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A methodology and database to quantify the confidence level of methods for gas–liquid two-phase flow pattern prediction

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ABSTRACT

A novel methodology is presented to quantify the confidence level in the prediction of gas–liquid two-phase flow patterns in pipes. An experimental flow pattern data base has been collected, consisting of 12 studies (a total of 9029 data points). The experimental data are compared with the predictions of the unified Barnea (1987) model (any other model/method can be used), and the confidence level in the predictions is quantified. Also, gaps in the data base are identified and future studies required in this are discussed.

Keywords: Flow pattern; Two phase flow; Mechanistic modeling; Confidence level

1. Introduction

The term "flow pattern" refers to the spatial distribution of the phases, which occur during gas–liquid two-phase flow in pipes. When gas and liquid flow simultaneously in a pipe, the two phases can distribute themselves in a variety of flow configurations. The flow configurations differ from each other in the interface distribution, resulting in different flow characteristics.

Determination of flow patterns is a fundamental problem in two-phase flow analysis. Indeed all the design variables, namely, phase velocity, pressure drop, liquid holdup, heat and mass transfer coefficients, residence time distribution, and rate of chemical reaction, are all strongly dependent on the existing flow pattern. Thus, knowledge of the existing flow pattern can help the industry carry out a better design of two-phase flow systems. These include accurate prediction of pressure drop and liquid inventory in pipe flow, and effective erosion corrosion planning, utilizing properly chemical additives, such as corrosion inhibitors and demulsifies. Also, segregated flow patterns are often desired for phase separation efficiency improvement. Nowadays, a downward inclined inlet section may be installed upstream of the separator, for promoting stratification and pre-separation of the phases. This can be designed utilizing flow pattern prediction to ensure stratified flow at the inlet section. Finally, the transport and deposition of solid particles, e.g., hydrates, paraffins and waxes, is an important flow assurance issue, which is strongly affected by the different flow patterns.

In designing the above applications risky decisions can be made based on the predicted flow pattern, which can result in severe economical losses. Thus, it is very important to determine the confidence level in the prediction of the existing flow pattern. However, no past studies have attempted to address the confidence level in such predictions.

Fig. 1 presents the different transition boundaries occurring in gas–liquid flow, as well as the different existing flow patterns. The physical mechanisms and respective models of the different transition boundaries can be found in Shoham (2006). Following is a summary of the commonly accepted flow patterns, for the entire range of inclination angles.

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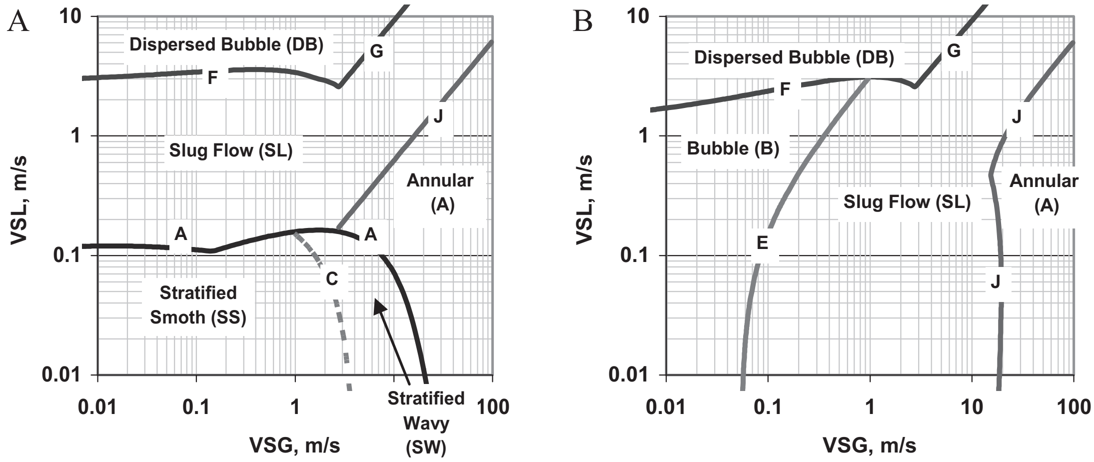

Fig. 1 – Transition boundaries and existing flow patterns in gas–liquid two-phase flow.

1.1. *Horizontal and near-horizontal flow*

The existing flow patterns in these configurations are classified as stratified flow, including stratified-smooth (ST) and stratified-wavy (SW), intermittent flow (I), which includes slug and elongated-bubble, annular flow (A) and dispersed-bubble flow (DB).

1.2. *Vertical and sharply inclined flow*

In this range of inclination angles, the stratified flow regime disappears and a different flow pattern is observed, namely, churn flow. Usually, the flow patterns are more symmetric around the pipe axis, and are less dominated by gravity. The considered flow patterns are bubble flow (B), slug flow (I), churn flow (CH), annular flow (A), and dispersed-bubble flow (DB).

1.3. *Downward inclined and vertical flow*

For downward inclined flow, the dominant flow pattern is stratified-wavy flow, occurring over a wide range of downward inclination angles, namely, from horizontal flow up to −80°. As observed in horizontal, upward inclined, and upward vertical flow, dispersed-bubble flow and annular flow occur for all inclination angles (including downward flow) at high liquid and high gas flow rates, respectively. For downward flow, the annular regime exists also at low gas flow rates, in the form of falling-film. The slug flow pattern in vertical downward flow is similar to that occurring in upward flow, except that usually the Taylor bubble is unstable, located eccentrically off the pipe axis. The Taylor bubble may either rise or descend, depending on the relative flow rates of the gas and liquid phases.

2. Experimental data base

An experimental data base has been collected, which consists of the most relevant studies on flow pattern prediction, as given by Table 1. The earliest set of data is Shoham (1982), which was acquired in 50.8 and 25.4 mm pipe diameters, utilizing air water at atmospheric conditions. This was the first study covering systematically all the inclinations angles, from −90° to +90°. At the same time, Lin (1982) carried out horizontal flow experiments in 25.4 and 95.4 mm diameter pipes, varying the superficial gas velocity from 0.8 to 200 m/s. Later, Kouba (1986) carried out an experimental study on slug flow in a horizontal 3 in. diameter pipe, using air-kerosene. Following, Kokal (1987) studied two-phase flow patterns in horizontal and near horizontal flow, utilizing pipe diameters of 25.8, 51.2 and 76.3 mm, with air and light oil as working fluid. Wilkens (1997) carried out studies on gas–liquid flow at 0°, 1° and 90°. Only his data for salty water and air have been considered in the present study. Later, Manabe (2001) studied the effect of pressure on flow patterns for 0°, 1° and 90°, using oil and natural

Table 1 – Summary of studies in the data base.

Authors	Year	Variables range	School	Points
Shoham	1982	Air water, ID = 2 and 1 in., from $\theta = -90°$ to +90°	TelAviv Univ.	5676
Lin	1982	Air water, ID = 25.4 and 95.4 mm, $\theta = 0°$	Univ. Illinois	141
Kouba	1986	Air-kerosene, $\theta = 0°$, ID = 3 in.; $\rho_L = 814$ kg/m^3; $\mu_L = 1.9$ cP	Univ. Tulsa	53
Kokal	1987	$\theta = 0°, \pm1°, \pm5°$ and $\pm9°$; ID = 25.8; 51.2 and 76.3 mm; $\rho_L = 858$ kg/m^3; $\mu_L = 7$ cP	Univ. Alberta, Canada	1668
Wilkens	1997	Salty water and oil; P = 40 psi; $\theta = 0°$, 1° and 90°	Univ. Ohio	204
Meng	2001	Annular stratified flow transition for $\theta = 0°, \pm1°, \pm2°$	Univ. Tulsa	153
Manabe	2001	P = 209.3 psi and 464.8 psi; $\theta = 0°$, 1° and 90°	Univ. Tulsa	247
Van Dresar and Siegwarth	2001	Nitrogen and hydrogen, $\theta = 1.5°$; ID = 8.43 mm	NASA	116
Mata et al.	2002	ID = 2 in., $\theta = 0°$, $\mu_L = 480$ cP	Intevep, Venezuela	80
Abduvayt et al.	2003	P = 592 and 2060 kPa; $\theta = 0°$, 1° and 3°; ID = 54.9 and 106.4 mm; nitrogen and water	Waseda Univ., Japan	443
Gokcal	2005	$\theta = 0°$; ID = 50.8; $\rho_L = 889$ kg/m^3; $\mu_L = 181$–587 cP	Univ. Tulsa	183
Omebere-Iyari et al.	2007	P = 2000 kPa, 9000 kPa; $\theta = 90°$; ID = 189 mm; nitrogen and water	SINTEF	98