Mathematical Modeling of Evaporator in Reheat Recovery Drum Boiler

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Abstract. The reheat recovery boiler is widely-used energy conservation equipment aiming to take advantage of the exit flue of gas turbine in combined cycle. Due to large amount of renewable energy getting access to grid, a more flexible and agile operation mode of reheat recovery boiler is in great need, and parameter distribution is arousing great attention of researchers. In present paper, a mathematical model of downcomer-riser-drum is established based on conversation equations. Four typical working condition of heat recovery boiler are studied, and detailed information is demonstrated.

1. Introduction
As an important component of combined cycle, reheat recovery boiler characteristic differs great from common fossil-fired boiler, and its working condition has direct influence on safe and economic operation of whole unit [1].

Researchers have conducted numerous investigations in character of natural circulation drum boiler. Astrom and Bell [2] established a model for water level in drum, and its result agreed well with experimental data, which is commonly known as Astrom-Bell model. Adam and Kim established a distributed parameter model to describe the dynamic character of evaporator, this model reveal the information more detailed.

In present study, a natural circulation heat recovery drum boiler is studied through mathematical model. Circulation rate, steam quality in risers and pressure distribution of four typical working conditions are in scope of present investigation.

2. Model and governing equations
The boiler in present paper is a natural circulation heat recovery drum boiler made in Wuxi Huaguang boiler plant, and relative parameters are listed in Table 1.

| Table 1. Boiler main parameter (Condensing condition). |
|----------------------------------|------|--------|--------|--------|--------|
| Item                             | Unit | 100% BRL | 75% BRL | 50% BRL | 30% BRL |
| Main steam flow                 | t/h  | 246      | 210     | 170     | 110     |
| Main steam pressure             | MPa (g) | 7.46    | 6.38    | 5.42    | 5.11    |
| Main steam temperature          | °C       | 523     | 527     | 517     | 417     |
| Drum pressure                   | MPa (g) | 8.19    | 6.80    | 5.64    | 5.20    |
| Feedwater temperature           | °C       | 291     | 278     | 268     | 268     |

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The circulation loop is shown in Fig 1. Assumptions below are indispensible for the establishment of model.

1. The feedwater from economizer, 1) part of feedwater are heated to saturate water, and 2) the other part directly goes into downcomer. Assume portion \( b \) is heated to saturate state, and \( b \) is constant in four steady conditions.

2. Downcomers are assumed to be adiabatic.

3. Even-distributed model of steam and water mixture is adopted, and sliding velocity is not in scope of consideration.

4. Pressure drop of media acceleration is neglected.

5. Heat load of heated surfaces is assumed to be same in present study.

Based on the assumptions above, the water circulation loop can be divided to several parts which are described with different equations.

### 2.1. Downcomer

The mass flow, pressure and temperature of feedwater from economizer is \( m_{fw}, P_{fw} \) and \( t_{fw} \). And drum pressure is \( P_{dr} \). \( h_d, h_r \) are heights of downcomer and riser, respectively. If the mass flow of downcomer is \( m_d \), the enthalpy of downcomer inlet is \( H_d \).

\[
(1 - b)m_{fw}H_{fw} + (m_d - (1 - b) \times m_{fw})H' = m_dH_d
\]  

where \( H_{fw} \) - Feedwater enthalpy, kJ/kg; \( H' \) - Saturate water enthalpy under the pressure of drum, kJ/kg.

The outlet of downcomer is calculated as:

\[
P_d = P_{dr} + \rho_dgh_d - \varepsilon_{xj} \frac{w^2_d \rho_d}{2}
\]  

where \( \varepsilon_{xj} \) - Total resistance coefficient of downcomer; \( \rho_d \) - Water density in downcomer, kg/m\(^3\).

### 2.2. Riser

The inlet parameters of risers can be obtained by calculating the downcomer outlet parameters. Due to the existence of subcool in feedwater, some part of riser still remains single phase. And the continuous, momentum and energy conservation equations are:

\[
\frac{d(\rho u)}{dz} = 0
\]  

\[
\frac{dp}{dz} = -\rho g \frac{\lambda \rho u^2}{d}
\]  

\[
\frac{d(\rho u h)}{dz} = q_w
\]  

Where \( u \) - Velocity, m/s; \( q_w \) - Heat absorbed by unit volume media, kW/m\(^3\); \( \lambda \) - Frictional coefficient.

Under the condition of inlet parameter known, combined with water and steam characteristic Runge-Kutta method can solve the ordinary differential equations above. A saturate water criterion is judged every step to determine the end of single phase flow in riser.

For two phase period in riser, the continuous, momentum and energy conservation equations are:

\[
\frac{d}{dz}(\epsilon \rho'' u + (1 - \epsilon) \rho' u) = 0
\]  

\[
\frac{d}{dz}[\epsilon \rho'' u^2 + (1 - \epsilon) \rho' u^2] + \frac{dp}{dz} = -[\epsilon \rho'' + (1 - \epsilon) \rho] g - \frac{4\tau_w}{d}
\]
where $\varepsilon$ - Sectional volumetric steam quality in risers; $\rho'$, $\rho''$ - Saturate water and steam density, kg/m$^3$; $\tau_w$ - Wall friction force, N/m$^2$; $H'$, $H''$ - Saturate water and steam enthalpy, kJ/kg.

After the water and steam mixture enters into drum, part of saturate steam is used to heat the subcool water from economizer:

$$bm_{fw}H_{fw} + cm_{d}x''H'' = (bm_{fw} + cm_{d}x')H'$$  \hspace{1cm} (9)

where $c$ - portion exhausted by feedwater; $x''$ - Sectional mass steam quality in risers.

Relative equations can be referred in literature [3]. And according construction data is shown in Table 2.

### Table 2. Mass and volume of heating surfaces.

| Item                                | Symbol | Unit | Value |
|-------------------------------------|--------|------|-------|
| Portion of feedwater heated to saturate | $b$   | -    | 0.8   |
| Internal diameter of downcomer       | $d_d$  | m    | 0.432 |
| Length of downcomer                 | $l_d$  | m    | 26.73 |
| Height of downcomer                 | $h_d$  | m    | 25.94 |
| Internal diameter of riser           | $d_r$  | m    | 0.051 |
| Height of riser                     | $h_r$  | m    | 22.54 |
| Roughness                           | $k$    | mm   | 0.06  |

3. Results and thermal analysis

In this section, four typical working condition of heat recovery boiler is studied through sectional mass steam quality in risers, circulation rate, and relative validation is made.

Calculated results demonstrate that the heights of evaporating points are 1.68m, 2.20m, 2.81m and 3.97m. And according circulation rate is shown in Fig 1. The formula in literature [4] provides a comparison with present model, which agrees well with present model. It can be also seen that with the decrease of boiler load, the circulation rate increases. It is mainly because the heat absorbed linearly, and water and steam density difference varies little.

![Figure 1. Circulation rate in different working condition.](image)
As shown in Figure 2, volumetric steam quality in risers of four working condition is exhibited. The original point leaving x-axis indicates the point of evaporating in riser. It can be figured out that the 30% BRL working condition evaporates latest and finally reaches 0.47 at riser outlet. It is mainly because the heat load is much less compared with other working condition. Besides 30% BRL working condition, the other working condition (50%, 75% and 100% BRL) shows same rule, namely the height of evaporation point increases as load decreases. However, as the load increases, the riser outlet volumetric steam quality is prone to converge. It is probably because the heat transfer coefficient of steam and water mixture’s characteristic limit the heat transfer efficiency.

![Figure 2. Volumetric steam quality distribution in riser.](image)

As shown in Fig. 3, velocity is solved through equations listed above. It can be found that point where velocity significantly rises is according to location of evaporation point. And the riser outlet velocity is only just above 2.5m/s in 30% BRL working condition, which indicates a possibility of formation of incrusting in tube’s water-side. As load increases, the circulation water flow and heat absorbed increases, thus the riser outlet velocity increases.

![Figure 3. Velocity distribution in riser.](image)

Present paper casts light on the steady working parameter of heat recovery boiler with the help of RK45 method to solve the conservation equation of mass, momentum and energy. The results obtained in present paper are rarely found in thermal design manual, but of great importance to the safe and economic operation of unit, which can be used as reference for operating staff or designers.
4. References

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