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A new method on fluid-to-fluid scaling for heat transfer in tubes at supercritical pressures

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ABSTRACT

Supercritical fluid heat transfer has great significance for the thermal-hydraulic design and safety performance of the SCWR (Super-Critical Water-cooled Reactor). Experimental studies on heat transfer at prototypical conditions of SCWRs would suffer a huge cost on safety and economy, which strongly limits the research of supercritical water heat transfer. One solution is to adopt model fluid technique which has been applied in thermal and fluids engineering widely. Therefore, finding the equivalent relationship between the experimental data in model fluid and those in prototype fluid becomes a key issue. It means a fluid-to-fluid scaling method is necessary for converting experimental data obtained by using model fluid into the prototype fluid. In the present study, from the perspective of thermo-physical properties similarity and conservation equations similarity, considering the comprehensive influence of the experimental conditions and fluid types, a theoretical study on fluid-to-fluid scaling is performed and most importantly, a new scaling method is proposed. The new scaling method adopts a modification on thermo-physical properties. Several dimensionless numbers are obtained according to the dimensionless momentum and energy governing equations. A new dimensionless number *En* is derived to present the comprehensive influence of experimental conditions and fluid types. According to the theoretical analysis, an entire set of scaling laws applied for supercritical fluid heat transfer in circular tubes was obtained. Based on the heat transfer data of supercritical R134a, the new scaling method was validated, indicating the feasibility and accuracy of the proposed new scaling method.

1. Introduction

The SCWR is one of six most promising GEN-IV (Generation IV) innovation nuclear reactors recommended by Generation IV International Forum. It has advantages in terms of compactness as well as simplicity and thermal efficiency compared with conventional water cooled reactors [1–3]. The coolant of the SCWR water is operated at the conditions higher than its thermodynamic critical point. The fluid thermo-physical properties show a dramatic variation when near to the thermo-dynamic critical point while the fluid does not undergo phase change in the supercritical region. The experimental research indicates that normal heat transfer, heat transfer enhancement and heat transfer deterioration would occur in trans-critical region and supercritical region [4–10]. Therefore, the heat transfer characteristics of supercritical water have a significant influence on thermal hydraulic design of the SCWR [11–14].

It is necessary to conduct supercritical fluid heat transfer experiments with the coolant water, however these experiments require huge technical and financial efforts and cannot cover all operation conditions of nuclear power plant [15] on account of the high critical parameters of water. Appling model fluid technique in fluid heat transfer field has been a practical approach for decades. More experimental data can be acquired through supercritical fluid heat experiments with model fluid. In addition, a better understanding on the essence of the supercritical fluid heat transfer physical process can be obtained through comparing the results in different fluids.

Many experimental investigations on supercritical fluid heat transfer have been carried out with H_2O [16,17], R134a [18–20] and CO_2 [21–23] as experimental medium. The following issue is to convert experimental conditions and data from one fluid into another. This becomes a key issue for the success of model fluid technique. Unfortunately, studies on fluid-to-fluid modeling are very limited and very few researchers focused their research on this field. Pioro et al. [24] chose three dimensionless parameters as the criterion numbers to transfer experimental conditions

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Nomenclature

C_p	specific heat at constant pressure (kJ/kg K)
D	diameter (m)
f	ratio
F	mass force
Fr	Froude number
G	mass flux
Δh	enthalpy rise (kJ/kg)
L	length (m)
n	exponent
P	pressure (MPa)
Pr	Prandtl number
q	heat flux (kW/m^2)
r	radial coordinate (m)
Re	Reynolds number
T	temperature (K)
u	velocity (m/s)
x	length (m)
z	compressibility factor

Subscripts

b	bulk
w	wall
cr	critical
l	anxial direction
r	radial direction
M	model
o	characteristic value
P	prototype
pc	pseudo critical
R	reduced parameter

Superscript

$*$	modified parameter

between two different fluids, the recommended criterion numbers in his study are shown as follows:

$$\left(\frac{P}{P_{cr}}\right)_{CO_2} = \left(\frac{P}{P_{cr}}\right)_{H_2O} \tag{1}$$

$$\left(\frac{T}{T_{cr}}\right)_{CO_2} = \left(\frac{T}{T_{cr}}\right)_{H_2O} \tag{2}$$

$$\left(\frac{GD}{\mu_b}\right)_{CO_2} = \left(\frac{GD}{\mu_b}\right)_{H_2O} \tag{3}$$

These three criterion numbers can solve the ratios of P, T and (GD) between the model fluid and prototype fluid, while another important parameter heat flux was not considered, indicating this scaling method was not complete.

Jackson analyzed the dimensionless equations for flow and heat transfer, based on which specified the similarity criteria for strict similarity between two geometrically-similar vertical-upward flows cooled by the same fluid at supercritical pressures [25,26]. These similarity criteria were strictly suitable for steady state forced convection in vertical tubes with uniform wall heat flux in condition of same fluid. Furthermore, Jackson pointed out that the pressure and the temperature must be same respectively in different experiments at the inlet of the test section and at the same dimensionless length L/D. Although Jackson did not provide the scaling method of heat transfer coefficient, one can derive a scaled heat transfer coefficient according to the energy equation.

Zwolinski et al. [27] modified Jackson's laws and extended them to fluid-to-fluid scaling. This method required that the inlet parameters P_{in}, T_{in}, Re_{in} and L/D should satisfy the following equations:

$$\left(\frac{L}{D}\right)_{CO_2} = \left(\frac{L}{D}\right)_{H_2O} \tag{4}$$

$$\left(\frac{P_{in}}{P_{cr}}\right)_{CO_2} = \left(\frac{P_{in}}{P_{cr}}\right)_{H_2O} \tag{5}$$

$$\left(\frac{T_{in}}{P_{cr}}\right)_{CO_2} = \left(\frac{T_{in}}{P_{cr}}\right)_{H_2O} \tag{6}$$

$$\left(\frac{GD}{\mu_{b,in}}\right)_{CO_2} = \left(\frac{GD}{\mu_{b,in}}\right)_{H_2O} \tag{7}$$

$$\left(\frac{qD}{\lambda_{b,in}T_{in}}\right)_{CO_2} = \left(\frac{qD}{\lambda_{b,in}T_{in}}\right)_{H_2O} \tag{8}$$

In the modified Jackson's laws, all the parameters involved were obtained at the inlet of the heated tube. To acquire the local parameters of prototype fluid, one needed to calculate the inlet parameters at first and then calculate the local cross-section parameters according to mass flux, heat flux, and inlet bulk enthalpy with the energy conservation equation.

Based on governing equations and boundary conditions, Cheng et al. [28] proposed a set of dimensionless numbers and illustrated requirements for fluid-to-fluid heat transfer scaling. A new dimensionless parameter containing the pseudo Boiling number, Reynolds number and Prandtl number was proposed to scale the heat flux. The Cheng's laws were shown as follows:

$$D_{CO_2} = D_{H_2O} \tag{9}$$

$$\left(\frac{P}{P_{cr}}\right)_{CO_2} = \left(\frac{P}{P_{cr}}\right)_{H_2O} \tag{10}$$

$$\left(\frac{T_b - T_{pc}}{T_{pc} - T_{cr}}\right)_{CO_2} = \left(\frac{T_b - T_{pc}}{T_{pc} - T_{cr}}\right)_{H_2O} \tag{11}$$

$$\left(\frac{qD}{\lambda_b(T_{pc} - T_{cr})}\right)_{CO_2} = \left(\frac{qD}{\lambda_b(T_{pc} - T_{cr})}\right)_{H_2O} \tag{12}$$

$$\left(\frac{GDPr_b^{\frac{5}{12}}}{\mu_b}\right)_{CO_2} = \left(\frac{GDPr_b^{\frac{5}{12}}}{\mu_b}\right)_{H_2O} \tag{13}$$

In Cheng's laws, the tube diameter D of model fluid experiment and prototype fluid experiment were set to be equal directly. However, the thermo-physical properties were obviously different in two fluids, which resulted in different flow and heat boundary layers even at the same geometry size [29]. Further, the velocity and temperature profile at the same diameter were different in different fluids, which was unreasonable for fluid-to-fluid scaling. In addition, the heat flux scaling dimensionless parameter $\pi_C\,(\pi_C = Re^{n_1}Pr^{n_2}Fr^{n_3})$ had the exponents $n_1 = 0.8$, $n_2 = 1/3$, $n_3 = 0$ and these exponents were obtained according to Dittus-Boelter correlation which was empirical and not suitable for supercritical pressure region.

Zahlan et al. [30] developed a set of fluid-to-fluid scaling laws suitable for supercritical and high supercritical pressure region. They modified the exponents of Re and Pr in heat flux scaling law