Annals of Nuclear Energy 76 (2015) 451–460

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

An assessment of correlations of forced convection heat transfer to water at supercritical pressure

Weiwei Chen, Xiande Fang*, Yu Xu, Xianghui Su

Institute of Air Conditioning and Refrigeration, Nanjing University of Aeronautics and Astronautics, 29 Yudao St, Nanjing 210016, China

ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form 18 June 2014
Accepted 22 October 2014
Available online 8 November 2014

Keywords:
Supercritical water
Heat transfer
Correlation
Vertical tubes
Nuclear reactor

ABSTRACT

The heat transfer of supercritical water is essential for supercritical water-cooled nuclear reactors. Many empirical correlations for heat transfer to supercritical water were proposed over the past few decades. Some evaluations of the correlations were conducted, and inconsistent conclusions appeared owing to limited correlations or experimental data. This work presents an extensive survey of the literature of correlations and experiments of forced convection heat transfer to water flowing upward in vertical tubes at supercritical pressure. There are 26 correlations found, and an experimental database containing 3220 data points from vertical tubes are compiled from nine independent laboratories. All available correlations are assessed against the experimental database. The results show that the best correlation has a mean absolute deviation of 12.8%, predicting 82.3% of the database within ±20%. The entire database is divided into three categories, and the correlations which can give the most accurate predictions of the experimental data from different categories are also identified. The results provide a guide to choosing a proper correlation for engineering practice. Some topics worthy of attention for future studies are indicated.

1. Introduction

Supercritical water is of great interest for its applications in nuclear reactor cooling since it has unique properties and favorable heat and mass transfer characteristics. A supercritical water-cooled nuclear reactor (SCWR) is a high pressure (about 25 MPa) and high temperature (up to 625 °C) reactor that operates above the critical point of water (22.064 MPa and 373.95 °C). The SCWR offers the potential for high thermal efficiencies, considerable plant simplifications, and better safety and economy (Mokry et al., 2010a). Empirical correlations with good predictions of heat transfer for supercritical water are of considerable significance for developing a SCWR.

Due to the strong variation of thermophysical properties in the vicinity of the critical and pseudo-critical point, water at supercritical pressure shows different heat transfer behaviors than at subcritical pressure, and conventional single-phase correlations cannot predict it (Song et al., 2008; Cheng et al., 2009).

The investigations of heat transfer of supercritical water have been carried out since the 1930s. Detailed reviews on the existing experimental and theoretical studies were performed by several authors (Petukhov, 1970; Jackson and Hall, 1979; Polyakov, 1991; Cheng and Schulenberg, 2001; Pioro et al., 2004; Pioro and Duffey, 2005; Pioro and Duffey, 2007). As the prediction of the heat transfer coefficient for supercritical water is mainly conducted using empirical approaches, a number of empirical correlations exist in the open literature, which were derived based on experimental data with limited parameter ranges (Bishop et al., 1964; Swenson et al., 1965; Krasnoshchekov et al., 1967; Yamagata et al., 1972; Griem, 1996; Mokry et al., 2010a). Subsequently, some evaluations were carried out to find out the best correlations.

Cheng and Schulenberg (2001) conducted a thorough review on heat transfer of supercritical water at the HPLWR condition. The HPLWR means the High Performance Light Water Reactor, a joined research project in Europe. Five heat transfer correlations for supercritical water (Bishop et al., 1964; Swenson et al., 1965; Yamagata et al., 1972; Krasnoshchekov et al., 1967; Griem, 1996) were implemented into the sub-channel analysis code to determine their applicability to the HPLWR fuel assembly. The number of the experimental data points used for their analysis was not given. As a result, the Bishop et al. (1964) correlation was recommended for calculating the heat transfer coefficient in an HPLWR fuel assembly, and the Yamagata et al. (1972) correlation was suggested to be used for determining the onset of heat transfer deterioration.

* Corresponding author. Tel./fax: +86 25 8489 6381.
E-mail address: xd_fang@yahoo.com (X. Fang).

http://dx.doi.org/10.1016/j.anucene.2014.10.027
0306-4549/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

Bu	buoyancy parameter $\left(\overline{Gr}/\left(Re^{2.7}\overline{Pr}^{0.5}\right)\right)$
c_p	specific heat at constant pressure (J/kg K)
$\overline{c_p}$	average specific heat at constant pressure (J/kg K), $(h_w - h_b)/(t_w - t_b)$
D	inner tube diameter (m)
G	mass flux (kg/m^2 s)
Gr	Grashof number $(gD^3(\rho_b - \rho_w)/\rho v^2)$
Gr^*	Grashof number based on heat flux $\left(g\beta D^4 q/\lambda v^2\right)$
$\overline{Gr}$	average Grashof number $\left(gD^3(\rho_b - \overline{\rho})/\rho v^2\right)$
g	acceleration due to gravity (m/s^2)
h	specific enthalpy (J/kg)
L	tube length (m)
Nu	Nusselt number $(\alpha D/\lambda)$
Pr	Prandtl number $(\mu c_p/\lambda)$
$\overline{Pr}$	average Prandtl number $(\mu\overline{c_p}/\lambda)$
p	pressure (Pa)
q	heat flux (W/m^2)
q^+	non-dimensional heat flux $(q\beta/(Gc_p))$
Re	Reynolds number (GD/μ)
T	temperature (K)
t	temperature (°C)

Greek symbols

α	heat transfer coefficient (W/m^2 K)
β	thermal expansion coefficient (1/K)
λ	thermal conductivity (W/mK)
μ	dynamic viscosity (Pa s)
v	kinematic viscosity (m^2/s)
ξ	friction coefficient
ρ	density (kg/m^3)
$\overline{\rho}$	average density (kg/m^3)

Subscripts

b	at bulk temperature
exp	experimental
in	inlet
pc	at pseudo-critical temperature
$pred$	predicted
w	at wall temperature

Jackson (2002) evaluated nine heat transfer correlations for water flowing in vertical tubes based on 1500 experimental data points. They modified the Krasnoshchekov and Protopopov (1959) correlation for forced convective heat transfer in water and carbon dioxide at supercritical pressures, capturing 97% of the experimental data within ±25%. The Results showed that the Krasnoshchekov et al. (1967) correlation and the newly modified correlation were the most accurate ones.

Pioro et al. (2004) conducted the literature survey of the work in the area of heat transfer at supercritical pressures. Eight correlations were compared based on the Shitsman (1963) experimental data for supercritical heat transfer in tubes and bundles to choose the most reliable ones. The comparisons showed that there was a significant difference in heat transfer coefficient values calculated according to various correlations. Only some correlations showed similar results, which were quite close to the experimental data for normal supercritical heat transfer in water. Also, no one correlation was able to accurately predict deteriorated or improved heat transfer in tubes. Based on the eight chosen correlations, the heat transfer coefficients and temperature profiles in the CANDU-X reactor cooled with supercritical water were calculated.

Licht et al. (2008) compared four selected heat transfer correlations with their own experimental results and found that the Jackson (2002) correlation predicted the test data best, capturing 86% of the data within ±25%. The Watts and Chou (1982) correlation showed a similar trend but under-predicted the measurements by 10% relative to the Jackson (2002) correlation.

Yu et al. (2009a) verified 14 supercritical heat transfer correlations based on 1142 experimental data points, and Yu et al. (2009b) compared 16 supercritical heat transfer correlations with the Styrikovich et al. (1967) data. The results showed that the Bishop et al. (1964) correlation performed best.

Zhu et al. (2009) compared five selected heat transfer correlations based on their own experimental results of the supercritical heat transfer of water and found that their own correlation and the Swenson et al. (1965) correlation were the best.

Mokry et al. (2010a) verified five selected heat transfer correlations and found that all of them deviated substantially from the experimental data within the pseudo-critical range. Therefore, they proposed their own correlation and recommended it to be used for SCWRs and supercritical water heat exchangers.

Jäger et al. (2011) summarized the activities of the TRACE code validation at the Institute for Neutron Physics and Reactor Technology (Germany) related to supercritical water conditions. The 15 existing heat transfer correlations were reviewed and implemented into TRACE, and six selected experimental data sources were used to identify the most suitable heat transfer correlation(s). The number of the experimental data used was not stated, and the overall performance of each correlation for predicting the entire database was not clear. As a result, they recommended the Bishop et al. (1964) model for design and safety evaluation of SCWRs.

The above evaluations presented inconsistent results due to limited experimental data or correlations. The most comprehensive reviews might be those by Jäger et al. (2011) and Yu et al. (2009a). The former evaluated 15 existing supercritical heat transfer correlations with the experimental data from six selected sources, and the latter assessed 14 based on 1142 experimental data points. This paper conducts an all-around survey of the correlations and experimental results, and 26 existing correlations for water supercritical heat transfer in vertical tubes are assessed with the supercritical water heat transfer database containing 3220 data points compiled from nine independent laboratories. The number of the correlations evaluated and the data used is far more than previous ones. Furthermore, the available experimental data are partitioned into three different heat transfer regimes, including the normal heat transfer regime, the enhanced heat transfer regime, and the deteriorated heat transfer regime. The evaluation of the surveyed correlations is implemented for each regime. To the best of the authors' knowledge, it is the first state-of-the-art review using a multiple-source database consisting of more than 1500 data points to evaluate more than 15 correlations for supercritical heat transfer to water, and it is the first practice to evaluate the correlations for each of the three heat transfer regimes. The evaluation results provide a guide to choosing a proper correlation for engineering practice. Some topics worthy of attention for future studies are indicated.