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Fluid-to-fluid scaling for convective heat transfer in tubes at supercritical and high subcritical pressures

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ABSTRACT

Following a review of two recent sets of fluid-to-fluid scaling laws for supercritical heat transfer and a discussion of their possible limitations, we have proposed two additional sets of scaling laws, which take into account empirically adjustable versions of the Dittus–Boelter correlation and which are applicable to both the supercritical and the high subcritical flow regions. We have compiled a database of heat transfer measurements in carbon dioxide flowing upwards in vertical heated tubes that are free of deterioration or enhancement. We then applied the four sets of scaling laws to these data to compute values of the water-equivalent heat transfer coefficient and compared these values to predictions of a transcritical look-up table, which was earlier shown to represent well a large compilation of measurements in water at supercritical and high subcritical pressures. It was shown that the two earlier methods systematically overestimated the heat transfer coefficient in water and also introduced significant imprecision. In contrast, the two proposed methods of scaling introduce no bias and have lower precision uncertainties than those of the previous scaling methods.

1. Introduction

Supercritical heat transfer experiments in water require high-pressure test facilities which are very expensive to construct. It is therefore more economical to perform tests in a modeling fluid at water-equivalent conditions and transform the modeling fluid data into water. Supercritical test facilities using modeling fluids such as CO_2 operate at much lower pressures, temperatures and powers and are less costly to construct. However the accuracy of transforming SCHT data obtained in modeling fluids into water-equivalent values has yet to be determined in a systematic manner.

Starting in the 1950s, heat transfer in supercritical (SC) water and other fluids was investigated in support of SC fossil-fuelled power plants. This topic has recently received renewed attention because of its relevance to Super Critical Water-cooled Reactors (SCWR), which are among the designs considered by the Generation IV International Forum as innovative nuclear energy systems with increased safety, more compact size, lower cost of energy production and reduced volume of nuclear waste, compared to existing systems. The present work is part of ongoing multi-faceted research at the University of Ottawa (UO) in support of the Canadian National Program for the development of the SCWR [11].

Prediction and modeling of the flow and heat transfer at SC pressures remain topics of intense research worldwide and are commonly described by empirical correlations that are fitted to measurements within suitable ranges of conditions. As an alternative to correlations, look-up tables (LUT) have been used successfully to predict complex heat transfer phenomena such as critical heat flux (CHF) and film boiling heat transfer with an accuracy that is much higher than the best available prediction methods [4,3]. The UO team is in the process of finalizing a trans-critical look-up table (TC LUT) for convective heat transfer at high subcritical and SC pressures [14]. The TC LUT is based on a large database of reliable near-critical and SC heat transfer measurements for water and other fluids, which includes compilations from three other universities [13]. It was found that the uncertainty in predicting the heat transfer coefficient using the TC LUT is much lower than that of the assessed correlations and so the use of the TC LUT is recommended for design and analysis of SCWR as a more accurate alternative to the use of correlations.

Experiments in SC water are necessary for the development of SCWR, however, they are difficult and expensive to perform. We have constructed a supercritical heat transfer flow loop (SCUOL) and conducted a series of experiments using carbon dioxide as a surrogate fluid [15]. One objective of this work is to supplement the available experimental database for CO_2 with measurements under conditions for which previous data are sparse or unavailable; moreover, these data are intended to fill some gaps in the

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Nomenclature

d	tube inner diameter
e	relative difference between the scaled and predicted heat transfer coefficients
f	average friction factor
H	specific enthalpy
h	heat transfer coefficient
k	thermal conductivity
L	heated length
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
U	bulk velocity
z	axial distance from the inlet of the heated section

Greek symbols

θ	parameter in the Cheng et al. scaling laws
μ	viscosity
ρ	density

Subscripts

avg	average
b	bulk
c	critical
fr	friction
in	inlet
LUT	look-up table
pc	pseudo-critical
sat	saturation
SC	scaled
SL	scaling law
Sub	subcritical
w	wall

Other notation

$\langle\ \rangle$	average
$(\ )'$	rms value

Acronyms

CHF	critical heat flux
HTC	heat transfer coefficient
NHT	normal heat transfer
SC	supercritical
SCUOL	supercritical University of Ottawa loop
SCWR	supercritical water-cooled reactor
TC LUT	trans-critical look-up table

experimental database of the TC LUT as well as in the databases for CHF and film boiling LUT and boiling heat transfer correlations for high subcritical pressures. In order to convert CO_2 data into water-equivalent values, it is necessary to use appropriate fluid-to-fluid scaling laws. Scaling laws for convective heat transfer at supercritical pressures were first developed for the purpose of estimating heat transfer to a fluid at some conditions from available values at different conditions but in the same fluid. Following customary dimensional analysis practices, the independent and dependent parameters were normalized by appropriate scales to form a set of dimensionless groups. The application of this concept was extended to scale convective heat transfer in two different fluids, in which case assumptions concerning the thermodynamic similarity of the two fluids needed to be introduced. [9] described briefly the thermodynamic similarity of fluids and referred this similarity to the Van der Waals equation of state in terms of pressure, temperature and specific volume "reduced" by the critical values; he then discussed its known applicability to different fluids, including fluids at supercritical pressures.

The objective of this article is to assess the accuracy of available and newly suggested fluid-to-fluid modeling (or fluid scaling) methods for heat transfer at high subcritical and supercritical pressures. The method that is deemed to be most appropriate will be used to convert the CO_2 experimental data that were obtained in SCUOL into their water equivalent values and then incorporate these values into the TC LUT.

Two previously suggested sets of scaling laws were evaluated in this work, namely the modified Jackson's [6] scaling laws, as proposed by Zwolinski et al. [16], and the Cheng et al. [2] scaling laws. Some limitations of these laws were discussed and new sets of scaling laws were developed by modifying earlier relationships; these laws contained an empirical coefficient, which was fitted to the TC LUT predictions separately for the SC region and for the high subcritical region.

2. Scaling laws

In accordance with general scaling procedures, scaling of convective heat transfer is based on a set of dimensionless groups, which can be derived from dimensionless forms of the governing equations or by application of the Buckingham π theorem. In either case, the choice of appropriate scales for the independent and dependent variables, the specification of the ranges of conditions to which such scaling is intended to apply, and possibly physical constraints that must be satisfied for a meaningful application of scaling are essential parts of the process. Scaling may refer to the same fluid in different channels or under different conditions, to different fluids or to a combination of these cases. The interest of the present work is on scaling heat transfer in different fluids. In this section, we will first summarize previously suggested scaling laws, then comment on their suitability for our specific objectives, and finally modify some of these laws to improve the accuracy of scaling heat transfer data in CO_2 to equivalent water values not only in the supercritical pressure region but also in the high subcritical one.

2.1. Previous scaling laws

Jackson's scaling laws for the same fluid: Jackson and Hall [8] and Jackson [5,6] analyzed the dimensionless equations for flow and heat transfer and specified the requirements for strict similarity between two geometrically-similar vertically-upward flows cooled by the same fluid at SC pressures. This similarity was restricted to steady-state forced convection in uniformly heated tubes. He specified that the pressure P_{in} and temperature T_{in} at the inlet of the heated section should be the same between the two cases considered and that the dimensionless distance z/d (z is the distance from the inlet and d is the tube diameter, to be replaced by the hydraulic diameter for channels with non-circular cross sections) along the tube should also be the same. This analysis specified that the Reynolds numbers Re_{in}, evaluated at inlet conditions, should be matched and further provided a scaling law for the wall heat flux q, which also contained properties at inlet conditions. Jackson did not identify a range of tube diameters to which this analysis would apply, but mentioned that the tube diameter should be small enough for the buoyancy effects to be small and large enough for viscous pressure losses not to have a significant effect on property variation. Jackson further noted that the presence of strong buoy-