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An improved correlation on the onset of heat transfer deterioration in supercritical water

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ABSTRACT

On the basis of the supercritical water experimental data, the distribution of onset heat flux is analyzed for the heat transfer deterioration. This study evaluates the performance of empirical correlations for the prediction of heat flux, causing the onset of heat transfer deterioration in vertical tubes of supercritical water. In light of the calculation results, it is shown that the onset of heat transfer deterioration effect is better predicted using the Mokry, Li and Schatte criterion. On the basis of experimental data, a new correlation is developed for predicting the heat flux, which causes the onset of heat transfer deterioration in supercritical water. The new calculation model has considered the influence of mass flux, pipe diameter, pressure and inlet temperature. The newly developed correlation has an average relative error of 0.020837 and an average absolute deviation of 0.1627. The improved criterion is more conducive for the design of supercritical water reactors in the future.

1. Introduction

Supercritical-Water-cooled Reactor is internationally recognized as one of the potential IV generation nuclear reactors. Due to its high thermal efficiency and lower economic costs, the supercritical water reactor is strongly competitive with other reactor concepts in the future. Based on its characteristics, the supercritical fluid heat transfer (in tubes and channels) has been a heavily-studied topic in the past five decades. A vast number of experiments have been carried out for the heat transfer in supercritical water. When supercritical water heat transfer deterioration (HTD) phenomenon occurs, the pipe wall temperature rises very quickly. This will lead to the emergence of wall temperature peak value. The heat transfer coefficient between the pipe wall and fluid becomes abnormally low around the location of this peak value. This is a serious threat to the safe and stable operation of the supercritical water reactor. Therefore the initial heat flux value, causing the onset of HTD for the design of the supercritical water reactor, has a crucial significance.

Through the analysis of the experimental study of supercritical water and supercritical CO_2, Pioro and Duffey (2005) showed that the deteriorated heat transfer usually appears at higher heat fluxes and lower mass fluxes. This phenomenon can be suppressed by increasing the turbulence level with flow obstructions. Zhang et al. (2012) presenting an improved k-ε/k_t-ε_t model. Near heat transfer deterioration, the wall temperature is well-predicted by the new model, compared with the traditional low-Reynolds models and traditional k-ε turbulence models. The results show that the buoyancy effect redistributes shear stress and radial flow velocity, leading to heat transfer deterioration and recovery. The new model can predict heat transfer deterioration more accurately. Sharabi et al. (2008) carried out an analysis on supercritical CO_2 within triangle and square channels. Due to the buoyancy effect, the heat transfer deterioration phenomenon is observed in supercritical CO_2. Through simulation the three-dimensional features of the fluid under strong buoyancy in different channel shapes is discussed. It facilitates a better understanding of the mechanism of heat transfer deterioration phenomenon. Wen and Gu (2011) found that the change of dynamic viscosity and specific heat (at constant pressure) can suppress the heat transfer deterioration. However, a decrease in thermal conductivity can promote the heat transfer deterioration phenomenon. Eter et al. (2016) carried out the supercritical CO_2 heat transfer deterioration experimental research in a three-rod bundle equipped with wire-wrap and grid spacers. When the mass flux is lower (200 kg/m^{2}s − 700 kg/m^{2}s), the heat flux exceeds a certain degree and heat transfer deterioration occurs. Gu et al. (2015) performed experimental research on supercritical water inside circular tubes. It was believed that when the DNB ratio (ratio of actual to

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calculated heat transfer co-efficient) is lower than 0.3, the heat transfer deterioration may occur at any random point. Because it was observed that when the ratio is 0.3, there is a continuous change. It is believed that the ratio of 0.3 does not represent any physical phenomena with a specific behavior. Thus, the change of heat transfer coefficient is mainly based on the acceleration number π_A and buoyancy number π_B. Hence the very definition of heat transfer deterioration is still controversial and having nounified conclusion. Podila and Rao (2015) simulated the heat transfer deterioration phenomenon in supercritical water reactor bundle channel tube. The study shows that when the mass flux is lower, an increase in the inlet temperature or system pressure can effectively suppress the occurrence of heat transfer deterioration phenomenon. Liu et al., 2013a,b) found that when the mass flux is high, the effect of acceleration plays a vital role in heat transfer deterioration. And at low mass flux, the buoyancy effect plays an important role for the heat transfer deterioration. When the pipe diameter is larger, it will result in a higher wall temperature, hence the heat transfer is more likely to deteriorate. At high mass flux, heat equivalent diameter is comparable with the hydraulic diameter, also playing an important role in heat transfer deterioration. Yildiz and Groeneveld (2014) analyzed and summarized the effect of pipe diameter size on the heat transfer deterioration in a supercritical medium (CO_2, water, R-22 and R-12). Studies show that increasing the pipe diameter will reduce the initial heat flux value, causing the heat transfer deterioration phenomenon. When the mass flow rate, heat flux and the axial length are constant, the fluid acceleration effect (due to fluid expansion) will be more obvious in pipes of smaller diameter. Whereby for pipes of larger diameter, it will have a more pronounced buoyancy effect. The thickness of the low density layer (near the wall) is increased in such pipes, hence resulting in more critical heat transfer deterioration. In solar central heating systems, Zhang et al. (2016) studied the heat transfer deterioration in vertical pipelines under unilateral non-uniform condition. Based on the non-uniform heating characteristics of solar energy, a suitable heat transfer deterioration criteria was proposed, along with the calculation scheme for that condition. Based on earlier experimental data for supercritical media, Jackson (2013) proposed an approach for describing the combined effects on heat transfer of buoyancy and acceleration. It can help to interpret experimental data on heat transfer at supercritical pressure. Thereby, it becomes possible to use the supercritical flow experimental data for guiding the thermal-hydraulic system design. At the same time, the mechanism of heat transfer deterioration is also analyzed. Jager et al. (2011) analyzed the calculation results of TRACE code for the heat transfer coefficient of supercritical water, comparing them with the results of different correction formulae. It is suggested that Bishop, Sandberg and Tong empirical formulae can be used as recommended formulae for nuclear reactor safety assessment and design. It is also suggested to evaluate and validate the experimental data of heat transfer deterioration, which occurs in high power and lower mass fluxes. Zahlan et al. (2015) and Loewenberg et al. (2008) analyzed the heat transfer characteristics of supercritical water in the form of a look-up table. Although this method has a higher accuracy, it is effective under the range of limited experimental parameters. Jingjing et al. (2014) used the sensitivity analysis method on some parameters of artificial neural network, getting the influence of different parameters on the sensitivity of critical heat flux (CHF). Huang et al. (2016) evaluated five different criterion for the prediction of heat transfer deterioration. It was pointed out that heat transfer deterioration is a very complicated phenomenon. This phenomenon has a close relationship with heat flux, mass flux, medium, pipe diameter, geometry, system pressure and so on.

In the above discussion, various studies have analyzed the heat transfer deterioration phenomenon from all kinds of aspects, such as the experimental research, numerical simulation analysis, calculation model optimization, code calculation analysis, mechanism analysis and the usage of look-up tables. Since the physical parameters of supercritical water change continuously during the process of pseudo-critical transition, it is affected by buoyancy as well as fluid acceleration at the same time. Therefore, the occurrence of heat transfer deterioration and its development mechanism in the supercritical water, is regarded as an extremely complex phenomenon. Amongst the academia, there is still a lack of unified conclusion on this subject. This article presents a study on the heat transfer deterioration calculation formula, based on an initial power value of the supercritical water, which is conducive to the design and development of future supercritical water reactors.

2. Calculation model

2.1. Definition of heat transfer deterioration

When heat transfer deterioration phenomenon occurs then the heat transfer coefficient decreases suddenly up to a very low value compared to the normal heat transfer. And the wall temperature will suddenly rise very quickly. So far in academia, the definition of deterioration of heat transfer of supercritical water is not specified in a widely accepted form. For comparing the formula about predicting deterioration heat transfer in supercritical water, a quantitative definition in terms of the heat transfer coefficient is necessary. The general definition of heat transfer deterioration has been proposed by Koshizuka et al. (1995). It is used frequently in research paper is the following:

$$\alpha < 0.3\cdot\alpha_{\mathrm{DB}} \tag{1}$$

In this definition, α_{DB} is the heat transfer coefficient under normal circumstances, as calculated by the Dittus-Boelter correlation. The D-B correlation is shown below:

$$\alpha_{\mathrm{DB}} = \frac{\lambda_{\mathrm{b}}\cdot Nu_{\mathrm{b}}}{d_{\mathrm{i}}} = \left(\frac{\lambda_{\mathrm{b}}}{d_{\mathrm{i}}}\right)\cdot 0.023\cdot \mathrm{Re}_{\mathrm{b}}^{0.8}\cdot \mathrm{Pr}_{\mathrm{b}}^{0.4} \tag{2}$$

$$\mathrm{Re}_{\mathrm{b}} = \frac{G\cdot d_{\mathrm{i}}}{\eta_{\mathrm{b}}} \tag{3}$$

$$\mathrm{Pr}_{\mathrm{b}} = \frac{\eta_{\mathrm{b}}\cdot c_{\mathrm{p,b}}}{\lambda_{\mathrm{b}}} \tag{4}$$

where λ_{b} is the bulk thermal conductivity (W/m K), d_{i} is the pipe diameter (mm), G is the mass flux (kg/m^{2}s), η_{b} is the bulk dynamic viscosity (Pa.s) and $c_{\mathrm{p,b}}$ is the bulk specific heat at constant pressure (J/kg K).

2.2. Existing criterion for the onset of heat transfer deterioration

There are nine different power criterion, proposed for the calculation of onset of heat transfer deterioration. These criterion are summarized in Table 1:

From the existing criterion, as listed in Table 1, it can be seen that most of the criterion consider only the mass flux, pipe diameter, or pressure alone. But there is a lack of criterion which consider the mass flux, pipe diameter and pressure altogether. Although the No. 9 criterion has considered the influence of flow pipe diameter, mass flux and pressure, but because the specific heat at constant pressure and coefficient of thermal expansion the pseudo-critical point change with the change of pressure, these two parameters are a function of pressure, generally not directly obtained, so they are need to be calculated first. So the use of this formula process increases the complexity. It is important to consider the influence of multiple parameters and that the criterion to be as simple as possible.

2.3. Model for regression analysis of heat transfer deterioration

When calculating the initial heat flux (causing heat transfer deterioration), four parameters considered; the mass flux, pipe diameter, pressure and the inlet temperature, respectively. The calculation form is shown in Eq. (5). This problem can be solved by multiple regression