Numerical simulation of scale deposition in boiler water wall with different structures

Wu xing¹, Zheng yangyan¹, Wang yining¹, Xie chuanyang², *

¹Special equipment safety supervision inspection institute of Jiangsu province, china
²School of energy science and engineering, Nanjing Tech University, Nanjing, Jiangsu, china
*201961208034@njtech.edu.cn

Abstract: The scale produced by the boiler water wall will affect the heat exchange and shorten its service life. In this paper, based on the Euler-Lagrangian method, the numerical simulation of the accretion rate of the water wall under different dip angles and different flow conditions is carried out. In this paper, the accretion rate is almost power-distributed with the dip angles. From 0° to 60°, accretion rate from $6.55 \times 10^{-2} \text{kg/m}^2\cdot\text{s}$ increases to $0.38 \text{kg/m}^2\cdot\text{s}$. As the Re number increases from about $6 \times 10^4$ to $7 \times 10^4$, the accretion rate declines rapidly and then flattens out. Compared with dip Angle, the influence of velocity on accretion rate is less.

1. Introduction:
Boiler and other heat exchangers generally have the problem of scaling on the heat transfer surface, which affects the flow and heat transfer, and seriously affects the service life of heat exchangers[1, 2]. The fouling formation speed, thickness and fastness are related to the operation condition and equipment scaling condition. In general, it is easy to scale when the flow rate is low, the temperature changes greatly or the temperature difference between the pipe and the wall is large[3]. Rough wall surface or structure with bypass, short circuit are prone to scaling [4].

Xu has deep research on fouling characteristics. He and his team conducted a number of experiments and numerical simulations on dirt deposition in tube heat exchangers[5], plate heat exchangers[6], vortex generators[7], and other heat exchangers. Chamra[8] studied the comparison of corrugated pipe, straight rib pipe and smooth pipe respectively, and obtained the relationship between fouling thermal resistance ratio and geometric size, particle concentration, particle size and wall shear stress. Tang[9] experimentally and numerically investigated turbulent flow of water and heat transfer characteristics in a rectangular channel with discontinuous crossed ribs and grooves. Fahmi Brahimi[10] developed a model which enables the calculation of the density of the fouling layer not only as a function of the local position within the fouling layer, but also as a function of the time-dependent total thickness of the fouling layer. To minimize heat exchanger fouling, Markus Förster[11] defined a modification of these interactions to reduce the corresponding adhesive strength favoring the removal process due to the wall shear stress. Tiina[12] investigated surface crystallization of CaCO₃ and crystallization in the bulk fluid and its effect on the fouling rate on a heated wall.

In this paper, the accretion of calcium and magnesium salts into dirt in the water-cooled wall is studied by numerical simulation, and the accretion rates of water-cooled wall under different structures (dip angles) are compared.
2. Numerical method and physical model

2.1 Geometry model
In this paper, the water wall tube with dip angles of 0°, 15°, 30°, 45° and 60° is used as the geometric model as shown in Fig.1.

Fig.1 Geometric model

2.2 Governing equations
The governing equation is a mathematical description of the nature of physical phenomena\[13, 14\]:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m
\]  

(1)

The equation for conservation of mass (continuity equation) can be written as Eq.(1), \(\rho\) is the density of fluid, \(\vec{v}\) is the velocity, \(S_m\) is the source term for mass transfer. For incompressible flow, the continuity equation is simplified as:

\[
\nabla \cdot (\rho \vec{v}) = S_m
\]  

(2)

The momentum equation:

\[
(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\vec{\tau}) + \rho g + \vec{F}
\]  

(3)

The stress tensor \(\vec{\tau}\) is given by

\[
\vec{\tau} = \mu \left[ \nabla \vec{u} + \nabla \vec{u}^T - \frac{2}{3} \nabla \cdot \vec{v} \right]
\]  

(4)

The energy equation

\[
\frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\rho \vec{v} (\rho E + p)) = \nabla \cdot \left( k_{eff} \nabla T - \sum h_j \vec{J}_j + \left( \vec{\tau}_{eff} \cdot \vec{v} \right) \right) + S_h
\]  

(5)

where \(k_{eff}\) is the effective conductivity \((k + k_t)\), where \(k_t\) is the turbulent thermal conductivity, defined according to the turbulence model being used), and \(\vec{J}_j\) is the diffusion flux of species \(j\). The first three terms on the right-hand side of represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. \(S_h\) includes the heat of chemical reaction which is not considered.

\[
E = h - \frac{p}{\rho} + \frac{\nu^2}{2}
\]  

(6)

For incompressible flows

\[
h = \sum Y_j h_j + \frac{p}{\rho}
\]  

(7)

For nearly turbulent with bulk Reynolds numbers between 3125 and 12500, RNG k- \(\epsilon\) which provides an analytically-derived differential formula for effective viscosity that accounts for low-Reynolds number effects is suitable for flow.

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_i} \left( \alpha_i \mu_{eff} \frac{\partial k}{\partial x_i} \right) + G_k + G_b - \rho \epsilon - Y_M + S_k
\]  

(8)
The accretion rate is defined as

\[ R_{\text{accretion}} = \sum_{p=1}^{N_{\text{particles}}} \frac{m_p}{A_{\text{face}}} \]  

(10)

3. Results and discussion

In this paper, Euler-Lagrange approach is adopted to investigate scale precipitation in boiler water wall. The fluid phase is treated as a continuum by solving the Navier-Stokes equations, while the dispersed phase is solved by tracking a large number of particles through the calculated flow field. The dispersed phase can exchange momentum, mass, and energy with the fluid phase. The particle rebounds off the boundary in question with a change in its momentum as defined by the coefficient of restitution.

3.1 Effect of dip angle

The accretion rate distribution of water wall at angle of 0 and 15 degrees are shown in the Fig 3. It can be seen from the figure that the accretion rate is significantly higher at the dip angle than at other areas.

Fig.3 Distribution of scale accretion
The average scale accretion rate of water cooling walls under different structures is shown in Fig.4. As can be seen, the accretion rate is almost power-distributed with the dip angle. From 0° to 60°, accretion rate from $6.55 \times 10^{-2}$ kg/m²·s increases to 0.38 kg/m²·s, which can be considered that the dip angle has a deep influence on the accretion rate. The relationship between accretion rate and dip angle is coupled as follows:

$$y = 0.0655 + 0.0012x + 5 \times 10^{-5}x^3 + 5 \times 10^{-7}x^3 - 5 \times 10^{-9}x^4$$

(11)

Where $y$ and $x$ represent accretion rate and angle of inclination.

### 3.2 Effect of Re

The accretion rate changes with the flow state, as shown in Fig. 5. As can be seen from the figure, the accretion rate gradually decreases as the flow slows down. As the Re number increases from about $6 \times 10^4$ kg/m²·s to $7 \times 10^4$ kg/m²·s, the accretion rate declines rapidly and then flattens out. Compared with dip angle, the influence of velocity on accretion rate is less.
4. Conclusions
In this paper, based on the Euler-Lagrangian method, the numerical simulation of the accretion rate of the water wall under different dip angles and different flow conditions is carried out. The accretion rate is almost power-distributed with the dip angle, where the corresponding relation is obtained by coupled.

The results show that: decreasing the dip angle can greatly reduce the deposition state. When the flow rate is small, the accretion rate is relatively large. Once Re in the flow state is greater than $7 \times 10^8 \text{kg/m}^2\cdot\text{s}$, there is no significant change in the accretion rate.

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