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Liquid holdup correlation for conditions affected by partial flow reversal

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ABSTRACT

A new method to predict liquid holdup in vertical upward gas–liquid flows is presented based on large scale steady-state experiments in a transparent 42-m long, 0.048-m ID vertical tube system. This work focuses on situations of particular significance in natural gas producing wells, when annular to churn flow-pattern transition brings about drastic holdup increase, leading to a rich group of phenomena in the field, known as "liquid loading". Under circumstances, believed to precede liquid loading, the still steady-state and stable liquid holdup may be several folds larger than the inlet volumetric fraction of the liquid, due to partial flow reversal. Standard two-phase correlations have difficulties in reproducing the observations in such situations. The proposed method is actually flow-pattern independent and relies on a measure of nearness of the flow condition to the specific condition when partial flow reversal starts to appear. Interestingly, the actual form of this correlation is quite simple, relying on the gas and liquid superficial velocities and mass fractions – in addition to the key parameter – the "critical" superficial gas velocity.

Introduction

Upward vertical gas–liquid flow behavior depends strongly on the in situ volumetric fraction of the liquid phase. Due to gravity, the in situ liquid volume fraction (H_L) is always larger than the inlet volume fraction (and hence often referred to simply as "holdup".) Predicting holdup from a mechanistic model based strictly on first principles seems to be out of reach at present. However, a great number of empirical models have been proposed, often separately, for flow pattern, void fraction ($1 - H_L$), and frictional pressure drop, possessing an impressive combination of simplicity and predictive capability.

Cioncolini and Thome (2012) presented a new void fraction prediction method specifically for vertical annular two-phase flow. This method is simpler than most of the previously suggested correlations. It is based on a large data-bank of annular flow in circular tubes. The method provides reliable void fractions, covering macroscale and microscale channels, as well as adiabatic and evaporating two-phase flow conditions. However, its suggested region of applicability is restricted in the sense that the flow cannot be affected by partial flow reversal.

In annular flow, part of the liquid travels as a film on the pipe walls with the rest being conveyed as droplets in the gas core. In "clear" annular flow the local velocity of liquid may vary with location, but its direction is always upward. For a fixed liquid rate, annular flow transits to churn flow as the gas rate is decreased. Levy (1999) describes annular flow near its transition to churn flow as unsteady, disturbed by flooding waves. However, in the words of Azzopardi (2008): "there is not a consensus about the nature of churn flow." It is recognized that there are large structures often called "huge waves" present, periodically interrupting the continuity of the gas core and the wall covering liquid film. The huge waves carry most of the liquid upward, and between them the liquid film may move downward "thus giving the strong impression of oscillation". At even lower gas rates, the essentially uni-directional upward movement of the liquid is re-established when the flow regime transits to slug flow.

Within the oil and gas industry the annular to churn flow-pattern transition is of special significance because it leads to increased resistance in the path-way of the produced gas, triggering instability in the coupled well-reservoir system and ultimately causing the end of the natural flow of gas from the reservoir. Extensive studies have been conducted in this particular area, the most influential being Turner et al. (1969). The work lists two hypotheses that can be summarized as follows: at a "critical gas velocity", liquid droplets in the gas core start to fall back *or* the liquid film at the wall undergoes partial flow reversal. While these concepts are formulated in the language of multi-phase flow, the authors use them only as starting point for developing a critical rate correlation, where the actual choice of the hypothesis to accept and the

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numerical constant are both decided upon using data solely from actual gas producing wells (not from laboratory observations). In our opinion this underlines the fact that the terms “liquid loading” and “critical gas rate” cannot be considered narrowly as mechanistic multi-phase flow concepts. Indeed, the richness of the related phenomena in the gas field comes from the interaction of multiphase flow in the well and in the underlying porous media and the actual phenomena of interest during “liquid loading” are virtually impossible to reproduce under laboratory conditions.

As far as the more fundamental multi-phase literature is considered, the co-current upward flow of gas and liquid already affected by partial flow reversal seems to be a grey area between annular flow studies and counter-current flow limitation studies. Traditionally, researchers either attempt to exclude such conditions when establishing void-fraction/holdup correlations as in the case of Cioncolini and Thome (2012) or focus on conditions allowing/excluding counter-current flow.

One of the difficulties regarding this grey area is associated with the fact that studying churn flow requires extremely long tubes Wallis (1969). Waltrich et al. (2013) observed continuing two-phase flow development as far from entrance as $L/D = 500$, especially for low liquid mass fluxes. These observations are in agreement with the experimental results reported by Kaji and Azzopardi (2010). Most existing liquid holdup prediction methods were derived from experimental measurements conducted in relatively short tubes ($L/D \ll 500$), so it is not surprising that some predictions might under/overestimate actual values by an order of magnitude in cases when partial flow reversal happens in the liquid.

Due to the rarity of measurements in long vertical tube and the restrictions on available correlations, it is still desirable to conduct experiments in the partial flow reversal affected region and develop new predictive methods.

Experimental setup

Waltrich et al. (2013) conducted experimental study of two-phase flow with mixed air and water flowing through a large-scale vertical flow-loop (42-m long and 0.048-m ID transparent PVC pipe). Local liquid holdup was measured at several tube locations relying on two-wire conductivity probes. The absolute pressures were measured at five vertical locations, corresponding to $L/D = 0, 189, 419, 671,$ and 817. The same flow-loop is used in this study, augmented with the capability of measuring the overall holdup by the volumetric method, using the simultaneously closing valves.

A comparison of the large-scale flow loop with several experimental facilities reported in the literature is presented in Table 1, where L/D is the non-dimensional distance between inlet and outlet. The key advantage of our loop is the large L/D ratio, which enables capturing axial development of the flow regime. The main disadvantages are: limitations on maximum pressure and on the type of the liquid and gas. The maximum operating pressure is 1.4 MPa and only air/water flows can be studied in this flow loop.

The two-wire conductivity probes read instantaneous electrical conductance proportional to the amount of liquid between the probes. Time averaging of the probe readings during steady-state period provides an approximation of the local film thickness. The amount of water travelling in the form of entrained liquid droplets is not measured directly, it is determined from an empirical correlation proposed by Barbosa et al. (2002).

The additional capability of measuring shut-in holdup by trapping the fluid between two valves installed at the inlet and outlet of the test section has proved crucial in this study. The inlet and outlet valves can be closed within 2–4 s, depending on the initial opening, where the distance between them is 42 m. A pressure transducer is positioned at the bottom providing the hydrostatic pressure and hence the height of the liquid column already in rest. The pressure measured holdup can be verified for those cases in which the water level reaches the transparent section of the pipe, confirming that the average liquid holdup measurement uncertainty is within ±0.02 absolute unit. Oddie et al. (2003) reported that in their experiments liquid holdup measured by probes gave less accurate results compared to the shut-in technique. However, Waltrich et al. (2013) emphasized that probes holdup measurement provides valuable insight into the axial development of the flow. Our observations coincide with both of the above opinions.

Observations

Stabilized liquid holdup

The objective of the current experimental series was to establish a data set for the development of liquid holdup correlation within the vicinity of partial flow reversal. Therefore, we included flow reversal and no flow reversal conditions. The liquid holdup measurements were conducted systematically with gas and liquid mass fluxes ranging from 3.9 to 37.4 $\text{kg m}^{-2}\,\text{s}^{-1}$ and 4.5 to 60.7 $\text{kg m}^{-2}\,\text{s}^{-1}$, respectively (see electronic annex in the online version of this article). The gas and liquid mass flux intervals correspond to possible situations in natural gas producing wells where volumetric liquid rates are moderate or low, and (initial) volumetric gas rates are high, while mass fluxes are of the same order. The comparison of the conditions in the present study with the experiment of Waltrich et al. (2013) is shown in Fig. 1. About 55% of liquid holdup data were measured with gas mass fluxes greater than liquid mass fluxes and more than 60% of experiments were performed around the annular-to-churn flow pattern transition as indicated by the Hewitt and Roberts (1969) flow pattern map. The experimental runs were conducted with average pressure between 110 and 150 kPa.

Table 1
Comparison of flow loop dimensions.

	Fluids	D (mm)	L (m)	L/D	(1)
Present Study	Air–Water	48.6	42.0	864	SCV
Anderson and Mantzouranis (1960)	Air–Water	10.7	1,3	118	QCV
Hall-Taylor et al. (1963)	Air–Water	31.8	6.7	211	FT
Nguyen and Spedding (1977)	Air–Water	45.4	2.0	44	QCV
Oddie et al. (2003)	N_2–Water	152.0	10.9	72	ND; CP; QCV
Kaji and Azzopardi (2010)	Air–Water	19.0	5.7	300	CP
Godbole et al. (2011)	Air–Water	12.7	2.2	173	QCV
Alamu (2012)	Air–Water	19.0	7	368	LD
Liu (2014)	Air–Water	40.0	6.0	150	QCV

Holdup measuring technique: CP = capacitance probe; FT = annular film thickness; LD = laser diffraction; ND = nuclear densitometer; QCV = quick closing valve; SCV = simultaneously closing valve.