Supercritical heat transfer phenomena in nuclear system

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1. Introduction

A supercritical water (SCW) power cycle has been considered as one of the viable candidates for advanced fission reactor designs. However, the dramatic variation of thermo-physical properties with a modest change of temperature near the pseudo-critical point make existing heat transfer correlations such as the Dittus-Boelter correlation [1, 5] not suitably accurate to calculate the heat transfer in supercritical fluid. Several other correlations [2] have also been suggested but none of them are able to predict the heat transfer over a parameter range, needed for reactor thermal-hydraulics simulation and design. This has prompted additional research to understand the characteristic of supercritical fluid heat transfer.

2. Approximation of FLUENT and review of supercritical water experiment

The commercially available CFD code, FLUENT, with the standard k-ε model and the standard wall function, was tested to determine its usefulness for heat transfer predictions over a large range of conditions.

When Reynolds decomposition was used for density as well as velocity and enthalpy, time-averaged equations for the turbulent supercritical flow contains several additional terms ($-\overline{u_j}\overline{\rho u_i{}'}-\overline{u_i}\overline{\rho u_j{}'}-\overline{\rho' u_j{}' u_i{}'}$, $-\overline{h}\overline{\rho' u_j{}'}-\overline{u_j}\overline{\rho' h'}-\overline{\rho' u_j{}' h'}$) dependent on variable properties. Assuming that the density and enthalpy fluctuation is neglected, the standard k-ε model in FLUENT, only developed for $\overline{\rho u_j{}' u_i{}'}$ and $\overline{\rho h' u_j{}'}$, can be employed in the supercritical fluid. The turbulence model might have to determine these parameters importance and to be modified to include the additional terms. It is necessary to measure and evaluate them experimentally or with DNS prediction. The standard wall function used for this study also has several assumptions that may not hold for application to supercritical fluids: neglecting buoyancy effect, considering all thermo-physical properties to be constant, and using the existing several empirical constants. Even though the above assumptions are expected to yield predictions of supercritical fluid heat transfer with limitations, the standard k-ε model and standard wall function were used at this stage of the analysis.

The computer model was compared with two sets of experimental data, Yamakata [3] and Shitsman [4], which covered several conditions with heat flux ranging from 220 - 930kW/m^2 and mass flux ranging 430 - 1260 kg/m^2-sec. The variable properties in these conditions were used to be only a function of the temperature with piece-wise linear methods. For the mesh generation, it was obtained with a sufficiently fine mesh in the region where the flow changes rapidly. The distance from the wall at the wall-adjacent cells, which the wall function was used for, was also determined by considering the range over which the law of the wall was valid (y^+=30).

3. Discussion of results and development of general criterion

3.1 Discussion of FLUENT results

As seen in Figure 1, FLUENT simulations with the existing model show good agreement with Yamakata's experimental results. In particular, the computed results in the low heat flux condition (233kW/m^2) were in excellent agreement with the experimental results. At high mass flux given our assumptions, FLUENT could predict the supercritical flow phenomena even in the region of $T_b < T_{psc} < T_w$.

In the case of Shitsman's data (low mass flux cases) however, of most interest was the fact that FLUENT could not predict the wall temperature peaking phenomena that was observed experimentally. This is thought to be due to the fact that the wall function neglects buoyancy effect according to density difference and the dramatically variable thermo-properties effect near the wall. It is clear that the FLUENT prediction would no longer be valid with the current models when these conditions are satisfied. As seen in Table 1, the temperature difference of cell region y^+>30 was small (ΔT<7^{o}C), but those near the wall (y^+<30) were larger (ΔT>20^{o}C). Therefore, the existing standard k-ε model, which was used in the main flow (y^+>30), may be an acceptable assumption in capturing the physics. The wall function model, which was used at the first calculational cell (y^+<30), played an important role in determining the wall temperature and heat transfer coefficient. When the temperature increased in the vicinity of T_{ps}, the thermo-physical properties changed dramatically. Since the change in the density in this region is so dramatic, it would lead to a critical buoyancy and acceleration effect and the velocity and temperature profile near the wall could change. Therefore in these cases, it may be more important to use a modified wall function model including variable properties, buoyancy and acceleration effect rather than concentrate on the turbulence model. This is an area of future work for our analysis.

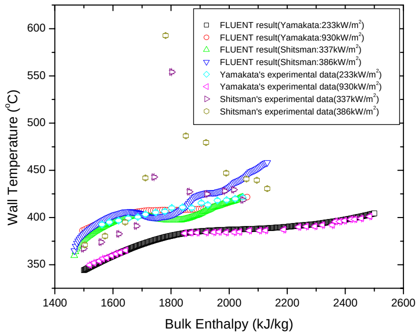

Figure 1. Bulk enthalpy vs. wall temperature

Table 1. Temperature difference at $y^+<30$ and $y^+>30$ (Shitsman's 386kW/m^2 case)

Region(m)	0.01	0.39	0.70	1.01	1.32	1.48
$y^+>30$(°C)	6.94	4.21	0.69	2.14	4.22	6.21
$y^+<30$(°C)	34.3	32.9	22.8	44.3	58.1	67.7

3.2 Development of new general criterion

As seen in the above results, FLUENT had a good agreement with the limited conditions where the buoyancy effects can not be neglected in the low mass flux condition, especially under the conditions where dramatic variations of thermophysical properties occur. There have been criteria proposed for classifying such conditions with supercritical fluids [2, 5]. However, the criteria need specific local values in fluid or do not successfully predict the observed behavior for several cases. From this perspective, a new general criterion dependent on the heat and mass flux but not on local conditions was developed to classify the conditions where this standard model was applicable.

$$\frac{1}{Fr} = \frac{1}{\mathrm{Re}^2}\frac{\rho g D^3}{\mu^2}\left(-\left.\frac{\partial \rho}{\partial T}\right|_p \frac{q_w''}{\left(\frac{k}{D}\right)Nu}\right) \tag{3}$$

Figure 2 shows a graph comparing this local criterion using experimental data with the proposed global criterion using Bishop's heat transfer correlation [2] and the average temperature defined by the mean of the inlet and pseudo-critical value without specific experimental data in flow. A global Froude number, 1/Fr for Yamakata's cases is below 0.01, but those of Shitsman's cases are above 0.01. This indicates that Shitsman's conditions are affected by buoyancy and heat transfer deterioration for these conditions. Therefore, global 1/Fr can be used as criterion which will determine under what conditions the buoyancy effect will be dominant and whether the heat transfer deterioration will occur because equation (3) is derived from the Froude number. In addition, global values of all cases are located between the maximum local 1/Fr and the averaged local values, which means that global values can be considered as a reasonable representation value for any condition. Given a more reasonable heat transfer correlation for supercritical fluid conditions from various experiments, the occurrence of local phenomena such as wall temperature excursions for supercritical fluids can be predicted using equation (3).

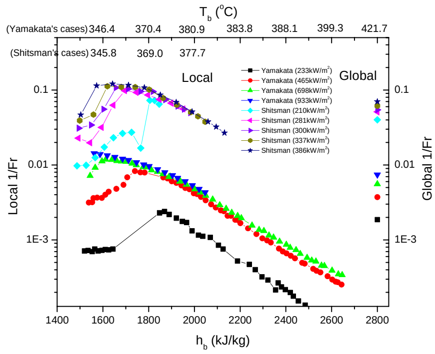

Figure 2. Local and global 1/Fr values

4. Conclusion

FLUENT employed several assumptions was tested to determine its usefulness for heat transfer predictions over a large range of conditions. The simulations showed a surprisingly good agreement with high mass flux conditions however, had difficulty predicting the localized heat transfer degradations seen in high heat flux and low mass flux conditions. Therefore, we are now pursuing theoretical modifications to handle variable property, buoyancy and acceleration effects, which could occur at low mass flux. A new criterion, global Froude number (Fr), dependent on the heat and mass flux, was developed to classify the conditions where this standard model was applicable and determine under what conditions the buoyancy effect will be dominant and whether the heat transfer deterioration will occur. This global criterion had similar trends with a local criterion which used the specific information from specific experimental data for the supercritical fluid.

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