CHEMICAL ENGINEERING RESEARCH AND DESIGN 102 (2015) 161–170

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

An experimental investigation of phase separation of gas–liquid two-phase flow through a small break

*Fachun Liang**, *Lianmin Song*, *Yuan Sun*

College of Pipeline and Civil Engineering, China University of Petroleum, No. 66 The Yangtze River West Road,
Qingdao 266580, Shandong, China

ARTICLE INFO

Article history:
Received 26 March 2015
Received in revised form 7 June 2015
Accepted 15 June 2015
Available online 22 June 2015

Keywords:
Two-phase flow
Phase separation
Break
Flow pattern

ABSTRACT

This paper proposes a specially designed splitting device to study the phase separation of gas–liquid two-phase flow through a small break. The inner pipe diameter of the main test section is 40 mm. A small hole with 2.5 mm diameter was drilled at the main pipe wall to simulate the break. Three break orientation angles were tested, including 0° (side), −45° (inclined) and −90° (bottom) from horizontal orientation. Experiments were conducted in an air–water two-phase flow loop with a horizontal test section. Stratified wavy, annular and slug flows were observed. Experimental results show that phase separation is affected by the break location, flow pattern and gas and liquid superficial velocities. The fraction of liquid taken off of slug flow is observed much larger than that of stratified wavy or annular flows due to its particular flow behavior. A simplified correlation of break pressure difference is proposed in terms of break outlet mass flow rate and gas quality.

1. Introduction

Gas–liquid two-phase flow is widely found in a variety of applications such as power generation, chemical process, nuclear energy, and hydrocarbon production industries. When gas–liquid mixture is introduced into a dividing T-junction, uneven distribution of the phases will inevitably take place, i.e., the qualities of the two outlets are different, which are not equal to that at the inlet (Roberts et al., 1997; Stacey et al., 2000; Mak et al., 2006). This phenomenon is called phase separation. In the last several decades, extensive studies have been carried out on phase separation at T-junctions (Seeger et al., 1986; Shoham et al., 1987; Azzopardi, 1999; Mohamed et al., 2011; Elazhary and Soliman, 2012; Chen et al., 2015).

When two-phase flow passes through a pipe with a break, severe phase separation may also occur, depending on the location of the gas–liquid interface relative to the break (Welter et al., 2004; Bartley et al., 2010). If the break is submerged in liquid phase, liquid will preferentially flow into the break. The opposite is observed when the entrance is above the liquid level and the discharge is gas predominantly. Zuber (1980) reviewed the two-phase phenomena at a small branch on the side of a large reservoir containing stratified layers of gas and liquid fluid phases. He pointed out that, if gas/liquid interface was below the break, liquid may be entrained into the gas predominating flow through the break. Similarly, gas may be entrained into the predominant liquid flow in form of vortex or vortex-free motion when the break is below the gas/liquid interface.

Prediction of the discharged mass flow rates from a small break is one of the most important safety issues in two-phase flow systems (Castiglia and Giardina, 2010). For instance, light water nuclear reactors (LWRs) during a loss-of-coolant accident (LOCA), pipeline networks transferring hazardous fluid, offshore oil-well lines, and chemical batch or continuous reactors (Reimann and Khan, 1984). Owing to the inherent complexity of the two-phase flow, it is still a challenge to accurately predict the discharged mass flow rate and quality. As mentioned above, phase separation has a significant influence on the gas and liquid flow rates through the break. Hence, knowledge of phase separation phenomena at the break is essential for developing a model

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* *Corresponding author.* Tel.: +86 15053259392; fax: +86 053286981822.
E-mail address: Liangfch@upc.edu.cn (F. Liang).

http://dx.doi.org/10.1016/j.cherd.2015.06.027

Table 1 – Experiments of two-phase flow through breaks.

Authors	Simulant	Flow pattern	D (mm)[a]	d (mm)[b]	Break structure	Orientation angle
Reimann and Khan (1984)	Air–water	Stratified flow	206	6, 12, 30	Branch	−90°
Smoglie and Reimann (1986, 1987)	Air–water	Stratified flow	206	6, 8, 12, 20	Branch	±90°, 0°
Yonomoto and Tasaka (1991)	Air water	Stratified flow	190(square duct)	10, 20	Branch	±90°, 0°
Maier et al. (2001)	Air–water	Stratified flow	255	6.35	Branch	0°, 10°, 30°, 60°, 90°
Lee et al. (2007)	Air–water	Stratified flow	184	16, 24.8	Branch	0°, ±30°, ±45°, ±60°, ±90°
Bartley et al. (2008)	Air–water	Stratified flow	104	6.35	Branch	0, ±30°, ±60°, ±90°
Bowden and Hassan (2011)	Air–water	Stratified flow	50.8	6.35	Branch	0°, −45°, −90°

[a] Main pipe diameter.
[b] Branch diameter.

that can predict the discharged mass flow rate and quality.

Many experiments have been performed on two-phase flow discharging through a small break in recent years, including analysis of air–water or steam–water flows through branches with different orientations and diameters, as well as various operating conditions. Typical experimental investigations are summarized in Table 1.

These publications mainly focused on the onset of gas or liquid entrainment, but the phase separation mechanism of gas–liquid two-phase flow at the break had not been studied thoroughly. However, as mentioned above, the knowledge of the phase separation phenomena involved is extremely vital for the break prediction model. Besides, the break was simulated by a T-junction, which consists of a small diameter branch attached to a main pipe with larger diameter or a container. The length of the branch is usually several times of its diameter. As well known, the branch resistance is different from that of the break, which may affect gas–liquid two-phase flow discharge characteristics of the break. The branch diameters in previous experimental studies were all larger than 6 mm. Experimental data of break smaller than 2.5 mm is not available yet. In addition, most of the previous experimental studies focused on steady stratified flow, which don't reflect the real gas–liquid two-phase pipe flow where the annular and slug flows are common flow patterns. Therefore, through literature review, studies about annular or slug flow discharge seem to be unavailable at this moment.

The objective of the present study is to experimentally and theoretically investigate the phase separation characteristics of two-phase flow discharge through a small break at the pipe wall. A splitting device was specially designed for experimental study and a 2.5 mm hole was used as the break. The phase separation influencing factors, such as the break location, flow pattern and gas/liquid superficial velocities were studied. In addition, a correlation was developed to describe the relationship among break pressure difference, break outlet quality and mass flow rate based on gas–liquid two-phase orifice equation.

2. Experimental setup

2.1. The structure of the small break splitting device

The schematic of the small hole splitting device in the present study is shown in Fig. 1. The splitting device mainly consists of two sections: Sections 1 and 2. The inner diameter and wall thickness of the two sections are 40.0 mm and 5.0 mm, respectively. The front of Section 1 and the end of Section 2 are connected to a gas liquid two phase flow loop. A circular hole with a 2.5 mm diameter is set on the wall of Section 2 to simulate the small break. The hole is surrounded by an annular fluid receiving room. When gas–liquid two-phase flow passes through the test section, the fluid through the hole will be collected in the fluid receiving room and then enter the side branch. The side branch is connected to a metering separator, where the gas–liquid mixture is separated and metered. The Rosemount pressure transducer and pressure difference transducers were used to monitor the pressure and pressure drop at the small hole.

Sections 1 and 2 are connected by flange 1 and flange 2. A packing plate is placed between the two flanges to prevent leakage. Section 2 can rotate around its axis, which results in the whole range of angles, $-90^\circ \le \theta \le 90^\circ$, could be covered. An angle indicator is applied to indicate the current location of the break. The orientation angle of the break is determined by the plumb line at the dial plate. Three orientation angles, including 0°, −45° and −90°, were experimentally investigated in this study.

2.2. Gas–liquid two-phase flow loop

The fractions of gas and liquid taken off are often used to describe the phase splitting behaviour of gas–liquid two-phase flow. The fractions of gas taken off, K_G, and liquid taken off, K_L, are defined by the following equations:

$$K_G = \frac{M_{3G}}{M_{1G}} \quad (1)$$

$$K_L = \frac{M_{3L}}{M_{1L}} \quad (2)$$

where M is mass flow rate in the main pipe 1, kg/s; K_G and K_L represent the fraction of gas or liquid taken off; subscripts 1 and 3 denote main pipe 1 and break 3, respectively; subscripts G and L represent gas and liquid phases.

Once M_{1G}, M_{1L}, M_{3G} and M_{3L} were measured, the fraction of gas and liquid taken off could be easily obtained according to Eqs. (1) and (2). Experiments were carried out in an air–water two-phase flow loop in order to obtain the fractions of gas and liquid taken off.

Fig. 2 presents the schematic of the gas–liquid two-phase flow loop, mainly consisting of an experimental splitting device, an outlet tank, an air–water metering separator, a water circulation pump, an air compressor, a water storage tank and pipelines.