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Mathematical modeling and thermal-hydraulic analysis of vertical water wall in an ultra supercritical boiler

Jie Pan [a,*], Dong Yang [a], Hui Yu [a], Qin-cheng Bi [a], Hong-yuan Hua [b], Feng Gao [b], Zhong-ming Yang [b]

[a] State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] Harbin Boiler Co. Ltd., Harbin 150046, China

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ABSTRACT

Water wall design is a key issue for an ultra supercritical boiler. In order to increase the steam–water mixture turbulization and to prevent the burnout of tubes walls, vertical rifled tubes are applied in Yuhuan power plant boiler which is the first 1000 MW ultra supercritical boiler in China and began to operate in December 2006. Mathematical modeling and thermal-hydraulic analysis are key factors for the successful design and operation of water walls. The water wall system is treated in this paper as a network consisting of circuits, pressure grids and connecting tubes. The mathematical model for predicting the mass flux distribution and metal temperature in water wall is based on the mass, momentum and energy conservation equations. An experiment on the heat transfer characteristics of vertical rifled tube was conducted with the aim to obtain the heat transfer performance and corresponding empirical correlations. The fitting computational formulas are applied in the mathematical model. The presented modeling method is more accurate than the conventional graphic method and can be applied to complex circuit structures. The mass flux distribution and the metal temperature in the water wall are calculated at 35%, 50% and 100% of the boiler maximum continuous rating (BMCR). The results show a good agreement with the plant data. The maximum relative difference between the calculated mass flux and the plant data is 9.7% at 50% BMCR load. The metal temperature difference in the tip of fins in lower circuit 8 is about 3–7 °C at 35% BMCR load. The results show that the vertical water wall in the ultra supercritical boiler of Yuhuan power plant can operate safely.

1. Introduction

Due to the high boiler efficiency and the low pollution emission, ultra supercritical power generation has become a dominant technology in coal-fired power plants. It is also an important clean coal power generation technology for the sustainable development of power industry in China [1]. The analysis and modeling on thermal-hydraulic characteristics is essential for the safe operation of ultra supercritical boiler and relates to the furnace combustion mode and the type of water wall. The purpose of research on thermal-hydraulic characteristics is to keep the heat transfer surface of water wall at reliable temperature and to confirm the pressure drop of whole steam–water system with the aim to choose the operating pressure head of feed pump [2]. The conventional graphic method is only applied to simple flow network system calculation. For complex water wall of ultra supercritical boiler, it is difficult to divide the flow network system into simple series–parallel circuits. In addition, the graphic method cannot be easily implemented on a computer.

According to the flow and heat transfer characteristics of the steam–water system in water wall, some domestic and international scholars built different mathematical models to calculate the mass flux distribution and metal temperature in natural circulation boiler and once-through boiler. Tucakovic et al. [3] built a hydraulic calculation model of drum boiler and analyzed the security of the water wall with rifled tubes. Adam et al. [4] and Kim et al. [5] separately built hydraulic calculation models of natural circulation boiler on the basis of homogeneous flow model. Dong Fan et al. [6] and Zhao Zhen-ning [7] also separately proposed new hydraulic calculation methods. However, all these references are on the modeling of drum boilers, and it is impossible to find any models of the ultra supercritical once-through boilers in the literature. Therefore, a good mathematical model for calculating the thermal-hydraulic characteristics of water wall in ultra supercritical coal-fired boiler is very meaningful for the development of power industry.

Yuhuan power plant is the first 1000 MW ultra supercritical power plant in China and began to operate in December 2006. Mitsubishi Heavy Industries provides technical support for the ultra supercritical coal-fired boiler. The vertical water wall with simple structure was applied in the water wall. The rifled tubes with

* Corresponding author. Tel.: +86 29 82668393; fax: +86 29 82669033.
E-mail address: jackpan2006@stu.xjtu.edu.cn (J. Pan).

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Nomenclature

$C(x)$	fitting coefficient
d_w	outer diameter of tube, m
G	mass flux, kg/m^2 s
h	enthalpy of working fluid, J/kg
H	furnace height, m
l	length of tube, m
$n(i)$	number of tubes in circuit i
Nu	Nusselt number
p	pressure, MPa
p_{cr}	critical pressure, MPa
$p(i)$	pressure of grid i, MPa
Pr_w	Prandtl number while the qualitative temperature is inner tube wall temperature
Δp_f	frictional pressure drop, MPa
Δp_g	gravitational pressure drop, MPa
Δp_{jb}	local pressure drop, MPa
Δp_{lo}	frictional pressure drop in single-phase flow zone, MPa
Δp_{tp}	frictional pressure drop in two-phase flow zone, MPa
q	furnace heat flux, W/m^2
q_{cr}	critical heat flux, W/m^2
q_w	heat flux of outer tube wall, W/m^2
Re_g	Reynolds number of the gas phase
s	pitch, m
T	inner wall temperature of vertical rifled tube
T_m	metal temperature in the middle of tube wall, °C
T_{qd}	metal temperature in the tip of fin, °C
T_{qg}	metal temperature in the root of fin, °C
T_w	metal temperature in outer tube wall, °C
w	mass flow rate, kg/s
$w(i)$	mass flow rate of circuit i, kg/s
x	quality of working fluid, kg/kg
x_{cr}	critical quality, kg/kg
Greek symbols	
δ	thickness of fin, m
η	non-uniformity coefficient of heat flux
λ	thermal conductivity, W/(m K)
λ_{cr}	critical thermal conductivity, W/(m K)
λ_g	thermal conductivity of gas phase, W/(m K)
ρ_g	density of the gas phase, kg/m^3
ρ_l	density of the liquid phase, kg/m^3
Superscript	
i	inlet of tube
o	outlet of tube
Subscript	
i, n	tube n in circuit i

good heat transfer performance were adopted in the water wall with the aim to ensure the reliable cooling of tube walls and prevent the evaporating tubes burnout. In order to decrease the outlet steam temperature difference, the mixed headers with secondary distributors and the restriction orifices are installed in the water wall for mass flux regulation. These advanced technologies complicated the water wall. On account of the high operating parameters and the sliding pressure operating mode, the operating condition of the water wall is complex and variable. Therefore, the thermal-hydraulic characteristics calculation of the vertical water wall has to meet higher engineering requirement.

According to the structure characteristics of Yuhuan power plant boiler, in this paper the flow network system of water wall is divided into three kinds of elements which include circuits, pressure grids and connecting tubes. A mathematical model for predicting mass flux distribution and metal temperature in the vertical water wall is based on the mass, momentum and energy conservation equations. In the State Key Laboratory of Multiphase Flow in Power Engineering, PR China, an in-depth experimental research on the heat transfer characteristics of vertical rifled tube was conducted with the aim to obtain the heat transfer performance and corresponding empirical correlations. The fitting empirical formulas are applied in the mathematical model. The mass flux distribution and metal temperature in water wall circuits at 35%, 50% and 100% of BMCR are obtained by directly solving these non-linear equations. The water wall safety is also analyzed. The results show a good agreement with the plant data.

2. Arrangement of water wall and circuits division

The vertical rifled tubes are applied in the water wall of Yuhuan power plant boiler, and the mixed headers are installed between the upper and the lower water wall. According to the heat absorption curve of circuits in the horizontal direction, the restriction orifices with different apertures are installed on the inlet tubes of water wall. The outlet fluid in the upper headers of front wall and two side walls through furnace roof tubes flows into the furnace roof outlet header. On account of the complex circuit structure, the upper rear wall is arranged alone. The working fluid in the upper rear wall through furnace arch incline, outlet header of rear wall, collection tube, connecting tube and two-sided horizontal flue wall enclosures flows into the sling tube of rear wall. Because the outlet fluid in the three parallel circuits through connecting tube directly flows into the furnace roof outlet header, the flow resistance in furnace roof tubes is low.

In order to calculate the mass flux distribution in the water wall under different operating loads, the flow network system in lower furnace is divided into 78 circuits and that in upper furnace is divided into 100 circuits. According to the characteristics of heat flux distribution curves along the furnace width and depth, the flow network system is divided into more circuits at the zone with abrupt heat flux change and is divided into fewer circuits at the zone with smooth heat flux change. In this way, the non-uniformity of heat flux distribution can be fully reflected in calculations. Fig. 1 shows the circuits distribution of the flow network system in water wall.

The maximum of the heat absorption relative difference between the tubes with the largest and the lowest heat absorption capacity in lower circuits is 28% and the minimum is 2%.

3. Mathematical model

3.1. Calculation model of mass flux distribution

Due to the complex circuit structure and the large non-uniformity of heat flux distribution in the water wall of Yuhuan Power Plant boiler, it is difficult to obtain good mass flux distribution through conventional graphic method. The mass flux and pressure are obtained by solving the conservation equations of grids and circuits. Fig. 1 shows the flow network system of the water wall. Because the water wall is too complex, we only present the simple flow network system of rear wall as an example. In Fig. 1, the serial