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Numerical investigation of spacer effects on heat transfer of supercritical fluid flow in an annular channel

Yao Xiao *, Jinsong Pan, Hanyang Gu

School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

This paper conducts a numerical investigation of spacer effects on heat transfer of supercritical R-134a flows in a vertical annular channel. The simulations are conducted with SST k-ω turbulent model in Fluent 15.0. The investigation range is in the normal and improved heat transfer region at supercritical pressure. The results show that the spacer end enthalpy has remarkably influence on the spacer effects at supercritical pressure, which is different from that at subcritical pressure. In the liquid-like region, the enhancement effectiveness of spacers increases with increasing spacer end bulk enthalpy. However, in the in the gas-like region, the enhancement effectiveness of spacers decreases with increasing spacer end bulk enthalpy. The enhancement effectiveness reaches a peak value near the pseudo-critical enthalpy. For the parameters sensitivity, besides the blockage ratio, spacer end enthalpy and dimensionless distance to the spacer end, the flow parameters and local enthalpy also have significant influences on the spacer effects. Mechanism analysis shows that the characteristic of the mechanism of disruption of boundary layer is the main cause for the appearance of peak value of enhancement effectiveness near the pseudo-critical region at supercritical pressure. The HTC ratio of bare channels can be used to help the prediction of the HTC ratio in the corresponding spacer downstream.

1. Introduction

The purposes of grid spacer in the reactor core are to support the fuel rods and contribute to mixing between sub channels. It has been proved that spacer grid promotes significant changes in the flow structures and heat transfer characteristics [1,2]. As one of the six Generation IV reactors proposed by GIF [3], supercritical water cooled reactor (SCWR) has advantages of higher thermal efficiency and system simplification [4]. The designs of SCWRs aim to directly limit the cladding surface temperature to ensure the safety of fuel rod assembly, and using grid spacer is an effective method to reduce cladding temperature [5].

For the effects of spacer grid on heat transfer is important to the safety analyses of nuclear reactors, many researchers have conducted studies for spacer effects at subcritical and supercritical pressures. For single phase heat transfer at subcritical pressure, Yao et al. [6] and Holloway et al. [7] reported that the *Nu* of an obstructed single-phase flow in bundles reaches a maximum at the flow obstacle. The decay of the heat transfer enhancement in the spacer downstream is exponential and the enhancement effects were noted up to 35 channel diameters. Correlations accounted for the effect of blockage ratio, axial distance downstream from the grid was proposed. Miller et al. [8] studied heat transfer to superheated steam in a typical 7×7 pressurized water reactor (PWR) bundle. An improved heat transfer correlation accounted for the effect of blockage ratio, axial distance downstream from the grid and flow Reynolds number was derived. Tanase and Groeneveld [9] investigated the spacer effect on heat transfer based on the experimental data of heat transfer of R-134a in a heated tube equipped with flow obstructions. The improved prediction method correlates the blockage ratio, *Re* number and the dimensionless distance from the obstacle end.

For heat transfer at supercritical pressure, the supercritical fluids have unique thermal physical properties compared with subcritical fluids. Spacer grids and wire spacers are the two major types of spacer used in SCWRs. For wire spacers, Kiss et al. [10] conducted numerical study of an HPLWR fuel assembly flow with wrapped wire spacers. Wang et al. [11,12] studied the enhanced effect of spiral spacer to heat transfer of supercritical pressure water in vertical annular channels. Gu et al. [13] conducted experimental investigation of heat transfer for supercritical pressure water flowing in 2×2 rod bundle with wire wraps. It was found that the strong geometry effect of the wires increases the mixing in fuel assembly and enhances the heat transfer. For the spacer

* Corresponding author.
E-mail address: yxiao@sjtu.edu.cn (Y. Xiao).

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Nomenclature

A	flow area (m^2)
C_p	specific heat (J/kg·K)
D	hydraulic diameter (m)
G	mass flux ($kg/m^2{\cdot}s$)
h	enthalpy (kJ/kg), heat transfer coefficient ($W/m^2{\cdot}K$)
ID	annular channel inside diameter (m)
k	thermal conductivity (W/m·K)
L	length (m)
OD	annular channel onside diameter (m)
P	pressure (Pa)
q	heat flux (kW/m^2)
T	temperature (°C)
W	mall flow rate (kg/s)
X	distance to the spacer end (m)
y^+	dimensionless distance normal to the wall

Greek symbols

ρ	density (kg/m^3)
μ	viscosity (Pa·s)
ε	blockage ratio

Abbreviation

HTC	Heat Transfer Coefficient

Dimensionless number

Nu	Nusselt number $Nu = h \cdot D/k$
Pr	Prandtl number $Pr = \mu c_p/k$
Re	Reynolds number $Re = G \cdot D/\mu$ Gdil
X/D	dimensionless distance to the spacer end

Subscripts

CFD	computational fluid dynamics
DB	Dittus-Boelter equation
pc	pseudo-critical
exp	experiment
h	hydraulic
J	correlation of Jackson
w	wall
∞	bare channel without spacer effect

grids and obstacles, Zhu et al. [1] conducted numerical study of a tight rod bundle with two types of grid spacer and found that the improved heat transfer performance downstream of the spacer grid with split vanes is more pronounced for the higher Reynolds number case. Eter et al. [14] conducted experimental investigation of heat transfer in supercritical flows of CO_2 in tubes with flow obstacles. It was found that, in the liquid-like region, the highest enhancement effectiveness of the obstacles was obtained at the high enthalpies.

In summary, for spacer effects at supercritical pressure, most of the empirical correlations correlate the blockage ratio and the dimensionless distance from the spacer end. Although some correlations also correlate Reynolds number, it has little influence on the results. For spacer effects at supercritical pressure, researchers have found that the Reynolds number and bulk enthalpy have influence on the spacer effect of spacer grids type spacer. However, the influence rules are still not illustrated and no accurate correlations have been proposed. To understand the spacer effect on heat transfer at supercritical pressure, this paper conducts a numerical investigation of spacer effects on heat transfer of supercritical R-134a flows in a vertical annular channel. The simulations are conducted with Fluent 15.0. The geometry of the channel refers to an ongoing experimental study in Shanghai Jiao Tong University to determine the effects of grid spacer to heat transfer performance at supercritical pressure. The spacer grids are simple round spacers and the blockage ratios range from 0.2 to 0.4. The investigation range is in the normal and improved heat transfer region [15] at supercritical pressure. The effects of spacer on heat transfer performance are studied in detail. The effects of spacer end bulk enthalpy, blockage ratio and flow parameters on the spacer effects are discussed. The mechanisms of the spacer effect are also investigated.

2. Numerical approach

2.1. Analysis geometry and boundary conditions

The interest of present study focuses on the spacer effects on heat transfer of supercritical fluid. The configuration employed in this study is schematically shown in Fig. 1. It is an annular channel consisting of a simple spacer with different blockage ratios. The outer diameter of the annular channel is 25 mm and the inner diameter is 19 mm. Thus the hydraulic diameter of the annular channel is 6 mm. The length of the channel is 1.0 m. The height of the spacers is 10 mm. Three simple spacers were investigated and the blockage ratios were 20%, 30% and 40% respectively. The distance of the spacer end to the inlet is 0.5 m, which is over 80 times of the hydraulic diameter to avoid entrance effect. This geometry refers to an ongoing experimental study in Shanghai Jiao Tong University, which aims to study the effects of grid spacer on heat transfer performance at supercritical pressure.

The working fluid is R-134a and the flow direction is vertically upward, which is consistent with the positive Z direction of the coordinate system. Considering the axisymmetric structure of the annular channel, a two-dimensional axisymmetric plane based on a cylindrical coordinate system is chosen as the numerical analysis region for all cases to save computing time. The mesh structure for present CFD simulations is illustrated in Fig. 2. The inlet of analysis region is set as mass flux inlet at which the mass flux, temperature, turbulent kinetic energy and kinetic energy dissipation rate are specified. The outlet is set as the pressure outlet with specified constant pressure. The inner wall of the channel is a smooth, no-slip adiabatic wall and the outer wall is

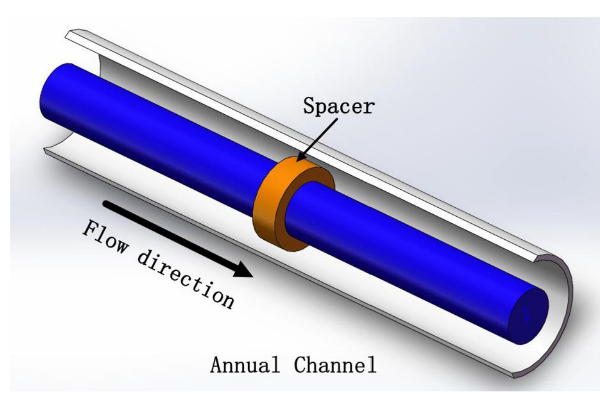

Fig. 1. Sketch of structure for annular channel with spacer.