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Experimental studies on heat transfer to supercritical water in circular tubes at high heat fluxes

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

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

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ABSTRACT

Experimental studies on heat transfer to supercritical water flowing upward in circular tubes are carried out at the SWAMUP test facility. Totally more than 10,000 test data were obtained in tubes of two different inner diameters, i.e. 10.0 mm and 7.6 mm 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 190 kW/m^2 to 1400 kW/m^2 and bulk temperature from 240 °C to 460 °C. Each test point is accompanied with systematic error analysis. It is found that for 90% of the test data the uncertainty of measured Nusselt number is less than 10%. Based on the test data obtained, the effect of various parameters on heat transfer is investigated, such pressure, mass flux, heat flux and tube diameter. In addition, the importance of several dimensionless numbers and the accuracy of five widely applied heat transfer correlations are assessed. It is concluded that the acceleration number π_A and the buoyancy parameter π_B show unique effect on heat transfer coefficient. Among the five selected heat transfer correlations, the correlation of Cheng et al. and Jackson show the best agreement with the present test data.

1. Introduction

Extensive research activities are ongoing worldwide to develop supercritical water cooled reactors (SCWR) with high thermal efficiency. One of the most challenging tasks in the design of SCWR fuel assembly is to keep the maximum cladding temperature well below the design upper limit, to guarantee the integrity of fuel rods. Thus, an accurate prediction of heat transfer behavior plays an important role and attracts extensive investigations worldwide. However, in the vicinity of the pseudo-critical temperature, the thermal–physical properties such as density, specific heat, viscosity and thermal conductivity experience sharp variations which will lead to strong coupling effect between flow field and temperature field This phenomenon results in surprising heat transfer characteristics. The heat transfer of supercritical water depends strongly on heat flux, especially at bulk temperatures close to the pseudo-critical point, which shows abnormal behavior compared to that of conventional fluids.

Studies of heat transfer of supercritical fluids have been performed since 50's, which are well reviewed by many authors Petukhov, [12], Polyakov, Cheng and Schulenberg, [20]. In spite of extensive studies of several decades, exact mechanisms affecting heat transfer are still not well understood, and prediction of heat transfer relays mainly on empirical correlations, which are derived based on experimental data. Most of the correlations in the open literature have the general form of a modified Dittus–Boelter equation:

$$Nu_B = C \cdot \mathrm{Re}_B^n \cdot \mathrm{Pr}_B^m \cdot F \quad (1)$$

The correction factor F takes into account the effects caused by heat flux, such as property variation, buoyancy and acceleration effect. Several widely applied correlations were reviewed and assessed in [19,20]. It was concluded that there exist a large number of heat transfer correlations proposed for supercritical fluids, the deviation between them, however, is large, especially for the case with high heat fluxes. Furthermore, the validity of such correlations is limited to conditions of experimental data used.

The experiments of Dickinson and Weich [6], Ackerman [1], Yamagata et al. [24], Griem [7] and Xu [11] were mainly related to the design of supercritical pressure fossil power plants. The tube diameter ranges from 7.5 mm up to 24 mm. 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 was obtained 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 works of Bishop et al. [5], Swenson et al. [23], Herkenrath

* Corresponding author.
E-mail address: guhanyang@sjtu.edu.cn (H.Y. Gu).

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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)
q_v	volumetric heat source (W m^{-3})
U	voltage (V)
Z	evaluated parameter (–)
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)
η	heating efficiency (–)
λ	thermal conductivity (W/m °C)
μ	dynamic viscosity (Pa s), average value of deviation
v	kinematic viscosity, $v = \mu/\rho$ (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
i	inner
j	index
in	inlet
m	measured in the experiments
out	outlet
max	maximum
w	wall surface

et al. [8] and Kirillov et al. [13], Kirillov et al. [14] were performed in the frame of designing supercritical light water reactors. In these experiments, mass flux, heat flux and the bulk temperature cover partially the design condition of the SCWR. In the work of Bishop, small diameter tubes were used, whereas in the work of Swenson, circular tubes of a larger diameter 9.4 mm was applied. In addition to smooth circular tubes, whistled circular tubes and annular channels were also used by Bishop. Nevertheless, no experimental data in annular channels with supercritical water are available in the open literature.

Due to high pressure, high temperature and high heating power required, experimental studies in supercritical water were limited. For fundamental studies, therefore, surrogate fluids such as CO_2 or Freon were often applied, to minimize technical and financial expenditure [15,12,21,22,2,18]. Several authors have performed tests with carbon dioxide studying systematically the effect of different parameters on heat transfer [22]. Extrapolation of the test data to water conditions requires reliable and well validated fluid-to-fluid scaling laws, which, however, are still not available.

A thorough literature review on existing experimental studies and a critical evaluation of experimental data bank reveals large deficiency in experimental data with respect to parameter ranges relevant to SCWR conditions [17]. Most of the previous experiments were carried out at relatively lower heat flux, which were mainly related to the design of supercritical pressure fossil power plants. In the present study, experimental investigations were carried out on heat transfer of supercritical water in two vertical tubes with different diameters. The effects of pressure, heat flux, mass flux and tube diameter were investigated. Based on test data, the importance of various dimensionless parameters was analyzed, and several heat transfer correlations were assessed.

2. Experimental techniques

2.1. Experimental facility

The SWAMUP test facility, shown in Fig. 1, is used to perform heat transfer tests in supercritical water. It consists of the main test loop, a cooling water loop, a water purification loop, and an I&C system. The main test loop 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. It consists of a circulating pump, pre-heater, mixing chamber, two heat exchangers, accumulator and test sections.

In the main loop, water is driven by the circulation pump. One part flows through the pre-heater, where it is heated up to a predefined value, and enters into the test section. It exits the test section with high temperature up to 550 °C. Another part is led through the bypass. Both parts merge in the mixing chamber. The water temperature is reduced, before it enters the heat exchangers. Water exiting the heat exchangers goes back to the circulation pump. Two Coriolis mass flow meters with different measurement ranges are installed in parallel in the main flow path, to determine the mass flow rate entering the test sections. The main technical parameters are listed below:

Design pressure:	30 MPa
Design temperature:	550 °C
DC power for test section:	0.9 MW
Heating power for pre-heater:	0.3 MW
Heat exchanger capacity:	1.2 MW
Max. flow rate:	5.0 m^3/h
Pump head at max. flow rate:	80 m