A NEW METHOD FOR CALCULATING HYDRODYNAMICS OF CORNER-TUBE BOILER BASED ON DIFFERENTIAL PRESSURE SOLUTION

by

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Corner-tube boiler is widely used in the production of industrial steam. For this boiler, it is difficult to conduct hydrodynamic calculation and check due to unique water cycle structure. A new method for hydrodynamic calculation of corner-tube steam boiler based on differential pressure solution is proposed in this article. The frictional pressure drop in the lower header has been taken into consideration by adding a direction discriminant factor, which can solve the inherent problem about the balance point. Meanwhile, taking a corner-tube steam boiler of 75 tonne per hour as an example, the circulation flow rates in each riser under different working conditions were calculated, and the cycle reliability was also checked. The calculation results showed that the hydrodynamic characteristic is good enough under the condition of full heat load. However, the riser in the tail shaft will surf from flow stagnation or backflow once the heat load is at or below 50%, which is generally consistent with the change trend of monitoring wall temperature during actual operation. This method proposed in this article is more accurate, by comparing with the traditional method, in predicting whether there is a risk of flow stagnation or backflow in the riser of the corner-tube steam boiler under lower heat load.

Key words: *corner-tube boiler, hydrodynamic characteristic, balance point, cyclic reliability*

Introduction

In recent years, as the energy conservation and emission reduction are actively promoted, the development of boiler technology has gradually advanced in the direction of high efficiency, low emissions and high operating parameters [1]. In this situation, some new high efficiency and energy-saving boilers are gradually popular in the industry. The corner-tube boiler was first invented by German expert Vorkauf in 1944. This type of boiler is named after the arrangement of four downcomers located in the corner of the boiler. Although these downcomers participates in overall hydraulic flow they are part of boiler's support frame [2]. The research of corner-tube boilers has been carried out for sever decades, but there are still many key issues that remain unsolved. The calculation and analysis of boiler hydrodynamic is one of them.

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The hydrodynamic calculations and safety analysis are considered as key techniques for the design of large capacity boilers. They are used to obtain the total pressure drop over the entire water vapor system, pipe temperature, and select the working head of the feed pump [3]. For traditional power station boilers, Jie *et al*. [4], Lin and Xu [5], Kim and Choi [6], Guo *et al.* [7] and others have also established different mathematical models to calculate the mass-flow distribution and wall temperature of natural circulation boilers. The current boiler hydrodynamic algorithm is relatively mature. However, the lay-out of the hydrodynamic circulation of the corner-tube boiler is complex.

Both downcomer and re-circulation downcomer are arranged in the front and back of the corner-tube boiler, respectively. It formed two water circulation, which named circulation loop and re-circulationloop, respectively. It is very different from the general boiler lay-out. The existing hydraulic calculation method is difficult to determine the hydrodynamics of the corner-tube boiler reasonably.

In response to this problem, many researchers have also carried out some theoretical and experimental investigations on its hydrodynamic characteristics. Zhuo and Zhou [8] proposed the hydrodynamic model of corner-tube hot water boiler, and analyzed the similar criteria that should be followed in the experimental study of corner-tube boiler molding. Yang and Ji [9] *et al.* analyzed the characteristics of the water wall with forced circulation for a corner-tube hot water boiler. They proposed the balance point problem for the first time, and gave the corresponding hydrodynamic calculation method. However, the aforementioned studies are for corner-tube hot water boilers. It is not completely applicable to corner-tube steam boilers. Meng *et al.* [10, 11] analyzed the circulation principle of the water wall of the diagonal-tube steam boiler, and conducted an experimental study on the re-circulation tube. They analyzed the influence of heat load and pre-separated header on the re-circulation tube. Liu [12] applied graph theory and pipe network hydraulic analysis theory to the hydrodynamic calculation of corner-tube steam boiler, and programmed the calculation, which greatly improved the efficiency of hydrodynamic calculation. Nevertheless, in this corner-tube boiler, the direction of water flow in the lower header box is known, which cannot solve the equilibrium point problem in most typical corner-tube steam boilers. Shen and Yuan [13] proposed a hydrodynamic calculation method for the characteristics of the water circulation system of the corner-tube boiler. They carried out numerical simulation of the steam water separation characteristics of the boiler pre-separation system. For the hydrodynamic calculation of the corner-tube boiler, it is generally necessary to find the balance point in the header box and judge the flow direction in the header before the hydrodynamic calculation. However, the position of the balance point is affected by many parameters such as heat load, tube diameter*, etc.*, resulting in different working conditions are not the same. The position of the balance point is difficult to determine. Although there are many researches on the hydrodynamic calculation of the corner-tube steam boiler currently, it is generally calculated on the basis of ignoring the pressure loss and balance point in the lower header. The accuracy of the calculation is difficult to guarantee when the corner-tube boiler hydrodynamic check is conducted in the design process.

Therefore, a new hydrodynamic calculation method for corner-tube steam boiler is proposed in this paper, which can evaluate the hydrodynamic characteristics of corner-tube boiler and predict the position of the equilibrium point under different heat loads. Furthermore, this method might be used for detection of undesirable flow regimes such as flow stagnation or backflow in risers. Compared with traditional one, this method solves the inherent problem of determining flow in the lower header, as well as calculating and analyzing hydrodynamic characteristic under various working conditions more accurately and efficiently.

Balance point problem

The schematic diagrams of the classic corner-tube steam boiler and the ordinary boiler water circulation have been shown in fig. 1. It can be seen that head for obtaining circulation in hydraulic circuit comes from working fluid density difference in downcomer and riser. Nevertheless, the water circulation network for the both is still very different. The water-vapor two-phase flow in the riser of the corner-tube enters the pre-separation header where vapor phase is separated from two-phase flow and is guided further toward boiler drum visa steam pipe-lines. The liquid part of mixture is partially guided toward boiler drum while the rest enters remains in this circulation loop by bringing it to the re-circulation downcomer. For ordinary natural circulation boiler, flow resistance in the lower header will increase once the position of riser is far away from downcomer. The head of re-circulation loop will be reduced. The re-circulation loop of the corner-tube steam boiler can improve the water circulation in this case. However, the existence of the re-circulation downcomer also makes the general hydrodynamic calculation method of the ordinary boiler no longer suitable for corner-tube steam boilers. It is necessary to study a new hydrodynamic algorithm on this basis.

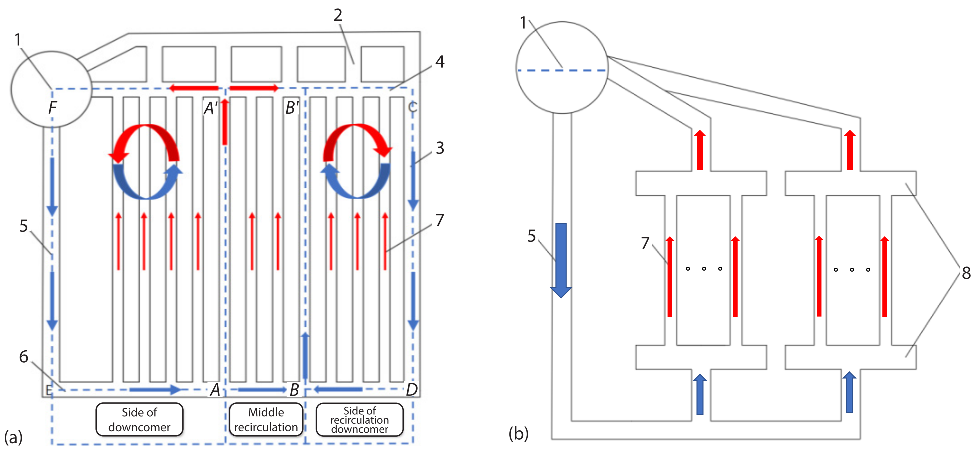

Figure 1. Water circulations of corner-tube steam boiler and ordinary boiler; (a) corner-tube steam boiler and (b) ordinary boiler water; *1 – boiler drum, 2 – steam pipe, 3 – re-circulation downcomer, 4 – pre-separation header, 5 – dowmcomer, 6 – lower header, 7 – riser, and 8 – parallel header*

Combined with fig. 1 , it can be seen that there are two downcomers that supply water to the lower header. It must be a pressure equilibrium Point B (flow stagnation point) in the lower header, which can be written as the following equations.

$$P_{B^-} = P_{B^+} \tag{1}$$

$$V_{B^-} = V_{B^+} = 0 \tag{2}$$

Similarly, for pre-separated headers, there is an equilibrium Point A′ (flow stagnation point) such that:

$$P_{A'^-} = P_{A'^+} \tag{3}$$

$$V_{A'^-} = V_{A'^+} = 0 \tag{4}$$

Since part of the water in the re-circulation loop is vaporized and flows into the steam pipe and drum, in order to maintain the water circulation stable, it is necessary to replenish water from the circulation loop. The balance point of the lower Header 6 and the pre-separated Header 4 is bound to not be in a vertical line. The actual position of A′ will be located to the left of B. The entire water cycle can be divided into three parts, namely the circulation loop (A′FEA A′), the replenish water circulation (A'B′BA), and the recirculating loop (B′CDBB′).

In the hydrodynamic calculation of the corner-tube steam boiler, however, the equilibrium point location (Point B) is not easy to determine. Therefore, it is not practical to find the equilibrium point before performing hydrodynamic calculations. Taking a 75 tonne per hour corner-tube steam boiler as an example, this paper proposes a new hydrodynamic calculation method, which realizes the automatic adjustment of the water flow direction inside the lower header.

Boiler structure and hydrodynamic system

Boiler structure

The structural diagram of the corner-tube steam boiler studied in this paper is shown in fig. 2. The body adopts the typical corner-tube boiler structure form, without steel frame support, all composed of membrane water walls and multiple large-diameter downcomers to form its overall framework. The flue gases from combustion pass sequentially through the furnace water wall, superheater, needle convective tube bundle, economizer and air preheater. The boiler steam production is 75 tonne per hour. The operation pressure is 4.2 MPa and the saturated temperature is 254 °C.

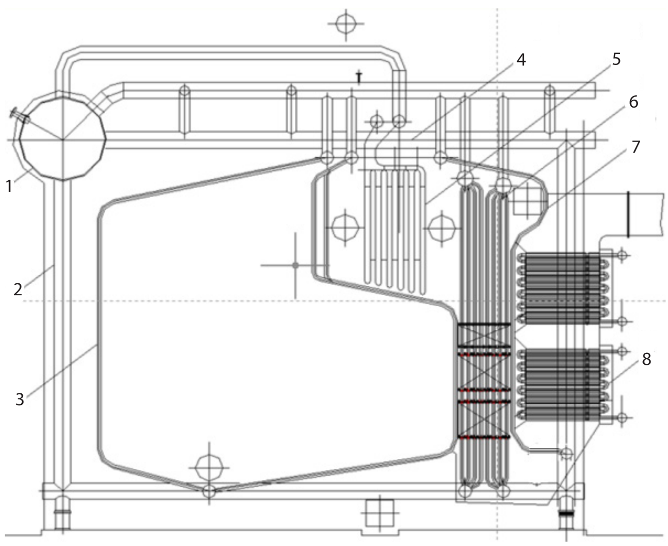

Figure 2; Schematic diagram of the structure of the corner-tube boiler: *1 – boiler drum, 2 – downcomer, 3 – front wall riser, 4 – pre-separation header, 5 – superheater, 6 – needle convective tube bundle, 7 – rear wall of the tail shaft, and 8 – economizer*

Hydrodynamic system

A schematic diagram of the hydrodynamic circulation system for this boiler is shown in fig. 3. The feed water enters the boiler drum from the economizer. It will be guided into the lower header and distributed into the heating wall. The water is heated into a vapor-liquid two-phase mixture, which will further enter the upper header via riser. The two-phase mixture is divided into two strands: one flows directly back into the boiler drum, while the other part of the water enters the re-circulation downcomer and flows to the lower header. The specific parameters of each heating wall and header have been shown in tab. 1.

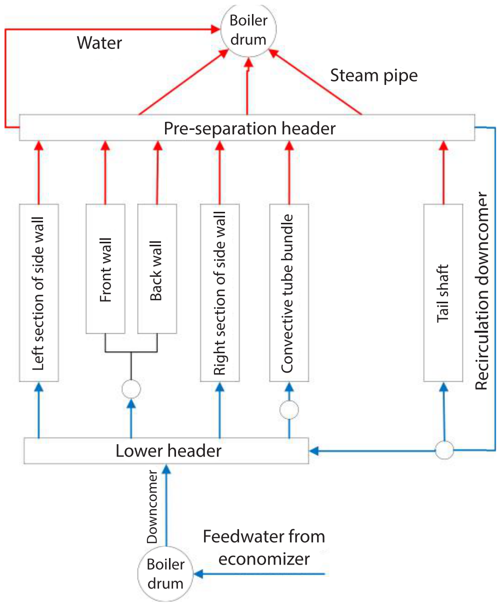

Figure 3. Schematic diagram of the hydrodynamic circulation system

Table 1. Pipe-line parameters of the boiler

Term	*D*×*S* [mm×mm]	*L*×*H* [mm×mm]	Heat load [kW]	Value
Downcomer	426×25	8.30×8.30	0	2
Re-circulation downcomer	426×25	8.30×8.30	0	2
Left section of side wall	60×4	8.30×8.30	53.81	28
Right section of side wall	60×4	8.30×8.30	58.87	73
Front wall	60×4	14.09×8.30	125.73	63
Back wall	60×4	14.55×8.30	132.02	63
Convective tube bundle	48×4	7.35×7.35	34.37	415
Tail shaft	60×4	8.30×8.30	20.04	63
Lower header	426×25	10.84×0	0	3

Hydrodynamic calculation methods

Theoretical model of hydrodynamics

The Bernoulli equation for the total flow:

$$P_1 + \rho_1 H_1 g + \frac{\rho_1 V_1^2}{2} = P_2 + \rho_2 H_2 g + \frac{\rho_2 V_2^2}{2} + \Delta P_{iz} \tag{5}$$

where P_1, P_2 are the pressure of Sections 1 and 2, ρ_1 and ρ_2 – the density of the fluid at Cross-sections 1 and 2, H_1, H_2 – the absolute height of Sections 1 and 2, V_1, V_2 – the flow velocity of the fluid at Cross-sections 1 and 2, ΔP_{lz} – the flow resistance from Sections 1 and 2, and g – the acceleration due to gravity.

In boiler hydrodynamic calculations, the total pressure drop of a pipe-line can be determined:

$$\Delta P = \Delta P_{\mathrm{g}} + \Delta P_{\mathrm{f}} + \Delta P_{\mathrm{a}} \tag{6}$$

where ΔP is the total pressure drop of the pipe section, ΔP_{g} – the gravitational pressure drop, ΔP_{f} – the frictional pressure drop, and the detailed calculation method can refer to the hydrodynamic calculation standard [14], and ΔP_{a} – the accelerated pressure drop. Because the accelerated pressure drop accounts for a small share of the total pressure drop, the accelerated pressure drop is generally not calculated. With stable flow and constant pipe diameter, the frictional resistance along the path of a single-phase fluid can be expressed:

$$\Delta P_{\mathrm{f}} = \lambda_0 l \frac{\rho V^2}{2} \overline{v} \tag{7}$$

where ρ [kgm^{-3}] is the density and λ_0 [m^{-1}] – the coefficient of frictional resistance per meter [14]. The formula for calculating the resistance along the two-phase zone:

$$\Delta P_{\mathrm{mc}} = \psi \lambda_0 l \frac{\rho_1 V_0^2}{2} \left[1 + \overline{x} \left(\frac{\rho_1}{\rho_{\mathrm{g}}} - 1 \right) \right] \tag{8}$$

where ρ_1 and ρ_2 [kgm^{-3}] are the saturated water and saturated vapor density under the working fluid pressure, V_0 [ms^{-1}] – the circulating flow velocity, $\overline{x}$ – the average dryness [15, 16], and ψ – the frictional resistance correction coefficient, and the calculation method can be referred to [17].

In addition, the hydrodynamic system should satisfy the flow conservation equation, that is, the sum of the flow rate of the downcomer and the flow rate of the re-circulation downcomer should be equal to the sum of the flow of all risers:

$$G_d + G_{cd} = \sum_{i=1}^{n} G_r \tag{9}$$

where n is the number of risers.

The strategy of solution

As shown in fig. 4, due to the interconnection of the upper and lower headers of the four walls of the corner-tube steam boiler and the presence of re-circulation downcomer, the hydrodynamic calculation of the corner-tube steam boiler is more complicated. In order to make the problem more intuitive and convenient to explain the solution strategy, the hydrodynamic system of fig. 3 is appropriately simplified in the form of fig. 1. Firstly, the water wall of the entire corner-tube boiler is divided into a single module according to the same pipe panel. The pipe-lines in the same pipe panel area are regarded as a single pipe (single pipe in the middle of the water wall) calculation.

The current solution focuses on the pressure drop loss in the lower header, as well as the flow rate and inlet static pressure of each riser based on the conservation of momentum and mass. The lower header of the front and the back wall are selected as the calculation point (the calculation points can be arbitrarily selected). For this point, P_{3^-} and P_{3^+} represent the pressure at this node. The following formula must be satisfied:

$$P_{3^-} = P_{3^+} \tag{10}$$

The flow velocity of the downcomer can first be assumed to be a constant. On this basis, the static pressure of P_{3^-} can be obtained. Similarly, the static pressure of P_{3+} can be obtained if the flow velocity of the re-circulation downcomer is known. Since $P_{3^-} = P_{3^+}$, the flow velocity of the re-circulation downcomer has been determined under the condition that the flow velocity of the downcomer is assumed. Therefore, the key now is how to determine the direction of the water flow and the frictional pressure drop in the lower header on both sides of the calculation point. As can be seen from fig. 4, in order to consider the frictional pressure drop in the lower header, the flow direction of water in the lower header should be judged. However, it is difficult to determine the flow direction without the balance Point B.

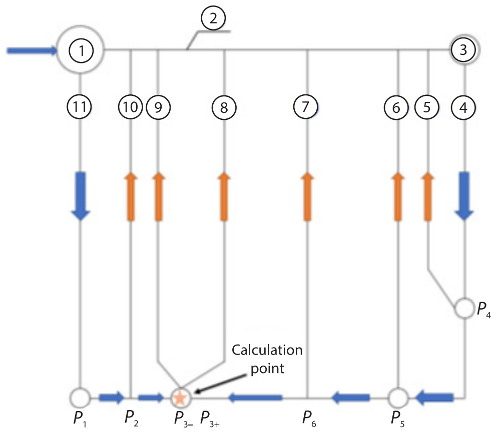

Figure 4. Simplified hydrodynamic system: *1 – boiler drum, 2 – pre-separated header, 3 – re-circulation header, 4 – re-circulation downcomer, 5 – tail shaft, 6 – convective tube bundle, 7 – right section of riser, 8 – back wall, 9 – front wall, 10 – left section of riser, and 11 – downcomer*

It is worth noting that the direction of flow and the frictional pressure drop is always opposite. Thus, for this problem, a directional discriminant factor can be added before eqs. (7) and (8), that is, β_G:

$$\beta_G = \frac{G_i}{|G_i|} \tag{11}$$

Meanwhile, a new frictional pressure drop calculation formula that automatically adjusts the frictional pressure drop direction according to the flow direction of the working fluid is obtained:

$$\Delta P_{\text{mc}} = \frac{Gi}{|Gi|}\lambda_0 l \frac{\rho V^2}{2}\overline{v} \tag{12}$$

$$\Delta P_{\text{mc}} = \frac{G_i}{|G_i|}\psi\lambda_0 l \frac{\rho_1 V_0^2}{2}\left[1+\overline{x}\left(\frac{\rho_1}{\rho_{\text{g}}}-1\right)\right] \tag{13}$$

Due to the complex flow of the pre-separated header, this paper mainly considers the flow resistance in the lower header. The outlet pressure of the risers and the pressure of the boiler drum are regarded as equal. The reference pressure of the whole system is set at the pre-separated header and the value is regarded as 0. The pressure drop of each riser can be determined:

$$\Delta P = P_i - 0 \tag{14}$$

Since the flow velocity of each riser has a corresponding functional relationship with ΔP, the flow velocity V_i of each riser can be determined:

$$V_i = f(\Delta P) = f(P_i) \tag{15}$$

The entire calculation process can be explained in detail as follows. As can be seen in fig. 5(a), the calculation can be started from the side of the downcomer. Firstly, assuming that the flow rate in the downcomer 11 is G_1, the velocity V_1 of the downcomer can also be obtained with the flow rate divided by flow area. The outlet static pressure P_1 of the downcomer can be obtained by calculating the pressure drop in the downcomer. The pressure drop ΔP_{f1} from P_1 to P_2 can be calculated with the flow rate G_1. Next, the flow velocity V_{10} and flow rate G_{10} of riser 10 can be obtained with P_2. Similarly, G_{23} and P_{3-} can also be calculated.

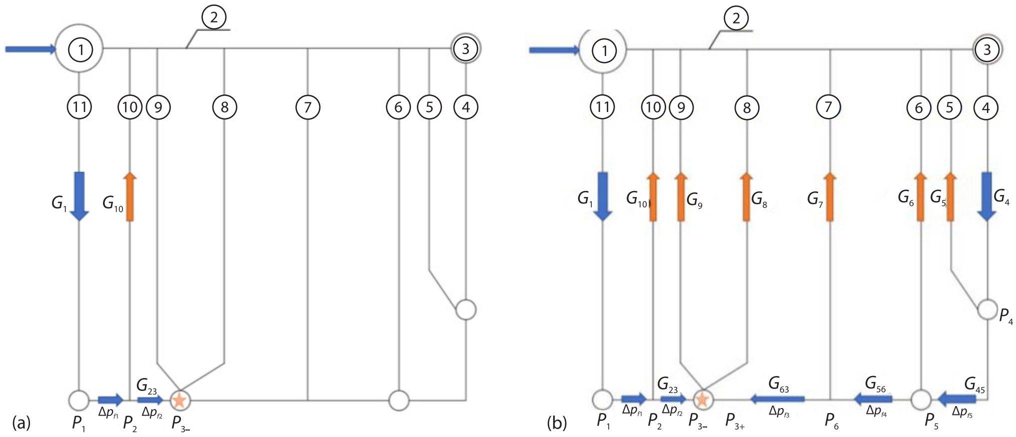

Figure 5. Calculation process for both sides; (a) the side of downcomer and (b) the side of the re-circulation downcomer

Secondly, as can be seen in fig. 5(b), assuming that the flow rate in the re-circulation pipe is G_4, the flow velocity V_4 in the re-circulation pipe can be calculated according to the flow area. The static pressure P_4 of the inlet header of the tail shaft can be obtained by calculating the pressure drop in the re-circulation downcomer. With the static pressure P_4, the circulating flow velocity V_5 and flow rate G_5 entering the riser can be obtained. Then the remaining flow rate G_{45} and the pressure drop loss ΔP_{f5} can be calculated. The static pressure P_5 of the inlet of the convective tube bundle can be obtained. Repeating the previous operation in the same way, the G_7, G_8, G_9, P_6, and P_{3+} can be calculated. Then, the pressure balance and flow rate balance check for the entire recirculating cycle can be carried out:

$$\left|P_{3-} - P_{3+}\right| < \xi_1 \tag{16}$$

$$\left|(G_8 + G_9) - (G_{63} + G_{23})\right| < \xi_2 \tag{17}$$

where ξ_1 and ξ_2 are the calculation convergence criterion and accuracy. The system will satisfy the conservation of momentum by iteratively calculating the V_4 by checking eq. (16) until the accuracy requirements are met. Then, the flow rate required for the lower header of the front and back wall ($G_8 + G_9$) is calculated when the static pressure P_3 is known. The remaining flow rate of the system ($G_{63} + G_{23}$) can be calculated to iterate the V_1 by checking eq. (17).

Programmatic solution

Following the calculation steps described in the previous section, the program flowchart is shown in fig. 6. The hydrodynamic characteristics under different working conditions can be calculated. The inlet dynamic pressure and flow rate in each tube in the corner-tube boiler can be obtained. The cycle reliability can be further tested by combining the program calculation results, which not only greatly improves the calculation efficiency, but also provides a reference for the design of the corner-tube boiler.

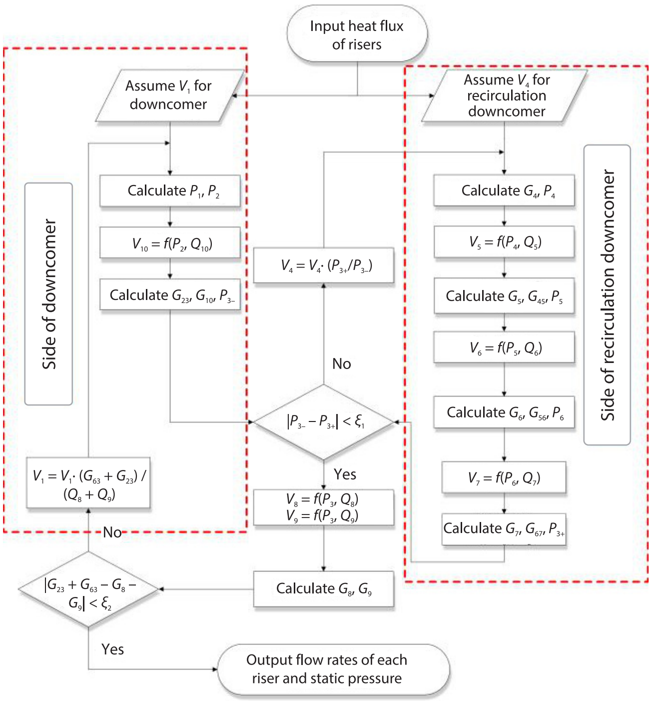

Figure 6. Flowchart of hydrodynamic calculation of corner-tube steam boiler

Analysis and discussion

Hydrodynamic calculation results

According to the structural characteristics and heat load distribution of the corner-tube boiler, as shown in fig. 2, the lower header of the front and back wall is selected as the calculation points. The calculation process is programmed in MATLAB according to the calculation process of fig. 7. The calculation results are shown in tab. 2 below for this case with the calculation error of 10^{-3}. It can be seen from tab. 2 that the calculation results meet the continuity and momentum conservation equations. Pressure drop in the downcomer and the re-circulation downcomer is positive, and pressure drop in the riser is negative. The flow rate in different risers change with the heat absorption. The flow rate in the riser with a large heat absorption is also large [17, 18].

The traditional pressure differential solution method for boiler hydrodynamic is to first assume three different velocity of riser and downcomer of circulation loop. The pressure drops under the three sets of flow condition can be calculated. Three points in the relationship map between flow rate and pressure drop can be drawn and connected into a line. Similarly, a line to reflect the relationship between flow rate and pressure drop for the downcomer can also be calculated and drawn in this map. The intersection of the two lines is the working point for this circulation loop. As can be seen, the pressure drop in the lower header cannot be taken into consideration in the traditional solution method. In addition, the working point is only determined by the fitting curve obtained from three or four sets of pressure drop calculation

Table 2. Calculation of hydraulic power of corner-tube steam boiler

Tube number	Position	Mass-flow rate [kgm^{-2}s^{-1}]	Evaporation [tonne per hour]	Flow rate [tonne per hour]	Static pressure [kPa]	Circulation ratio	Flow stagnation pressure ratio	Backflow pressure ratio
4	Re-circulation downcomer	2641.72	–	1056.50	54.07	–	–	–
5	Trail shaft	218.10	1.31	51.58	–51.36	39.49	1.09	1.06
6	Convective tube bundle	864.45	14.95	808.85	–53.86	54.07	1.20	1.14
7	Right section of riser	927.10	8.25	516.97	–53.84	62.59	1.16	1.14
8	Back wall	1247.5	8.19	295.47	–53.88	36.09	1.31	1.36
9	Front wall	1204.67	8.60	285.41	–53.88	33.20	1.31	1.38
10	Left section of riser	938.20	3.17	200.77	–54.05	63.46	1.16	1.14
11	Downcomer	2764.64	–	1105.19	54.30	–	–	–

values. The accuracy cannot be guaranteed. Given the complex hydrodynamic characteristics of the corner-tube steam boiler, the traditional solution method is difficult to apply. The new solution method proposed in this paper is optimized on the basis of the traditional differential pressure solution. The relationship of flow rate and pressure drop can be constructed for riser and downcomer, respectively. Iteration solution is used to obtain the final working point, which can guarantee a more accurate result. This new method not only considers the structure of the corner-tube steam boiler, but also take the pressure loss in the lower header. After programming and calculating it in MATLAB, the calculation efficiency can be greatly improved. The hydrodynamic characteristics of the corner-tube boiler under various working conditions can be calculated and simulated once the boiler structure and thermal design is completed.

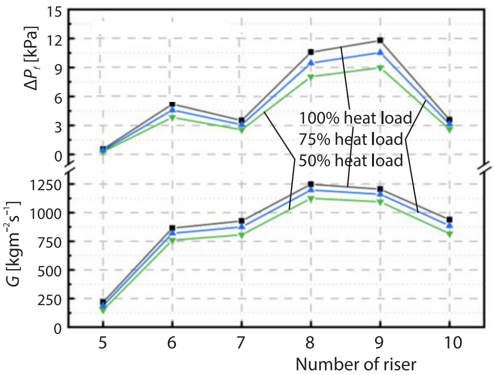

Figure 7. The mass-flow rate distribution of the corner-tube boiler under different heat loads

The hydrodynamic characteristics of each tube in the corner-tube boiler under different heat loads are shown in fig. 7. The change of heat load affects the flow rate and pressure drop of risers to a certain extent. The trend is similar for different heat loads. It can be seen from the figure that the distribution trend of flow rate is basically the same as the distribution trend of heat load, indicating that the flow rate of different risers is greatly affected by the heat load. Therefore, reducing the uneven performance of heat load distribution can effectively improve the hydrodynamic characteristics of the corner-tube steam boiler.

Check of flow stagnation and backflow

In order to explore the hydrodynamic characteristics of the corner-tube steam boiler, the calculation results are checked for flow stagnation pressure ratio and backflow pressure ratio. The flow stagnation pressure ratio represents the ratio of the current pressure drop of the riser to the pressure drop when flow stagnation occurs in this flow condition:

$$\Delta P_{tz}/\Delta P_{yx} \geq 1.05$$

Similarly, the backflow pressure ratio represents the ratio of the current pressure drop of the riser to the pressure drop when backflow occurs in this flow condition:

$$\Delta P_{dl}/\Delta P_{yx} \geq 1.05$$

The value of the pressure ratio usually needs to be greater than 1.05, which keeps a safety margin of 5%. The check results are shown in fig. 8. From the calculation results in the figure, it can be seen that the flow stagnation pressure ratio and the backflow pressure ratio gradually decrease with the decrease of heat load. At the heat load of 100% and 75%, the calculated flow stagnation and backflow pressure ratios are greater than the minimum pressure ratio of 1.05 for flow stagnation, indicating that the risk of flow stagnation and backflow for the riser of the corner-tube steam boiler is low. However, at the 50% heat load, the flow stagnation and backflow pressure ratio of the No. 5 riser (tail shaft) is generally lower than 1.05. It indicates that the flow stagnation or backflow may occur. For this boiler, if it is operated at 50% heat load for a long time, it may cause water circulation failure, which is a potential safety hazard.

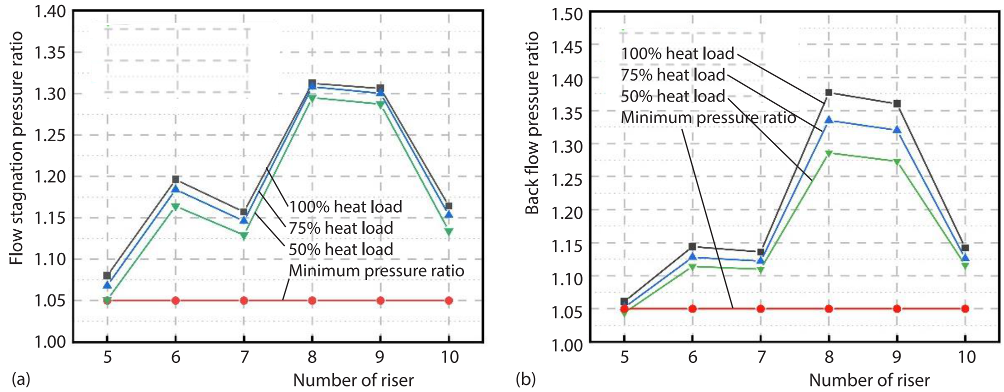

Figure 8. Check results of the corner-tube steam boiler; (a) flow stagnation pressure ratio and (b) backflow pressure ratio

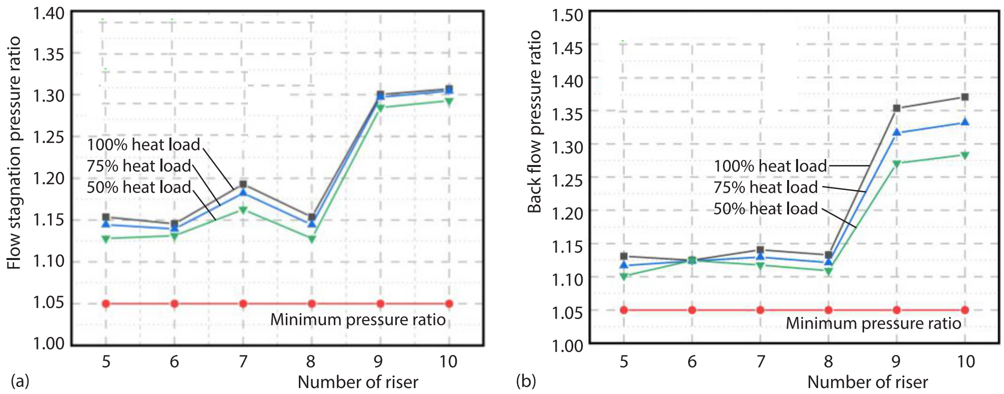

Figure 9. Check results of the corner-tube steam boiler using traditional method; (a) flow stagnation pressure ratio and (b) backflow pressure ratio

In the actual operation, the online temperature monitoring at the tail shaft showed a tendency to increase when heat load is reduced to almost 60%. This means that the flow stagnation or backflow may have occurred in the riser. As compared, the check results of this corner-tube steam boiler using traditional method have shown in fig. 9. As can be seen, the check results using traditional method showed that the hydrodynamic performance is still operating safely and reliably even if the heat load of this boiler is reduced to 50%. The comparation of calculation results showed that the new model is more accurate in predicting whether there is a risk of flow stagnation or backflow for the corner-tube steam boiler compared to the traditional method.

Conclusions

- For the unique hydrodynamic characteristics of the corner-tube steam boiler, a new method based on differential pressure solution is proposed in this article. The frictional pressure drop in the lower header is taken into consideration by adding the flow direction discriminant factor, which can solve the problem about the balance point in the lower header.
- The check of flow stagnation and backflow is carried out for this corner-tube steam boiler and it is found that the flow stagnation pressure ratio and backflow pressure ratio are generally greater than 1.05 in full heat load. Although the corner-tube steam boiler has an excellent hydrodynamic characteristic, it may still surf from flow stagnation or backflow for the riser once the heat flux distribution is very uneven.
- By comparing with the traditional method, it can be found that the method proposed in this article is more accurate in predicting whether there is a risk of flow stagnation or backflow in the riser of the corner-tube steam boiler under lower heat load.

Acknowledgment

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Nomenclature

D – diameter, [mm]
G – rate of flow, [kgs^{-1}]
H – height, [mm]
L – length, [mm]
P – dynamic pressure, [Pa]
ΔP – pressure drop, [Pa]
S – wall thickness, [mm]
V – velocity of flow, [ms^{-1}]
$\bar{v}$ – average specific volume, [m^{3}kg^{-1}]
$\bar{x}$ – average dryness

Greek symbols

β_G – flow direction discriminant factor
λ_0 – friction resistance coefficient, [m^{-1}]
ξ – error factor
ρ – density, [kgm^{-3}]
ψ – friction resistance correction coefficient

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