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On the characteristics of the roll waves in gas–liquid stratified-wavy flow: A two-dimensional perspective

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ABSTRACT

The characteristics of the roll waves in the oil–gas, stratified-wavy flow are studied experimentally in a 0.152 m ID horizontal pipe for superficial gas velocities between 7.45 m/s and 12.62 m/s at two different liquid superficial velocities, 1 and 2 cm/s. The liquid holdup, liquid film height, wetted wall perimeter decrease with the increasing superficial gas velocity. The interfacial surface area is calculated from the distinct interface between the phases from the experimental data without any assumptions on the interface geometry. The variation of the interfacial surface area is found to be closely related to the liquid holdup.

The region where the interface fluctuations spread in the pipe cross-section is analyzed. For low gas flow rates, a small region exists where the fluctuations are negligible implying a continuous liquid contact with the pipe bottom. However, an increase in the superficial gas velocity extends the spatial reach of the interface fluctuations very close to the pipe wall at the bottom where the continuous liquid region diminishes. For all experimental conditions examined, the interface fluctuations occurring at a frequency range of 10 Hz < f < 40 Hz is hypothesized to be related to the capillary waves.

At low superficial gas velocities, the roll wave topology is stretched toward the sides of the pipe. Moreover, the oscillations of these waves at different transverse locations are out-of-phase. With an increase in the gas flow rate, the wave oscillations are observed to be in-phase with each other and more coherent structures are detected.

1. Introduction

The physical understanding of the gas–liquid two-phase flow in a circular pipe is important for the flow assurance purposes in petroleum engineering applications, but it poses a great challenge due to the complexity of the flow field. In pursuit of a systematic investigation of this multi-phase flow phenomenon, past researchers have identified several flow regimes depending on a wide range of influential parameters such as the pipe geometry, flow conditions and physical properties of the fluids [1]. The segregated coflow of the liquid phase with the gas phase, referred to as stratified flow, is one of the flow regimes occurring in a horizontal pipe. Stratified flow with low liquid loading conditions is common in gas production wells and transmission pipelines, where low liquid loading refers to a ratio of the liquid volumetric flow rate to the gas volumetric flow rate (at standard conditions) less than 1100 m^3/MMsm^3 [2]. In addition, small amounts of liquid present in this flow configuration is representative of the operational conditions for the wet-gas pipelines, where liquid condensation occurs during the transport of the single-phase natural gas through the pipe. This can lead to a considerable increase in the pressure drop compared to the single-phase case [3]. Therefore, accurate predictions of in-situ liquid holdup and pressure drop within in a pipeline is important especially for determining the pigging frequency, the design of the receiving facilities, and the required size and material of the pipe [4].

Several models have been proposed for the predictions of the pressure gradient and the liquid holdup related to the gas–liquid two-phase flow in horizontal pipes [1,3,5–10]. In these two-fluid models, the flow topology and friction factors are the major closure relationships in the combined momentum balance, and have direct impact on the accuracy of the predictions. The gas–liquid interface is one of the important closure parameters, and is subject to different approaches in the modeling such as *flat interface* [1,6], *double circle* [9] and *apparent rough surface* [3,8]. While these definitions aim to represent the time-average interface topology, the underlying physics is still not well understood.

The flow structures at the interface are summarized by Hewitt and Hall-Taylor [11], and Chen et al. [9]. According to these studies, the interface changes from a smooth, flat surface to a wavy surface

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List of symbols

α_G	gas void fraction
c_1, c_2	arbitrary constants
C_{h_L}	wave celerity based on h_L
C_θ	wave celerity based on θ
D	pipe diameter
Δt	time resolution
dp/dL	pressure drop
ε_L	dielectric constant of the liquid
ε_G	dielectric constant of the gas
ε_m	instantaneous permittivity values based on the Wire Mesh measurements
$\in_{H_L}$	uncertainty in liquid holdup
ϵ_q	uncertainty in the variable of interest
f	frequency
Δf	frequency resolution
h_L	liquid film height
H_L	liquid holdup
i, j, k, m	indices
M, M'	number of intervals
m	degrees of freedom
μ	dynamic viscosity
ρ	density
τ	surface tension
V_L	calibration measurements for the liquid
V_G	calibration measurements for the gas
$V_{\log}$	measured logarithmic signals at the crossings of the Wire Mesh sensor
v_{SG}	superficial gas velocity
v_{SL}	superficial liquid velocity
Q_j	normalized parameter
q_j	mean of the variable of interest in the jth interval
$\bar{\bar{q}}$	total mean of the variable of interest
s, s'	standard deviations
t	time
$t_{M,0.05}$	t percentile distribution with 95% confidence
x, y	cartesian coordinates centered at the pipe center
θ	wetted wall perimeter
θ_L	wetted wall perimeter on the left side of the pipe
θ_R	wetted wall perimeter on the right side of the pipe
w	weighting coefficient matrix
w_i	ith wave defined based on the interface topology

Abbreviations

QCV	quick closing valve
WMS	Wire Mesh Sensor
IC	interface coordinate vector
DFT	Discrete Fourier Transformation
PSD	power spectrum density
sys	systematic
ran	random

as the superficial gas velocity is increased. These waves are classified as two-dimensional, three-dimensional (squalls) and roll waves (Kelvin–Helmholtz waves) with increasing gas flow rate. After a critical superficial gas velocity is achieved, the droplets of liquid are sheared from the interfacial waves and entrained into the gas phase. These flow structures are illustrated in Fig. 1, which is taken from Chen et al. [9]. Related to these flow structures, different mechanisms are proposed for the transport of the liquid phase; *secondary gas flow structures* [12], *wave spreading* [13], and *entrainment/deposition* [14,15]. There are several research studies on low-liquid loading [4,14–17]. Meng et al. [14] showed that liquid entrainment into the gas phase plays an important role in the variation of the liquid holdup. Badie et al. [15] showed that the intermittent waves on the gas–liquid interface are responsible for liquid entrainment. Fan [16] compared his experimental data with the Beggs and Brill correlation [18], Zhang et al. model [19] and Hart et al. model [8]. He showed that these models do not predict the pressure drop and the liquid holdup accurately, especially for larger pipe diameters.

The incorporation of the flow physics associated with the stratified-wavy flow into the current mechanistical models is limited to one-dimensional analysis due to the complex flow field. The dynamics of the axial waves are not studied in detail from a two-dimensional perspective, which can limit our knowledge on the unsteady flow phenomenon occurring at the phase interface. It is also clear from the presented literature that there is still need for further understanding on the flow topology for larger pipe diameters, which will improve the closure relationships in the two-fluid models. In recent years, high-speed cameras and Wire Mesh sensors are used for the flow diagnostics tools in multiphase research, and yield detailed quantitative and qualitative information on the flow topology [20–22]. Therefore, this study focuses on the features of the interface topology and the wave dynamics in oil–gas, two-phase stratified-wavy flow at a large pipe diameter by facilitating the Wire Mesh sensors and a hi-speed camera.

2. Experimental setup and data processing techniques

2.1. Experimental Setup

The experiments are conducted at the Tulsa University Fluid Flow Projects (TUFFP) low pressure flow loop (see Fig. 2). This flow loop is able to handle two-phase oil–gas flow. The test section consists of two runs, and each run is built with 0.152 m ID pipes running for 56.4 m in length. The pipe is made of acrylic glass at the section of data acquisition. The inclination angle of the test section is set to be horizontal. The liquid phase is mineral oil (IsoparL™, ρ = 760 kg/m^3, μ = 1.35 cP, τ = 24 dynes/cm), and is pumped from the container tank by using a Blackmer™ progressive cavity pump (PV20B) with maximum pumping capacity of 11.5 GPM for the pressure and temperature conditions prevailing in the experiments. Compressed air is continuously supplied to the flow loop by a diesel powered portable rotary screw compressor, and an electric powered stationary two-stage compressor connected in parallel with a combined capacity of 1030 SCFM at 100 psig. The oil and the air are mixed using a specially designed mixing tee (for details, see Gawas [17]). After the oil and the air flow through the flow loop, the phases are separated by a preliminary separator followed by a vertical final separator. The air is vented out to the atmosphere, and the oil is re-circulated to the storage tank.

During the experiments, the air flow rate is measured using Micro Motion CMF300 Coriolis mass flow meter located before the mixing tee. Oil flow rate and density are monitored using Micro Motion CMF100 mass flow meter. The calibrations of the flow meters are performed by the manufacturer and have a mass flow rate uncertainty of ±0.1% of the measured flow rate. The density measurements have an uncertainty of ±0.5% of the measured value. Table 1 presents the superficial velocities of the gas and the liquid phase for the cases investigated in this study. The uncertainty in the superficial velocities, also given in Table 1, represents the standard deviation of the flow rate measurements at the inlet by the aforementioned flow meters.