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A method of extending subcritical heat transfer correlations to supercritical conditions

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HIGHLIGHTS

- A new method of developing heat transfer formulas under supercritical conditions was proposed.
- The method was based on the modified thermal wall law.
- Based on this method, the Dittus-Boelter formula and Gnielinski formula were extended to supercritical water.
- The comparison of experimental data and predicted values shows good agreement.

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ABSTRACT

An analytical method was proposed up for the prediction of heat transfer coefficient under supercritical conditions. The new heat transfer correlation was based on the modified thermal law of the wall which could take account of the fluid property variation across the boundary layer and could help clarify the basic heat transfer mechanism of supercritical water. Based on this method, the Dittus-Boelter correlation and Gnielinski correlation were extended to supercritical water. The comparisons of experimental data and predicted values showed good agreement which confirmed the physical validity of this method. Moreover, this method could build a bridge between subcritical region and supercritical region.

1. Introduction

The development of supercritical water reactors requires more accurate predictions of water and steam heat transfer coefficients over a wide range of operating conditions. Many experiments have been performed to investigate the forced convective heat transfer phenomena, together with the numerical simulations and theoretical analysis. Yamagata et al. (1972), Swenson et al. (1965), Bishop et al. (1964), Shitsman (1963), and so on carried out experiments in the earlier years in last 60s. In recent years, more and more activities are being devoted to the R&D development of SCWR, such as Licht et al. (2008), Mokry et al. (2010), Misawa et al. (2009) and Zahlan et al. (2011). Pioro and Duffey (2007), Cheng and Schulenberg (2001) and OKa et al. (2010) gave a review of ongoing research about these activities. Pioro et al. (2011) assessed the work related with the heat transfer and pressure drop characteristics at supercritical pressures based on the experiments of water and carbon dioxide. Most of the studies have found that the heat transfer near the pseudocritical point has unusual behaviors where the specific heat capacity arrives at its maximum value. In some cases, at relatively high mass fluxes, an enhancement of heat transfer occurs in the pseudocritical region at low heat flux whose heat transfer coefficient is bigger than the value predicted by subcritical correlations. But as the heat flux increases, its magnitude is reduced. In other cases, when the mass flow rate is small, while the heat flux is relatively large, heat transfer deterioration may occur, in companion with local wall peak temperature. This unusual behavior is believed to be related with the sharp variation of the fluid property in the neighborhood of pseudocritical point where small change in fluid temperature will lead to big variation in fluid properties, as shown in Fig. 1. This is especially possible in a heated tube under supercritical conditions when the pseudocritical point is just between the wall temperature and the bulk fluid temperature. The crossing of the pseudocritical line may have big influence on the velocity and temperature profile in the wall boundary layer. At least, the physical property could not assume to be constant, and the traditional law of the wall may be dependent on the physical properties.

Abbreviations: HTC, heat transfer coefficient; NPIC, Nuclear Power Institute of China; NIST, National Institute of Standards and Technology (USA); R&D, research and development; SCWR, supercritical-water-cooled nuclear reactor.

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Nomenclature

$B_t(Pr)$	the function of Prandtl number
c_f	Fanning frictional coefficient
c_p	specific heat at constant pressure (J/kg K)
$\bar{c}_p$	average specific heat within range of $(Tw-Tb)$: $(h_w-h_b)/(Tw-Tb)$ (J/kg K)
c_{pw}	specific heat evaluated at wall temperature (J/kg K)
d	the pipe diameter (m)
d_h	the hydraulic diameter (m)
f	Darcy–Weisbach frictional coefficient
$F(\theta)$	function of θ
h	fluid enthalpy (kJ/kg)
h'	the fluctuation of fluid enthalpy (kJ/kg)
k	thermal conductivity (W/m K)
Nu	the Nusselt number (hk/d)
P or $\bar{p}$	pressure (Pa)
Pr	the Prandtl number $(\mu c_p/k)$
$\overline{Pr}$	the average Prandtl number $(\mu\bar{c}_p/k)$
Pr_t	turbulent Prandtl number
$\langle Pr\rangle_1$, $\langle Pr\rangle_2$	the average Prandtl number in laminar conduction and turbulent layer
q_0 or, q	the wall heat flux (W/m^2)
Re	the Reynolds number
r_0	pipe radius (m)
r_0^+	non-dimensional pipe radius $\rho u_\tau r_0/\mu$
t	temperature (°C)
t_m	the average fluid temperature (°C)
t_w	the temperature at the wall (°C)
t_1	temperature at the upper bound of the laminar conduction layer (°C)
t_c	temperature at the centerline of the pipe (°C)
t_1^+, t_2^+	dimensionless temperature in laminar and turbulent region
$T_{\tau1}$, $T_{\tau2}$	friction temperature in laminar and turbulent region (°C)
u_τ	friction velocity (m/s)
u,v	velocity component in flow direction and normal direction (m/s)
u',v'	fluctuation velocity component in flow direction and wall normal direction (m/s)
$u_{c,l}^+$	non-dimensional velocity in viscous sublayer
$u_{c,t}^+$	non-dimensional velocity in turbulent sublayer
u_m	average velocity (m/s)
x_i	the coordinate component (m)
y	distance from the wall (m)
y^+	non-dimensional distance from the wall $(\rho u_\tau y/\mu)$
y_l^+ or y_t^+	non-dimensional distance of the upper bound of the laminar conduction layer
y_0^+	non-dimensional distance of the upper bound of the viscous layer

Greek symbols

α	molecular thermal diffusivity (m^2/s)
β_1,β_2	the geometry parameters
ε_M	turbulent viscosity (m^2/s)
ε_H	turbulent viscosity of heat transfer (m^2/s)
κ	Von Karman constant
μ	molecular viscosity (kg/m s)
μ_t	turbulent viscosity (kg/m s)
μ_w	molecular viscosity at the wall (kg/m s)
μ_{bl}	molecular viscosity in the viscous sub layer (kg/m s)
μ_b	bulk average molecular viscosity (kg/m s)
ν	momentum viscosity (m^2/s)
ρ	fluid density (kg/m^3)
ρ_{bt}	fluid density in the turbulent sublayer (kg/m^3)
ρ_{aver}	the bulk average density (kg/m^3)
ρ_w	fluid density evaluated at the wall temperature (kg/m^3)
τ	shear stress (kg/m s^2)
τ_w	wall shear stress (kg/m s^2)

Subscript

aver	bulk average
b	bulk
bl or 1	viscous sublayer
bt or 2	turbulent sublayer
iso	isothermal
l	laminar
pc	pseudocritical
t	turbulent
w	wall

Although many correlations have been proposed up to predict such unusual heat transfer behaviors as mentioned above, the theoretical analysis is relatively few, attributed to the fact of the difficulty in dealing with the complex variation of the physical properties. In this paper, a method of predicting the heat transfer coefficient based on the new thermal function of the wall was proposed up and could provide some explanations to the strange heat transfer characteristics.

2. The derivation of the thermal law of the wall

Generally, two kinds of mechanisms dominate the heat transfer behaviors in the boundary layer: the molecule diffusion and the turbulent fluctuation. And according to each of their contributions, two zones are distinguished: the molecule heat conduction layer and the turbulent heat diffusion layer. Based on the boundary layer assumption, Boussinesq hypothesis and the Reynolds analogy rule, a new thermal function of the wall could be derived in account of the fluid property variation across the boundary layer.

The general energy conservation equation:

$$\frac{\partial\overline{\rho h}}{\partial t}+\frac{\partial\overline{\rho u_i h}}{\partial x_i}=-\frac{\partial}{\partial x_i}\left(-k\frac{\partial t}{\partial x_i}+\overline{\rho u_i' h'}\right)+\frac{\partial\bar{p}}{\partial t}+u_i\frac{\partial\bar{p}}{\partial x_i}+(\tau_{ij}-\rho\overline{u_i' u_j'})\frac{\partial\overline{u_i}}{\partial x_i} \quad (1)$$

In steady equilibrium two dimensional heated boundary flows, the transient term, kinetic energy dissipation term and the pressure drop term are neglected. According to the boundary layer assumption, the flow direction scale was far larger than the wall normal direction scale. So the axial gradient of some quantities would be ignored in contrast with the normal direction gradients. The thermal boundary equation was obtained as below:

$$\rho u\frac{\partial h}{\partial x}+\rho v\frac{\partial h}{\partial y}=\frac{\partial}{\partial y}\left(k\frac{\partial t}{\partial y}-\rho\overline{v'h'}\right) \quad (2)$$

The Reynolds heat flux term $\overline{v'h'}$ could be modeled directly with the Boussinesq eddy viscous hypothesis:

$$\rho\overline{v'h'}=\rho c_p\overline{v't'}=-\rho c_p\varepsilon_H\frac{\partial t}{\partial y} \quad (3)$$