Numerical Study on the Coupling Process of Supercritical Heat Transfer and Combustion in the Boiler

Z X Zhao¹, C Ma¹, Y Q Li¹, D Lu¹, Y S Lin¹, Y Liu¹, C H Dai¹, Q Xiao¹ and J L Gou¹,²

¹Science and Technology on Thermal Energy and Power Laboratory, Wuhan Second Ship Design and Research Institute, Wuhan 430205, China
E-mail: zzxxjtu@163.com

Abstract. The conjugate heat transfer from in-furnace combustion to in-tube supercritical fluid has been numerically investigated in this study. The mathematic model of the conjugate heat transfer process has been constructed. The effects of the heat transfer phenomenons of supercritical fluid in tube and combustion status change in the furnace on the conjugate heat transfer process were analyzed. The results show that the RNG (Renormalization-group) model can better simulate the heat transfer process in the tube and the combustion process in the furnace than the AKN (Abe-Kondoh-Nagano) model. The difference between the two turbulence models for the furnace simulation focuses on the distribution in the high temperature region and the region of the recirculation region.

1. Introduction
Supercritical units have become important development directions for the power industry [1, 2]. In supercritical boilers, vertical water-wall has found wider application than spirally coiled water wall. Since water-wall tube has simple structure and can be easily manufactured and installed, it is commonly used in water wall of the boiler, as well as in heat exchanger in nuclear reactor and other heat transfer equipment. However, the working fluid in the supercritical vertical tube water-wall boiler significantly differs from that in the subcritical boiler in heat transfer characteristics.

Research work on convection heat transfer to the fluid at supercritical pressure has attracted great attention worldwide. Many experiments of heated circular tubes cooled with water or CO₂ have been performed. Comprehensive reviews of earlier experimental studies on heat transfer to supercritical water and CO₂ were provided in [3, 4].

As far as the author concerned, the previous studies were focused mostly on the heat transfer performance of supercritical fluids under the constant heat flux condition instead of practical thermal boundary condition [5]. However, in actual boilers, the heat flux on the water-cooled wall varies significantly along with the furnace height. This is due to the coupling effect of the combustion process in the furnace and the heat transfer process in the water-cooled wall. Therefore, the constant heat flow assumption to study the heat transfer process of supercritical fluid is far from the actual situation in the furnace. To better study the effect of the supercritical heat transfer on the coupled heat transfer process, this study will directly simulate the coupled heat transfer process in the furnace and the tube. The influence of different turbulence models on the simulation results of coupled heat transfer was analyzed.
2. Physical model
This research takes a small vertical kerosene boiler as the research object. The exothermic fuel is burned in the furnace, and the supercritical fluid absorbs heat in the tube. The inner diameter of the furnace is 300 mm, and the inner diameter of the water cooling pipe is 6 mm. The length of the furnace and water cooling pipe is 2.5 m.

3. Methodology
There are processes of evaporation, homogeneous reaction, radiation and convective heat transfer in the furnace, and forced convective heat transfer processes in the tube with supercritical fluid. In this study, the coupled process is simplified to a two-dimensional steady-state process [6].

Continuity equation:
\[
\frac{\partial}{\partial x_i} (\rho u_i) = 0
\]  

Momentum equation:
\[
\frac{\partial}{\partial x_j} (\rho u_j u_i) = \frac{\partial}{\partial x_j} [\mu_m (\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}) - \frac{2}{3} \mu_m \frac{\partial u_i}{\partial x_i}] - \frac{\partial p}{\partial x_j} + \rho g_i
\]  

Energy equation:
\[
\frac{\partial}{\partial x_j} \left( u_i (\rho E + p) \right) = \frac{\partial}{\partial x_j} \left( k_m \frac{\partial T}{\partial x_j} - \sum_j h_j J_{ji} + u_i \langle \tau_{ij} \rangle_{\text{eff}} \right) + \sum_j \left[ \frac{K_f^j}{M_f^j} \int_{r_{\text{ref}}^j} \tau_{ij} c_{p,ij} dT \right] R_j
\]  

Material transport equation:
\[
\frac{\partial}{\partial t} (\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \vec{J}_i + R_i
\]

where, the reaction is assumed one-step, and \( R_i \) is reaction rate based on the Arrhenius law.

The AKN and RNG k–ε models will be applied to this study. In an actual furnace, liquid fuel is rapidly evaporated and burned. The Discrete Ordinates model and the Grey Gas Weighted Average Model (WSGGM). The NIST (National Institute of Standards and Technology) Standard Reference Database was used for calculating the temperature and pressure dependent properties of CO₂. The sensitivity of calculation results to mesh was carefully checked, and the grid independent solutions are obtained. The QUICK scheme was used for discretization of momentum and energy equations [7, 8].

4. Results and discussion
The empirical correlations obtained from previous studies were used to verify the accuracy of this study. As the research on the heat transfer of supercritical fluid has been extensive, a number of empirical correlations [9-13] for different application region have been summarized. Figure 1 shows the comparison of Nu predictions under simulation and previous empirical correlations. The prediction results of different empirical correlations are very different, with a maximum deviation of 100%. This is due to the different experimental conditions, application range and the large-scale test uncertainty. Therefore, it can be seen that the prediction result of XU’s correlation is much higher than other formulas. Except for the empirical correlations of XU, Bishop and HU, the prediction results of other correlations are relatively close. The Nu calculated by the RNG and AKN models are in good agreement with most empirical formulas, and the calculated results of the RNG model agree better.
Figure 1. Comparison of Nu under different models and empirical correlation

Figure 1c shows the relative errors between the simulation results and the empirical correlation results. The calculation errors of the two turbulence models are similar, and the relative errors of the calculation errors of the RNG model are smaller. It can be seen that the deviations of the prediction results of the empirical correlations of XU, Bishop and HU were 70%, 25% and 15%, respectively. But the deviations of the prediction results of other empirical correlations are less than 10%. Therefore, most of the empirical correlations have a good prediction effect on the heat transfer coefficient of the supercritical fluid. The RNG model and AKN model are also relatively accurate for simulating the heat transfer of supercritical fluids.

Figure 2 compares the wall temperature and heat flux distributions calculated by different turbulence models. Overall, the calculation results of the two turbulence models are very close. However, the prediction results of the two models at the enthalpy value of 2343kJ/kg showed a significant deviation. The wall temperature difference is the only 2K, but the heat flux density deviation reaches 26%. This phenomenon shows that when the simulation results of the supercritical fluid heat transfer process in the tube are close, the combustion process in the furnace will also show different phenomena. The region of high-temperature combustion causes local heat flux to increase, but the heat flux has not reached the critical value of heat transfer deterioration. In general, the calculation results of both models are acceptable for the numerical calculation of the process in the tube.

Figure 2. Temperature and heat flux distributions under two turbulence models

Figure 3 compares the trend of the dimensionless Bo* and Kv numbers with enthalpy in the tube under the two turbulence models. As can be seen from Figure 3, the calculated dimensionless numbers of the two turbulence models are also very close. The local difference is also caused by the change in the high temperature combustion zone in the furnace, which corresponds to the change in heat flux in Figure 2. Therefore, based on the calculation results of dimensionless numbers, the simulation results of the two models are very close.
Figure 3. Dimensionless number changes in the tube

Since two different turbulence models are used, it is necessary to compare the effects of the heat transfer phenomena on the combustion process in the furnace. As can be seen from Figure 4, even if the heat transfer process in the tube is very close under different turbulence models, the temperature distribution in the furnace is very different. The main differences focus on the distribution of the high temperature zone and the size of the recirculation zone. It can be seen that the high temperature combustion region calculated by the AKN model is longer by 30%, while the recirculation zone calculated by the RNG model is shorter due to the stronger turbulent mixing and faster combustion.

Figure 4. Comparison of temperature field in the furnace

Figure 5 shows the total wall heat flux and radiant heat flux calculated by two turbulence models. There are many differences in the calculation results of the two turbulence models. The first difference is the heat flux at the position of the recirculation zone. The total heat flux of the RNG is higher, but the peak region is shorter. This is due to the higher temperature and smaller range of the recirculation zone calculated by the RNG model, resulting in higher peak heat flux. The recirculation zone of AKN is relatively longer, which causes the heat flux of the AKN model to be higher than the RNG model after the heat flux peak. In the second half of the furnace, the total heat flux calculated by the two turbulence models are quite close, and the results from the RNG model are slightly higher. The radiant heat flux is closely related to the temperature distribution in the furnace. The radiant heat flux calculated by the two turbulence models is almost equal in the second half of the furnace.
Figure 5. Heat flux distribution under different turbulence models

Figure 6 shows the temperature distribution from different sections. It can be seen that the temperature distributions also differ greatly for the two turbulence models. On the whole, the calculation results of the AKN model have a longer central high temperature region. At x=2000mm, the temperature in the center zone still reached 1600K, while the result of the corresponding RNG model has been reduced to 1300K. In addition, the recirculation zone calculated by the AKN model is relatively backward. When the high temperature recirculation zone of temperature 1600K still exists at x=500mm. Because the main reaction region calculated by different turbulence models are different. The AKN model and RNG model have different simulation results for the combustion and heat transfer phenomena in the furnace. The reaction region calculated by the RNG model is faster, leading to the central high temperature zone. The combustion reaction rate calculated by the AKN model is slower, resulting in a longer temperature combustion zone.

Figure 6. Temperature distribution of different cross sections

5. Conclusions
Numerical simulations have been performed to investigate on coupling process of supercritical heat transfer and combustion. By analyzing the flow field structure and dimensionless parameters, the RNG model can better simulate the heat transfer in the tube than the AKN model. Due to different combustion region, the wall temperature difference is the only 2K, but the heat flux density increases 26%. But, the heat flux has not reached the critical value of heat transfer deterioration due to the high mass flow rate in the tube. The difference between the two turbulence models for the furnace simulation focuses on the distribution in the high temperature region and the size of the recirculation
region. This phenomenon reflects the significant influence of two different turbulence models on the combustion rate in the furnace.

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