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Study on identification method of heat transfer deterioration of supercritical fluids in vertically heated tubes

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ABSTRACT

Prediction of the heat transfer of supercritical fluids (SCFs), especially for heat transfer deterioration (HTD), is highly significant to the design and safe operation of supercritical boilers and advanced nuclear systems. To achieve higher predictive accuracy, heat transfer datasets of SCFs are usually classified as HTD cases and non-HTD cases using certain HTD identification methods, and prediction models, including empirical correlations and criteria of HTD occurrence, have been separately developed for HTD cases and non-HTD cases. Therefore, the rationality of HTD identification methods are crucial to the data classification and further development of high-precision prediction models but is seldom discussed in research. This paper first summarizes the existing identification methods of HTD to SCFs, and respective heat transfer datasets of supercritical water (SCW) and CO_2 ($SCCO_2$) are compiled. Based on these datasets, the accuracy of existing methods in identifying HTD cases and non-HTD cases is evaluated. The results show that, the most common identification method ($Nu/Nu_{db} < 0.3$) can mistake typical non-HTD case for HTD case and cannot reflect the actual location where HTD occurs. The Lokshin et al. method and Zhang et al. method ($htc/htc_0 < 1.0$) can accurately recognize HTD cases but are prone to error in detecting non-HTD cases. It is believed that the reference value representing normal heat transfer is the key to judging the heat transfer state of SCFs, and should be considered specifically in the pseudo-phase-change influenced region. Finally, an improved identification method of HTD suitable for SCW and $SCCO_2$ is proposed. Compared with previous methods, the new method shows favorable accuracy in discerning both HTD cases and non-HTD cases, and is helpful for classifying heat transfer cases and developing precise heat transfer correlations and HTD criteria of SCFs.

1. Introduction

Based on thermodynamic laws, when the initial parameters of main steam/gas in power cycles (e.g., Rankine-cycle and Brayton-cycle) increase to a supercritical level, the energy conversion efficiency of power systems can be enhanced dramatically. Supercritical fluids (SCFs), such as supercritical water (SCW) and supercritical CO_2 ($SCCO_2$), therefore have been widely applied in ultra-supercritical units [1], advanced nuclear reactors [2], and solar-thermal power systems [3,4] among others. Undoubtedly, the design and optimization of these new systems require a thorough understanding of the unique thermo-hydraulic characteristics of SCFs.

Though no phase-change occurs in SCFs, strong variations in fluid thermophysical properties still exist near the pseudo-critical point. For flows in heated tubes, the buoyancy effect and thermal acceleration effect can be induced by a large density gradient and interact with other property variations, causing more complex heat transfer laws in SCFs. Three different heat transfer modes appear under different ratios of heat flux to mass flux (q/G) [5]: normal heat transfer, heat transfer enhancement (HTE), and heat transfer deterioration (HTD). Normal heat transfer and HTE are collectively called a non-HTD mode in general. As shown in Fig. 1, when q/G is small (about 0.2 kJ/kg), the wall temperature (T_w) increases smoothly along with the bulk fluid enthalpy (h_b) of water, demonstrating typical non-HTD behavior. When q/G is large (about 1.0 kJ/kg), the T_w rises abruptly, and typical HTD phenomenon appears before the pseudo-critical point. Similar to the boiling crisis (departure from nucleate boiling; DNB) at subcritical pressures, HTD of SCFs can cause drastic temperature differences (ΔT) between the tube wall and the bulk coolant along with a much lower coolability, which is prone to overheating and burst accidents of tubes. Thus, models for predicting HTD of SCFs are necessary for the safety design of these systems.

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Nomenclature

c_p	specific heat (kJ/kg K)
d	inner diameter of tubes (m)
E_q	thermal expansion parameter
E_q^0	E_q of ideal gas
G	mass flux (kg/m^2 s)
h	fluid enthalpy (kJ/kg)
htc	heat transfer coefficient (kW/m^2 K)
M	molar mass (g/mol)
Nu	Nusselt number, $= htc \cdot d/\lambda$
P	pressure (MPa)
Pr	Prandtl number, $= c_p \cdot \mu/\lambda$
q	heat flux (kW/m^2)
q_{cr}	critical heat flux of HTD occurrence (kW/m^2)
Re	Reynolds number, $= G \cdot d/\mu$
R	universal gas constant, = 8.31451 (J/mol K)
T	temperature (°C)
ΔT	temperature difference between the tube wall and core fluid (°C)
x	axial distance (m)

Greek symbols

β	thermal expansion coefficient (1/K)
λ	thermal conductivity (kW/m K)
ρ	density (kg/m$^{3)}$
μ	dynamic viscosity (Pa s)

Subscripts

b	at bulk fluid temperature
db	calculated by D-B correlation
exp	experimental
nht	normal heat transfer
pc	at pseudo-critical temperature
pg	at pseudo-saturated gas point
pl	at pseudo-saturated liquid point
pl0	at the start point of the PCIR
pm	at the pseudo-homogeneous mixture
ref	reference value of the HTD definition
w	at wall temperature
0	at h_b = 840 kJ/kg of SCW; at h_b = 120 kJ/kg of $SCCO_2$

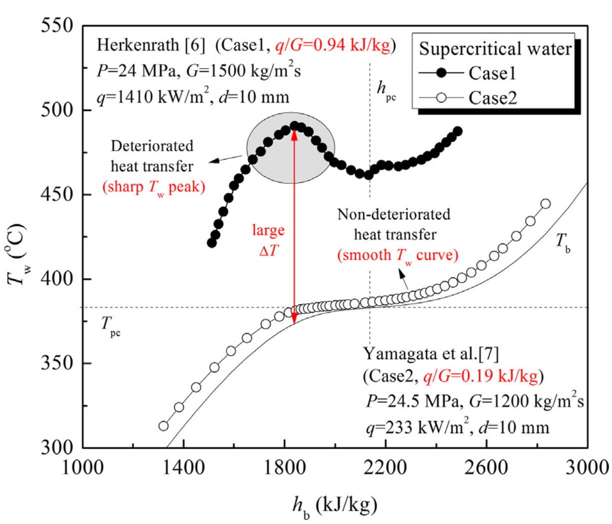

Fig. 1. Variations of T_w versus h_b in typical HTD case and non-HTD case of SCW.

It is essential to pre-judge whether and when HTD will occur in the absence of experiments. Numerous studies [6–9] have found there exists a critical heat flux (q_{cr}) at the onset of HTD, and substantial efforts [10–14] have been devoted to predicting the q_{cr} by proposing various HTD criteria, most of which are associated with design parameters (e.g., pressure P, mass flux G, tube diameter d, and heat flux q). It should be noted that, during the development of these HTD criteria, researchers often classify experimental results as either HTD cases or non-HTD cases using certain HTD identification methods (otherwise known as the definition of HTD) to determine the boundary of HTD occurrence. It means that the accuracy of the proposed HTD criteria for predicting q_{cr} is completely dependent on the rationality of the HTD identification method employed by researchers when classifying HTD cases and non-HTD cases. Table 1 lists the existing criteria of HTD for SCFs upward-flowing in heated tubes, and most criteria were developed as a form of $q_{cr} = aG^b$. As Table 1 illustrates, different methods for identifying HTD have been used by researchers to classify experimental cases, and divergent boundaries between HTD cases and non-HTD cases are yielded and applied to develop prediction models of HTD onset. This process inevitably leads to inconsistencies among the predicted q_{cr}. As shown in Fig. 2(a), large discrepancies exist between q_{cr} values predicted by different HTD criteria for water at P = 23 MPa, especially with high mass flux. Specifically, when d = 22 mm and G = 2000 kg/m^2 s, the q_{cr} calculated by the Schatte model is about 773.1 kW/m^2, while Yamagata model predicts HTD when q reaches up to 1829.2 kW/m^2, over twice the q_{cr} value predicted by the Schatte model. Such disparities will seriously affect the setting of the safety boundary during boiler design.

Besides the criterion of HTD, another type of important model is the empirical correlation for predicting heat transfer coefficient (htc) of SCFs under different conditions. In general, owing to the different physical mechanisms in HTD cases and non-HTD cases, researchers separately developed empirical correlations for HTD cases and non-HTD cases based on classified datasets, to improve the prediction accuracy. However, due to different HTD identification methods employed by researchers, different heat transfer datasets have been obtained and fitted to develop heat transfer correlations [10,19]. This causes large gaps in the predicted htc of different correlations [7,17,21–23], as shown in Fig. 2(b), and no general correlation has yet been established that can accurately predict the HTD characteristics of SCFs [24].

Given the above background, studies on identification methods of HTD are crucial to the precise classification of HTD cases and non-HTD cases in experiments, and are also central to the developments of high-accuracy heat transfer correlations and HTD criteria. Cheng et al. [25] suggested that, compared with the "DNB" at subcritical pressure, the rise in deteriorated T_w at supercritical pressure was much milder, making it difficult to distinguish the onset of HTD of SCFs, hence, no unique definition of HTD was determined. Schatte et al. [12] pointed out that, the lack of consensus over quantitative HTD identification methods led to poor predictive credibility of existing HTD criteria, and analyses of the currently available methods were necessary. Schatte et al. [12] and Li et al. [14] focused on developing new HTD criteria for SCW and qualitatively summarized the existing definitions of HTD, but no further analyses were conducted. Kline et al. [13] recently proposed a modified reference value representing normal