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Sub-channel flow regime maps in vertical rod bundles with spacer grids

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ABSTRACT

The accurate prediction of thermal-hydraulic parameters is based on the flow regime maps for rod bundle, which is important for the safety of nuclear reactor. An air-water two phase flow experiment has been performed to study the sub-channel flow regime (SCFR) maps in 5×5 rod bundles section with two distinct spacer grids, including simplified spacer grid (SSG) and mixing vane spacer grid (MVSG). To obtain the objective SCFR maps in rod bundles, a sub-channel impedance void meter is newly developed to measure the time series void fraction in sub-channels. Besides, the random forest clustering algorithm has been adopted to identify the sub-channel flow regimes objectively based on a training sample and 13 selected feature values of time series void fraction. The feature values include mean value, standard deviation value, sample entropy value and 10 proportion values. In this way, the objective sub-channel flow regime maps are obtained at four different locations with different spacer grids. Distinct features have been observed for different SCFRs. As for the SCFR transitions in different sub-channels over the same cross-section, almost all of them arise in the inner sub-channel firstly for the effect of casing tube. Moreover, the dissipation length of spacer grid is larger than 19.5 L/D. In the influencing region of spacer grid, the transition from cap bubbly to cap turbulent flow occurs in the corner sub-channel at 19.5 L/D downstream of spacer grid firstly and then at 6.8 L/D for low liquid velocity, while firstly occurs at 6.8 L/D for high liquid velocity. The magnitude of the spacer grid effect on SCFR transition depends on the superficial liquid and gas velocity, as well as the structure of spacer grid for current flow conditions. Only Liu and Hibiki's model is applicable for the transition from bubbly to cap bubbly flow in sub-channel. Therefore, new transition models or correlations should be developed for other sub-channel flow regime transitions.

1. Introduction

Gas-liquid two phase flow is a complex phenomenon, and widely exists in many important industrial applications, e.g., nuclear engineering, boilers, petroleum transportation, evaporator, various chemical reactors etc. The investigation on two phase flow in rod bundles is of great significance for the safety design and operation of these applications. Distinct geometrical structures and internal interfaces of two phase flow are defined as flow regimes at different flow conditions, which governs the mass, momentum and heat transfer between two phases. Nowadays most of the reactor safety analysis codes, such as RELAP5 and TRACE, are based on flow regime maps. Moreover, some sub-channel analysis codes, for instance COBRA, SILFEED, FIDAS and NASCA, play an important role in analyzing thermal-hydraulic characteristics in rod bundles. However, most of these codes adopt flow regime transition models which are not verified in the sub-channel of rod bundles [1]. Therefore, it is significant to analyze the typical features of different sub-channel flow regimes, acquire sub-channel flow regime maps and discuss the influences of L/D and spacer grids.

1.1. Definition of flow regimes in rod bundles

The flow regimes in rod bundles are complicated with easily distorted interfaces, which are affected by many parameters, such as the superficial liquid and gas velocity, void fraction, gas and liquid physical property, slip ratio and geometrical parameters etc. Researchers have not come to a consensus on the definition on flow regimes in rod bundles, let alone accurate transition boundary, which is important for the reactor safety analysis codes. A comprehensive literature survey and existing flow regime researches on rod bundles are summarized in Table 1. As can be seen, whether the situations of diabatic steam-water or adiabatic

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Table 1
Existing experimental researches on two phase flow regime maps in vertical rod bundles.

References	Working fluids	Flow conditions	Geometry		Flow regime Identification	Flow regime transitions
			P/D (mm)	# of rods		
Williams et al. [2]	Steam-water	Boiling	8.64/6.35	1 × 4	Visualization	High pressure (8.37/13.89 MPa): Bubble → Froth → Annular Low pressure (2.86 MPa): Bubble → Slug → Annular
Venkateswararao et al. [4]	Air-water	Adiabatic	17.5/12.7	24	Visualization	Bubble → Slug → Churn → Annular
Harvel et al. [5]	Air-water	Adiabatic	–/7.8	36	Visualization & Signal of capacitance	Bubbly → Slug → Churn (→ Annular)
Paranjape et al. [6,7]	Air-water	Adiabatic	16.7/12.7	8 × 8	CPDF of Void fraction	Bubbly → Cap bubbly → Cap turbulent → Churn-turbulent (→ Annular)
Zhou et al. [3]	Steam-water	Adiabatic	15/10	3 × 3	Visualization	Bubble → Bubble churn → Churn → Annular
Mizutani et al. [1]	Air-water	Adiabatic	16/12	4 × 4	Visualization	Bubbly → Churn → Annular

air-water two phase flow in rod bundles, there is no the same definition on flow regimes. Regarding to the steam-water two phase flow, Williams et al. [2] performed an experimental investigation in a 1 × 4 heated rod bundles section focusing on the flow regimes respectively at pressures of 2.86, 8.37, 13.89 MPa. In their experiment, bubble, froth, slug and annular flow regimes were subjectively identified based on visualization. It should be noted that slug flow did not exist at pressure of 8.37 and 13.89 MPa while froth flow did not appear at the pressure of 2.86 MPa due to the effect of surface tension. In addition, Zhou et al. [3] conducted steam-water experiments in 3 × 3 heated rod bundles at atmospheric condition. Four flow regimes, including bubble, bubble-churn, churn and annular flow, were observed and identified, while slug flow was not observed due to the surface instability of large bubbles.

However, most of the experimental researches [1,4–7] on flow regime maps were conducted in adiabatic air-water two phase flow for its simplicity. Venkateswararao et al. [4] performed experiments in 24 rod bundles arranged in a circular casing tube, among which there were about 8 half rods. Based on visual observations, four flow regimes were defined and observed subjectively, namely, bubbly, slug, churn and annular flow. Moreover, flow regime maps were developed experimentally for a vertical hexagonal flow channel with/without a 36-finned rod hexagonal bundle based on visual observation and waveforms measured by a capacitance-type void fraction meter by Harvel et al. [5]. Likewise, bubbly, slug, churn and annular flow were observed by Harvel et al. [5], whose definitions were slightly different with Venkateswararao et al. [4]. Air-water two phase flow regimes in 4 × 4 rod bundles and the sub-channels [1] were observed with a high speed video camera, FEP (fluorinated ethylene propylene) tubes for rods and a fiberscope inserted in a rod with less optical distortion. Bubbly, churn and annular flow regimes and their transitions were all observed in global flow channel and the sub-channels by Mizutani et al. [1]. Furthermore, global impedance void meters were adopted to obtain the dynamic void fractions [6,7], which were applied to identify the flow regimes objectively in 8 × 8 rod bundles using neural network methodology. In this way, bubbly, cap bubbly, cap turbulent and churn turbulent flow regimes were identified by Parajanpe et al. [6,7].

As shown in Table 1, the similarities and differences are both presented for flow regimes and their transitions in rod bundles. Although the definitions and names of flow regimes are different, some similarities have been shown for bubbly/bubble, churn (turbulent) and annular flow in different researches. The differences mainly exist in the region from bubbly flow to churn (turbulent) flow. Some researchers [2,4,5] defined it as slug flow while others defined it as cap bubbly and cap turbulent flow [6,7] or bubbly to churn flow [1,3]. What called for special attention is that the slug flow defined by Hravel et al. [5] and Venkateswararao et al. [4] is similar to the cap turbulent flow defined by Paranjape [6,7], which agrees with the claim that slug flow regime does not exist for the bubble surface instability [8]. Moreover, Liu and Hibiki [9] adopted the Paranjape's definition of flow regimes and developed the flow regime transition model. Therefore, the flow regimes in rod bundles and sub-channels could be defined as bubbly flow (B), cap bubbly flow (CB), Cap turbulent flow (CT), Churn turbulent flow (C), and Annular flow (A), respectively. Detailed definitions are discussed in Section 3.1.

1.2. Flow regime identification

Taking the flow regime identification in common flow channels into consideration, some objective methods have been proposed. Based on the cumulative probability distribution functions (CPDFs) of void fraction measured by impedance meter, Pan et al. [10] used fuzzy C-means clustering algorithm and ReliefF attribute weighting technique to identify the flow regimes in pipes. Julia et al. [11,12] adopted self-organized neural network to identify the CPDFs of bubble chord length measured by double sensor conductivity probe. Pouryoussefi and Zhang [13] used fuzzy logic and genetic algorithm to recognize the simulated flow regimes. Many researches [14–25] focused on the objective flow regime identification on account of different clustering algorithms and flow parameters, which showed relatively good results.

However, regarding to the complex flow channel (rod bundles), most flow regimes were subjectively identified based on visualization as shown in Table 1, which is less convincing for the light refraction and shade from rods for the observation on internal region. Only neural network was adopted to distinguish CPDFs of void fraction measured by global impedance meter into different flow regimes objectively [6,7]. The reason that the objective flow regime maps are scarce may be for two considerations. One is due to its intrinsic complexities: the existence of rods makes it hard to visualize the internal phase distribution; stronger secondary flow and turbulence is induced by spacer grids and rods; the bubbles are more distorted for the confining of rods. The other is due to the limitation of measurements: although many techniques, such as wire mesh sensor [26,27], four sensor conductivity probe [28], Gamma ray attenuation technique [29] etc., were adopted to measure the parameters, only void fraction measured by global impedance meter was adopted for flow regime identification due to the complex signal, measuring field or response time for other measurements.

In view of the above discussions on existing work on two phase flow regimes in rod bundles, very limited information on sub-channel flow regime (SCFR) has been acquired while scarce studies on objective flow regime identification have been conducted [9]. In