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Heat transfer of supercritical water in annuli with spacers

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ABSTRACT

Experimental investigations on heat transfer of supercritical water in vertical annular channel equipped with spacers have been carried out at the SWAMUP-II facility in Shanghai Jiao Tong University. The test section consists of a heated outer rod of 15.0 mm inner diameter and a concentric unheated inner rod of 7.41 mm outer diameter. The simplified spacers with blockage ratio of 0.2 and 0.3 are equipped into the annular channel. The water flows upward cooling the heated tube. The pressure and mass flux ranges are 23–25 MPa and 450–1200 kg/(m^2·s), respectively. Moreover, the heat flux ranges from 400 to 1000 kW/m^2, and the fluid temperature is in the range of 240–450 °C. The heat transfer behaviors downstream from the spacers are analyzed. The effects of seven parameters on the heat transfer enhancement downstream from the spacer are presented. At a certain location downstream from the spacer, the further heat transfer impairment may occur on the basis of the previous deterioration. Conventional heat transfer enhancement prediction methods are compared with the experimental data. The correlations based on the subcritical conditions show the limitations at the supercritical pressure. An improved correlation has been derived.

1. Introduction

The supercritical water-cooled reactor (SCWR) has the decent technical continuity by incorporating the developed technologies in the fossil fuel plants (FFPs) and the conventional light water reactors (LWRs). The SCWR offers economical and secure nuclear power. Its design concepts have been developed in various countries such as Canada [1], China [2], Euratom [3], Japan [4], Korea [5], Russia [6] etc. Keeping the maximum cladding temperature below the design upper limit and ensuring the integrity of fuel rods are the challenging tasks in the design of SCWR fuel assembly.

The heat transfer characteristics of supercritical water behave peculiarly due to the dramatic varied properties in the vicinity of pseudo-critical temperature. Research activities on heat transfer of supercritical water in simple channels have been widely carried out. The review article on experimental investigation conducted by Pioro and Duffey [7] showed that the heat transfer coefficient (HTC) always reached a maximum at the pseudo-critical region. The normal, deteriorated and enhanced heat transfer phenomena were observed in circular tube. The heat transfer may deteriorate when given low mass flux and high heat flux working conditions. Although much work has been carried out, the unified understanding on heat transfer in supercritical fluids has not been achieved.

The spacers including wire wrap spacers (e.g. HPLWR, [8]) and grid spacers (e.g. Super LWR, [4]) are used in the reactor's core design to maintain the relative position of fuel rods. The spacers disturb the flow and enhance the turbulence, leading to an additional multifaceted heat transfer pattern. Thus, attention is focused on the effect of spacers on downstream heat transfer.

The early researches [9–12] on supercritical water in annuli without spacers testified that the heat transfer behaviors in annular channel were similar in circular tube. Xi'an Jiao Tong university [13–16] has been performed a series of experiments on heat transfer of supercritical water in annuli with spiral or grid spacers. The authors claimed that spacers strengthened the downstream heat transfer and the increment of HTC was relative to the flow conditions. The heat transfer enhancement attenuated with the increase of the distance from the spacer. However, quantitative analysis on heat transfer enhancement downstream from the spacer was insufficient.

At the subcritical pressure conditions, impactful work has been devoted to estimating the spacer-induced heat transfer enhancement. Summarizing the previous research works, Yao et al. [17] developed a universal correlation by the analogy between the frictional pressure drop and the wall heat transfer. The enhancement ratio (Nu/Nu_0), which is the Nusselt number downstream from the spacer divided by the Nusselt number in the bare tube, decays exponentially with the dimensionless distance (x/D_h) downstream from the spacer. The $Nu/Nu_0 - 1$ is square relationship with the blockage ratio ε which is defined as the ratio of section area of

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Nomenclature

Bo	buoyancy parameter proposed by Jackson (–)
C_p	specific heat at constant pressure (J/(kg·°C))
D	diameter (m)
Ø	outer diameter (mm)
e	error (–)
F	correction factor (–)
G	mass flux (kg/(m^2·s))
Gr	Grashof number (–)
H	specific enthalpy (J/kg)
I	current (A)
L	heated length (m)
N	Total number of data points (–)
Nu	Nusselt number (–)
P	pressure (MPa)
Pr	Prandtl number (–)
q	heat flux (W/m^2)
q_v	volumetric heat source (W/m^3)
T	temperature (°C)
U	voltage (V)
W	power (W)
x	axial distance from the immediate downstream of the spacer (m)
z	axial location along the heated length (m)

Greek symbols

ρ	density (kg/m^3)
μ	average deviation (–)
σ	standard deviation (–)
α	heat transfer coefficient (W/(m^2·°C))
λ	thermal conductivity (W/(m·°C))
ε	blockage ratio (–)
η	heating efficiency (–)

Subscripts and superscripts

b	bulk
0	reference
ave	average
$corr$	correlation value
exp	experimental data
h	hydraulic
i	inner
in	inlet
j	index
o	outer
out	outlet
pc	pseudo-critical
s	spacer end
w	wall

Acronyms

AC	alternating current
DC	direct current
HTD	heat transfer deterioration
HTC	heat transfer coefficient
OD	out diameter
SCWR	supercritical water-cooled reactor

the spacer and the annular channel. Holloway et al. [18] conducted an experimental study on effect of standard support grid features on single phase heat transfer in rod bundles at *Re* numbers of 28,000 and 42,000. They declared that the decay of enhancement along with the dimensionless distance could be described in power-law or exponential functions.

Miller et al. [19] performed a single phase steam heat transfer experiment in a rod bundle. The results indicated that the grid-enhanced heat transfer depended not only on the grid blockage ratio but also on the flow Reynolds number. A new heat transfer enhancement correlation based on the single phase steam data has been developed. The new correlation takes into account the effect of Reynolds number. Moon et al. [20] carried out heat transfer experimental study in a 6-rod bundle with single phase steam. Several correlations on heat transfer enhancement downstream of spacers were selected to be assessed with experimental data. They reported that exiting correlations were not applicable at low Reynolds number; the maximum heat transfer rate was over-predicted. An experimental study conducted by Tanase and Groeneveld [21] used three kinds of obstacles (annular, blunt, rounded) in circular heated tubes. The results showed that blockage ratio, dimensionless axial distance x/D_h and *Re* number were the most significant effects on heat transfer enhancement downstream of obstacle.

Bae [22] performed an experimental study of heat transfer to supercritical carbon dioxide in a tube with built-in wire. Data indicated that the heat transfer was enhanced considerably due to the wire. It enhanced at least 100% HTC in the tube rather than bare tube. A simple function was proposed to reckon the HTC increment. The effects of pressure, mass flux and heat flux on heat transfer were discussed.

Overall, the spacer-induced heat transfer enhancement in subcritical and supercritical pressures has been partly investigated. Still, there are lacking a valid quantitative approach to assess the heat transfer behavior downstream grid spacer at supercritical pressure. In support of SCWR design, experimental study has been carried out on heat transfer of supercritical water in vertically upward annular channel equipped with simplified grid spacers.

2. Experimental process

2.1. Experimental facility

The experiment has been performed at the Supercritical Water Multipurpose Test Loop II (SWAMUP-II) in Shanghai Jiao Tong University, as shown in Fig. 1. The SWAMUP-II facility consists of the main test loop, cooling water loop, and I&C system. The main loop consists of two plunger pumps, a pre-heater, re-heater, mixing chamber, heat exchanger, deionized water tank and test section. It is designed for pressure up to 35 MPa, temperature up to 550 °C, mass flow rate up to 2.8 kg/s and electrical power up to 1.2 MW. The description and technical parameters of SWAMUP-II can be consulted in the Ref. (Gu et al. [23]) for details.

2.2. Test section

The annular test section, as shown in Fig. 2, consists of a 304 stainless steel tube (heated, Ø 20.0 mm × 2.5 mm) and a concentric ceramic rod (unheated, Ø 7.41 mm), forming a gap of 3.80 mm and a hydraulics diameter of 7.59 mm. Four grid spacers are inserted into the annular channel with isometric distance of 485 mm between the adjacent spacers. The inlet and outlet spacers play the part of locating spacer. The middle two spacers shown in Fig. 3 with blockage ratio of 0.2 and 0.3 are the objects of study. NiCr-NiSi thermocouples (OD of 0.3 mm each wire) are welded to the surface of the heated tube along a straight line to measure