Annals of Nuclear Energy 63 (2014) 339–349

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Experimental study on heat transfer of supercritical water flowing downward in circular tubes

M. Zhao *, H.Y. Gu, X. Cheng

School of Nuclear Science and Engineering, Shanghai Jiao Tong University, Dongchuan Road 800, 200240 Shanghai, China

ARTICLE INFO

Article history:
Received 22 March 2013
Received in revised form 2 July 2013
Accepted 2 July 2013
Available online 28 August 2013

Keywords:
Supercritical water
Heat transfer
Circular tubes
Downward flow

ABSTRACT

An experimental study on heat transfer of supercritical water flowing downward in circular tubes with 7.6 mm inner diameter was carried out on the SWAMUP test facility. More than 3500 test data were obtained with the following test conditions: pressure from 23.0 MPa to 26.0 MPa, mass flux from 450 kg/m^2 s to 1500 kg/m^2 s, heat flux from 0.17 MW/m^2 to 1.4 MW/m^2 and bulk temperature from 280 °C to 410 °C. Effect of various parameters on heat transfer was investigated. Test data in the present study were also compared with those obtained in tubes with upward flow. In addition, comparison of the test data with available correlations indicates that none of the correlations give an accurate prediction. Based on the test data and sensitivity study of various dimensionless numbers, a new correlation was developed which introduced one additional dimensionless number π_B to correct the conventional Dittus–Boelter equation and gives a satisfying agreement with the test data.

1. Introduction

Heat transfer of supercritical water shows abnormal behavior compared with that of conventional fluids, especially when the bulk temperature is close to the pseudo-critical point, due to drastic variation of thermal–physical properties in the vicinity of the pseudo-critical point (Cheng and Schulenberg, 2001). Mainly motivated by the design of supercritical pressure fossil power plants, supercritical water heat transfer experiments in tubes with diameter ranging from 7.5 mm up to 24 mm have been performed since 1950s, e.g. experiments by Dickinson and Welch (1958), Ackerman (1970), Yamagata et al (1972), Griem (1995,1996) and Xu (2004). These studies have been well documented by many reviewers (Petuhkov, 1970, Jackson and Hall, 1979; Polyakov, 1991; Yoshida and Mori, 2000; Cheng and Schulenberg, 2001; Pioro and Duffey, 2005).

Generally the experimental data show a good agreement with the Dittus–Boelter equation at a wall temperature far below the pseudo-critical point. Large deviation appears at a wall temperature in the vicinity of the pseudo-critical point. Compared to Dittus–Boelter equation, heat transfer is enhanced at low heat fluxes, whereas significant heat transfer impairment, also called heat transfer deterioration in the open literature, is observed at high heat fluxes. The experimental work of Bishop et al. (1964), Swenson et al. (1965), Herkanrath et al. (1967) and Kirillov et al. (1986, 2005) was performed in the frame of designing supercritical fossil fuel fired power plant and supercritical water-cooled reactor (SCWR). In these experiments, mass flux, heat flux and bulk temperature cover partially the design condition of SCWR (Schulenberg et al., 2008; Cheng et al., 2008). Most of the studies available in the open literature are related to upward flow in circular tubes. Based on the previous studies, an experimental data bank with more than 10,000 test data points in upward-flow supercritical water heat transfer in circular tubes has been established at Shanghai Jiao Tong University (SJTU) (Kuang et al., 2008). More recently, upward-flow supercritical water heat transfer experiments were carried out in circular tubes of different diameters at the SWAMUP test facility of SJTU (Gu et al., in press).

In most of the SCWR design concepts (Schulenberg et al., 2008, Oka et al., 2000, Cheng et al., 2008) reactor core with multiple flow passes has been proposed. The reactor core is divided into several zones where supercritical water flows in different directions, i.e. both upward flow and downward flow exist in such design concepts. However, comparing to upward flow, studies on supercritical water heat transfer in downward flow conditions are very limited.

Shitsman (1968) carried out experiments of heat transfer to supercritical water in 16 mm circular tubes with both upward and downward flow directions. Tests were performed at low mass flux conditions. Remarkable effect of flow direction on wall temperature, and subsequently on heat transfer coefficient, is obtained at high heat flux to mass flux ratios. For downward flow, the wall temperature shows smooth increase along with bulk temperature, whereas a fluctuation of wall temperature, i.e. in heat transfer coefficient, is observed.

---

* Corresponding author. Tel.: +86 21 34202944; fax: +86 21 34205182.
E-mail address: zhaomeng@sjtu.edu.cn (M. Zhao).

0306-4549/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.anucene.2013.07.003

Nomenclature

Bo	dimensionless parameter, representing buoyancy effect
C	coefficient in Dittus–Boelter equation
C_P	specific heat
D	diameter (m)
e	total error of the evaluated parameter, deviation
e_s	systematic error of the evaluated parameter
$e_{s,i}$	systematic error of the input parameters
g	acceleration of gravity (m/s^2)
G	mass flow rate
Gr	Grashof number
h	enthalpy
L	length (m)
Nu	Nusselt number
Nu_f	representing Nusselt number calculated from Dittus–Boelter equation
Pr	Prandtl number
q	heat flux (W/m^2)
Re	Reynolds number
T	temperature (°C)
Z	evaluated parameter
$Z_1,Z_2,\ldots,Z_n$	input parameters

Greek

α	heat transfer coefficient (W/m^2°C)
β	volume expansion coefficient (1/°C)
λ	thermal conductivity (W/m°C)
μ	dynamic viscosity (Pa∗s), average value of deviation
ν	kinematic viscosity, $\nu = \mu/\rho$ (m^2/s)
π_A	dimensionless parameter, representing acceleration effect
π_B	dimensionless parameter, representing buoyancy effect
π_C	dimensionless parameter, representing specific heat ratio
ρ	density (kg/m^3)
σ	statistic error of the evaluated parameter
σ_i	statistic error of the input parameter

Subscripts

a	average
b	bulk
m	measured in the experiments
max	maximum
w	wall surface
outer	outer side

Yamagata et al. (1972) carried experimental investigation in circular tubes with both upward and downward flow. No significant effect of flow direction was observed.

A literature review on existing experimental studies reveals large deficiency in experimental data with respect to parameter ranges relevant to SCWR conditions (Kuang et al., 2008), especially for downward flow conditions. Generally it is believed that downward flow shows a better heat transfer behavior than that in upward flow conditions. Heat transfer enhancement is more significant in downward flow conditions, whereas heat transfer deterioration is hardly observed (Jackson and Hall, 1979).

As a supplement to the existing data bank, the downward flow supercritical water heat transfer experiments are carried out in a circular tube of 7.6 mm in diameter. Effects of pressure, heat flux and mass flux are investigated. Based on test data, the importance of various dimensionless parameters was analyzed, and several heat transfer correlations were assessed. Based on the obtained experiment data, a new correlation to predict heat transfer coefficient in downward flow was developed by including the dimensionless number π_B proposed by Cheng et al. (2009). Similar to Cheng's correlation, the new correlation also contains a single dimensionless number to correlate the correction factor and excludes the direct dependence of heat transfer coefficient on the wall temperature.

2. Experimental techniques

2.1. SWAMUP test facility

The SWAMUP test facility, shown in Fig. 1, is used to perform heat transfer tests in supercritical water. The facility consists of the main test loop, a cooling water loop, a water purification loop, and the IandC system. The main test loop, consisting of a circulating pump, pre-heater, mixing chamber, two heat exchangers, accumulator and test sections, is constructed for pressure up to 30 MPa, temperature up to 550 °C, mass flow rate up to 1.3 kg/s and electrical power up to 1.2 MW.

In the test loop, part of water flow is not heated and flows through the bypass line which is designed for rough adjustment of the flow rate through the test section. The rest portion of flow first passes the pre-heater, where water flow is heated up to a pre-defined test inlet temperature. In the test section water can be heated to 550 °C. Both parts merge in the mixing chamber where water temperature is reduced to reduce the potential corrosion in the downstream. The two parallel heat exchangers are used to further cool down the water flow before it enters the pump. Two flow meters with different measurement ranges are installed in parallel in the main flow path, to measure the mass flow rate entering the test sections. The main technical parameters are listed in Table 1:

2.2. Test sections

The test section, as shown in Fig. 2, is made of Inconel 625 smooth tube with inner diameter of 7.6 mm. The tube thickness is 2.2 mm. Supercritical water flows vertically downward through the tube. The tube is heated with DC power supply over a length of 2640 mm. Fifty sheathed thermocouples are attached to the outer surface of the tube to measure the temperature distribution. A sketch of the test section including the axial location of the thermocouples is shown in Fig. 2. In the experiments, flow rate, fluid temperature at the inlet and outlet of the test section, operating pressure, electric current and electric voltage are measured. The location of various measurements is depicted in Fig. 2.

2.3. Test parameters

The test parameter ranges of the present experiments were summarized in Table 1. Three pressure values were selected, i.e. 23, 25 and 26 MPa, which are 1.04, 1.13 and 1.17 times of the critical pressure of water (22.1 MPa) respectively. The mass flux varied from 450 to 1500 kg/m^2 s. The heat flux is up to 1400 kW/m^2. The parameter ranges cover the design parameter of SCWR designs. The tube diameter 7.6 mm was selected based on two considerations. Based on experiments in the same diameter tubes with