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Study on heat transfer behavior in rod bundles with spacer grid

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ABSTRACT

Experiments have been carried out to investigate the heat transfer downstream of spacer grids in a vertical 5×5 rod bundle cooled by single phase water. Wide ranges of mass flow rate (*Re* from 2000 to 30,000) and heating power (25–150 kW/m^2) are examined. Buoyancy force as a prominent factor to influence the development of heat transfer downstream of spacers is observed for the first time. For small buoyancy affected conditions, the heat transfer downstream of spacers decay exponentially to the fully developed values, while for highly buoyancy effect conditions, the heat transfer development downstream of spacers shows complicate behaviors. An explanation of the effect of buoyancy force on heat transfer downstream of spacers is addressed. Existing correlations perform unfavorable predictions with current experiments because of the ignorance of buoyancy effect. Based on the current experimental data, a new correlation accounts for the buoyancy effect has been proposed and shows good predictions.

1. Introduction

In a nuclear fuel assembly, spacer grids not only maintain the relative position of rods, increase the rigidity of fuel assembly, but also influence the thermal and hydrodynamic performance in fuel rods to increase the safety margin. Understanding the effect of spacer grid on heat transfer is important for designing the integral structure of fuel assemblies.

Spacer grids in fuel assemblies as a specific class of obstacles in flow channels tend to enhance the heat transfer and has been broadly investigated since the early 1970s. Yao et al. [1] compared the experimental data from former investigators that conducted in various flow channels, with different blockage ratios and fluid property and proposed a correlation (Eq. (1)) to characterize single phase heat transfer downstream of spacer grid.

$$Nu/Nu_0 = 1 + 5.5\varepsilon^2 \exp(-0.13x/D_h) \tag{1}$$

where Nu represents the local Nusselt number, Nu_0 is the fully developed Nusselt number without the influence of spacer grid, ε stands for the blockage ratio and x/D_h the dimensionless distance from the downstream edge of the spacer grid. Due to the simple form of Yao et al.'s [1] correlation, it's always been used to compare with kinds of experiment data [2–6]. For Reynolds numbers higher than 10^4, it gave favorable predictions. Hassan and Rehme [7] experimentally investigated the influence of spacer grid on heat transfer to gas flowing in rod bundles for Reynolds number ranges from 600 to 2×10^5 and found that the maximum Nusselt number ratio Nu/Nu_0 is influenced by Reynolds number, and the peak value appears at $Re \approx 3000$. With the increasing of Reynolds number, the maximum Nusselt number ratio decreases. But when $Re \geq 2 \times 10^4$, the maximum Nusselt number ratio is almost constant. Besides, Miller et al. [3], Kim et al. [4], Moon et al. [5] and recently Tanase et al. [6] reported the Reynolds number effects on the heat transfer downstream of a spacer grid. A common conclusion can be obtained from these researches, over a threshold of Reynolds number, the heat transfer augmentation decreases with an increase of flow Reynolds number. However, the values of threshold Reynolds number are different from different literatures. Hassan and Rehme [7] considered the threshold Reynolds number to be about 3000, Kim et al. [4] indicated it to be about 10,000, and Miller et al. [3] regarded the transition value to be about 5000. It can be noted that the effect of Reynolds number transits at low values. It is known that when flow rate is low, mixed convection may occur [8]. In the mixed convection the buoyancy force has a great impact on heat transfer [9]. Huang et al. [10] reported that buoyancy effect cannot be neglected even when Reynolds number is higher than 10,000. The effect of Reynolds number on heat transfer downstream of spacer has been investigated, but the buoyancy effect has never been taking into consideration. It is reasonable to suppose that the heat transfer downstream of spacer grid is influenced by buoyancy force. But the effect of buoyancy force on the heat transfer development downstream of obstacles is rarely reported.

Therefore, in current study, experiments covering a wide range of operating parameters are performed to investigate the effect of buoyancy force on heat transfer downstream of spacer grids.

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Nomenclature

a, *b*, *c*, *m*, *n*	constant in correlation (–)
A_f	flow area (m^2)
Bo^*	buoyancy parameter (–)
C_p	specific heat at constant pressure (J kg^{-1} K^{-1})
D, *d*	diameter (m)
D_h	hydraulic diameter of rod bundle, without housing wall (mm)
D_e	equivalent hydraulic diameter, within housing wall (mm)
e	error (–)
G	mass flux (kg m^{-2} s^{-1})
Gr^*	Grashof number based on heat flux (–)
g	gravity acceleration (m s^{-2})
h	specific enthalpy (J kg^{-1})
I	current (A)
L	length (m)
N	total number of data points (–)
Nu	Nusselt number (–)
Nu_0	fully developed Nusselt number (–)
P	pressure (Pa)
Pr	Prandtl number (–)
P_w	wetted perimeter
q	heat flux (W/m^2)
q_v	volumetric heat source (W m^{-3})
Re	Reynolds number (–)
T, *t*	temperature (°C)
U	voltage (V)
x	axial location (m)
X, *Y*	variables
Z	system error

Greek symbols

α	heat transfer coefficient (W/m^2 K^{-1})
β	volumetric thermal expansion coefficient (K^{-1})
Δ	error parameter for least square method (–)
E	expectation (–)
η	heating efficiency (–)
λ	thermal conductivity (W m^{-1} K^{-1})
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})
σ	standard deviation (–)

Subscripts and superscripts

b	bulk
c	calculated
i	inner
j	index
in	inlet
o	out
out	outlet
s	systematic
w	wall

2. Experiment facilities and method

2.1. Test loop

The experiments are performed on SWAMUP-II test facility as shown in Fig. 1 at Shanghai Jiao Tong University.

The distilled and de-ionized water (DI water) stored in the water tank is circulated by two piston pumps and then delivered to the testing branches and the bypass branch. The flow rate of the test is regulated by the electrical regulating valve in each branch and measured by the venturi flowmeter with the measurement range of 2–50 kg/min. The water is re-heated by the re- heater and preheated by the pre-heater to a desired temperature before it is supplied to the test section. The pre-heater is directly heated by an AC power supply with maximal heating capacity of 500 kW while the test section is heated by a DC power supply with a maximal heating capacity of 900 kW. After the water passes through the test section, it is cooled by the re-heater and mixes with the water from bypass branch in the mixer. When the water is further cooled down to a temperature under 60 °C, it returns back into the storage tank. The pressure in the system is regulated by the pressure regulating system at the outlet of the loop. The pressure at the inlet of the test section is measured by a Yokogawa EJA-150A capacitance-type pressure transducer and the pressure drop over the test section is obtained using a Yokogawa EJA-130A capacitance-type differential pressure transducer. Fluid temperatures at the inlet and the outlet of the test section are measured by two ungrounded N-type thermocouples with sheath outer diameters of 0.5 mm. All data are collected and recorded by a National Instrument data acquisition system.

2.2. Test section and measurement method

Fig. 2 shows the cross-sectional views of the 5 × 5 rod bundle test section. The test section consists of 23 heated rods and 2 unheated rods enclosed in a square shroud, the inner dimension of the square shroud is 69.8 mm. The heated rods are Inconel-625 tubes (10 mm o.d. and 0.8 mm thick) welded with copper bars (10 mm) at the bottom ends, and the two unheated rods are 12.9 mm o.d. stainless steel tubes isolated from the heated tubes. Pitch of the heated rods is 13.3 mm. The DC power is supplied to the copper conductor and the copper bars. Due to the resistance of the copper rods is extremely small, heat power released from the copper bars can be ignored, the effective heated length of the rods is 2782 mm.

The test section is equipped with 8 spacer grids, and the relative positions of the spacer grids in the test section can be seen in Fig. 2, the gaps of each spacer grids is 450 mm, except the first gap, which is 466 mm. The spacer grid used in the present experiments is shown in Fig. 3, and the blockage ratio is 0.185.

The water temperatures at the inlet and outlet are measured by two N-type sheath thermocouples respectively. Sixteen N-type thermocouples with diameter of 0.5 mm are installed in a specially designed temperature measurement instrument to measure the axial inner wall temperature distributions of the central eight heated rods. The measurement points for a single section are shown in Fig. 2. There are totally ninety measuring sections in the axial direction for each heated rod, eighteen measurement sections with pace of 25 mm for every spacer gaps.

The whole test section is thermally insulated by two layers of glass wool with a thickness of about 6 cm.

2.3. Test procedure

Experiments are performed at a pressure of 6 MPa. Eight mass fluxes (25, 50, 75, 100, 150, 200, 300 and 400 kg/m^2s), and five heat fluxes (25, 50, 75, 100 and 150 kW/m^2) are set as the test conditions with the corresponding Reynolds number from 2000 to 30,000, Grashof number (based on heat flux) from 10^9 to 2×10^{10}, and Bo^* number from 1×10^{-6} to 5×10^{-2}. Inlet temperature