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Experimental investigations on single-phase convection and steam-water two-phase flow boiling in a vertical rod bundle

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ABSTRACT

Single-phase convective heat transfer and steam-water two-phase flow boiling heat transfer experiments have been carried out with a vertical seven-rod bundle at low flow conditions near atmospheric pressure. With respect to single-phase experimental results, new correlations were developed to predict convective heat transfer coefficients of laminar flow and Reynolds numbers at the transition from the laminar region to the turbulent region. Two-phase experimental results show that the rod bundle geometry enhanced heat transfer compared with circular tubes. An obvious mass velocity effect on the flow boiling heat transfer coefficient was observed. This conclusion indicates that forced convection, instead of nucleate boiling heat transfer, dominated two-phase flow boiling heat transfer under the experimental conditions. In addition, two-phase flow boiling heat transfer coefficients in the vertical rod bundle increased first and then decreased with the quality increases for a given mass velocity. By taking the enhancement factor of forced convection and the suppression factor of nucleate boiling into account, a new correlation in terms of Boiling number, Reynolds number and Martinelli number was developed to be successful in predicting predict two-phase flow boiling heat transfer coefficients.

1. Introduction

Single-phase convection and steam-water two-phase flow boiling in rod bundles are popularly encountered in heat exchangers such as condensers, evaporators and reboilers. Specifically, heat transfer characteristics in the inverted U-tube bundle of a steam generator are of vital importance in its safe and reliable operations. Heat transfer deterioration in steam generators can result in serious failures of tubes, which may lead to a release of contaminative primary coolant to the conventional island. Though several experimental and theoretical studies [1–4] have been performed on heat transfer characteristics in vertical rod bundles of steam generators, few steam-water two-phase flow boiling heat transfer data were published. Then, a literature review on single-phase convection and steam-water two-phase flow boiling heat transfer investigations in vertical rod bundle was conducted as follows.

1.1. Single-phase experiments in vertical rod bundles

Since the primary concern of the design of steam generators is the turbulent flow region, most investigations have been carried out on single-phase convective heat transfer in vertical rod bundles for Reynolds numbers above 6×10^4 [5–8]. Miller et al. [6] proposed that the heat transfer coefficient data could be fit well by use of the following equation when C factor equaled to 0.032.

$$\frac{h_f d_e}{k} = CRe^{0.8}Pr^{1/3} \tag{1}$$

Weisman [7] concluded that the value of C factor in a vertical rod bundle with a square arrangement was larger than that with a triangular arrangement. Based on the experimental data, he also developed a widely used correlation to predict C factors. Deissler and Taylor [9] found that convective heat transfer coefficients increased with pitch-to-diameter ratios (s/d) increased for a given Reynolds number. However, their results were not presented in a form readily adaptable to engineering design. Kalinin et al. [10] obtained heat transfer data of parallel flow across staggered rod bundles with $s/d = 1.16 - 1.5$ at Reynolds numbers ranging from 2×10^3 to 7×10^4. It is worth noting that only the center rod was heated. Inayatov [11] conducted an experimental investigation on heat transfer for longitudinal water flow in a staggered tube bundle, which consisted of 19 copper tubes with $s/d = 1.22$. Reynolds number ranged between 1000 and 12,000. However, similar to the experiment a carried out by Kalinin et al. [10], only the central tube was heated. Since an internal circulation due to buoyancy at low flow could affect the heat transfer process in the test section, the heat transfer data obtained by Kalinin et al. [10] and

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Nomenclature

a	independent variable (–)
A	total heating surface area of seven rods (m^2)
Bo	boiling number (–)
c	constant-pressure specific heat (J/(kg °C))
d	rod diameter (m)
E	enhancement factor (–)
G	mass velocity (kg m^{-2} s^{-1})
h	heat transfer coefficient (W/(m^2 °C))
H	enthalpy (J/kg)
k	thermal conductivity (W/(m °C))
l	thickness (m)
L	length (m)
Nu	Nusselt number (–)
P	pressure (Pa)
Pr	Prandtl number (–)
q	hear flux (W/m^2)
Re	Reynolds number (–)
s	pitch of the rod bundle (m)
S	suppression factor (–)
T	temperature (°C)
u	standard uncertainty (–)
W	mass flow rate (kg/s)
x	quality (–)

Greek symbols

ρ	density (kg/m^3)
δ	instrumental errors (–)
Δ	difference (–)
X	Martinelli parameter (–)
μ	dynamic viscosity (Pa s)
η	deviation (–)

Subscripts and superscripts

acq	acquisition system
c	sheath
ci	inner wall
cs	outer wall
e	equivalent
exp	experimental data
f	liquid phase
fg	saturated water turn into saturated vapor
fs	saturated water
g	vapor phase
gf	saturated steam condenses into saturated water
gs	saturated vapor
h	hydrodynamical
in	inlet of the test section
ins	instrument
nb	nucleate boiling heat transfer
out	outlet of the test section
pre	predictions
s	saturated
sp	single-phase convective heat transfer
tp	two-phase
T	transition from the laminar region to the turbulent region
w	heating wall

Inayatov [11] may not be applicable to all heating rods. Dwyer and Berry [12] conducted a theoretical study on heat transfer for laminar, in-line flow through rod bundles. An obvious pitch-to-diameter ratio effect was observed for laminar flow heat transfer coefficients. Besides, though numerous theoretical studies on heat transfer for laminar flow in vertical rod bundles have also been reported by several investigators [13–15], these results lacked of experimental verification. Gruszczysnki and Viskanta [16] and Hallinan and Viskanta [17] investigated heat transfer characteristics of laminar flow in 7 and 21 rod bundles, respectively. However, the applicability of their results may be limited due to the narrow range of Reynolds numbers ($70 < Re < 500$) and very low surface heat fluxes (7.84 kW/m^2). Sung-Ho and El-Genk [18] carried out heat transfer experiments for turbulent and laminar up-flows of water through seven uniformly heating rod bundles with s/d = 1.25, 1.38 and 1.5. The dependence of heat transfer coefficient in laminar flow on Reynolds number tended to be weaker than that in turbulent flow. In addition, a correlation to predict Reynolds numbers at the transition from the laminar region to the turbulent region was developed. However, the correlation may not be applicable to all heating rods because the data of Kalinin et al. [10] and Inayatov [11] were employed. El-Genk et al. [19] obtained heat transfer data for turbulent and laminar down-flows of water in a heating seven-rod bundle with s/d = 1.38. The heat transfer coefficient in down-flows was in good agreement with that in up-flows. In general, further experimental investigations on heat transfer in vertical rod bundles for laminar flow and turbulent flow at low Reynolds numbers are needed to be conducted.

1.2. Two-phase experiments in vertical rod bundles

Numerous experimental investigations on post-dryout heat transfer in vertical rod bundles have been conducted. However, to the authors' knowledge, very few experimental data of pre-dryout heat transfer in steam-water two-phase flow were published. In the pre-dryout region, the heat transfer is primarily from surfaces to the liquid in contact with them, corresponding to a high heat transfer coefficient and a small wall superheat. Therefore, to obtain accurate experimental data of pre-dryout heat transfer, small measurement errors for temperatures of heating surfaces and working fluids are required. Koizumi and Tasaka [20] and Kumamaru et al. [21] conducted pre-dryout heat transfer experiments for steam-water two-phase flow in a single rod and a 5×5 rod bundle. It is worth noting that the measurement error of thermocouples in their experiments was 5 °C while the wall superheat was in the range of 3–9 °C. Therefore, the error of pre-dryout heat transfer coefficients was quite large and the experimental data could not be generally used. Though numerous experiments [22–25] have been carried out on flow boiling heat transfer of steam-water two-phase flow in single tubes, the application of the results obtained with a single tube to predict heat transfer coefficients in vertical rod bundles has not been verified. Therefore, in order to obtain accurate pre-dryout heat transfer data, it is necessary to carry out further experimental investigations on flow boiling heat transfer of steam-water two-phase flow in vertical rod bundles.

The literature review indicates that both convective heat transfer of single-phase flow and flow boiling heat transfer of steam-water two-phase flow in vertical rod bundles need further experimental investigations. In the present study, heat transfer coefficient data were compared with predictions calculated by several existing correlations. New correlations were developed to predict single-phase convective heat transfer coefficients and steam-water two-phase flow boiling heat transfer coefficients in a vertical rod bundle.