International Journal of Heat and Mass Transfer 125 (2018) 552–558

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Study on spacer-induced heat transfer deterioration of supercritical water in annular channel

Zhen-xiao Hu, Da Liu, Han-yang Gu *

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

ARTICLE INFO

Article history:
Received 6 February 2018
Received in revised form 1 April 2018
Accepted 15 April 2018

Keywords:
Heat transfer deterioration
Spacer
Supercritical water
Buoyancy force
Eddy viscosity
Turbulence

ABSTRACT

Experimental and numerical investigations on spacer-induced heat transfer deterioration of supercritical water in annular channel have been carried out. 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, forming a 3.80-mm-wide annular channel. A spacer with block ratio of 0.3 is equipped into the channel. The experimental conditions are the pressure of 23–25 MPa, mass flux of 450–1200 kg/(m^{2}s), heat flux of 400–1000 kW/m^2 and fluid temperature of 240–450 °C. The spacer-induced heat transfer deterioration occurs at the conditions of mass flux 450 kg/(m^2 s), heat flux 400 kW/m^2 and specific fluid temperature region. Based on the experimental data, the criteria for the occurrence of deterioration are obtained. For the case that heat transfer deteriorates, the wall temperature experiences a couple of oscillations before recovering to the fully developed state. In order to study the mechanism of this complicated heat transfer behavior, numerical simulation has been performed with FLUENT and a reasonable explanation has been proposed.

1. Introduction

The spacers are used in the reactor's core design to maintain the relative position of fuel rods and prevent vibration and bending. The spacers disturb the flow, leading to an additional multifaceted heat transfer pattern. Thus, attention is focused on the effect of spacers on downstream heat transfer.

At the subcritical pressure conditions, impactful work has been devoted to estimating the grid spacer effects. An agreement on the spacer-induced heat transfer enhancement has been reached by Yao et al. [1], Holloway et al. [2], Miller et al. [3], Moon et al. [4], Tanase and Groeneveld [5] via experimental investigation. They declared that the decay of enhancement along with the dimensionless distance could be described in power-law or exponential functions, and developed some empirical correlations to predict the heat transfer enhancement ratio.

The heat transfer characteristics of supercritical water behave peculiarly due to the dramatically varied properties in the vicinity of pseudo-critical temperature. The review article on the experimental investigation conducted by Pioro and Duffey [6] showed that the normal, deteriorated and enhanced heat transfer phenomena were observed. The heat transfer may deteriorate when given low mass flux and high heat flux working conditions. Xi'an Jiao Tong University [7–10] 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. They all only found the heat transfer enhancement at the downstream of the spacer.

Recently, we [11] have performed an experimental investigation on heat transfer to supercritical water in the annular channel with spacer. Under the normal heat transfer conditions, the spacer indeed enhanced the heat transfer, and we summarized seven parameters that affected the heat transfer enhancement downstream from the spacer. An improved correlation which is applicable to the supercritical conditions has been derived. Besides, there was another finding that the spacer induced the additional heat transfer deterioration (HTD) when operating at the HTD conditions, i.e. mass flux of 450 kg/(m^2·s) and heat flux of 400 kW/m^2. The maximum increment of wall temperature was over 100 °C on the basis of the previous deterioration. Eter et al. [12] performed an experimental study on heat transfer of supercritical CO_2 in tubes with flow obstacles. They reported that the HTD might occur in a tube equipped with cylindrical flow obstacles and claimed that it was similar to the entrance effect.

As an important auxiliary mean of the experiment, the CFD numerical study [13–16] has important application value in recent decades. The experimental and numerical investigation of

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

https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.066
0017-9310/

Nomenclature

Bo_b	buoyancy parameter proposed by Jackson (–)
Bu	buoyancy parameter proposed by Bae and Kim (–)
C_p	specific heat at constant pressure (J/(kg·°C))
D	diameter (m)
g	gravity (m/s^2)
G	mass flux (kg/(m^2·s))
Gr	Grashof number (–)
$\overline{Gr}$	average Grashof number (–)
H	specific enthalpy (J/kg)
K	turbulent kinetic energy (m^2/s^2)
L	heated length (m)
Nu	Nusselt number (–)
P	pressure (MPa)
Pr	Prandtl number (–)
Pr_t	turbulent Prandtl number (–)
q	heat flux (W/m^2)
r	radial dimensionless radius (–)
Re	Reynolds number (–)
T, t	temperature (°C)
$T_{b,\ s}$	bulk fluid temperature of the spacer end
x	axial distance from the immediate downstream of the spacer (m)

Greek symbols

δ	Kronecker delta (–)
Φ	viscous dissipation (–)
ρ	density (kg/m^3)
ε	blockage ratio (–)
ν	kinematic viscosity (m^2/s)
μ_t	eddy viscosity (Pa·s)
τ	shear stress (N/m^2)
Γ_t	turbulent diffusivity (–)
ω	specific dissipation rate (–)

Subscripts and superscripts

b	bulk fluid
0	reference
h	hydraulic
i	index
s	spacer end
w	wall

Acronyms

HTD	heat transfer deterioration
OD	out diameter
TC	thermocouple

supercritical CO_2 in a vertical tube performed by Jiang et al. [17] revealed that the increasing heat flux leaded to an M-shape velocity distribution. Wang et al. [18] performed the numerical simulation with SSG turbulence model and experimental validation on heat transfer of supercritical water in a 2 × 2 rod bundle. They reported that the mass and momentum exchange existed on the cross-section of the flow channel, leading to a large non-uniformity in bulk and wall temperature. Wang et al. [8] also carried out an investigation on the heat transfer enhancement of spiral spacer of supercritical water in annular channels via experimental and numerical methods. They revealed that the turbulence kinetic energy and the near-wall fluid velocity at the downstream of the spacer were raised significantly, resulting in an enhanced heat transfer effect.

We [11] have done some experimental analysis on the heat transfer characteristic of supercritical water at the downstream of the spacer in the annular channel. The regularity of heat transfer enhancement has been discussed, and a correlation for calculating the enhancement ratio has been derived. However, the explanation of spacer-induced additional HTD remains vague. The occurrence criterion of HTD is also lacking. Therefore, on the basis of the previous research, we further analyze the experimental data and discuss the mechanism of spacer-induced additional HTD.

2. Experimental process

The experiment has been performed at the Supercritical Water Multipurpose Test Loop II (SWAMUP-II) in Shanghai Jiao Tong University. 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 annular test section, as shown in Fig. 1, consists of a 304 stainless steel tube (heated, outer diameter of 20.0 mm, thickness of 2.5 mm) and a concentric ceramic rod (unheated, outer diameter of 7.41 mm), forming a gap of 3.80 mm and a hydraulic diameter of 7.59 mm. Four grid spacers are inserted into the annular channel with an isometric distance of 485 mm between the adjacent spacers. The inlet and outlet spacers play the part of immobilization. The blockage ratio ε of spacer is defined as the ratio of section area of the spacer and the annular channel. The spacer-2 with $\varepsilon = 0.3$ is the object of this 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 the temperature distribution. The arrangements of thermocouples in the downstream of spacer-1 and spacer-2 are coincident, as shown in Fig. 2. The first measurement point is 10 mm downstream from the spacer end and the last is 450 mm, x/D_h = 1.32 and x/D_h = 59.3, respectively.

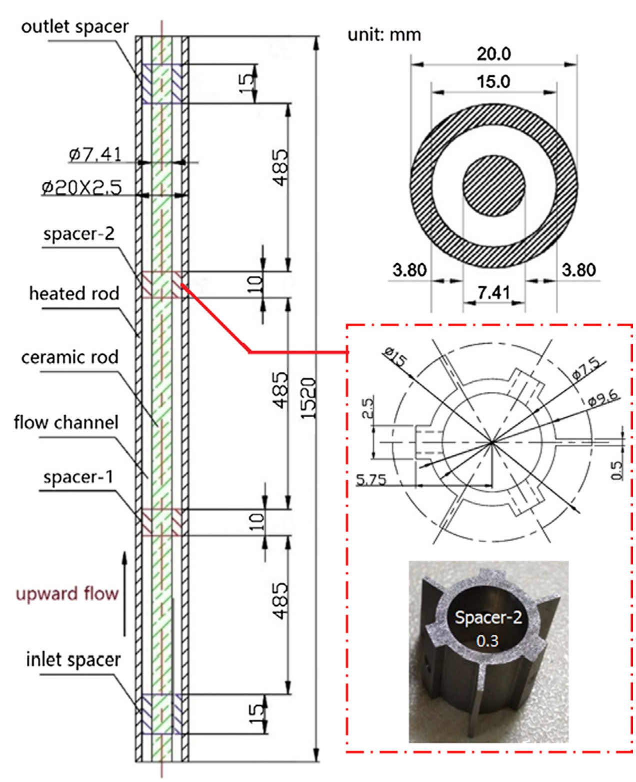

Fig. 1. Scheme of test section.