Numerical Study on the Influence of Supercritical Heat Transfer Deterioration on the Combustion Process

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Abstract. The conjugate heat transfer from in-furnace combustion to in–tube supercritical fluid has been numerically investigated in this study. The mathematical model of the conjugate heat transfer process has been constructed. The effects of the abnormal heat transfer phenomena of supercritical fluid in tube and combustion status change in the furnace on the conjugate heat transfer process were analyzed. The results demonstrate that the Renormalization-group (RNG) model has better prediction ability. The Abe-Kondoh-Nagano (AKN) model will have an over-prediction problem for the abnormal heat transfer. The RNG model is also more accurate in simulating the combustion process in the furnace.

1. Introduction

Supercritical units have the advantages of high efficiency and good variable-load performance [1, 2]. Kim et al. [3] studied a number of turbulence models for upward flow at supercritical condition. They concluded that the RNG model can obtain the most outstanding prediction with the enhanced near-wall treatment. Koshizuka et al. [4] conducted numerical research about convection to water and CO₂ at supercritical condition. Among the studies [5, 6], many low-Re turbulence models have been checked and compared with experiments under various conditions. It has been found that most low-Re turbulence models can reproduce the deterioration of heat transfer under the influence of buoyancy.

The current research on the heat transfer characteristics of supercritical fluid is mainly simplified by the assumption of constant wall heat flux. 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. As discussed above, the heat transfer of the S-CO₂ flowing in actual boilers is more complex compared to constant wall heat flux. Therefore, the constant heat flow assumption to study the heat transfer process of supercritical fluid is far from the actual situation. In addition, the mass flow of the fluid in the tube will be significantly reduced during low-load operation of the boiler, which will cause the deterioration of supercritical fluid heat transfer. The heat transfer deterioration will not only harmful to equipment but also threaten the stability of the power system. Hence, to promote the overall power system efficiency, it is crucial to get insight the heat transfer characteristics and suppress the heat transfer deterioration.

From the above mentioned researches, few investigations on the coupled heat transfer process were conducted. The objective of this study is to get further insight into the effect of the supercritical heat transfer deterioration 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. Moreover, the influence of heat transfer deterioration in the tube on the furnace process was analyzed.

2. Physical model
This research takes a small vertical fuel-oil boiler as the object, as shown in Figure 1. The fuel combustion of heat release is in the furnace, and heat absorption of supercritical fluid is in the tube. The inside diameter of the furnace is 300 mm. The inside diameter of the water-cooled tube is 6 mm. The length of the furnace and the water-cooled tube is 2.5 m, and the water-cooled wall material is Super304H steel. The operating parameters are shown in Table 1.

![Figure 1. Schematic diagram of vertical fuel oil furnace](image)

Table 1. Operating parameters of the vertical fuel oil furnace

| Parameter                      | Value     |
|-------------------------------|-----------|
| Inlet air temperature         | 303 K     |
| Air inlet velocity            | Axial      |
|                               | 6 m·s⁻¹    |
|                               | Radial     |
|                               | 40 m·s⁻¹   |
| Fuel outlet velocity          | Axial      |
|                               | 40 m·s⁻¹   |
|                               | Radial     |
|                               | 25 m·s⁻¹   |
|                               | Tangential |
|                               | 25 m·s⁻¹   |
| Fuel temperature              | 303 K      |
| Fuel particle size            | 0.1 mm     |
| Fuel mass flow                | 5 g·s⁻¹    |
| Inlet water temperature       | 300-665 K  |
| Inlet water pressure          | 26 MPa     |
| Water mass flow rate          | 0.24 kg·s⁻¹|

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 [7].

Continuity equation:

$$\frac{\partial}{\partial x_i} (\rho u_i) = S_m$$  \hspace{1cm} (1)

Momentum equation:

$$\frac{\partial}{\partial x_i} (\rho u_i u_i) = \frac{\partial}{\partial x_j} (\mu \frac{\partial u_i}{\partial x_j}) - \frac{2}{3} \mu \frac{\partial (u_i u_j)}{\partial x_j} - \frac{\partial p}{\partial x_i} + F_i$$  \hspace{1cm} (2)

Energy equation:

$$\frac{\partial}{\partial x_i} (u_i (\rho E + p)) = \frac{\partial}{\partial x_i} \left( k \frac{\partial T}{\partial x_i} - \sum_h \dot{J}_h + u_i (\tau_{ij})_{ij} \right) + \sum_j \left[ \frac{\dot{h}_p}{M_j} + \int_{c_{ij}}^{c_{ij}} c_{ij} dT \right] R_j + S_i$$  \hspace{1cm} (3)

Material transport equation:

Different scholars are inconclusive as to which turbulence model can better simulate the heat transfer deterioration of supercritical fluids. AKN and RNG $k-\varepsilon$ models have been recommended by many scholars to obtain good prediction results, and all variables and their units can be seen in Ref. [3]. Therefore, the above two turbulence models will be applied to this study. In an actual furnace, liquid fuel is rapidly evaporated and burned. The combustion reaction rate is controlled by turbulent mixing, so a vortex dissipative combustion model is used to simulate the homogeneous combustion process in the furnace [8, 9]. In addition, the DO (Discrete Ordinates) model and the Grey Gas Weighted Average Model (WSGGM) were used to calculate the radiative heat transfer process [10, 11].

4. Results and discussion

Figure 2 compares the wall temperature and heat flux distributions calculated by different turbulence models. The calculation results of the AKN model show obvious wall temperature jump, and the maximum temperature difference between the main body and the wall can reach 70K. The temperature difference calculated by the RNG model is only 30K. This results in the difference in the heat transfer coefficients between the two turbulence models. When the results of the two turbulence models show the deterioration of heat transfer, the corresponding initial heat flux is above the critical heat flux. This heat flux calculated by RNG model was 41250 W/m$^2$, while the heat flux calculated by AKN model was less than 31000 W/m$^2$. The predicted value of the critical heat flux for heat transfer deterioration by Yamagata’s correlation ($q_c = 0.20G^{1.2}$) is 57.8 kW/m$^2$, while the predicted value by Styrikovich’s correlation ($q_c = 0.58G$) is 48.3 kW/m$^2$. The calculated result of the RNG model is closer to the previous empirical correlation, while the calculated result of the AKN model is at least 40% smaller than predicted result of empirical correlation. From the critical heat flux, the calculation result of RNG model is better than that of AKN model.

Under the AKN model, the temperature difference between the wall surface and the main fluid is not higher than 70K. When the heat transfer is normal, this temperature difference is about 10K. Under the deterioration, the heat transfer coefficient is reduced to 20%. The temperature difference is increased by 5 times. However, this wall temperature change has little effect on the combustion process in the furnace.

![Figure 2. Temperature and heat flux distributions under two turbulence models](image)

The empirical formulas 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 in the different applications have been summarized (Table 2).
Table 2. Empirical correlations in different applications

| Empirical correlation          | Parameters                                                                 |
|-------------------------------|-----------------------------------------------------------------------------|
| Dittus-Boelter[12]            | \( Nu = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} \)                           |
| McAdams[13]                   | \( Nu = 0.0243 \text{Re}^{0.8} \text{Pr}^{0.4} \)                          |
| Jackson[14]                   | \( Nu = 0.0183 \text{Re}^{0.82} \text{Pr}^{0.4} \cdot \left( \frac{\rho_u}{\rho} \right)^{0.3} \) |
| Bishop[15]                    | \( Nu = 0.0069 \text{Re}^{0.8} \text{Pr}^{0.66} \cdot \left( \frac{\rho_u}{\rho} \right)^{0.40} \cdot \left( 1 + 2.4 \frac{D}{L} \right) \) |
| Swenson[16]                   | \( Nu = 0.00459 \text{Re}^{0.923} \text{Pr}^{0.613} \cdot \left( \frac{\rho_u}{\rho} \right)^{0.231} \) |
| Chou and Watts                | \( Nu = 0.021 \text{Re}^{0.8} \text{Pr}^{0.55} \cdot \left( \frac{\rho_u}{\rho} \right)^{0.35} \) |
| HU                            | \( Nu = 0.0068 \text{Re}^{0.8} \text{Pr}^{0.63} \cdot \left( \frac{\rho_u}{\rho} \right)^{0.17} \cdot \left( \frac{\lambda_u}{\lambda} \right)^{0.29} \) |
| XU                            | \( Nu = 0.02269 \text{Re}^{0.877} \text{Pr}^{0.9213} \cdot \left( \frac{\rho_u}{\rho} \right)^{0.628} \cdot \left( \frac{\eta}{\eta} \right)^{0.3607} \) |

Figure 3 shows the comparison of Nu predictions under the two models and previous empirical correlations. Nu calculated by RNG model agrees well with most empirical correlations. Especially, these calculation results are in good agreement with the empirical correlations of Xu and Jackson, and these correlations are also the most widely applicable empirical correlations, indicating that the calculation results of the RNG model have certain accuracy. Nu calculated by the AKN turbulence model does not agree well with most empirical correlations. In the most regions, the heat transfer coefficient predicted by the AKN model is much smaller than the predicted value of the empirical calculation. The AKN model has the problem of over-prediction in predicting the deterioration phenomenon. The predicted region and amplitude of deterioration are larger than the empirical results.

![Figure 3](image1.png)  
![Figure 3](image2.png)

**Figure 3.** Comparison of Nu under different models and empirical correlation

Figure 4 shows the relative errors between the calculation results and the empirical correlation. The relative error of the AKN model is much larger than that of the RNG model. The relative error of the RNG model is positive or negative, and the specific error value is not more than 25%. The calculation results of the AKN model are all positive values, indicating that the calculation results are less than the predicted value of the empirical correlation. Moreover, the specific value of its relative error is much larger than the result of the RNG model, and maximum deviation reached 250%. Therefore, it can be considered that the results of the RNG model are more accurate than that of the AKN model.

![Figure 4](image3.png)

**Figure 4.** Comparison of the relative errors between the calculation results and the empirical correlation.
Since two different turbulence models are used to obtain two different heat transfer phenomena, it is necessary to compare the effects of the two heat transfer deterioration phenomena on the combustion process in the furnace. Figure 5 shows that the temperature distribution in the furnace calculated by the two turbulence models is quite different. The flame length calculated by the AKN model is relatively longer, and the outlet temperature is relatively higher. In addition, the size and location of the recirculation zone are significantly different.

Figure 6 shows the temperature, velocity and CO₂ concentration distribution in the furnace calculated by the two turbulence models. The distributions calculated by the two models are quite different. There are two reasons for this phenomenon. The first reason is that the AKN model and RNG model have different simulation results for the combustion and heat transfer phenomena in the furnace. The second reason is that the local wall temperature rise has been calculated by the AKN model. This wall temperature rise phenomenon has affected the distribution of various fields in the furnace. The two reasons together lead to the difference in the calculation results of the furnace process.

Figure 4. Average error of calculation result and empirical correlation

Figure 5. Comparison of temperature field in the furnace

Figure 6. Velocity, temperature and CO₂ distribution in the furnace
5. Conclusions
Numerical simulations have been performed to investigate on coupling process of supercritical heat transfer deterioration and combustion. The wall temperature calculated by the AKN model and the RNG model is very different. The wall temperature predicted by the AKN model has a sudden rise. By comparing with previous empirical correlations, it can be considered that the RNG model has better prediction ability. The AKN model will have an over-prediction problem for the abnormal heat transfer. The RNG model is also more accurate in simulating the combustion process in the furnace. The change in wall temperature has a slight influence on the combustion process in the furnace.

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