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An improved modeling on convection heat transfer of supercritical fluids for several advanced energy systems

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ABSTRACT

An improved convection heat transfer correlation for supercritical fluids was developed based on the underlying physical mechanism of turbulent flow of working fluids with variable properties. The new correlation employs a more physically reasonable property-averaging technique, Probability Density Function (PDF)-based time-averaged properties, to account for the effect of nonlinear dependency of properties on instantaneous temperature. In addition, the buoyancy and thermally induced acceleration modification equations proposed by Jackson can also be used with the new correlation and work well in evaluating the buoyancy and thermally induced acceleration effect on the normal convection heat transfer. The new correlation was validated with a large amount of heat transfer experimental data including forced convection heat transfer data for supercritical CO_2 flow in a horizontal semicircular printed circuit heat exchanger, convection heat transfer data considering buoyancy for supercritical water upward flow in a square annular channel, and convection heat transfer data considering effect of thermally induced flow acceleration for supercritical methane flow in a horizontal miniature circular tube. Comparison of experimental data with the correlation prediction results reveals that the new correlation predicts more accurate than conventional correlations for typical supercritical working fluids of several advanced energy systems.

1. Introduction

In the past decades, supercritical fluids, due to their highly efficient heat transfer effectiveness [1], have been worldwide extensively concerned to be used in many promising advanced energy conversion and power systems such as supercritical CO_2 power cycles configured to operate with a variety of heat sources (e.g. fossil, nuclear, solar and waste heat), supercritical water fossil and nuclear power technology and supercritical hydrocarbon fuels rocket and supersonic combustion scramjet engines [1–12]. Supercritical fluids are an excellent choice for an advanced power cycle as they experience no phase change above critical pressure. At high temperatures and low pressures, relative to the critical point, they behave as a gas, while at low temperatures and high pressures they resemble a liquid. This results in low compressor work while maintaining gas like behavior in the rest of the cycle. The heat transfer and fluid flow behaviors of supercritical fluids are significantly different from those of constant property fluids. Although there is no strict distinction between liquid and gas above the critical pressure, the strong variation of thermo-physical properties in the vicinity of the pseudo-critical temperature (which is defined as the temperature, for a given pressure, at which the specific heat exhibits a maximum) may result in unusual heat transfer behaviors, such as local heat transfer deterioration due to buoyancy or thermally induced flow acceleration effect and the inhibition of the heat exchange rate due to the presence of a pinch point inside the recuperators. (Pinch point is the position inside the heat exchanger where the temperature difference between the hot side and cold side heat transfer fluids approaches infinitesimal. In this case, the heat exchange rate will be inhibited.) Therefore, it is of great importance to figure out such heat transfer and fluid flow regime and to evaluate the local heat transfer coefficients and flow regime throughout the components, for the purpose of accurate design and efficient safe operation of these advanced energy systems. Furthermore, due to the similar trend of the properties variations for different supercritical fluids, it is of great interest and necessity to pay attention to these common features and attempt to develop a generalized correlation in non-dimensional form, which allows the experimental data for several supercritical fluids to be combined into one set.

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Nomenclature

A	area (m^2)
Ac_b	acceleration number, $\frac{\beta_b q_w d}{k_b Re_b^{1.625} Pr_b}$
Bo_b	buoyancy number, $\frac{Gr_b}{Re_b^{3.425} Pr_b^{0.8}}$
C_p	specific heat (J/(kg K))
$\overline{C_p}$	integrated specific heat (J/(kg K)), $\frac{i_w - i_b}{T_w - T_b}$
d	hydraulic diameter (m)
erf (x)	error function
F(x)	cumulative distribution function
g	gravity (m/s^2)
G	mass velocity (kg/(m^2 s))
Gr_b	Grashof number, $\frac{g_b \beta_b q_w d^4}{k_b v_b^2}$
h	heat transfer coefficient (W/(m^2 K))
i	enthalpy (J/kg)
k	thermal conductivity (W/(m K))
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number, $\frac{hd}{k_b}$
Pr	Prandtl number
q	heat flux (W/m^2)
Re	Reynolds number, $\frac{Gd}{\mu_b}$
t	time (s)
T	temperature (°C)
β	volume expansion coefficient (1/K)
$\phi(T, \overline{T})$	probability density function (1/K)
μ	dynamic viscosity (kg/(m s))
$\bar{\mu}$	integrated dynamic viscosity (kg/m^3), $\frac{1}{T_w - T_b}\int_{T_b}^{T_w} \mu dT$
v	kinematic viscosity (m^2/s), $\frac{\mu}{\rho}$
ρ	density (kg/m^3)
$\bar{\rho}$	integrated density (kg/m^3), $\frac{1}{T_w - T_b}\int_{T_b}^{T_w} \rho dT$
σ	variance in probability density function (K)

Subscripts

b	bulk
COR	correlations
EXP	experiments
pc	pseudo-critical
pdf	probability density function
w	wall

Abbreviation

DB	Dittus-Boelter
PCHE	printed circuit heat exchanger
PDF	probability density function

Comprehensive literature reviews of earlier studies on heat transfer and fluid flow characteristics of supercritical fluids can be found in Rao et al. [13], Jackson [14], Kurganov et al. [15–17] and Pioro and Duffey [18]. A large amount of previous experimental and numerical studies concerning supercritical water, carbon dioxide and hydrocarbon fuels have demonstrated that conventional forced convection heat transfer correlations fail to accurately predict the heat transfer of supercritical fluids with deviations larger than 60% from the experimental data [5], especially near the pseudo-critical point, indicating that due to rapid changes in thermal physical properties of supercritical fluids near the pseudo-critical point, the heat transfer and fluid flow regime at supercritical pressures could be significantly different from that of constant property fluids. This disparity necessitates an intensive study on developing better physically improved heat transfer models for supercritical fluids. This is also the major objective of the present study.

In the past decades the authors have done a great number of studies with regard to heat transfer characteristics of various supercritical fluids such as supercritical carbon dioxide [4–6], water [7,8], methane [9] and kerosene [10]. Based on these previous studies, the authors found that the existing conventional heat transfer models cannot accurately predict the heat transfer performance especially in the vicinity of pseudo critical point as they could not capture certain common heat transfer features among different supercritical fluids. In the present study, we will focus on these disparities and the general features of convection heat transfer of supercritical fluids. A physically improved generalized heat transfer correlation was developed and validated by the previous re-organized experimental data of several supercritical fluids.

2. General features of convection heat transfer of supercritical fluids

The exact definition of supercritical fluid is a fluid that is at a pressure and temperature above its critical pressure and temperature, respectively. But in practically, a supercritical fluid can be defined as a fluid that is only at a pressure above its critical pressure. Based upon the temperature of the fluid it may resemble a gas or a liquid, but always remains a single phase. The heat transfer and fluid flow regime at supercritical pressures could be significantly influenced by the thermal physical properties which present drastic variations within the vicinity of the critical point. The values of critical point for several fluids were shown in Table 1. In order to better illustrate the similar trends of properties variations in the vicinity of critical point, the thermal physical properties based on NIST Standard Reference Database-REFPROP, Version 8.0 [19] were normalized to the values of critical point and were plotted in Fig. 1 against to normalized bulk temperature. It can be seen from Fig. 1 that the normalized properties of different supercritical fluids shown similar trend in the vicinity of critical points. The specific heat exhibits a peak near the critical point. The density as well as the thermal conductivity and the dynamic viscosity decrease dramatically within a very narrow temperature range, especially near the critical point. Besides, the thermal conductivity has a local peak near the critical point. These trends would become less pronounced with an increase in pressure, which would in turn bring differences in heat transfer features at different supercritical pressures.

Previous studies revealed that the effectiveness of heat transfer at supercritical pressures could be significantly influenced by the ratio of heat flux to mass flux [4–7,9,10]. At high mass flux with relatively low heat flux the heat transfer coefficient could be enhanced near the pseudo-critical temperature due to the large value of specific heat capacity under such conditions. However, the enhancement of heat transfer can be reduced with the increase

Table 1
The values of critical point for several fluids.

	P_c/MPa	T_c/°C
H_2O	22.064	374
CO_2	7.38	30.98
CH_4	4.6	−82.6