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Flow regime transition criteria for upward two-phase flow in vertical rod bundles

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ABSTRACT

The demand of accurate prediction for two-phase flow behavior in a nuclear reactor core composed of fuel rod bundles or a heat exchanger composed of heat transfer tube bundles requires comprehensive understanding of flow regime, void fraction, heat transfer and pressure drop. In comparison with the great success in developing the two-phase flow regime transition criteria for simple geometries such as pipes, annulus and rectangular channels, limited researches have been performed for developing the flow regime transition criteria of upward two-phase flow in vertical rod bundles. In the vertical rod bundles, slug bubbles spanning the bundle casing cannot exist due to their surface instability and the two-phase flow characteristics in the vertical rod bundles are different from those in pipes, annulus or rectangular channels whose channel size are smaller than the length scale of the surface instability. This study has proposed a new flow regime transition criteria model based on the analysis on the underlying physics of the upward two-phase flow behavior in the vertical rod bundles. A reliable drift-flux correlation to predict void fraction in the vertical rod bundle developed recently has been used in modeling the flow regime transition criteria. This study has classified the flow regime into 6 distinct flow regime such as bubbly, finely dispersed bubbly, cap-bubbly, cap-turbulent, churn and annular flows. The newly developed flow regime transition criteria have been compared with existing 4 flow regime maps obtained in vertical rod bundles. The fluid systems include air-water and steam-water. A fairly good agreement with some discrepancies has been obtained between the newly developed transition criteria and the measured flow regime maps.

1. Introduction

Internal two-phase interface structure governs mass, momentum and energy transfer and the internal structure is characterized by flow regime or flow pattern. Since constitutive equations heavily depend on the flow regime, the flow regime identification is indispensable in any two-phase flow analyses. Since the flow regime depends on physical properties, flow conditions, flow orientation, channel geometries and channel size, tremendous efforts have been made to model the flow regime transition criteria. The flow regime in vertical upward internal flows has been defined such as bubbly, slug (or cap and cap-turbulent), churn and annular flows depending on the channel size. Some attempts to identify the flow regime objectively have been also applied [1] and flow regime transition mechanisms have been well-characterized. Great success has been made for developing two-phase flow regime transition criteria in internal flow channels with various simple geometries such as pipes, annulus and rectangular channels [2–7]. However, two-phase flow regime in vertical rod bundles is more complex and its transition criteria have not been well-developed. In the vertical rod bundles, slug bubbles spanning the bundle casing cannot exist due to their surface instability and the two-phase flow characteristics in the vertical rod bundles are anticipated to be different from those in pipes, annulus or rectangular channels whose channel size are smaller than the length scale of the surface instability.

Limited researches on the flow regime identification in vertical rod bundles have been performed [8–13] and empirical flow regime maps were proposed for the rod bundles. Most common approach to identify the flow regimes in the rod bundle is the flow visualization [8,10,13], but more advanced and objective approach are also used to find the relationship between the flow regime and the time series signals obtained from various instruments such as differential pressure cell, void probe and so on through neural network [12,14,15]. Limited researches on the flow regime transition

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Nomenclature

A	flow area of channel
C_0	distribution parameter
D_0	rod diameter
D_H	hydraulic diameter
D_H^*	non-dimensional superficial gas velocity
$D_{\max}$	maximum spherical bubble diameter
f_i	friction coefficient for interfacial shear stress
f_W	friction coefficient for wall shear stress
G	mass velocity
g	gravitational acceleration
j	mixture volumetric flux
j_{c0}	mixture volumetric flux at center of sub-channel
j_f	superficial liquid velocity
j_g	superficial gas velocity
j_g^+	non-dimensional superficial gas velocity
m	exponent
n	exponent
$N_{\mu f}$	viscous number
N_{Re}	Reynold number
$N_{We_{crit}}$	critical Weber number
P	pressure
P_0	rod pitch
R_0	rod radius
r_0	radial distance measured from rod surface
v_{gj}	local drift velocity
V_{gj}	drift velocity
V_{gj}^+	non-dimensional drift velocity
v_r	relative velocity
v_t	turbulence velocity
z	axial direction

Greek symbols

α	void fraction
α_B	void fraction of small bubbly
α_{B-CB}	void fraction at bubbly-to-cap bubbly flow transition
α_{c0}	void fraction at center of sub-channel
α_{CB}	void fraction of cap bubble
α_{FD}	maximum allowable void fraction in finely dispersed flow
$\Delta\rho$	density difference between phases
ε	energy dissipation rate per unit mass
ε_B	energy dissipation rate per unit mass due to bubble expansion
ε_F	energy dissipation rate per unit mass due to wall friction
θ	angle measured from x-axis
ρ_f	liquid density
ρ_g	gas density
ρ_m	two-phase mixture density
σ	surface tension
τ_i	interfacial shear stress
τ_{wf}	wall shear stress

Subscripts

B	bubbly flow
P	pool condition

Mathematical symbols

$\langle\rangle$	area-averaged quantity
$\langle\langle\rangle\rangle$	void-fraction-averaged mean quantity

criteria modeling in vertical rod bundles have been also performed for developing the flow regime transition criteria. Venkateswararao et al. [9] proposed an analytical model of the flow regime transition criteria in a vertical rod bundle in view of its importance in predicting the behavior of a pressurized water reactor during a loss of coolant accident. They modeled the bubbly-to-slug flow, slug or bubbly-to-dispersed bubbly flow, slug-to-churn flow and churn-to-annular flow transitions and compared them with their own flow regime transition boundaries measured in a rod bundle composed of 24 rods with a square pitch in a cylindrical shell.

In view of the limited flow regime transition criteria models, the current study is aiming at developing the flow regime transition criteria in vertical rod bundles. This study first reviews existing flow regime maps and the definition of the flow regime. Next, this study classifies the flow regime into 6 distinct flow regimes such as bubbly, finely dispersed bubbly, cap bubbly, cap turbulent, churn and annular flows because slug flow regime may not appear due to the surface instability of large slug bubbles spanning the bundle casing. Based on the identified flow regimes, flow regime transition criteria for upward two-phase flow in vertical rod bundles are developed. The newly developed two-phase flow transition criteria are compared with 4 existing flow regime maps obtained in vertical rod bundles.

2. Flow regimes in vertical rod bundles

This chapter will perform an extensive literature survey of flow regime map measured for upward two-phase flow in vertical rod bundles. Table 1 summarizes existing works of flow regime identification for upward two-phase flow in vertical rod bundles including the flow regime maps proposed by Venkateswararao et al. [9], Mizutani et al. [10], Paranjape et al. [12] and Zhou et al. [13]. The flow regime maps observed by Williams and Peterson [8] and Lu et al. [11] for 1 × 4 rod bundle and 2 × 2 rod bundle, respectively, are excluded due to their small bundle size.

2.1. Venkateswararao et al. [9]

Venkateswararao et al. [9] performed an experiment of vertical adiabatic air–water flow in a rod bundle under an atmospheric pressure condition. The experimental facility was composed of 24 rods arranged on a square pitch in a cylindrical shell with 12.7 mm outside diameter and 17.5 mm pitch. The flow regime identification was done by visual observation. An analytical model was proposed for predicting the flow regime transition boundaries based on the model developed by Taitel et al. [2]. Venkateswararao et al. [9] classified the flow structure into 5 distinct flow regimes such as bubbly, finely dispersed bubbly, slug, churn and annular flows.

Bubbly flow (B): The bubble size is smaller than the characteristic spacing between the rods, and the bubbles are distributed in liquid phase.

Finely dispersed bubbly flow (F): Liquid turbulence force destroys large bubbles into small bubbles even when void fraction is relatively high. The small bubbles are distributed in liquid phase.

Slug flow (S): Large Taylor type bubbles (or shroud Taylor bubble) and nearly spherically cap shaped bubbles (or cell Taylor bubble) are defined. The shroud Taylor bubble occupies a large part of