COUPLED ANALYSIS OF HEAT TRANSFER AND FLOW OF SUPERCRITICAL WATER IN VERTICAL TUBES

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Abstract

Convective heat transfer of supercritical water is compled with flow due to the sharp variation of thermo-physical properties in the neighborhood of the pesudo-critical temperature.The compled analysis of heat transfer and flow of supercritical water is performed. Based on the analytical results, buoyancy and acceleration effect both reduce the Reynolds stress in the boundary layer due to increase the pressure grads in the bulk kinetic position. The empirical correlations of heat transfer are feasible and applicable which involve the coupled connection of convective heat transfer and flow of .supercrtical water.

Keyword: Supercritical Water Reactor (SCWR); coupled analysis， heat transfer, flow, empirical correlation

1. Introduction

Supercritical water-cooled reactor (SCWR) system has been regarded as an innovative system due to its high thermal efficiency over 40% and simplified direct steam cycle and selected as one of Generation IV reactor concepts. Reactor core designs adopting supercritical pressure water cooling have been successively achieved. Since supercritical pressure water is single phase over all operation temperature, there is no phenomenon associated with burnout or dry-out along the fuel rod unlike in current light water reactor. For this reason, peak cladding surface temperature (PCST) has been a crucial design criterion rather than DNB or CPR to avoid cladding overheating over the fuel lifetime.

Due to the strong variation of thermal-physical properties in the vicinity of the pseudo-critical point, heat transfer of supercritical fluids shows abnormal behavior compared to that of conventional fluids. In spite of extensive studies in the past five decades and a large number of prediction models, prediction of heat transfer of SC fluids uses mainly empirical approaches. In the open literature there exist a large number of empirical correlations, which were derived based on experimental data with limited parameter ranges (Bishop 1964[1], Swenson 1965[2], Krasnoshchekov 1966[3], Watts 1982[4], Jackson 2002[5]). But these empirical corrlations have much difference from each other when they are used to predict heat transfer deterioration and PCST of SC water. There are few empirical correlations which are always applicable under the conditions of normal heat transfer, enhanced heat tranfer and heat transfer deterioration of SC water.

Based on the coupled analysis of heat transfer and flow of SC water, this paper presents a new approach to founded prediction correlation of heat transfer in supercritical fluids. The Pranlt boundary theory is adopted to analysis how Reynolds stress influence heat transfer and flow of SC water. The paper show that heat transfer of SC water is mainly influenced by two factors such as thermo-physical property effect and Reynolds stress attenuation effect. The new heat transfer correlation is compared with the selected test data in NPIC.

2. Analysis of heat transfer and flow in the boundary layer

Before analysis, there are some hypotheses which is needed to simplified the analysis process, mainly include:

(1) Transition layer is ignored, and the boundary layer is just composed of viscosity layer and logarithm layer.

(2) Heat transfer only depend on turbulent convection $-\overline{\rho u'h'}$, and thermal conductibility is ignored.

(3) The viscosity shear stress in logarithm layer is ignored.

(4) The dimensionless scale of inner and outer boundary line of logarithm layer is constant.

Based on the above hypotheses, momentum equations in the logarithm layer is:

$$\frac{\partial \tau}{\partial y} - \left(\frac{dP}{dz}\right)_{layer} - \overline{\rho} g = 0 \tag{1}$$

$$\frac{dP}{dy} = 0 \tag{2}$$

where z is the bulk kinetic position ,y is the normal positon of wall, and $\overline{\rho}$ is the averaged density of the boundary layer:

$$\overline{\rho} = \frac{1}{T_W - T_b} \int_{T_b}^{T_W} \rho dT \tag{3}$$

Equation (2) shows that the pressure grads in the bulk kinetic position is the same at the same z,so:

$$\left(\frac{dP}{dz}\right)_{layer} = \left(\frac{dP}{dz}\right)_b \tag{4}$$

and

$$\frac{\partial \tau}{\partial y} - \left(\frac{dP}{dz}\right)_b - \overline{\rho} g = 0 \tag{5}$$

For vertical tubes, the pressure grads $-(dp/dz)_b$ is:

$$-\left(\frac{dP}{dz}\right)_b = \frac{4\tau_W}{d} + \frac{d}{dz}\left(\frac{G^2}{\rho_b}\right) + \rho_b g \tag{6}$$

Variable a is the attenuation slope of the shear stress of fluid in boundary layer, so, a is shown as:

$$a = -\frac{\partial \tau}{\partial y} = \frac{4\tau_W}{d} + \frac{d}{dz}\left(\frac{G^2}{\rho_b}\right) + \left(\rho_b - \overline{\rho}\right) g \tag{7}$$

Based on the Pranlt boundary theory, the shear stress is:

$$\tau = -\overline{\rho u'u'} = \mu_t \frac{\partial u}{\partial y} = \rho l_m^2 y^2 \left|\frac{\partial u}{\partial y}\right| \frac{\partial u}{\partial y} \tag{8}$$

Due to the second hypothesis, heat flux is:

$$q = -\overline{\rho u'h'} = \frac{\mu_t}{\sigma_h}\frac{dh}{dy} = \frac{l_m y\sqrt{\tau\rho}}{\sigma_h}\frac{dh}{dy} \tag{9}$$

So,

$$dh = \frac{q\sigma_h dy}{l_m y\sqrt{\tau\rho}} = \frac{q\sigma_h dy}{l_m y\sqrt{\rho(\tau_W - ay)}} \tag{10}$$

Equation (11) is integraled from $y^+ = l_1^+$ to $y^+ = l_2{}^+$,where l_1^+ 、l_2^+ are separately the inner and outer dimensionless scale of the logarithm layer. The integraled equation is:

$$\frac{q}{T_W - T_b} = \frac{\overline{c_P} l_m \sqrt{\rho\tau_W}}{\sigma_h\left(\ln\left(\frac{l_2^+}{l_1^+}\right) + 2\ln\frac{\left(1+\sqrt{1-\frac{\varphi l_1^+}{20}}\right)}{\left(1+\sqrt{1-\frac{\varphi l_2^+}{20}}\right)}\right)} \tag{11}$$

where y* is the standard scale of dimensionlessing, and the density ρ is supposed to be constant. Variable φ is defined as the percent how to Reynolds tress reduce when y+=20. φ is:

$$\varphi = \frac{20ay^*}{\tau_W} \tag{12}$$

where $y^* = \frac{\mu_W}{\sqrt{\rho_W \tau_W}}$, $\overline{c_p} = \frac{h_w - h_b}{T_W - T_b}$.

Due to equation (14), the heat tranfer in logarithm layer is influenced by the thermal property of the water (such as $\overline{c_P}$) and the Reynolds stress attenuation percent (φ). Eqution (14) is not able to predict the heat transfer of SC water directly, but the above qualitative results are logical due to the similar characteristic between the hypotheses and the practice.

3. Reynolds stress attenuation effect

Due to equation (14), heat transfer of SC water is influenced by thermal property (such as $\overline{c_P}$). There must be the averaged property (such as $\overline{c_P}$), the thermal property involved with bulk temperature and wall temperature in the prediction correlation of heat transfer. So, the correlation which consider only the thermal property of SC water is:

$$Nu_0 = 0.021\mathrm{Re}_b^{0.82}\,\mathrm{Pr}_b^{0.5}\left(\frac{\rho_W}{\rho_b}\right)^{0.4}\left(\frac{\overline{c_p}}{c_{pb}}\right)^{0.41} \tag{13}$$

The distribution of the Reynolds stress in boundary layer is similarly shown as Fig.1.Though there is some diffence from the practice in Fig.1, there is something consistent with the practice ,for example, linear attenuation of Reynolds stress and the inner and outer dimensionless scale of logarithm layer.

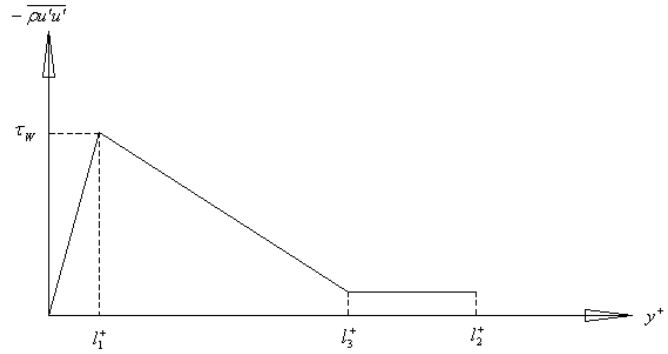

Fig.1 The ditribution of Reynolds stress $-\overline{\rho u'u'}$ along the normal position of wall

Due to Fig.1, the average of Reynolds stress $-\overline{\rho u'u'}$ is:

$$ave(-\overline{\rho u'u'}) = \frac{20\tau_W}{\varphi\left(l_2^+ - l_1^+\right)} \tag{14}$$

When thermal acceleration effect and gravity effect do not exist, the average of Reynolds stress $-\overline{\rho u'u'}$ is:

$$ave(-\overline{\rho u'u'}) = \frac{20\tau_W}{\varphi'\left(l_2^+ - l_1^+\right)} \tag{15}$$

where φ' is the attenuation percent of Reynolds stress when thermal acceleration effect and gravity effect do not exist.

Due to equation (17) and (18), The ratio of the average of Reynolds stress is φ'/φ when thermal acceleration effect and gravity effect do and don’t exist. Reynolds stress $-\overline{\rho u'u'}$ directly influences the turbluent velocity u', and the turbluent velocity u' directly influences turbulent convection $-\overline{\rho u'h'}$, so φ'/φ is regarded as the scale parameter of thermal acceleration effect and gravity effect.

So, the prediction correlation of heat transfer of SC water which consider the Reynolds stress attenuation effect is :

$$Nu = Nu_0\left(\frac{\varphi'}{\varphi}\right)^n \tag{16}$$

where n consider the similarity between the SC water and two-phase water, and n is:

$$n = \left(\frac{h_b}{h\left(1.25T_{pc}\right)}\right)^{2.1} \tag{17}$$

4. Assessment of the new heat transfer correlation

Fig.2 shown the comparison between the experiment data in NPIC and the value calculated by the new heat transfer correlation. Due to Fig.2, there is 92% data which have less than 25% error between the experiment data and the value calculated by the new heat transfer correlation. In Fig.2, the new correlation is very applicable under the conditon of small Nu, so the new correlation is applicable when heat transfer deterioration occurs(shown as Fig.3). Due to Fig.2, the error between the experiment data and the value calculated by the new correlation under the condition of large Nu may be caused by the measure error of expriment data.

The parameter of the the experiment in NPIC is:
Fluid: SC water
Diameter: 6mm
Pressure: 23.0 24.0, 25.0 MPa
Mass flux: 600~ 1200kg/m^{2}s
Heat flux:0.5~1.1MW/m^2
Bulk temperature:250~500℃

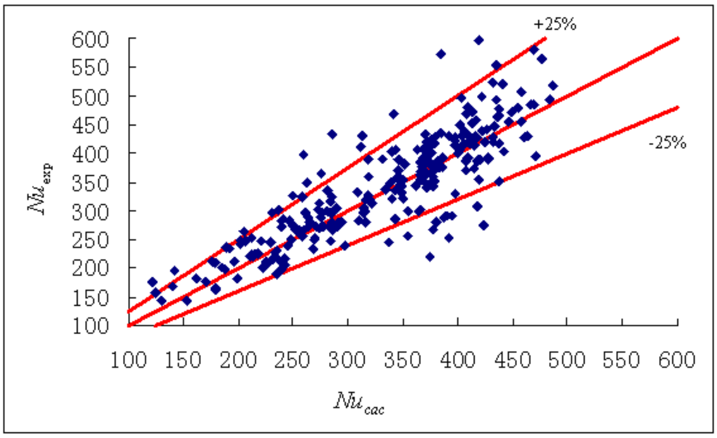

Fig.2 the comparison between the experiment data and the value calculated by the new correlation

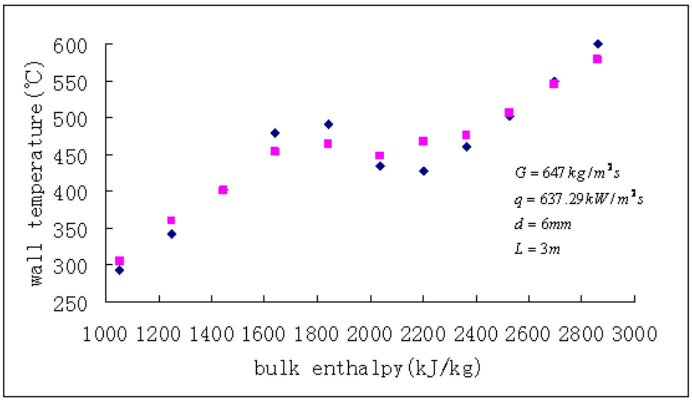

Fig.3 the comparison between the experiment data(red) and the value(black) calculated by the new correlation when heat transfer deterioration occurs.

5. Conclusion

The compled analysis of heat transfer and flow of supercritical water is performed to gain a better prediction correlation of heat transfer of SC water. The main results can be summarized as:

(1) Based on Prantl boundary theory, heat transfer of SC water in logarithm layer is involved with the thermal property of the water (such as $\overline{c_p}$) and the Reynolds stress attenuation percent. So, heat transfer of SC water is mainly influenced by two factors such as thermo-physical property effect and Reynolds stress attenuation effect.

(2) The new prediction correlation of heat transfer of SC water which consider the Reynolds stress attenuation effect and thermo-physical property effect is.gained, which is shown as equation (16). Compared by the experiment data in NPIC, the new correlation the new correlation is very applicable under the conditon of small Nu and large Nu.

6. References

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