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Research Paper

Start-Up and dynamic processes simulation of supercritical once-through boiler

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HIGHLIGHTS

- Detailed component model of supercritical once-through boiler start-up system is established.
- Six-equation solution of two-phase flow is employed in developing the model of evaporator.
- Validated against design data of steady state showing a very good agreement.
- Dynamic simulations of two different cold start-up processes are conducted and validated.

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ABSTRACT

The rapid expansion of the electricity demand causes the gap between the peak load and valley load increasing in China. Since the coal-fired supercritical power plant needs to be started up frequently, the operations of power plant become more flexible. During the start-up process, the operation parameters are off-designed, the multi-transient phenomenon is inevitable and the intensive emission always appears during varying working condition, it is difficult to ensure the operator of the real power plant to start up the boiler following the design curve. In this work, a new dynamic model for simulating start-up dynamic process of a 600 MW supercritical boiler is introduced in this paper. The six-equation solution of two-phase flow was applied to modeling the evaporator, and the process from ignition to the load at 30% Boiler Maximum Continuous Rating (BMCR) was simulated. The results demonstrate that the model is reasonable and dynamic behavior can be observed clearly. Also, these prove that the control strategy is advisable. Moreover, the fuel consumption of the start-up process can offer a reference to operator of the real power plant. The validated model is of high relevance for further optimizing the boiler start-up process.

1. Introduction

In recent years, the demand for electricity has increased rapidly due to the fast development of China's economy [1]. And the energy resource structure of China determines that more than 65% of the electric energy production depends on the fossil fired plants [2]. The traditional power plants, burning fossil fuel, contribute significantly to exhausting emission that leads to greenhouse effect. In order to solve the problems of large energy consumption and serious pollution emission, the development of the high steam parameter and large capacity units is the inevitable current [3,4]. Therefore, the evolution of supercritical unit and ultra-supercritical unit becomes an important solution. The characterizations of these plants need to be well understood.

In China, the electric demand difference between peak load and valley load is more than 30% [5]. Power plants, which are frequently operated, are expected to operate flexibly. Since nuclear power plants generally run with base-load and the share of the hydroelectric power plants is smaller than fossil-fired power plants, fossil-fired power plants have to start up frequently. For start-up process, since the operation parameters are off-designed, the multi-transient phenomenon is quite complex and the intensive emission always appears during varying working condition, it is essential to ensure the dynamic parameter of the boiler to follow the design curves [6–8]. Moreover, the working state of the separator have to complete dry and wet states transition process smoothly, the control strategy of the start-up system is critical. This brings a big challenge to the start-up operation and the

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operators of the power plant. To avoid shortening the service life of the unit, the operating characteristics of the start-up process have to be well known. However, due to the potential risk, it is very costly and severe to do experiments on a commercial fossil-fired plant. Mathematical simulation becomes a useful tool in research. Several researches have dealt with one of the important components of the boiler system. Such as vertical water wall in ultra-supercritical boiler system [9], evaporation system in ultra-supercritical supercritical boiler system [10,11] and water wall in supercritical boiler system [12].

Recently, some studies about supercritical once-through unit modeling were published. Alobaid et al. [13] modeled a supercritical once-through boiler system, which included a heat recovery generator. The system model was developed in a commercial simulation software named Advanced Process Simulation software (APROS). The model was validated with the design parameter for the full load and several part load conditions.

A Drum Boiler Start-up Simulation Program (DBSSP) was written by Li et al. [14] to simulate the start-up process of the fossil-fired power plant. The program developed by Fortran language with a modular structure was capable of modeling the process from ignition to 35% Boiler Maximum Continuous Rating (BMCR).

A complete system model of the subcritical power plant was illustrated by Starkloff et al. [15]. To validate the model, two kinds of steady state simulations (100% load and 105% load) were performed in the paper. Then, the dynamic characteristic has been investigated in the load range from 27.5% to 100%. Oko et al. [16] established a large model of the 500 MW subcritical coal-fired power plant by the simulation tool gPROMS. And the steady state validation at 100% load proved that the relation errors between simulating results and measuring values were less than 5%. Then, some dynamic validation showed that the model could predict the performance of the power plant between 100% and 70% load properly.

Schuhbauer et al. [17] have developed a coupling model of the 700 °C boiler. The steam/water side was simulated by a modular modeling software. The combustion section was calculated in a three-dimensional computational fluid dynamic software. The validation of the system model for the full load was carried out through comparing the simulation results of the heat flow in all heat exchangers with the thermodynamic design values. Then, ranging from 20% to 80% load, the effect of the tilting burner angle on the temperature of the reheated steam was studied by the dynamic simulation of the coupled model.

Liu et al. [18] have established a supercritical once-through boiler model which can be used for the design of overall system control strategy. The model validation between 50% load and 100% load proved that the model was accurate and the dynamic simulation illustrated that the responses of the model were in complete agreement with the actual unit.

Both steady state validation and dynamic validation were performed in these researches. However, the low load simulation of the supercritical once-through boiler was not involved. To ensure the power plant start steadily and provide a referenced fuel curve for the operator, it is significant to investigate the start-up process simulations based on 600 MW supercritical once-through boilers, which is manufactured by Dongfang boiler company. The start-up system includes the separator, the storage tank, and the water lever control valve. The start-up system, running from 0% load to 30% load, is controlled by both water lever control valve and the recirculating pump [19]. Furthermore, in some researches, the dynamic characteristics of the power plant were described well by modeling the dynamic behaviors of main steam temperature, pressure and mass flow, and the water level of drum of nature circulation boiler or water storage tank of once-through boiler [7,13,20]. These parameters were also taken into consideration to estimate the dynamic characteristics of the supercritical once-through boiler start-up process in this work.

The structure of this paper is as follows, firstly, the equation of the boiler model is represented and the two-phase flow of evaporator is accurately solved by six equations. Secondly, the model is validated by comparing the steady state simulation results with the design values. Then, the dynamic simulation of a 600 MW supercritical once-through boiler is performed, and the main dynamic characteristic of start-up system is discussed by comparing of the main steam temperature, pressure and mass flow between simulated results and designed values, and observing the water level and the change of the separator temperature. For validation, the simulations are conducted under two sets of design parameters. The simulation results are discussed and the conclusions are summarized in the end.

2. Mathematical model

2.1. Unit description

In the model presented in this paper, the major components of the supercritical once-through boiler were simulated, including the furnace, water wall, separator, water storage tank, circulating pump, superheater, economizer, etc. The diagram of the start-up system of the supercritical once-through boiler is shown in Fig. 1.

The economizer is located in the lower shaft of rear part of the boiler and it is aligned arrangement along the flow direction. The feed water is directed to the economizer be pre-heated. Then, the water is routed to the outlet header of the boiler. The water enters the inlet header of the water wall via the concentrated downcomer. The water is heated by the hot gases in the bottom of the furnace before going into the mixed header below the furnace arch. After intensive mixing, the water is diverted to the upper water wall and the separator.

In order to recycle working medium and heat, an established-in start-up circulation system with recirculating pump is used [21]. The start-up circulation system consists of a separator, a water storage tank, a boiler circulation pump (BCP), a BCP flow rate control valve, a storage tank water level control valve, a drain flash tank, and a drain pump. With the boiler firing, the saturated steam generates in the evaporator. Then the steam separated from the separator is taken to the superheaters. Meanwhile, the water is directly pumped into the water storage tank. Through the BCP, most of the water recycles back into the economizer where it is mixed with the feedwater. The rest of the water is diverted to the drain flash tank.

2.2. General assumptions and basic equations

Besides, some simplify were considered for getting the derivation of the equation. Some assumptions, which are needed while the system is simulated, were made:

- The spatial distribution of the temperature in the furnace in each simulated section was omitted. Whereas, it was corrected by separating furnace to many sections.
- Completed combustion with stable flame was assumed. Therefore, the combustion was modeled by one node.
- The required amount of the air was consistent with the theoretical air consumption for combustion.
- The flue-gas flow was not a concern for start-up process relative to full load, only radiation heat transfer was modeled in the platen superheater. The convection heat transfer was omitted.