International Journal of Heat and Mass Transfer 123 (2018) 1005–1020

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Experimental study of horizontal air-water plug-to-slug transition flow in different pipe sizes

Ran Kong [a], Adam Rau [b], Seungjin Kim [a,*], Stephen Bajorek [c], Kirk Tien [c], Chris Hoxie [c]

[a] School of Nuclear Engineering, Purdue University, Nuclear Engineering Building, 400 Central Drive, West Lafayette, IN 47907, United States
[b] Department of Mechanical and Nuclear Engineering, The Pennsylvania State University, Reber Building, University Park, PA 16082, United States
[c] United States Nuclear Regulatory Commission, 11555 Rockville Pike, Rockville, MD 20852, United States

ARTICLE INFO

*Article history:*
Received 31 August 2017
Received in revised form 5 March 2018
Accepted 6 March 2018

*Keywords:*
Horizontal two-phase flow
Plug-to-slug transition
Local two-phase flow parameters
Pipe size effect

ABSTRACT

The current work investigates the plug-to-slug transition in horizontal air–water two-phase flow in small (38.1 mm) and large (101.6 mm) diameter pipes. An extensive database is established to study the local interfacial structure in plug-to-slug transition flow. Detailed measurements across the flow area are performed for nine and six test conditions in small and large pipes, respectively, at three different axial locations downstream of the inlet using the local four-sensor conductivity probe. The effects of $j_g$, $j_f$, development length and pipe size are investigated. It is found that the number of small bubbles in the liquid plug/slug increases significantly in plug-to-slug transition with increasing $j_g$, which are generated by the strong shear between the gas slug and liquid film. Due to the relative motion, these small bubbles either coalesce with the nose of the following plug/slug bubble, or slide between the plug/slug bubble and the wall, and then travel around the pipe circumference to reside beneath the large bubbles. This explains the large number of small bubbles observed at the top of the liquid film for the conditions at high gas flow rates. In the process of traveling downwards, some of the small bubbles coalesce with the slug bubbles. It is also found that increasing $j_g$ or $j_f$ decreases the size of the small bubbles. While shearing-off is believed to dominate as $j_g$ increases, turbulent-impact is enhanced as $j_f$ increases due to the increasing turbulence level in the liquid phase. Increasing $j_g$, development length, or decreasing $j_f$ slightly increases the depths of the plug/slug bubbles; however, significant growth of plug/slug bubbles is observed in the axial direction. For the same condition, the contribution from large bubbles to total void fraction increases as pipe size increases, while the distribution of total void fraction is similar. The size of both small and large bubbles is found to be larger in the large diameter pipe. Due to the current bubble injection mechanism, small bubbles are generated at the inlet; they coalesce into large bubbles as the flow develops. The large bubble is found to accelerate as it grows along the axial direction, which can lead to a decreasing void fraction although pressure keeps decreasing.



## 1. Introduction

Plug and slug flows exist over a wide range of flow conditions in horizontal two-phase flow, which are characterized by alternating appearance of elongated bubbles that occupy the upper portion of the pipe and liquid regions that occupy the entire cross-sectional area of the pipe. In previous studies, plug and slug flows were assumed to consist of a repeatable plug/slug unit as shown in Fig. 1, which includes the elongated bubble region and the following liquid region. While these two flow regimes were usually classified into a general 'intermittent' flow in many previous studies, a large number of small bubbles was observed in the liquid slug [1–3], which differentiates slug flow from plug flow. The presence of these small bubbles can provide large interfacial area for interfacial mass, momentum and energy transfer. Therefore, additional work needs to be performed to investigate the transition from plug to slug flow.

Due to the quasi-periodic gas pocket, plug and slug flows are inherently unsteady with large variation of mass flow rate, pressure, and velocity in both radial and axial directions even when the gas and liquid flows supplied to the system are steady. This can cause severe vibrations of the support structure, especially when the flow direction is changed. Such an unstable nature must be considered in the design of two-phase flow systems; therefore, some efforts have been made to investigate the plug and slug flows. However, most of these studies were focusing on flow

* Corresponding author.
*E-mail address:* seungjin@purdue.edu (S. Kim).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.027
0017-9310/

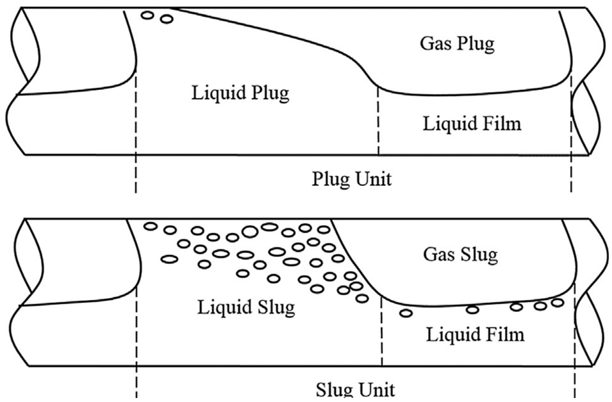


**Fig. 1.** Simplified sketch of plug (upper) and slug (lower) unit in horizontal two-phase flow. Flow direction: from left to right.

visualization [1–4] or investigating plug/slug flow using image analysis method [5,6], or investigating statistical distribution of plug/slug flow parameters [7–12]. Despite that the local liquid velocity measurements were performed in some studies [8,13–16], very limited work has been performed to obtain the local distributions of void and interface across the entire cross-sectional area in plug/slug flow at multiple locations, which is necessary to understand and model the local interfacial transport phenomena.

Among the limited studies with local measurements, Andreussi et al. [8] measured the local void fraction in the liquid slug using optical probe. The void distribution was found to change from a top wall peaking profile to a symmetric profile as gas flow rate increases. Kvernvold et al. [13] performed LDV measurements of liquid velocity in horizontal slug flow. The velocity profiles in both liquid film and liquid slug were obtained. A strong shear layer was observed at the top of the liquid film. Sharma et al. [14] measured the liquid velocity in slug flow using the hot-film anemometry. The liquid velocity in the liquid film was found to reach a minimum value at the end of the gas slug, which confirms the conclusion by Kvernvold et al. [13]. Lewis et al. [15] extended the work by Sharma et al. [14] and performed the most detailed study to date on the interfacial structure of slug flow. The bubbles were divided into two groups based on their sizes. The statistical distribution of chord length for small bubbles was obtained by assuming the liquid velocity equals to the bubble velocity. The void fraction of small bubbles was observed to increase toward the top wall while that of large bubbles was relatively flat above the liquid film. The mean liquid velocity was found to be asymmetric with the largest values located at the upper part of the pipe. Meanwhile, a strong shear layer was also observed at the top of the liquid film. Additionally, the turbulence in the liquid phase was found to increase due to the bubble-induced turbulence. Increasing gas flow rate not only increased the absolute turbulence, but also increased the turbulent intensity in the liquid phase. More recently, Thaker and Banerjee [16] measured the liquid velocity in liquid slug and liquid film using the LDV system.

However, the above local measurements of void fraction and bubble chord length were only performed along the vertical radial direction at one axial location [8,15]. No detailed distributions of void fraction and bubble size were obtained over the entire cross-sectional area at multiple locations. Due to the asymmetric gas distribution in horizontal plug/slug flow, these local measurements cannot generate reliable area-averaged two-phase flow parameters. Meanwhile, since the hot-film anemometry cannot measure the interfacial or gas velocity, using liquid velocity to estimate the chord length of small bubbles [15] may reach incorrect conclusions. Additionally, the application of hot-film anemometry is limited to the low void fraction condition. To employ this measurement technique to highly aerated horizontal slug flow may be challenging due to the large number of small bubbles in the liquid slug.

The current work performs detailed experimental study to investigate the local interfacial structure in plug-to-slug transition flow in two different pipe sizes. The local distributions of void fraction, interfacial area concentration, bubble size and bubble velocity due to small and large bubbles are obtained across the entire flow area using the local four-sensor conductivity probe. Considering that the ratio between the characteristic bubble length scale (e.g. bubble Sauter mean diameter or bubble chord length) and the pipe diameter may govern the severity of the asymmetry in the bubble distribution in horizontal plug/slug flow, the local data obtained in the current study are also employed to quantitatively investigate the effect of pipe size on the local interfacial structure.

## 2. Experimental facility and test conditions

Experiments are performed in horizontal plug and slug flows in two test facilities with inner diameter of 38.1 mm and 101.6 mm, under atmospheric pressure condition at room temperature. Air and water are supplied to the test section as working fluids through the two-phase injectors. Both injectors employ a double annulus design to ensure that nearly constant size bubbles (2–3 mm) are generated even when the liquid flow rate is different [17,18]. Simplified schematic drawings of the test facilities are shown in Fig. 2. The test sections are constructed from acrylic pipe segments in both small (38.1 mm) and large (101.6 mm) diameter test facilities. The maximum lengths of the straight section downstream of the two-phase injectors are 9.5 m (or 250 $D$) for the small pipe and 9.1 m (or 90 $D$) for the large pipe. Along each test section, at least three instrumentation ports are prepared as shown in Fig. 2, which are designed for flow visualization study, measurements of two-phase static pressure and local two-phase flow parameters. In the current work, the miniaturized four-sensor conductivity probe [19] is employed to investigate the local interfacial structure in plug and slug flows. Database is established including various two-phase flow parameters such as void fraction ($\alpha$), interfacial area concentration ($a_i$), bubble velocity ($v_g$), and Sauter-mean diameter ($D_{sm}$). The measurement of $a_i$ from the multi-sensor conductivity probe is based on the definition of local time-averaged interfacial area concentration [20,21]:

$$\overline{a}_i^t = \frac{1}{T}\sum_{j=1}^{N}\left(\frac{1}{|\boldsymbol{v}_i \cdot \boldsymbol{n}_i|}\right)_j \tag{1}$$

where $\boldsymbol{v}_i$, $\boldsymbol{n}_i$ and $N$ are the interfacial velocity, interfacial unit normal vectors for the $j^{th}$ interface, and the number of interfaces passing a point within the time interval $T$. Since this miniaturized four-sensor conductivity probe along with its signal-processing scheme was introduced, significant efforts have been made to improve this measurement technique [22,23]. By accounting for the missing bubbles due to lateral motion of the bubbles and the probe geometry, Wu and Ishii [24] have shown that the uncertainty for $a_i$ measurement of small bubbles using double-sensor conductivity probe is ±7%. Since large bubbles (elongated plug/slug bubbles) are confined by the pipe wall and have lower possibilities to be missed, the contribution from missing bubbles should be less. As such, ±7% uncertainty is considered as the highest possible uncertainty for the two-phase flows investigated in the current work. Recently, Wang et al. [25] confirmed that the difference for $v_g$ between double-sensor probe and imaging system measurement is about ±7%. For horizontal flow, Rau et al. [26] obtained a similar percentage difference between four-sensor conductivity probe and image analysis method for $v_g$ measurement of plug bubbles. Since the $a_i$ is calcu-