Prediction of the Heat Transfer Deterioration for a Supercritical Pressure Water Flowing Vertically Upward in a Heated Tube

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1. Introduction

The Supercritical Water Cooled Reactor(SCWR) is being developed with it's operational conditions of a pressure over 25MPa and temperature of 290~550°C[1]. Many experiments have observed that the heat transfer coefficient of a fluid in the pseudo-critical region shows a different behavior from that of the conventional forced convection. One very specific characteristic of the heat transfer is called the 'heat transfer enhancement', or 'normal heat transfer' which shows a larger heat transfer coefficient than the Dittus-Boelter correlation in a relatively low and moderate ratio of the wall heat flux to the mass velocity(q/G). At a high heat flux, the wall temperature increases sharply and the heat transfer coefficient becomes low. This phenomenon is called 'heat transfer deterioration'[2, 3]. This paper is focused on the prediction capability of the heat transfer deterioration. In order to examine the reliability of the embedded turbulence models of FLUENT at a supercritical pressure, a series of simulations for the vertical upward flow of water in a heated tube were performed.

2. Numerical Methods

The schematic diagram of the computational domain is shown in Figure 1. We deal with the steady state and the computational domain as axisymmetric for simplicity. To obtain a fully developed flow field before a heated region, additional lengths of an unheated tube are attached to the domain before the heated length. For a comparison with the Yamagata et el.[4]'s experiment, the mass velocity of the simulation is assumed as 410kg/m^2·s and the wall heat fluxes have 230, 350, and 465kW/m^2, respectively. The diameter of the heated tube is 10 mm. Inlet temperature in the simulation is selected to obtain a similar range for the bulk enthalpy to the experiment.

The selected turbulence models for the test are; Standard k-ε(SKE), RNG k-ε(RNG), k-ω(KW), and the Abid(AB) model. The last model is one of the candidates among the low-Reynolds k-ε models and selected for this study.

In supercritical pressure conditions, the influence of a large variation of the fluid properties near the wall region is very important. So, for the SKE and RNG models, enhanced wall treatments are used as wall boundary conditions. The low Reynolds turbulence AB model requires that the first grid off the wall has a height of $y_1^+ < 1$ [5, 6]. Thus all the models have a fine grid at the wall and the grid size and therefore the aspect ratio of the grid becomes very large.

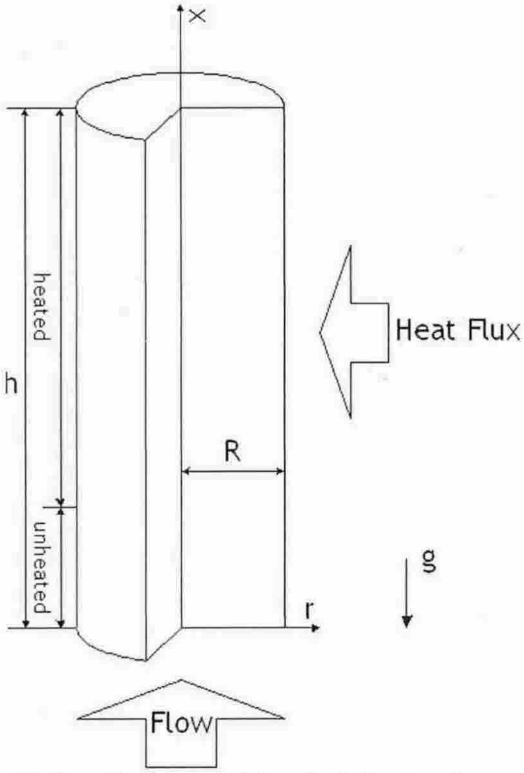

Figure 1 Schematic diagram of the calculation domain

3. Results and Discussions

3.1 Wall Temperature Distributions

At the heat flux of 465kW/m^2, the predictions by the SKE and RNG models do not reproduce the experiment any more, especially at the pseudo-critical region as shown in Figure 2. On the other hand, the KW and AB models show a qualitatively localized wall temperature peak at the entrance region and a broad peak which extends over a wide range of the bulk fluid enthalpy below the pseudo-critical point as shown in the experiment. But the temperature difference is too big to be called a prediction. At the high enthalpy region beyond the pseudo-critical point, the SKE and RNG models predict the experiment well.

The low-Reynolds model uses damping functions which are included in the eddy viscosity deduction equation and the production and dissipation terms in the dissipation rate transport equation. The damping functions are developed to be compatible with the incompressible simple flow. In the simulations at a supercritical condition, the variation of property changes may alter the behavior of the damping functions. This change reduces the turbulence level drastically, and results in a wall temperature increase. The models with a specific dissipation rate transport equation are better than low-Reynolds number models for the heat transfer deterioration region.

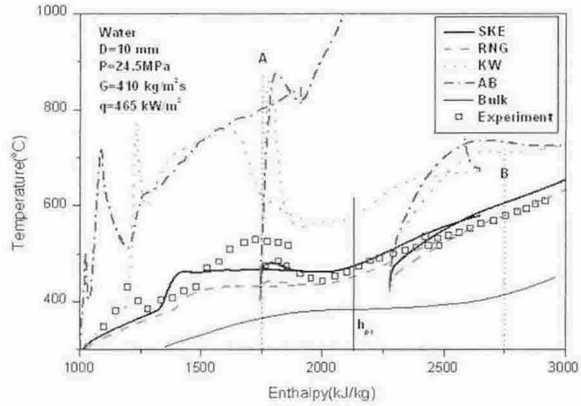

Figure 2 Comparison of the wall temperature according to the turbulence models at q_w=465 kW/m^2

3.2 Heat Transfer Deterioration Mechanism

To study the mechanism of the heat transfer deterioration, the cross-sectional mean stream-wise velocity, temperature distributions and turbulence kinetic energy were compared between the models for the case of a heat flux of 465kW/m^2.

The flow patterns near the pseudo-critical point (point A in Figure 2) predicted by all the models are laminar near the wall. It is well known that the flow near the pseudo-critical point experiences a rapid acceleration when a strong heat flux is imposed. This flow acceleration changes the turbulence structure and leads to a re-laminarization when its magnitude is large. Figure 3 shows that the SKE and RNG models overestimate $<k/u_{center}^2>$. And their net effect leads to a dissipation of the thermal energy to the neighboring region and consequently lowers the wall temperature. On the other hand, the KW and AB models underestimate $<k/u_{center}^2>$ and fail to dissipate the thermal energy. Especially, all the models need some modifications to improve their accuracy in their predictions for the regions near the pseudo-critical point. At a higher enthalpy region downstream of the pseudo-critical (point B I Figure 2), the SKE and RNG models seems to predict a wall temperature approximately similar to the experimental data by assuming the flow pattern as a turbulent one. But the KW and AB models still assume the flow as laminar, the remarkable differences in the wall temperature result from that difference in the flow pattern.

It can be interpreted that the flow pattern near the wall at the pseudo-critical point region was laminar but changed to a turbulent one as the flow reached sufficiently far downstream of that point.

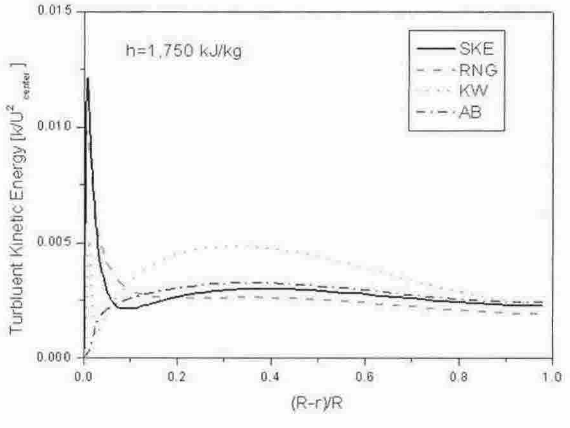

Figure 3 Comparison of the predicted turbulent kinetic energy when q_w=465 kW/m^2 (at point A)

4. Conclusion

In the normal heat transfer enhancement regions, the RNG k-ε model with on enhanced wall treatment option reproduced best the experiment. But, in the heat transfer deterioration regions, the difference between this model and the experiment was remarkable. The heat transfer trend predicted by the KW and AB models were qualitatively similar to that of the experiment. Therefore, in the heat transfer deterioration regions, one of the low–Reynolds number k-ε models could be a candidate for a reasonable solution if some modifications are made.

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