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Research Paper

# Experimental and theoretical analysis on the safety and efficiency of an ultra-supercritical pulverized coal-fired boiler with low mass flux vertical water wall

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ABSTRACT

The heat transfer safety of low mass flux vertical water wall suitable for a high efficiency and wide-load ultra-supercritical coal-fired boiler is investigated experimentally. The pressure drop characteristics of supercritical water are discussed. The net thermal efficiency of an ultra-supercritical pulverized coal-fired power plant is analyzed theoretically by considering the power consumption of the feed water pump. The experimental results demonstrate the test water wall tube exhibits good heat transfer and low pressure drop characteristics at low mass flux and in the normal heat flux range. However, the self-compensation characteristic between parallel tubes can be destroyed at high test heat flux when the test pressure is near the critical value. In this case, the metal temperature and pressure drop of the water wall tube increase fast and abnormally. This phenomenon indicates the distributions of in-tube mass flux and furnace heat flux no longer match, which threatens the heat transfer safety of the water wall. Corresponding analysis demonstrates that on the premise of ensuring the heat transfer safety of the water wall, adopting the low mass flux technology can improve net thermal efficiency of the power plant.

## 1. Introduction

In China, current composition of the power supply demonstrates clearly that the coal-fired power generation accounts for an absolutely large proportion. Therefore, the development of efficient and clean coal-fired power generation is the basis for developing other energy technologies. At present, a huge peak-shaving demand arises in the domestic grid, but only the well-developed coal-fired power generation is capable to undertake the task even though the renewable power generation, such as the wind, solar, and nuclear power, has developed unprecedentedly [1–6]. Meanwhile, the rapid growth of renewable power generation also requires long-term low-load operation to the ultra-supercritical coal-fired units. As a result, energy utilization efficiency of these units was reduced greatly [1,7]. For example, as presented in Fig. 1 [7], coal consumptions of the two units increase with the decrease of load rate, thereby indicating that the low coal consumption advantage of the ultra-supercritical unit is lost at low loads. Under the aforementioned background, it is performed to develop a high efficiency and wide-load ultra-supercritical coal-fired unit through the conduction of funding project of present paper, which aims to improve the thermal efficiency of current ultra-supercritical coal-fired units that operate at low loads.

Successful development of the desired unit is inseparable from breakthroughs of the core technologies, such as a safe and efficient steam-water circulating system that is suitable for the high efficiency and wide-load ultra-supercritical coal-fired boiler. Applicable evaporator system types for ultra-supercritical boilers are mainly spiral and vertical water walls [8]. Compared with the high mass flux spiral and vertical water walls, the Benson vertical tube with low mass flux is a promising choice [8–10]. At low mass flux condition, the gravitational pressure drop predominates in the tube flow because of its decrement being much higher than the increment of the frictional pressure drop. For a set of parallel vertical tubes, a higher heat input single tube can draw more fluid as its overall pressure drop decreases during the heating process. The so-called self-compensation characteristic enables the distribution of mass flux to match that of the furnace heat flux adaptively. Therefore, the use of throttle orifices, which increases the pressure drop of the boiler, can be canceled out. As a consequence, the power consumption of the feed water pump decreases, which is beneficial for power plants to achieve the goal of energy conservation.

The flow and heat transfer characteristics of the water wall tube and the safe ranges of mass and heat fluxes, which can be obtained through

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**Nomenclature**

| | |
|---|---|
| $A_w$ | $w_{pu}/(w_i-w_{pu})$ |
| $d_{in}$ | inside diameter, m |
| $d_{out}$ | outside diameter, m |
| $G$ | mass flux, kg·m$^{-2}$·s$^{-1}$ |
| $g$ | gravitational acceleration, m·s$^{-2}$ |
| $H$ | enthalpy, kJ·kg$^{-1}$ |
| $\Delta H$ | added enthalpy, kJ·kg$^{-1}$ |
| $L$ | test tube length, m |
| $Nu$ | Nusselt number |
| $P$ | pressure, MPa |
| $\Delta P$ | pressure drop, MPa |
| $POW$ | electric power |
| $Pr$ | Prandtl number |
| $\bar{Pr}$ | Averaged Prandtl number |
| $q$ | inside heat flux, kW·m$^{-2}$ |
| $Re$ | Reynolds number |
| $t$ | temperature, °C |
| $x$ | vapor quality, kg·kg$^{-1}$ |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | heat transfer coefficient, kW·m$^{-2}$·K$^{-1}$ |
| $\eta$ | efficiency, % |
| $\lambda$ | thermal conductivity, W·m$^{-1}$·K$^{-1}$ |
| $\mu$ | dynamic viscosity, kg· m$^{-1}$·s$^{-1}$ |
| $\rho$ | density, kg·m$^3$ |
| $\xi$ | frictional factor |
| $\zeta$ | pressure drop ratio |

*Subscripts*

| | |
|---|---|
| $b$ | bulk fluid |
| $cr$ | critical |
| $g$ | gas |
| $in$ | inlet |
| $iw$ | inside wall |
| $l$ | liquid |
| $out$ | outlet |
| $ow$ | outer wall |
| $tp$ | two phase |
| $w$ | wall |

the conduction of corresponding experimental investigations, are of great significance to the design and optimization of the low mass flux vertical water wall. On the basis of previous studies, the low mass flux technology should prevent the occurrence of critical heat flux (CHF) events at subcritical and near-critical pressures [11–13]. By using internally rifled tubes, dryout occurring at an elevation higher than that of the burner zone is expected [14–17]. At supercritical pressures, the abnormal heat transfer is related closely to the drastic variations of thermal physical properties of supercritical water, so that the mixed heat transfer deterioration is possible for the low mass flux technology [18–25]. In present paper, experimental investigations were conducted to obtain the heat transfer and pressure drop characteristics of the test tube and the safe ranges of mass and heat fluxes. The safe ranges of mass and heat fluxes, law of wall temperature rising, and parametric influences obtained in the experimental investigations can provide valuable references to the determination of operating parameter of the high efficiency and wide-load ultra-supercritical coal-fired boiler. Further in addition, the adverse influence of deteriorated heat transfer on the pressure drop characteristic is presented, which is also an alert to the application of low mass flux technology. Furthermore, the net thermal efficiency of a pulverized coal-fired power plant with the Rankine cycle is analyzed theoretically by considering the power consumption of the feed water pump. The experimental and theoretical analysis demonstrates that on the premise of ensuring the heat transfer safety, the use of low mass flux technology with internally rifled tubes enables the ultra-supercritical coal-fired boiler a low flow resistance, and an adaptive matching characteristic between the mass flux distribution and the furnace heat flux distribution. The aforementioned two advantages are of great importance to the wide load operation and fast response to load change of the high efficiency and wide-load ultra-supercritical coal-fired boiler. And, an excellent boiler operating characteristic is indispensable for developing the high efficiency and wide-load ultra-supercritical coal-fired unit.

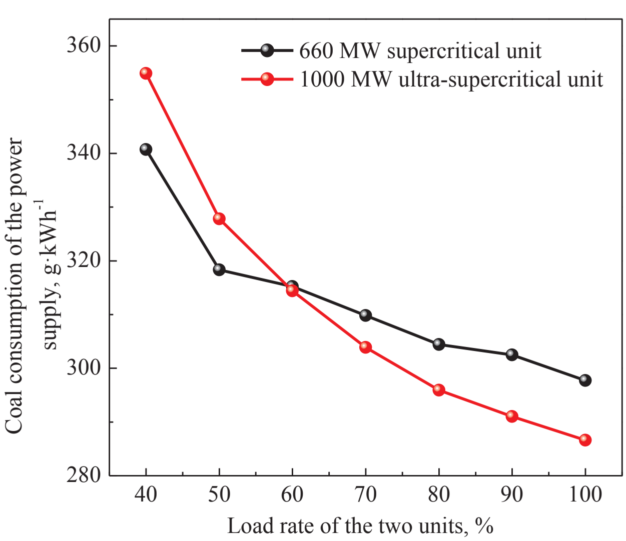


**Fig. 1.** Coal consumption variations of the 660 MW supercritical and 1000 MW ultra-supercritical units versus the load rate.

## 2. Experimental system and test section

Fig. 2 schematically depicts the experimental system, and detail information on the experimental system and the measuring instruments are presented in [6]. Table 1 and Fig. 3 present the geometry information and measurement arrangement of the test tube. It is a six-rib multi-lead modified internally rifled tube with a material of SA213-T12. The outside wall temperature is measured at 11 cross-sections. The feed water temperature is measured at the inlet and outlet, which are next to the measuring points of pressure and pressure drop. Thermal preservation cotton is coated outside the test tube for heat insulation. By considering heat loss, the heat flux can be gauged from the input electric power.

## 3. Experimental method and reduction procedure

The experimental method is illustrated in Fig. 4. The height limitation means the length of test tube cannot be as long as that of typical water wall tubes. In the experiment, at each test condition, the heating power of the experimental section is set to a constant to maintain the heat flux at a predetermined value. The constant pressure and mass flux are controlled precisely by regulating the valves. Then the heating power of the preheating section is raised continuously to increase the inlet fluid enthalpy of the test tube. Consequently, the fluid inside the test tube transforms gradually from subcooled state to superheated state. When the fluid is superheated or heat transfer deterioration