Development and engineering application of high-precision and multi-function simulation system for double reheat ultra-supercritical units

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Abstract. Laiwu ultra-supercritical double reheat unit is the highest ultra-supercritical double reheat unit, with the highest parameters in China, from the safe and economical to run level put forward higher requirements. Taking ultra-supercritical double reheat unit as the research object, a high-precision and multi-functional simulation system for ultra-supercritical double reheat unit was developed before the unit was generated, to realize the dynamic analysis of ultra-supercritical double reheat unit, control strategy verification and operation technique validation; and conduct operator operation and accident management training. provides technical support for the smooth construction, and safe and stable operation of the ultra-supercritical double reheat unit.

1. Introduction
The resource characteristics of "rich coal, poor oil and little gas" determine the important position of coal-fired power generation in China's energy structure. "700℃" Ultra-supercritical power generation technology, as new high temperature resistant material is still in the development phase, the double reheat super critical technology can effectively improve the thermal efficiency of thermal power unit and unit capacity of CO2 emission reduction, so the double reheat application of the ultra-supercritical technology (USCT) is the practical choice, to solve the efficiency and environmental protection. China double reheat ultra-supercritical (DRUC) unit design, manufacture and operation maintenance technology are at the exploratory stage, Anyuan and laiwu ultra-supercritical double reheat units are the first batch of DRUC units in China,. The lack of the DRUC unit actual operation experience related to the higher economic and safe requirement which make the solution is required. This paper describes the development of a high precision and multi-functional simulation system for the DRUC unit, which can analyze the dynamic characteristics of the unit, verify the control strategy, and verify the operation technology before the unit generates electricity. In addition, training on operation personnel and accident handling was conducted by providing technical support for the smooth construction, and stable operation of the double reheat ultra-supercritical unit [1-3].
2. Double reheat ultra-supercritical unit model

2.1. Simulation support platform software
The APROS (Advanced Process Simulator) simulation supporting is used with the 3-equation, 5-equation and 6-equation calculation modules for one-dimensional two-phase flow calculation, which can be used in various stages of preliminary feasibility study and system design. Training of operators, operation guidance, safety analysis and technical transformation of power plants. Using the process model of thermal power units developed by APROS, physical phenomena such as false water level, pump vaporization, fan scavenging, working medium expansion, working medium pulsation and furnace deflagration can be reflected naturally by improper operation model calculation, without any special treatment or fault setting [4].

2.2. The double reheat ultra-supercritical unit
HuaNeng LaiWu 1000 MW boiler has highest parameter in the world: the double reheat boiler main steam pressure is 32.87 MPa, the main steam temperature/high pressure reheat steam temperature /low pressure reheat steam temperature of 605/623/623℃ respectively. The boiler type is dc Benson furnace, tower layout, two intermediates reheat, square chamber, the bottom chamber of the furnace coil water cooling wall, low NOx thick-light burner with SOFA wind, Quadrangle tangential combustion mode. Tail double flue duct layout, low temperature reheater inlet layout flue gas regulation baffle. The smoke re-circulation extraction position is at the induced draft fan outlet. Tail flue design flue gas waste heat utilization system (high- and low-pressure economizer), heater system. The steam turbine is a super critical condensing steam turbine with double reheat, which adopts a series arrangement of ultra-high-pressure cylinder, high pressure cylinder, medium pressure cylinder and two low pressure cylinders, 10-stage reheat system, and no. 2 and no. 4 high pre-installed steam cooler (See figure 1).

![Figure 1. A simplified diagram of the thermal system of double reheat Ultra-supercritical units.](image)

2.3. Thermodynamic process model
The model is divided into several subsystems. The divide reason is thermal system function and process flow of 1000 MW ultra-supercritical double reheat unit. Each subsystem model is composed of several calculation modules. Each module corresponds to an equipment unit or a physical process of the thermal system, and has clear physical significance and mathematical independence. Nodes with little fluctuation of temperature, pressure and other parameters were selected as the connection points between subsystem models. The boiler turbine generator body model describes detailed steam turbine
system, and auxiliary system of the double reheat ultra-supercritical boiler, which meets the requirements of real-time calculation while meeting the calculation precision of mode [5, 6].

Boiler model is strictly divided into several parts. They are the boiler economizer, water wall, steam separator, two-stage super heater, high and low pressure reheater, bypass economizer, flue gas deep waste heat utilization system, combustion system, pulverization system, air preheater, three-stage bypass and other subsystems according to boiler steam flow and flue gas flow. Taking the water wall as an example, the model calculation reflects the change rule of working medium reserves, evaporation pressure and outlet enthalpy of the water wall in the dynamic and static process of boiler.

Key technical problems solved in the model development and debugging process include 1. The ultra-supercritical double reheat unit boiler is tower furnace, the convection heating surface series increase, bilateral arrangement and left and right cross, superheater and reheater system is more complex than the primary reheat unit. It is difficult to calculate the heat balance of boiler model and the resistance of flue. 2. Steam turbine part is to increase the ultra-high-pressure cylinder, the process extension, extraction and heat recovery series increase, three-stage bypass layout, increase the high and low temperature economizer system. Therefore, the thermal system of steam turbine is more complex, the computational nodes of fluid network increase, and the difficulty of model development and debugging increases. Unit based on the design data and parameters (including the system P & ID diagram, operating procedures, equipment and system specifications, the I/O point table, etc.), isolators to boiler thermodynamic calculation, heat balance diagram and other structural design parameters (such as heat transfer surface size, elevation, pipe diameter, material, and pump, fan and adjustable valve characteristic curve data, etc.) as input data, ensure the unit model calculation value of the main parameters and design values, to ensure the simulation calculation results true, credible, and conform to the laws of physics [7-12].

The calculated data of this model were compared with the design value of the unit in the conditions of 100%, 75% and 50%. The deviation between the calculated data of the main parameter model and the design value met the requirements of engineering analysis. The data of 100%THA conditions are shown in table 1:

| Project                             | Design value | Model values |
|-------------------------------------|--------------|--------------|
| 1 Power/MW                          | 1000.0       | 993.9        |
| 2 Main steam flow/(t/h)             | 2562.8       | 2718.0       |
| 3 Main steam pressure/MPa           | 30.79        | 29.85        |
| 4 Main steam temperature/℃          | 600.0        | 599.1        |
| 5 Primary reheat steam pressure /MPa| 10.32        | 10.39        |
| 6 Primary reheat steam temperature /℃| 620.0       | 621.4        |
| 7 Secondary reheat steam pressure /MPa| 3.06       | 3.15         |
| 8 Secondary reheat steam temperature /℃| 620.0       | 621.5        |
| 9 Feed water pressure /MPa          | 34.43        | 33.96        |
| 10 Feed temperature /℃             | 324.6        | 316.5        |
| 11 The total amount of coal /(t/h)   | 351.6        | 365.0        |
| 12 The total air volume /(t/h)       | 3209         | 3169         |
| 13 Proportion of recycled flue gas /%| 12.12        | 10.62        |
| 14 Exhaust temperature /℃           | 112.0        | 137.8        |
2.4. Control model
The control model adopts virtual DCS technology, that is, "VDCS" replaces the operation process of control logic in the actual DPU and outputs the operation results to realize all control functions of the unit. The control system of the double reheat ultra-supercritical unit is Emerson DCS system, and the DEH control system is Siemens T3000 system, so the system adopts Emerson virtual DCS system + DEH Siemens T3000 virtual system. The actual unit configuration engineering files are translated separately to achieve a high consistency between the control algorithm block and the actual control system. The operator interface is simulated at 1:1 [13,14].

3. Analysis and research on dynamic characteristics
Take the DRUC process models + virtual DCS way, firstly the actual unit construction structures, close to the actual project the DRUC running environment, dynamic response analysis under different load condition, get the detailed test data for research and development. The control strategy of the unit operation is to provide theoretical basis for the establishment of procedures and technical support. In addition, the whole start up and shutdown simulation test of the double reheat ultra-supercritical unit is carried out, and the full range real-time dynamic simulation verification of the unit control strategy is carried out [15].

The reheater of double reheat ultra-supercritical unit is divided into high and low pressure reheater. Therefore, the dynamic characteristics of primary and secondary reheat steam temperature are the focus of research.

Through the research and analysis of the dynamic response characteristics of the ultra-supercritical double reheat unit, the influence law of various means of temperature regulation on the key operating parameters of the boiler is obtained. Examples are as follows:

3.1. Recirculation smoke volume dynamic characteristics test

![Figure 2. Recurrent flue gas dynamic characteristics test data curve.](image)

After the step of the recirculation flue gas increased by 10% (accounting for about 1% of the total flue gas), the temperature of the main steam decreased slightly, and the temperature of the first and second reheated steam gradually increased, from the initial steady state value until reaching a new stable
value. The actual unit operation shows that the conclusion is correct (As shown in figure 2)

3.2. Dynamic characteristics test of burner swing angle
Burner angular swing up 10%, furnace flame centre position up, exports in final stage super heater of superheated steam temperature is gradually reduced, the primary and secondary reheat steam temperature increased 1.9°C and 3.06°C. The dynamic characteristics of primary and secondary reheat steam temperature are similar, to that of flue gas recirculation when the burner swing Angle changes, as shown in figure 3. The actual unit operation shows that the conclusion is correct.

![Figure 3. Test data curve of dynamic characteristics of burner swing angle.](image)

![Figure 4. Flue gas baffle dynamic characteristic test data curve.](image)
3.3. Dynamic test of flue gas baffle
After the flue gas baffle on the high-pressure side was opened up by 10% (while the flue gas baffle on the low-pressure side was closed down by 10%), the pressure and temperature of the main steam remained basically unchanged, and the temperature of the primary reheat steam gradually increased, and that of the secondary reheat steam gradually decreased. Flue gas baffle represents the means to adjust the deviation of primary and secondary reheat steam temperature, as shown in figure 4. The actual unit operation shows that the conclusion is correct [16,17].

4. Verification of control strategy and operation technology
Through the DRUC advocate complementary equipment configuration, process flow, operation characteristics and control requirements, combined with dynamic response study conclusion, develop a complete set of large double reheat ultra-supercritical coal-fired power generating units of the automatic control system scheme, to ensure that the type of double reheat the safe and stable operation of the unit. It mainly includes coordinated control, water-coal ratio control, superheated steam temperature control, primary and secondary reheat steam temperature control scheme, etc.

The control strategy of superheated steam temperature adopts the way of coal-water ratio + two-stage water spraying to reduce the temperature, and considers the influence factors of flue gas recirculation on the superheated steam temperature. According to the analysis results of the dynamic response characteristics of flue gas recirculation, flue gas baffle, burner swing Angle, and reheater accident water spray step disturbance, the first and second reheat steam temperature control is developed to adopt the combined regulation mode, of flue gas recirculation + flue gas baffle + burner swing Angle + reheater accident water spray (particularity of double reheat unit). The flue gas recirculation control input is the sum of the temperature deviation of primary reheat steam and that of secondary reheat steam. The flue gas baffle control input is from the difference between the temperature deviation of primary reheat steam and secondary reheat steam.

![Figure 5. Real-time data curve of increase load simulation test at 1.5% rated load /min.](image)

To engineering analysis of simulation system test platform verifies the control strategy. The investment unit coordinated control mode. The another main control loop is put into automatic, continuous lift load test, the load change rate of 1.5% of the rated load according to the unit/min, 3%/
min, 2% / min verification experiment was carried out respectively, analysis of the unit under different rate changes of the main parameters. Figure 5 shows the real-time simulation dynamic process test of load change, and the load change rate is 1.5% of the rated load /min.

The test results show that the key to the control of the double reheat ultra-supercritical unit is still to control the coal-water ratio and the wind-coal ratio. The superheated steam temperature is controlled by the coal-water ratio + the secondary water-jet temperature reduction method. The primary and secondary reheat steam temperature is controlled by the flue gas recirculation + burner swing Angle + flue gas baffle + reheater accident water-jet temperature reduction method. The variable load rate below 1.5% can be controlled within a reasonable range. Laiwu double reheat ultra-supercritical unit was officially put into commercial operation in 2016 after 168 hours of trial operation. During the trial operation, thermal protection and automatic input rate of the unit were both 100%, which verified the correctness of the overall control strategy of the unit. Figure 6 shows the load variation process at 1.5% rated load /min after the unit was put into commercial operation. According to the trend of the two figures and comparative data analysis, the simulated load variation test conducted on the engineering analysis test platform is basically consistent with the actual load variation test process after the unit is put into operation.

Figure 6. Unit actual operation 1.5% load rate increase load test.

The operating regulations of units are compiled in the design stage according to the design parameters of units. The operating regulations of similar units in operation. The running technology verification is carried out through the real-time dynamic test of the starting and stopping of the simulation unit and the fault process, which provides the basis for the modification of the unit's operating regulations, and makes the performance of the actual unit's operating operation reach the optimal level.

5. Conclusion
The high-precision and multi-function simulation system of the ultra-supercritical unit for double reheat is developed, to realize the dynamic characteristic analysis, control strategy verification and operation technology verification of the ultra-supercritical unit for double reheat before generating, so as to shorten the start-up and commissioning time of the actual unit.
Operating personnel training and operation accidents exercise, which make them to the new unit running characteristics of various equipment and systems, logic, the function of the control circuit, man-machine interface of monitoring content and way of operation and all kinds of accidents and the unit start-up condition of correct operation and treatment, etc.

Sum it up, The new unit was put into operation. Skillfully Control operation of the unit reduces the occurrence of wrong operation. It solved DRUC lack the practical operation experience. The problem of the operation with the lack of professional and technical personnel, for the smooth construction double reheat ultra-super critical unit provides the technical support with the safe and stable operation.

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