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The mechanism of bubbly to slug flow regime transition in air-water two phase flow: A new transition criterion

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ABSTRACT

Air-water two-phase upward flow experiments are conducted in a tubular test section with the inner diameter of 25.4 mm in order to investigate the transition mechanism of bubbly flow to slug flow. Flow regime identification is carried out by using ReliefF-FCM clustering algorithm, i.e., a new objective flow regime identification method. It is found that the velocity ratio decreases with the increase of superficial gas velocity in bubbly flow at the constant liquid superficial velocity. And the velocity ratio always reaches its minimum during the flow regime transition. The present research finds that the changes of bubble size and shape may result in the decrease of velocity ratio in bubbly flow. From this point of view, a new mechanism for bubbly to slug flow regime transition has been proposed. A transition criterion based on the mechanism is also built. The comparison of the transition criterion with the experimental results at different flow conditions is carried out. Although the transition criterion is empirically modified based on the present experimental data, it shows the reasonable agreements.

1. Introduction

In gas-liquid two-phase flow, the flow regime transition from bubbly flow to slug flow has attracted much attention of researchers in recent decades due to its frequent occurrence in chemical, biological and nuclear industries. The flow characteristics, such as interfacial structure, heat and mass transfer mechanism, drag force and pressure drop, show significant differences between the flow regimes. The proper estimation of transition boundary is necessary to distinguish the characteristics and to establish constitutive equations [1,2]. Details of physical mechanism involved in the transition process are of most importance for better prediction of flow regime. However, the complex interactions between bubbles and influence of the liquid phase make it very difficult to identify.

The early work of Radovcich and Moissis [3] suggested it was the bubble coalescence that induced to the transition: bubbly flow is characterized by random bubbles scattering in the liquid phase accompany with some coalescence or break-up. When the rate of coalescence is higher than that of break-up, the transition occurs. Guided by the mechanism, criteria have been proposed by experimental observation and theoretical analysis.

Taitel et al. [1] suggested the critical value of gas volume fraction as the transition criterion based on experimental phenomenon: when the gas volume fraction reached 25%, the bubble coalescence rate remarkably increased and the transition happened. This phenomenon was explained by the maximum allowable packing of the bubbles. Many other researchers presented different values of void fraction as the transition criteria at different flow conditions. Mishima and Ishii [4] presented 0.3 for 25.4 mm and 50.8 mm round tube. Hibiki and Mishima [5] proposed 0.2 for small size rectangular channel. These criteria showed reasonable agreements with the experimental data over a wide range of flow conditions and became well accepted. Nevertheless, the criteria cannot reveal the physical reality during the transition process, i.e., the behavior of bubble swarm and its dynamical characteristics during the transition process.

In order to overcome the shortcomings of aforementioned void fraction criteria, new criteria based on the bubble dynamics have been proposed. Unlike the void fraction criteria, new criteria took the basic bubble behavior into account by using population balance model (PBM) to describe the coalescence and breakage process [2,6,7] of scattering bubbles in bubbly flow. The model predicted the bubble size distribution to make flow regime prediction. Another similar method is to describe the interfacial area transport process based on interfacial area transport equation (IATE) [8,9]. The IATE was firstly developed to determine the clo-

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Nomenclature

a, b	major axis and the minor axis of bubble
a_i	interfacial area concentration
C_D	drag coefficient
C_0	distribution parameter
c	coefficient of liquid turbulence
c_α	the velocity of void fraction wave
c^-	critical velocity of void fraction wave
D	tube diameter
d_b	the equivalent diameter of a distorted bubble
E	aspect ratio
F_D	drag force
F_B	buoyancy force
g	gravity
j	superficial velocity
k_i	complex wave number
N	bubble number density
n	number of bubbles
s	channel gap of rectangular tube
u	velocity of each phase
u_r	relative velocity between two phases
$\overline{u_{sm}}$	bubble mean velocity in swarm
u_t	terminal velocity of single bubble
V	bubble volume
V_{gj}	drift velocity

Greek letters

α	void fraction
β	ratio of minor axis
γ	distortion factor
ε	energy dissipation rate per unit mass
ν	kinematic viscosity
ρ	density
σ	surface tension

Subscripts

crt	critical value for flow regime transition
f	liquid phase
g	gas phase
m	mixture

sure relation for the interfacial transfer terms in two-fluid model. The two-phase flow structure can be predicted dynamically based on sink and source terms which are derived from the mechanism of bubble coalescence and breakup in IATE. It reflects the evolvement of IAC with the development of bubbly flow and can be applied to predict the transition. However, either PBM or IATE strongly depends on the mechanisms of bubbles behavior in the complex flow field around them. Despite the influences of different flow fields on bubble swarm, the basic mechanism of bubble coalescence and break-up is still now unsettled. The improvement of IATE as well as PBM criterion relies on further research on the behavior of bubble swarm. Although a lot of work on the bubble dynamics needs to be done for completing this kind of transition criteria, the idea that the transition criteria need to be built on the bubble dynamics is constructive.

Another transition mechanism was firstly proposed by Wallis [10] who associated bubble-to-slug transition with the instabilities of void fraction waves due to low-frequency perturbations of local bubble concentration. The mechanism was supported by experimental phenomenon that the transition occurred simultaneously throughout the channel without gradual coalescence process [11,12]. It was observed that the waves were firstly damped and then amplified when the gas void fraction increased. The transition was triggered by the amplified wave. Many researchers tested the mechanism and supplied some experimental evidences [13–15]. Sun et al. [15] used attenuation coefficient of void fraction wave, which was calculated by power spectrum density function (PSDF) as well as cross-power spectrum density function (CSDF), to trigger the transition. León et al. [16] applied the linear analysis to evaluate the conditions in which the perturbation was amplified. Nevertheless, some experimental phenomena in particular flow conditions indicated that the proposed mechanism probably cannot describe all the aspect of transition process [17]. For example, Cheng et al. [12] found that if the flow regime transition was triggered by decreasing the liquid flow rate, there was no wave amplification appearance. Furthermore, by using new flow regime identification method, Pan et al. [18] found that different flow regime existed in one tube at different axial positions due to flow development. In conclusion, the mechanism based on the instabilities of void fraction waves was controvertible. More experimental evidence is needed in the wide range of flow conditions.

In addition to aforementioned mechanisms, some other mechanisms for bubbly-to-slug flow transition were only suitable for particular flow conditions. For example, Shephard et al. [19] suggested that it was the increasing thickness of laminar layer on the tube wall that caused to the transition from bubbly flow to slug flow in micro-gravity round tube. Considering these mechanisms were strictly confined by the range of application, they are ignored in the present research. All the mechanisms as well as the criteria mentioned above are summarized in Table 1.

The present research starts from the phenomenon observed from the experiments. At a constant superficial liquid velocity, the velocity ratio of gas phase to liquid phase keeps decreasing with the increase of superficial gas velocity in the bubbly flow until the flow regime transition begins. The velocity ratio between phases is an important hydrodynamic parameter in two-phase flow, which is defined as follows:

$$\frac{u_g}{u_f} = \frac{j_g/\alpha}{j_f/(1-\alpha)} \tag{1}$$

j_g, j_f and α are the superficial gas velocity, superficial liquid velocity and void fraction respectively. In experiment, it is hard to directly measure the velocity of each phase. Thus the velocity ratio is obtained by measuring the superficial velocity and void fraction in present research. Considering the measured void fraction and superficial velocity are all area-averaged in experiment, averaging method is applied in calculating the velocity ratio as shown in Eq. (2):

$$\frac{\langle\langle u_g\rangle\rangle}{\langle\langle u_f\rangle\rangle} = \frac{\langle j_g\rangle/\langle\alpha\rangle}{\langle j_f\rangle/(1-\langle\alpha\rangle)} \tag{2}$$

the brackets of $\langle\rangle$ and $\langle\langle\rangle\rangle$ indicate the area averaged flow properties and the void weighted area averaged flow properties respectively. In present research, the velocity ratio calculated from experimental results is the void weighted area averaged value. For convenience, the followed discussion only uses velocity ratio to represent for void weighted area averaged velocity ratio.