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A novel approach for the optimal arrangement of tube bundles in a 1000-MW condenser

Key words:

Condenser, Shell-side flow field, Steam condensation model,
Bundle arrangement, Air leakage

Motivation

- The condenser has a multi-phase and multi-component flow field on the shell side.
- The numerical simulation research method most often used is the porous media model.
- However, it has limitations when it comes to capturing the influence of the complexity and heterogeneity of pore structure on the flow field.

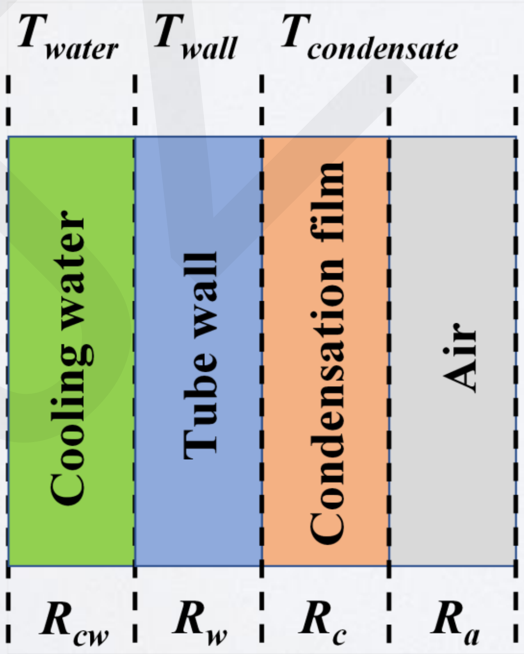
- A novel approach is proposed to address the shortcomings of the porous media model and optimize the condenser tube-bundle arrangement.

Innovation

This work proposes a novel approach to address the shortcomings of the traditional porous media model and optimize the condenser tube bundle layout. In this method, the flow field is divided into two regions, i.e., the condensation region and the non-condensation region. A relatively fine mesh is used in the condensation region, and a source term is added to the governing equations to describe the condensation process of steam.

- **Thell-side flow field**
  - **Non-condensation area**
    - ➢**Area not containing cooling tubes**
    - ➢**Assuming no vapour condensation**
  - **Condensation area**
    - ➢ **Area near containing cooling tubes**
    - ➢ **Area where vapor condensation occurs**
    - ➢ **Steam-condensation model**

Steam-condensation model

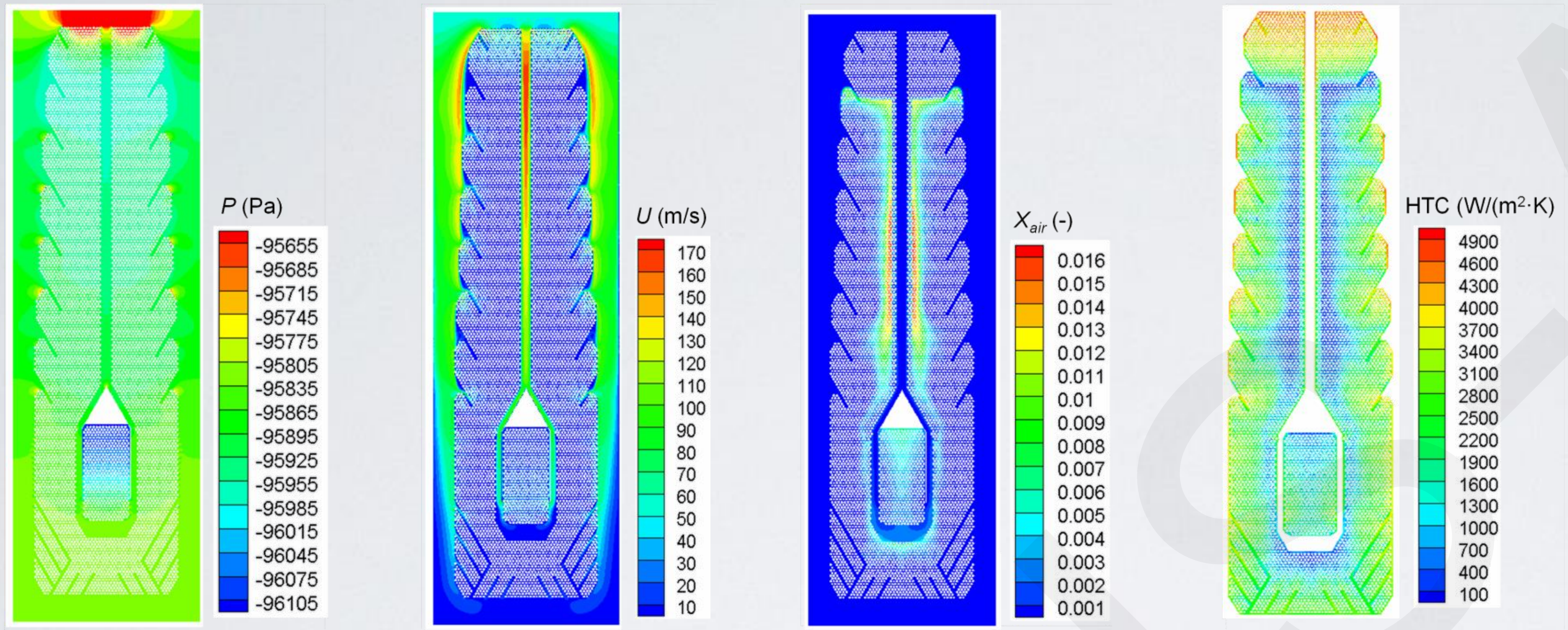


Four-part thermal resistance of the heat transfer process is calculated using relevant empirical equations.

$$R_{total} = R_{cw} + R_w + R_c + R_a$$

$$h = \frac{1}{R_{total}} \qquad \dot{m} = \frac{\Delta t_m A}{R_{total} L}$$

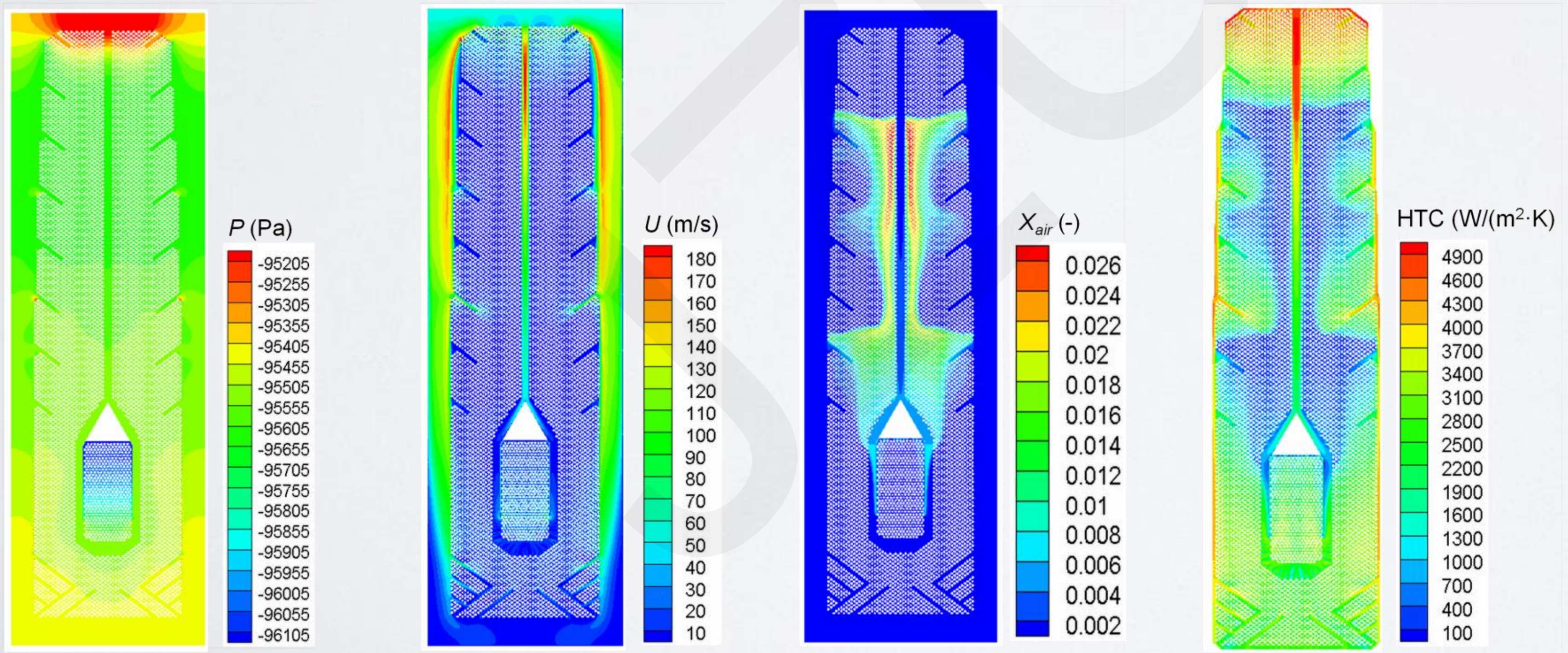
Results of two arrangements



(a) Pressure(Pa) (b) Velocity (m/s) (c) air mass fraction (-) (d) heat-transfer coefficient (W/(m^2·K))

Fig. 1. Contour plots of the condenser with a uniform tube-bundle arrangement

- ➢ From the periphery to the interior of the tube bundle, along with the flow direction of the gas mixture, the water vapor is continuously condensed, resulting in a continuous decrease in the vapor concentration and a gradual increase in the air concentration.



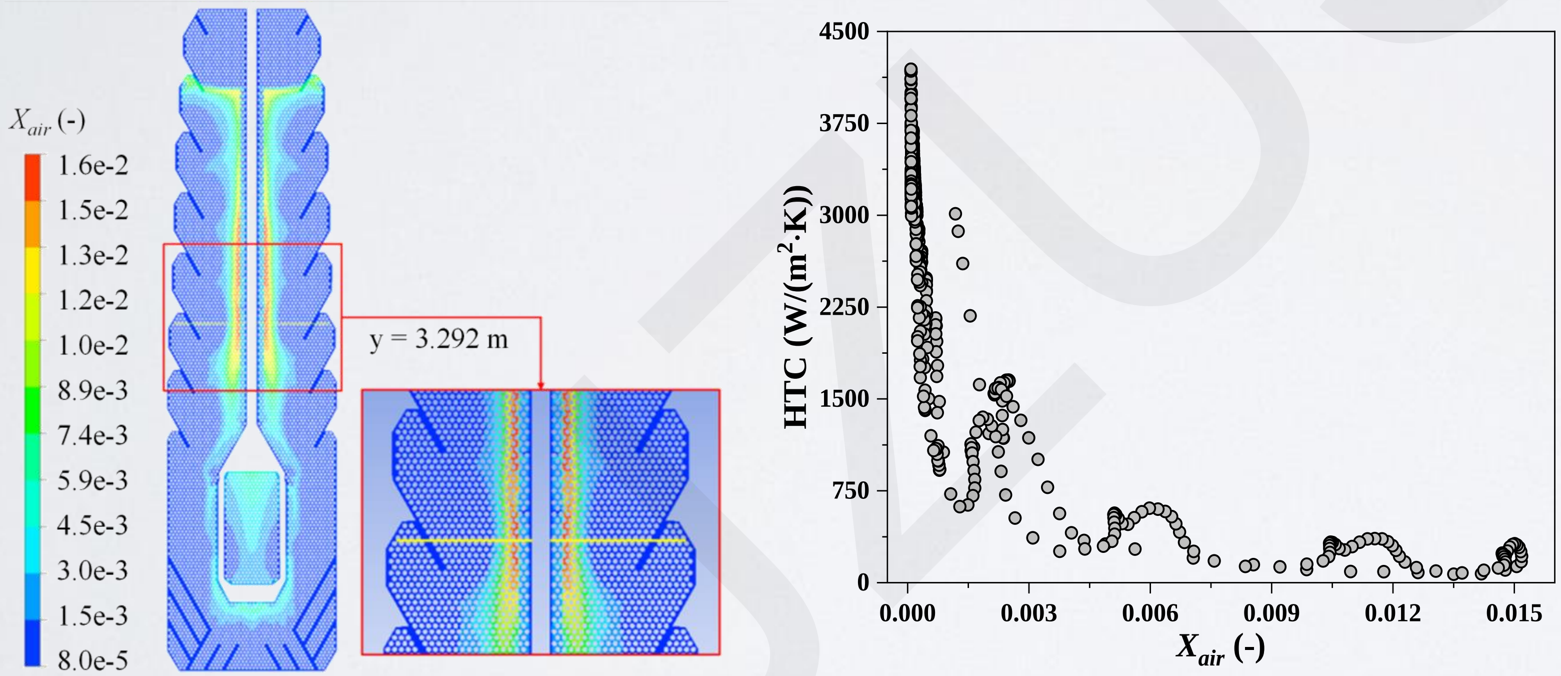
(a) Pressure(Pa) (b) Velocity (m/s) (c) air mass fraction (-) (d) heat-transfer coefficient (W/(m^2·K))

Fig. 2. Contour plots of the condenser with non-uniform tube-bundle arrangement

- ➢ The heat-transfer coefficient has a negative correlation with air concentration.

Underlying mechanism

- With continuous condensation, the partial pressure of water vapor decreases while the partial pressure of air increases, leading to formation of an air layer.
- The water-vapor/air mixture has to diffuse through the air layer before reaching the surface of the liquid film for condensation so that the flow resistance is increased.
- When the diffusion of air molecules leaving the air layer and being carried into it by the main flow reaches a dynamic balance, the air layer is relatively stable.



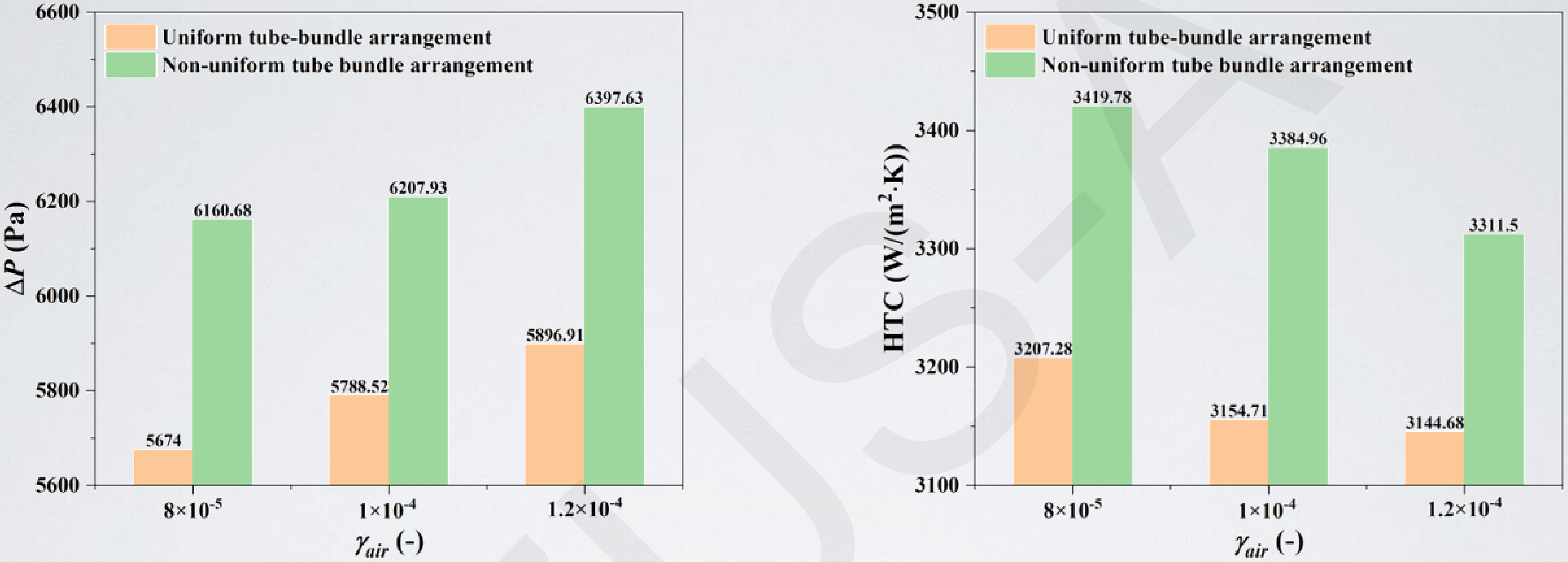
(a) location of the line;

(b) relationship between air mass fraction and heat-transfer coefficient.

Fig. 3. The effect of air concentration on the heat-transfer coefficient.

- As can be inferred from Fig. 3(b), the critical value of the air mass fraction is about 0.001.
- When the air mass fraction increases to 0.001, the heat-transfer coefficient decreases from 4250 W/(m^2·K) to 155 W/(m^2·K), a decrease of 96.35%.

Comparison between two arrangements



(a)

(b)

Fig. 4. Comparison of performance indicators of the condenser with different tube-bundle arrangements: (a) pressure drop (Pa); (b) heat-transfer coefficient (W/(m^2·K)).

- The uniform tube bundle arrangement exhibits a 51.73% lower pressure drop than the non-uniform tube bundle arrangement under rated air leakage conditions. However, the non-uniform arrangement achieves a higher heat transfer coefficient of approximately 200 W/(m^2·K).
- While increasing the leakage air volume increases air concentration and inlet pressure, it leads to a decrease in steam condensation rate. Furthermore, the heat transfer efficiency decreases as the air concentration increases with an increased leakage air volume, resulting in a decrease in the heat transfer coefficient.

Conclusions

- The model we developed demonstrates reasonable accuracy in simulating flow dynamics, as well as the condensation process inside a 1000-MW condenser. Specifically, the predicted pressure drop, condensation ratio, and heat-transfer coefficient exhibit relative errors of 13.5%, 0.3%, and 2.01%, respectively, when compared to the designed values.
- The dynamic balance of the air layer in the main flow is achieved when the air mass fraction reaches a critical value of approximately 0.001. Below this critical value, the heat-transfer coefficient undergoes a dramatic reduction from 4250 $W/(m^2\cdot K)$ to 155 $W/(m^2\cdot K)$, equivalent to a decrease of 96.35%. The region in which the air mass fraction exceeds 0.001 is referred to as the air-accumulation area.
- The uniform tube-bundle arrangement exhibits a 51.73% lower pressure drop than the non-uniform tube-bundle arrangement under rated air-leakage conditions. However, the non-uniform arrangement achieves a higher heat-transfer coefficient of approximately 200 $W/(m^2\cdot K)$. While increasing the air-leakage volume increases air concentration and inlet pressure, it leads to a drop in steam-condensation rate. Furthermore, heat-transfer efficiency decreases as air concentration increases with higher air-leakage volume, resulting in a decrease in the heat-transfer coefficient.