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Equal split of gas–liquid two-phase flow at variable extraction ratio

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ABSTRACT

In this work, a special distributor is proposed to distribute gas–liquid two-phase flow equally at different extraction ratio. A swirl vane is inserted at the entrance to achieve uniform swirling annular flow and ensure all the splitting holes have identical inlet conditions. A balance pipe is also applied to balance the pressure difference between the sample fluid loop and main fluid loop. Experiments were conducted in an air–water two-phase flow loop. The effect of gas and liquid superficial velocity, inlet flow pattern and splitting hole's diameter were investigated. The results demonstrate that the extraction ratio is only dependent on the ratio of sample fluid hole number to that of main fluid. The fraction of gas and liquid taken off is not influenced by flow gas and liquid velocity, inlet flow pattern and size of the splitting hole. The desired extraction ratio can be obtained by regulating the number of sample fluid holes.

1. Introduction

Gas–liquid two-phase flow is widely found in industrial fields that involve heat exchangers, chemical reaction engineering, plant evaporation-separation technology and environmental chemistry. When two-phase mixture is introduced to a distributor, for example a junction, phase separation is most likely to occur, resulting in non-uniform quality splits to each exit branch (Azzopardi, 1999). In general, a heat exchanger performs better when the gas and liquid are uniformly distributed. Mal-distribution may greatly deteriorate the heat exchanger thermal and hydraulic performance. Lalot et al. (1999) investigated the fluid flow in heat exchanges, and their results indicated that phase separation leads to an efficiency loss of 25% for cross flow exchangers. What is more, uneven split can even leads to dry out phenomenon, which may result in the damage to the device.

During the last several decades, a significant amount of works have been published on the phase split of gas–liquid two-phase flow. Owing to the simple structure and easy processing, T-junctions are extensively studied. The sizes of the T-junction studied are ranged from micro scale to macro scale (Rea and Azzopardi, 2001; Wren and Azzopardi, 2004, 2005; Mak et al., 2006; Li et al., 2017; Mahdi et al., 2017; Sun et al., 2018). Various phase split influencing factors have been investigated, including the inlet and outlet directions, inlet flow pattern, the mass velocity, the physical properties of working fluids, the branch angle of T-junction (Saba and Lahey, 1984; Azzopardi, 1999; Zheng et al., 2017; He et al., 2011; Chen et al., 2013).

There are two typical types of T-junctions: branching T-junction and impacting T-junction. When gas–liquid two-phase flows through a horizontal branching T-junction, the lighter phase tends to be preferentially diverted into the side arm, while the heavier phase will flow straight through the main arm (Issa and Oliveira, 1994). For branching T-junction with a horizontal main pipe and a vertically upward side arm, the condition is even worse. For example, under certain mass split ratios, only single-phase gas flows in the side arm (Azzopardi et al., 2002). The impacting T-junction is characterized by the two outlet branches are oriented symmetrically about the inlet. Owing to it's symmetrically structure, distribution performance separation is expected to be greatly improved compared with that of the branching T-junction.

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Nomenclature

A_h	Sampling hole flow area, m^2
C_d	Discharge coefficient
Err	Relative error
K	Fraction of taken off
M	Mass flow rate, kg/s
N	Total splitting holes number
n	Sample fluid hole number
ΔP	Pressure difference, Pa
ΔP_{12}	Pressure drop of main fluid hole, Pa
ΔP_{13}	Pressure drop of sample fluid hole, Pa
U_{SL}	Superficial liquid velocity, m/s
U_{SG}	Superficial gas velocity, m/s
X	Gas quality

Greek symbols

ρ	Density, kg/m^3
β	Diameter ratio
ψ	Thermal correction factor
θ	Modification factor

Subscripts

1	Total fluid
2	Main fluid
3	Sample fluid
h	Splitting hole
G	Gas
L	Liquid
T	Theoretical value
TP	Two phase flow

Unfortunately, both laboratory and field test confirmed that uneven quality splits occurred when the flow rate entering each side arm deviates from a 50%–50% split (Azzopardi et al.,1987; Hwang et al., 1989; El-Shaboury et al., 2007; Mohamed et al., 2011).

In order to achieve equal distribution, some special structures were proposed in the last several decades. The approaches can be basically divided into two categories: time based distribution method and space based distribution method.

Time based distribution method uses a special sampler to switch full fluid flow alternatively between each outlets of downstream on a timed basis. In other words, the incoming fluid is divided into time segments, and each segment has only one possible path to exit the distributor. Boyles et al. (2000) inserted a winging plate at the entrance of a junction to alternately direct the incoming steam to each of the two outlet legs of a junction. Wang et al. (2012) and Liang et al. (2014) invented a rotational wheel type sampler to switch the total flow to a sample loop periodically. The flow switch device is the core element of the distributor. However, it is a moving part, which reduces the distributor reliability and increases maintenance costs.

As to the space based distribution method, the fluid flow thorough each channel are extracted from one part of the main pipe instead of the whole flow section. It can be further divided into separation method and non-separation method.

The separation method separates the gas–liquid mixture into gas and liquid first, and then the gas and liquid flows are recombined at the desired gas–liquid ratio. The split process is completed under the single phase environment and the even split can be obtained if complete gas liquid separation is achieved. Berger et al. (1997) designed an apparatus called SpliTigator for controlling phase split. The stream of flow was separated into liquid and vapor phases at the upstream of the junction, and recombined them just downstream of the junction in proportion to the vapor mass rate flowing in each outlet leg. Zhang et al. (2013) invented an a dual-header two-phase distribution system and the gas–liquid separation process was conducted by a series of T-junction with upper and lower manifolds. The major disadvantage of the separation method is that a gas–liquid separation system must be employed. Moreover, in order to control the outlet quality and flow rate, flow rate measurement and control devices are often required, which increases the distributor size and cost.

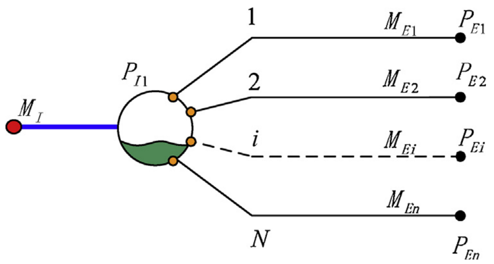

Fig. 1 – The split system of gas–liquid two-phase flow.

The non-separation method conducts the distribution without separation. Therefore, the distributor size can be greatly reduced. According to Azzopardi's finding, the fluid emerging through the branch outlet is mainly extracted from the fluid close to the inlet of each splitting channel, which is called zone of influence (Azzopardi, 1999). In order to reduce the phase separation, efforts have been focused on how to adjust the upstream flow pattern to ensure all the channels have identical zone of influence.

Jones (1989) invented an internal pipe structure for improving the division of fluid between two branches of a pipe. The internals included a static mixer, which is followed by a flow tractifier and a flow divider. Hong and Griston (1998) inserted an orifice and a static mixer at the entrance of the branching T-junction to mix the gas–liquid mixture before distribution. Later, Stoisits and Pinto (1999) proposed an improved static mixer, called the Packed Bed Static Mixer. This method often causes rather large pressure loss and is susceptible to plugging as it captures scales and other debris in the flow lines.

From the reviews above it is clear that the phase split phenomena are very complex and no universal method or design rule is available to achieve even split of two-phase flow. As shown in Fig. 1, the gas–liquid split is conducted at a unified hydraulic system. The pressure difference of each channel is the function of mass flow rate (M_i), gas quality (X_i), leg length (L_i) and diameter (d_i).

$$P_{I1} - P_{Ei} = f\,(M_i, X_i, L_i, d_i) \tag{1}$$

Eq. (1) indicates that the phase split of gas–liquid two phase flow depends not only on the inlet condition (mass velocity, gas weight fraction, flow pattern) but also the outlet pressure of each splitting channel. The fundamental reason of phase separation is due to the large density difference between the gas phase and the liquid phase. The gas is very sensitive to the resistance change due to its low momentum. If the downstream channels differ in resistance, the gas will change its flow path to the channel with less resistance.

The aim of this paper is to propose a novel method to overcome phase separation by adjustment of inlet flow pattern and pressure difference of each distributing channel simultaneously. Equal split of gas–liquid two-phase flow is achieved at variable split ratio. A series of experiments have been carried out in wide ranges of gas and liquid velocities to investigate the split performance of the proposed distributor.

2. Structure of experimental distributor

The experimental distributor in the present study is shown schematically in Fig. 2. It mainly consisted of a main pipe, a swirl vane, a stationary plate and a moving plate, a sample fluid room and a main fluid room. The inner diameter of the main pipe is 32 mm. There are 20 splitting holes evenly arranged along circumference of the main pipe. The swirl vane