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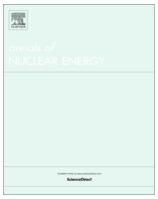

Discussion on the fluid-to-fluid scaling of heat transfer at supercritical pressures

Han Wang [a,b,*], Daogang Lu [a,b], Yintao Wang [c]

[a] School of Nuclear Science and Engineering, North China Electric Power University, Beijing 102206, China
[b] Beijing Key Laboratory of Passive Safety Technology for Nuclear Energy, North China Electric Power University, Beijing 102206, China
[c] Department of Mechanical Engineering, Texas A&M University, 3133 TAMU, College Station, TX, USA

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ABSTRACT

Supercritical carbon dioxide (SCO_2) has been extensively adopted in heat-transfer experiments due to its low critical point compared to supercritical water (SCW). While it helps to largely reduce the technical difficulty and cost, the experimental results need to be extrapolated to SCW using a set of reliable and well-validated fluid-to-fluid scaling criteria. In the present paper, a criterion for scaling the mass flux in normal and enhanced heat transfer regimes was achieved by using Computational Fluid Dynamic (CFD) approaches. This criterion as well as the available scaling laws were assessed based on a wide range of the experimental data. It was found that Prandtl number shows a significant and nonmonotone effect on the scaling of mass flux (and consequently Nusselt number). Similar exponents of the Prandtl number were obtained using different approaches, but a constant exponent failed to capture the nonmonotone effect, especially when the bulk temperature surpasses the pseudo-critical temperature where large variations in the thermophysical properties appear. A modified scaling criterion, which is applicable to the heat transfer deterioration occurred at low mass fluxes, was proposed for the Nusselt number. The deviation from the experimental data was significantly reduced after Grashof number was incorporated into the criterion.

1. Introduction

Heat transfer to supercritical pressure water (SCW) has been extensively investigated in the 1960s in support of developing supercritical fossil-fuel power plants. Since 2000, there is a renewed interest on this topic because it is relevant to Supercritical Water-cooled Reactor (SCWR), a Generation IV nuclear design concept that is currently under R&D worldwide for its improved features (US DOE, 2002). Benefited from its high operating conditions which are above the critical point of water (i.e. 22.1 MPa, 374 °C), a SCWR power plant can provide a thermal efficiency up to 45% compared to that of 33% for pressurized water-cooled reactors (Su et al., 2014). Since the direct once-through cycle was adopted in the conceptual design, the steam generator is removed which not only simplifies the system components, but also lowers the capital cost. In addition, SCWR offers a higher safety because the undesirable departure from nucleate boiling could be avoided at supercritical pressures.

In spite of these promising advantages, challenges have been encountered in the thermal-hydraulic analysis of SCWRs mainly due to the severe and nonlinear variations in the thermophysical properties of SCW near the pseudo-critical temperature. These drastic variations could lead to either heat transfer enhancement or deterioration, depending on the imposed heat flux and flow conditions (Rahman et al., 2016). To understand the characteristics and mechanisms of these unusual heat transfer phenomena, a number of experimental investigations have been performed within the last 50 years, as summarized by Pioro and Duffey (2007). However, experiments performed with SCW require both high pressure and high temperature, which are extremely costly and sometimes may encounter insurmountable technical difficulties, especially for flow and heat transfer in complex geometries (e.g. rod bundles). To avoid these disadvantages, heat transfer experiments were often conducted with surrogate fluids such as supercritical carbon dioxide (SCO_2) or Freon. These fluids have much lower critical points, but the thermophysical and transport properties are similar to SCW. In order to extrapolate the experimental results obtained from the model fluids to the prototypical fluid (SCW), a set of reliable and well-validated fluid-to-fluid scaling criterion should be available beforehand.

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* Corresponding author at: School of Nuclear Science and Engineering, North China Electric Power University, Beijing 102206, China.

E-mail address: wanghan@ncepu.edu.cn (H. Wang).

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Nomenclature

c_p	specific heat [kJ/kgK]
$\bar{c}_p$	mean specific heat, $\frac{H_w-H_b}{T_w-T_b}$ [kJ/kgK]
D	diameter [mm]
G	mass flux [kg/m^{2}s]
Gr	Grashof number, $\frac{(\rho_b-\rho_w)gD^3}{\rho v^2}$ [-]
$\bar{Gr}$	average Grashof number $\frac{(\rho_b-\bar{\rho})D^3 g}{\rho v^2}$ [-]
Gr^*	Grashof number based on heat flux, $\frac{g\beta D^4 q}{\lambda v^2}$ [-]
h	heat transfer coefficient [kW/m^{2}K]
H	enthalpy [kJ/kg]
K	temperature [K]
n	exponent of Prandtl number
Nu	Nusselt number, $\frac{hD}{\lambda}$ [-]
P	pressure [MPa]
Pr	Prandtl number, $\frac{\mu c_p}{\lambda}$ [-]
$\bar{Pr}$	mean Prandtl number, $\frac{\mu \bar{c}_p}{\lambda}$ [-]
q	heat flux [kW/m^2]
Re	Reynolds number, $\frac{GD}{\mu}$ [-]
T	temperature [°C]
y^+	non-dimensional distance from the wall [-]
z	distance from inlet [m]

Greek letters

β	thermal expansion coefficient [1/K]
λ	thermal conductivity [W/mK]
μ	dynamic viscosity [Pa·s]
ρ	density [kg/m^3]
v	kinematic viscosity [m^2/s]

Subscripts

b	bulk
c	critical
in	inlet
M	model
P	prototypical
pc	pseudo-critical
w	wall

As will be discussed in the next section, several criteria concerning the fluid-to-fluid scaling of heat transfer at supercritical pressures have been proposed in literature. These criteria differ in the choice of the reference parameter, the nondimensional number or the empirical coefficient. A unique set of combination has not been achieved. Moreover, assessments to these criteria are limited due to the difficulty in obtaining the data of the model and prototypical fluids at the same experimental conditions, which restricts the applicability of these scaling laws. Furthermore, current scaling laws are applicable only to normal and enhanced heat transfer regimes. In the case of heat transfer deterioration, a relatively simple solution is inadequate because the effects of buoyancy, thermal acceleration and the variation of the thermophysical properties cannot be fully addressed. Thus, the objectives of the present paper are: i) develop a scaling criterion between SCO_2 and SCW using Computational Fluids Dynamic (CFD) approach; ii) assess the newly-proposed and available scaling laws based on a wide range of experimental data and iii) discuss the accuracy and applicability of these criteria in normal, enhanced and deteriorated heat transfer regimes and provide suggestions for further studies.

2. Fluid-to-fluid scaling criteria

By analyzing the dimensionless governing equations and the boundary conditions, Jackson and Hall (1979) stated that, a complete similarity between two systems at supercritical pressures requires 12 non-dimensional groups. In practice, however, these requirements are nearly impossible to be satisfied at the same time. The following criteria could be adopted to scale the prototypical and model fluids, provided that the influence of compressibility, dissipation and buoyancy are negligible.

$$\text{Geometry similarity}: \left(\frac{z}{D}\right)_M = \left(\frac{z}{D}\right)_P \tag{1}$$

$$\text{Pressure ratio}: \left(\frac{P}{P_c}\right)_M = \left(\frac{P}{P_c}\right)_P \tag{2}$$

$$\text{Bulk temperature}: \left(\frac{T_b}{T_c}\right)_M = \left(\frac{T_b}{T_c}\right)_P \tag{3}$$

$$\text{Heat flux}: \left(\frac{qD}{\lambda_b T_b}\right)_M = \left(\frac{qD}{\lambda_b T_b}\right)_P \tag{4}$$

$$\text{Mass flux}: \left(\frac{GD}{\mu_b}\right)_M = \left(\frac{GD}{\mu_b}\right)_P \tag{5}$$

$$\text{Heat transfer coefficient}: \left(\frac{hD}{\lambda_b}\right)_M = \left(\frac{hD}{\lambda_b}\right)_P \tag{6}$$

Pioro and Duffey (2007) suggested using Eqs. (2), (3) and (5) to scale pressure, bulk temperature and mass flux, while the thermophysical property of each fluid should be calculated by NIST database (Lemmon et al., 2002). Due to the simplicity of the scaling parameters, special behavior of the thermophysical properties and complex processes (e.g. mass discontinuity) may exist. The criterion for heat flux was not provided it their non-dimensional group.

Jackson (2008) specified several requirements for the scaling of heat transfer at supercritical pressures. He believed that the reduced inlet pressure $\frac{P_{in}}{P_c}$ and inlet temperature $\frac{T_{in}}{T_c}$ should be the same for each system to ensure the dimensionless fluid property and compressibility are similar. Besides, the pressure should not change significantly along the tube to ensure the dimensionless fluid properties vary in a similar manner. Finally, the geometry must be small enough to minimize the effects of buoyancy on the flow field, but large enough that the effects of viscous dissipation on the thermal field are negligible. Zwolinski et al. (2011) scaled the experimental conditions of SCW to corresponding SCO_2 based on the requirements proposed by Jackson (2008). They argued that the dependence of the properties on the reduced temperature, $\frac{T_{in}}{T_c}$, can vary significantly between fluids, especially for SCO_2 due to the small difference between the critical point and the freezing temperature compared to SCW. The pseudo-critical temperature (T_{pc}) was recommended to more accurately scale the bulk temperature. The scaling laws of Zwolinski et al. (2011) are listed as follows:

$$\left(\frac{P_{in}}{P_c}\right)_{CO_2} = \left(\frac{P_{in}}{P_c}\right)_{H_2O} \tag{7}$$

$$\left(\frac{T_{in}}{T_{pc}}\right)_{CO_2} = \left(\frac{T_{in}}{T_{pc}}\right)_{H_2O} \tag{8}$$

$$\left(\frac{qD}{\lambda_{in,b} T_{in}}\right)_{CO_2} = \left(\frac{qD}{\lambda_{in,b} T_{in}}\right)_{H_2O} \tag{9}$$