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Spatial void fraction measurement in an upward gas–liquid flow on the slug regime

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ABSTRACT

Spatial void fraction measurements of a vertical upward air–water flow on the slug regime are made. The experimental technique uses simultaneously a contact needle and two single wire sensors. The data processing combines the information of both types of sensors. The liquid slug local void fractions along the radial and axial directions are estimated employing time and ensemble averages. The spatial void fraction along the axial direction disclosed two patterns, one associated to the pipe core and the other near the wall. The data is further processed to render the average void fraction along the radial and axial directions and the slug unit void fraction profile. Uncertainty analysis and data consistency tests are applied the check data reliability.

1. Introduction

Slug flow is a gas–liquid flow regime occurring over a wide range of flow rates and found in many industrial processes. The regime is characterized by a quasi-periodic succession of aerated liquid slugs trailed by gas pockets surrounded by liquid films which do not repeat in time or in space. In vertical upward slug flow the gas pockets become axis-symmetric with a bullet shape, also called by Taylor bubble. The Taylor bubble moving faster than its upstream liquid slug transfers a fraction of the displaced volume to the downstream liquid slug as a free falling film. The gas is entrained into the downstream liquid slug due to the liquid film fragmentation at the Taylor bubble rear.

The intermittent slug flow behavior allied to the intrinsic gas–liquid interactions is a complex phenomenon. One successful attempt to model slug flow is based on a steady state approximation by considering the existence of a repeating cell or unit cell [5]. There are several models employing the unit cell concept, among them we cite Taitel and Barnea [6] model as representative of this class. Unfortunately all the unit cell based models have more unknowns than equations and frequently the void fraction is supplied by closure equations. The accuracy of the void fraction estimate has influence on the predicted slug properties, certainly the most obvious one regards to the gas transport. Despite the major fraction of the gas is transported by the Taylor bubble, the aerated liquid piston may transport not a negligible fraction of the total gas as we shall see through the experimental data.

Relevant experimental data on liquid slug void fraction in vertical upward flow appeared during the late 70's. A selection of a few experimental databases concerning the volumetric averaged liquid slug void fractions are presented on Table 1. These databases were used to validate empirical liquid slug void fraction correlation, for example Felizola and Shoham [14] and Gomez et al. [15]. The empirical correlations are easy to evaluate but their usefulness is restricted to scenarios close to the experimental condition where they were developed. In an attempt to overcome this limitation new models based on a Taylor bubble gas balance were developed: Fernandes et al. [10], Kockx [21], Brauner and Ulmann [16] and Guet et al. [17]. These mechanistic models estimate the volumetric averaged void fraction of the liquid slug by modeling the liquid slug aeration process based on the downward gas flow induced by the liquid film [10] and [21], on the flux of energy [16] or on the pressure jump at the rear of the Taylor bubble [17].

Despite the available databases and the resourceful void fraction models there is little information regarding spatial void fraction measurements, a valuable source of information to develop mechanistic models to void fraction prediction. Nakoryakov et al. [1] and Mao and Dukler [2] were the first to address this issue in 1989. Nakoryakov et al. [1] measured: the radial and axial velocity profiles at the liquid slug employing a hot wire, the wall shear stress using a double wall shear stress probe and the radial void fraction profiles of the Taylor bubble region employing a

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Nomenclature

List of symbols

A	pipe cross sectional area (m^2)
A_t	flow attachment point
C_0	dimensionless distribution parameter for the kinematic law
$C_{0,B}$	dimensionless distribution parameter for the kinematic law
C_∞	dimensionless drift parameter
D	pipe diameter (m)
D_t	flow detachment point
F	slug frequency (Hz)
Fr_m	Froude number
g	gravity acceleration (m/s^2)
J	mixture velocity (m/s)
J_G	gas superficial velocity (m/s)
J_L	liquid superficial velocity (m/s)
L_F	liquid film length (m)
L_S	liquid slug length (m)
L_U	slug unit length (m)
N	number of samples
Q	volumetric flow rate (m^3/s)
r	radial coordinate (m)
R_0	pipe radius (m)
Re_m	Reynolds number
S	sensors axial spacing (m)
t	time (s)
tb	residence time of the elongated bubble (s)
ts	residence time of the liquid slug (s)
TB	time of the bubble front (s)
TS	time of the slug front (s)
TV*	dimensionless threshold value
$v_{G,J}$	drift velocity (m/s)
V	voltage (v)
V^*	dimensionless voltage
U_b	dispersed bubble velocity (m/s) within the liquid slug (m/s)
U_T	bubble nose translational velocity (m/s)
X_L	liquid phase indicator function
z	axial distance from the slug head (m)

Greek letters

$\alpha_{S,T}$	liquid slug void fraction employing time average
$\alpha_{S,E}$	liquid slug void fraction employing ensemble average
α_U	unit void fraction
β	dimensionless intermittence factor
η	dimensionless radius
μ_L	liquid viscosity (N.s/m^2)
ξ	dimensionless axial distance
ρ_G	gas phase density (kg/m^3)
ρ_L	liquid phase density (kg/m^3)
$\Delta\rho$	density difference (kg/m^3)
σ	surface tension (N/m)

Operators

$\langle\ \rangle$	cross sectional average
$\{.\}$	pipe axial average
$\{\langle.\rangle\}$	mixed average
$\langle\langle.\rangle\rangle$	global average

Subscripts

G	gas phase
L	liquid phase

Table 1
Experimental database for averaged liquid slug void fraction.

Authors	Year	Fluids	Pipe diameter (cm)	Data points
Schmidt [8]	1977	Air–kerosene	5.10	15
Koeck [9]	1980	Air–water	4.40	25
Fernandes et al. [10]	1981	Air–water	5.07	24
Fréchou [11]	1986	Air–water	5.36	7
Fréchou [11]	1986	Air–oil	5.36	7
Nakoryakov et al. [1]	1989	Air–water solution	1.5	6
Mao and Dukler [2]	1989	Air–water solution	5.08	5
Van Hout et al. [12]	1992	Air–water	5.00	6
Felizola [13]	1992	Air–kerosene	5.10	9

contact needle probe. The experimental test section was a vertical 15 mm internal diameter pipe and the measurements were performed at 166*D* downstream the gas–liquid mixer. The working fluids were air and an electrolyte water based solution. Mao and Dukler [2] employed a double mass transfer sensors and a radio frequency local probe to disclose measurements of the wall shear stress and axial distribution of the void fraction at the pipe centerline. The data were taken in a vertical pipe with 5.08 cm in diameter and 175*D* in length. The working fluids were air and an electrolyte water based solution. The gas and liquid superficial velocities range were of (76–342) cm/s and (5–32) cm/s respectively. The experimental data disclose that the void fraction is high just at the slug head and decays continuously throughout the measurement interval.

Barnea and Shermer [18], in 1989, focused on slug flow characteristics and transition. They used a contact needle probe to detect the passage of the interfaces at the centerline of a vertical tube with 50 mm in diameter and 10 m long operating with air–water mixture. The experiments were carried out at constant liquid velocity of 1 cm/s and gas velocities spanning from (3–400) cm/s encompassing bubbly, slug and churn regimes. The centerline void fraction measurements were taken at distances up to 5*D* downstream the slug head to reinsure the voidage decaying behavior observed by Mao and Dukler [2]. Furthermore, the liquid slug void fraction at the centerline was around 0.25 which is the bubbly flow transition for air–water flow.

Van Hout et al. [12], in 1992, employed two fiber optic probes to measure the spatial distribution of the liquid slug void fraction in a vertical 50 mm internal diameter pipe. The measurements were carried out at a distance of 120*D* downstream the air–water mixer. The air and water superficial velocities range were of (10–156) cm/s and (1–75) cm/s respectively. They found that the radial profiles were nearly flat with a tendency to peak near the wall. Reference [12] concluded that at distances greater than 10*D* from the Taylor bubble rear the radial and axial void fraction profile no longer change and exhibit values lower than the ones observed on the wake region.

To get insight into the air entrainment process Delfos [19], in 1996, measured the gas loss at the rear of a Taylor bubble held stationary in vertical tube and proposed a gas entrainment model.