate at the outlet of the water wall and the boiler feedwater flow rate during the load-up process from 150 MW to 320 MW are shown in Figure 4. In order to reduce the instability of flow in the water wall and maintain the water wall temperature below the maximum allowable value, it is necessary to ensure that the flow rate in boiler water wall tubes does not fall below the minimum value. When operating at a load of 150 MW, this unit operates with a minimum water wall flow rate, resulting in steam generated by the water wall being less than the minimum allowed flow rate. The excess saturated water from the water wall is either recirculated or discharged through control systems. At this time, the steam flow rate at the outlet of the water wall is approximately 146 kg/s, the water flow rate is approximately 67 kg/s, and the boiler feedwater flowrate remains near its minimum value around 213 kg/s throughout.

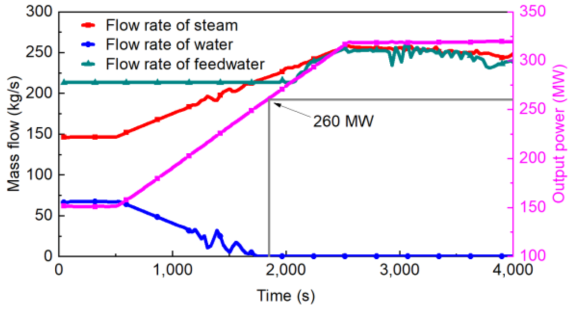

Figure 4: Water wall outlet flow and boiler feed water flow

During the process of load variation, the output power of the unit gradually increases. There is a gradual increase in the steam flow rate at the outlet of the water wall while the water flow rate decreases. At approximately 260 MW, the water flow rate reaches zero. This signifies a transition from wet operation to dry operation for the water wall as steam generation by the boiler exceeds its minimum required water flow rate.

3.2 Energy consumption characteristics

Variation characteristics of coal supply during the load-up process

The dynamic characteristics of coal supply during the load-up process in the range of 150-320 MW and 830-1,000 MW are shown in Figure 5a and Figure 5b. It can be observed from the figures that within the range of 150-320 MW, the coal supply rate initially increases rapidly and then gradually decreases with significant fluctuations. In contrast, within the range of 830-1,000 MW, the variation in coal supply rate follows a slow and steady increase along with the load. The main reason for this phenomenon is that within the range of 150-320 MW, there is a need for rapid coal supply due to wet-dry transition occurring in the water wall. Additionally, during this process, there are certain fluctuations in hydraulic conditions of the water wall which contribute to large variations in coal supply rate. On the other hand, within the range of 830-1,000 MW, hydraulic conditions remain stable for the water wall resulting in no drastic fluctuations in coal feeding rate as it gradually increases following load changes. In the study of Huang and Sheng (2020) and Niu et al. (2019), the energy consumption characteristics of the unit were not clearly given in the results, which is supplemented in this study.

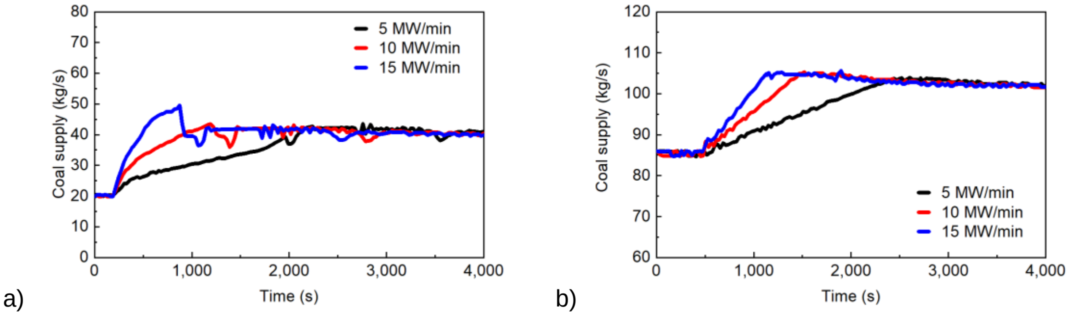

Figure 5: a) Dynamic characteristics of coal supply during the load-up process in 150-310 MW range. b) Dynamic characteristics of coal supply during the load-up process in 830-1,000 MW range

Effect of load intervals on energy consumption during load-up process

The total coal supply and average coal consumption rate during the load-up process at different intervals are depicted in Figure 6. It is evident from the graph that as the load interval increases, there is a gradual rise in the total coal supply during the load-up process, ranging from 66 t to 196 t, exhibiting a linear trend. This can be primarily attributed to higher power generation by units throughout the load-up process in high-load intervals, necessitating greater energy consumption. The average coal consumption decreases with increasing load interval, declining from 491.24 g/kWh in the 150-320 MW interval to 373.62 g/kWh in the 830-1,000 MW interval, with a diminishing reduction magnitude. This decrease can be mainly attributed to improved efficiency of units operating within high-load intervals.

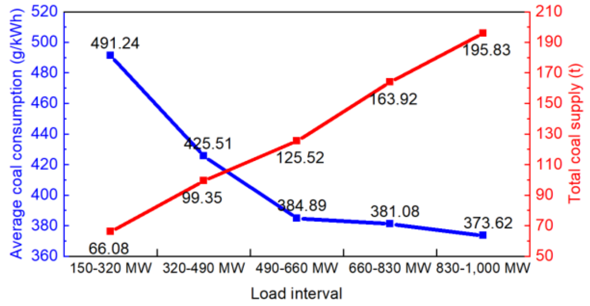

Figure 6: Energy consumption characteristics in different load intervals at 5 MW/min load-up rate

Effect of load-up rates on energy consumption in load-up process

The total coal supply and average coal consumption rate during the load-up process within the interval of 830-1,000 MW are depicted in Figure 7. It is evident that, within this interval, as the load-up rates increase from 5 MW/min to 10 MW/min and subsequently to 15 MW/min, the total coal consumption gradually decreases with values of 195.83 t, 99.5 t, and 67.86 t. This trend can be attributed to the fact that a faster load-up rate leads to a shorter duration for power generation by the unit, resulting in reduced overall coal supply.

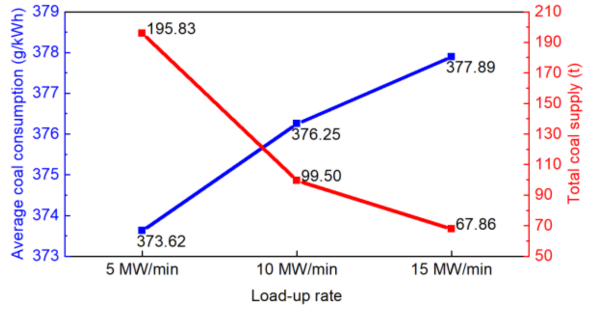

Figure 7: Energy consumption characteristics under different load-up rates in the 830-1,000 MW interval

During the entire process, the average coal consumption rate gradually increases with the increase of load-up rates. The average coal consumption rates for load-up rates of 5 MW/min, 10 MW/min, and 15 MW/min are recorded as 373.62 g/kWh, 376.25 g/kWh, and 377.89 g/kWh. This phenomenon can primarily be attributed to the thermal storage effect in the heat system and adjustments in the control system during rapid load-up process of the unit, resulting in real-time coal supply deviating from steady-state design values. As a result, overall system efficiency decreases and average coal consumption increases.

4. Conclusions

This study focuses on a 1,000 MW ultra-supercritical unit and utilizes GSE software to establish a wide-load operation model for the unit. The dynamic characteristics of thermal parameters and the energy consumption under different load-up rates within the interval of 150-1,000 MW are investigated. A comparison is made between different intervals and load-up rates in terms of energy consumption characteristics. The main findings are as follows:

- With the increase of the load-up rate, the maximum deviation of the live steam pressure gradually increases.
- During the load-up process within the range of 150-320 MW, the water wall undergoes a transition from wet operation to dry operation, which is completed at approximately 260 MW.
- In the range of 830-1,000 MW, as the load-up rate increases during the load-up process, there is a gradual decrease in total coal supply from 195.83 t at a rate of 5 MW/min to 67.86 t at a rate of 15 MW/min. With the increase in load-up rate, there is an observed gradual increase in average coal consumption during the load-up process from 373.62 g/kWh at a rate of 5 MW/min to 377.89 g/kWh at a rate of 15 MW/min.
- In the case of the same load-up rate, a higher load interval leads to increased total coal supply and decreased average coal consumption. Specifically, under a load-up rate of 5 MW/min, as the load range gradually increases, the overall amount of coal supply during the entire load-up process increases from 66 t to 196 t. And the average coal consumption decreased from 491.24 g/kWh to 373.62 g/kWh.

In the present study, the effect of perturbations in actual operation on the results was not considered. This effect will be improved in the future work. In addition, the present model and results will be used to develop efficient and intelligent operation strategy of the unit, which is the final aim of the whole study.

Acknowledgments

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