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A general method for developing friction factor formulas under supercritical conditions and in different geometries

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ABSTRACT

A general method for developing friction factor formulas in different geometries and under supercritical conditions was set up in this paper. The method was based on the two-layer wall function theory which could account for both the laminar viscous layer and turbulent layer. This characteristic led to its good agreement with empirical correlations in a wide range of Reynolds numbers, especially the prediction accuracy was improved at low Reynolds numbers in comparison with the previous work. This method could be extended to the flows over rough surfaces or with axial pressure gradient as long as the appropriate wall function is provided. Moreover, the wall function is based on Van Direst transformation which could take account of the fluid property variation across the boundary layer and thus the friction formula could be applied to supercritical flow. This formula could explain the special features of friction coefficient and showed good agreement with the experimental data performed by Nuclear Power Institute of China.

1. Introduction

The Supercritical Water-Cooled nuclear Reactor (SCWR) has become attractive as the ultimate development path for water cooling because of its high thermal efficiency and low capital and operational costs. SCWR has much higher operating parameters with pressure up to 25 MPa and outlet temperature up to 500 °C (Cheng and Schulenberg, 2001; Pioro and Duffey, 2007). The nuclear fuel rods are arranged into arrays in square pitched patterns for thermal spectrum SCWR fuel assembly. The flow geometry is non-circular and may be classified into the compound channel. The significant changes in the thermal physical properties may have big influence on the flow resistance characteristics. When the wall temperature is greater than the pseudocritical point and bulk fluid temperature is below, large variation of fluid property will happen across the boundary layer. In such situation, the friction coefficient will not depend solely on the bulk Reynolds number, but also bonds tightly with the physical property of the boundary layer. The variation of fluid property could bring about apparent axial pressure gradient including the buoyancy effect and acceleration effect (Jackson and Hall, 1979a,b). In engineering applications, the surface roughness should be considered in some cases. The design and reliable operation of fuel assembly needs accurate knowledge of the friction factor of turbulent flow. So various factors should be considered including the geometry shape, the axial pressure gradient, the roughness and the fluid property variations.

Many studies have been carried out in the past on turbulent flow in different geometry shapes under subcritical conditions. Hartnett et al. (1962) developed a kind of analytical prediction of friction factor for non-circular geometry by integration the law of the wall over the cross section. Rehme (1973) proposed a simple method for the prediction of friction factors in non-circular channels if only the geometry factor of the pressure drop relationship for laminar flow is known. The proposed method was tested with experimental results with respect to non-circular channels such as triangular shaped ducts, eccentric annuli, rod bundles and provided a good description of the experimental data. Lee (1995) applied the similar methods to an infinite rod array with a low pitch to diameter by taking account of the variation of local wall shear stress. Su and Freire (2002) followed the same way, but presented the friction factor equation in a different form which is similar to that in a circular pipe. They further extended the methods to rough surface and prediction of Nusselt number in turbulent convection flow. In Su and Freire's (2002)'s work, the one layer wall function theory was adopted. It shows good agreement with Cheng and Todreas method in high Reynolds number. But as Reynolds is getting small, the discrepancy is increased. The reason is believed to be the lack of considering viscous effect in the viscous layer.

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Nomenclature

Letters

A	flow area (m^2)
A_2, G^*	geometry parameters in Eq. (29)
b	constant in wall function Eq. (1)
c_f	fanning friction coefficient
D	tube diameter (m)
d_h	hydraulic equivalent diameters (m)
f	Darcy friction coefficient
$f(y)$	function of y
$F(\theta)$	Function of θ
g	gravity acceleration (m s^{-2})
G	mass flux (kg m^{-2} s)
H_b	bulk fluid enthalpy (kJ kg^{-1})
k	Roughness height (m)
P	Pitch of rod (m)/pressure (MPa)
p^+	dimensionless pressure gradient
p_a^+	acceleration parameter
p_g^+	buoyancy parameter
p_w^+	wall shear parameter
P_h	wetted perimeter (m)
Pr	Prandtl number
Q	heat flux (kW m^{-2})
r	radius (m)
r_0^+	dimensionless distance of r_0
Re	Reynolds number
T_b	bulk fluid temperature (°C)
T_w	wall temperature (°C)
T_{mid}	interpolated temperature (°C)
u	velocity (m s^{-1})
u_m	average velocity (m s^{-1})
u^+	dimensionless velocity normalized by the friction velocity
u_1^+	dimensionless velocity in the laminar layer
u_2^+	dimensionless velocity in the turbulent layer
u_τ	friction velocity (m s^{-1})
$\bar{u}_\tau$	average friction velocity (m s^{-1})
$u_{\tau 1}$	friction velocity for the laminar layer (m s^{-1})
$u_{\tau 2}$	friction velocity for the turbulent layer (m s^{-1})
y	normal distance from the wall (m)
y+	dimensionless distance from the wall
y_l+	the dimensionless division line between the laminar viscous layer and the turbulent core region

Greek letters

α_1, α_2	velocity profile parameters in Eq. (10)
β	pressure gradient parameter in Eq. (35)
δ_1	the displacement thickness of momentum boundary layer (m)
ε	Roughness height in Eq. (34) (m)
ϕ_l	the material factor in the laminar layer
ϕ_t	the material factor in the turbulent layer
κ	Von Karman's constant (=0.41)
μ	dynamic viscosity (kg m^{-1} s^{-1})
μ_w	dynamic viscosity evaluated at the wall temperature (kg m^{-1} s^{-1})
μ_{bl}	dynamic viscosity evaluated at the laminar boundary layer (kg m^{-1} s^{-1})
ν	Momentum viscosity (m^2 s)
θ	the angle position
ρ	density (kg m^{-3})
$\bar{\rho}$	average density (kg m^{-3})
ρ_w	density evaluated at the wall temperature (kg m^{-3})
ρ_{bt}	density evaluated at the turbulent boundary layer (kg m^{-3})
τ_w	wall shear stress (N m^{-2})

Subscripts

1 or l	the laminar layer
2 or t	the turbulent layer
b	bulk
i	in
iso	isothermal
m	average
o	out
w	wall

Bae and Park (2011) derived the turbulent geometry parameters for a rod bundle in consideration with the influences of the channel wall and the local shear stress distribution. For a typical geometry of a rod bundle, each type of subchannel could be further subdivided into basic elements by the zero stress line. So the turbulent geometry parameters and the friction factors for a rod bundle could be obtained by combining the geometry parameters of these subchannels.

Compared with the majority of studies under subcritical conditions, relatively few studies are devoted to applying wall function method to investigating hydraulic resistance of supercritical water. Most studies have been performed by means of experiments in circular tube (Pioro et al., 2004) and obtained experimental correlations by data fitting. The experimental results show that the friction factors of supercritical water were largely dependant on the thermal physical properties.

In this paper, we provided a method based on two-layer wall function theory instead of single layer. Moreover, this new method could be applied to supercritical water and had good prediction accuracy with the experiments. The basic idea is to adopt the two-layer wall function law with Van Direst transformation that could account for the fluid property variation along the wall normal direction. After integrated through the cross section, the average fluid velocity is obtained and also the friction coefficient. This paper further improves this job to apply it to other geometries and account for other factors, such as roughness, pressure gradient parameter.

2. Developing the new friction factor formula

In order to extend the new frictional formula to supercritical water, a modified wall function based on Van Direst transformation was adopted. It has the similar form as the traditional wall function, but with different definitions of dimensionless velocity. The expression is below:

$$\begin{cases} u_1^+ = y^+, & y^+ \leqslant y_l^+ \\ u_2^+ = \frac{1}{\kappa}\ln y^+ + b, & y^+ > y_l^+ \end{cases} \tag{1}$$

Here y^+ is the dimensionless distance from the wall, defined as below:

$$y^+ = \frac{\rho u_\tau y}{\mu}$$