Experimental Thermal and Fluid Science 64 (2015) 81–93

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Experimental characterization of vertical gas–liquid pipe flow for annular and liquid loading conditions using dual Wire-Mesh Sensor

Ronald E. Vieira [a,*], Mazdak Parsi [a], Carlos F. Torres [b], Brenton S. McLaury [a], Siamack A. Shirazi [a], Eckhard Schleicher [c], Uwe Hampel [c]

[a] Department of Mechanical Engineering, The University of Tulsa, 800 South Tucker Drive, Tulsa, OK 74104, USA
[b] Thermal Science Department, University of Los Andes, Mérida, Mérida 5101, Venezuela
[c] Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Dresden, Saxony 01328, Germany

ARTICLE INFO

Article history:
Received 19 October 2014
Received in revised form 9 February 2015
Accepted 9 February 2015
Available online 19 February 2015

Keywords:
Wire-Mesh Sensor
Gas–liquid flow
Void fraction
Phase distribution
Flow visualization

ABSTRACT

In gas well production, liquid is produced in two forms, droplets entrained in the gas core and liquid film flowing on the tubing wall. For most of the gas well life cycle, the predominant flow pattern is annular flow. As gas wells mature, the produced gas flow rate reduces decreasing the liquid carrying capability initiating the condition where the liquid film is unstable and flow pattern changes from fully cocurrent annular flow to partially cocurrent annular flow. The measurement and visualization of annular flow and liquid loading characteristics is of great importance from a technical point of view for process control or from a theoretical point of view for the improvement and validation of current modeling approaches. In this experimental investigation, a Wire-Mesh technique based on conductance measurements was applied to enhance the understanding of the air-water flow in vertical pipes. The flow test section consisting of a 76 mm ID pipe, 18 m long was employed to generate annular flow and liquid loading at low pressure conditions. A 16 $\times$ 16 wire configuration sensor is used to determine the void fraction within the cross-section of the pipe. Data sets were collected with a sampling frequency of 10,000 Hz. Physical flow parameters were extracted based on processed raw measured data obtained by the sensors using signal processing. In this work, the principle of Wire-Mesh Sensors and the methodology of flow parameter extraction are described. From the obtained raw data, time series of void fraction, mean local void fraction distribution, characteristic frequencies and structure velocities are determined for different superficial liquid and gas velocities that ranged from 0.005 to 0.1 m/s and from 10 to 40 m/s, respectively. In order to investigate dependence of liquid loading phenomenon on viscosity, three different liquid viscosities were used. Results from the Wire-Mesh Sensors are compared with results obtained from previous experimental work using Quick Closing Valves and existing modeling approaches available in the literature.

1. Introduction

Two-phase flow is encountered in a wide range of engineering applications. For instance, in the petroleum industry, the common problems associated with gas–liquid two-phase flow include calculation of flow rate, pressure loss, and liquid holdup/void fraction in the pipeline. These parameters are essential in design of production tubing, gathering and separation system, sizing of gas lines, heat exchanger design and gas condensate line design [1]. Model underestimation of flow characteristics (e.g., hold up and liquid film velocity) results in inappropriate pipe size selection and possible solids dropout and corrosion issues [2].

Gas and gas condensate lines operate in the annular flow regime. Annular flow is characterized by a fast moving gas core with entrained liquid droplets and a slow-moving liquid film flowing around the pipe wall. The flow is associated with a wavy interfacial structure, which results in a high interfacial shear stress [3]. In annular vertical up-flow, the average liquid film thickness around the pipe wall is considered uniform.

Experimental evidences have shown that the entrained liquid fraction is responsible for a significant part of the pressure drop in annular two-phase flow [4]. In a producing gas and gas condensate well, as reservoir pressure decreases, entrained liquid forms

* Corresponding author.
E-mail addresses: rev87@utulsa.edu (R.E. Vieira), mazdak-parsi@utulsa.edu (M. Parsi), ctorres@ula.ve (C.F. Torres), brenton-mclaury@utulsa.edu (B.S. McLaury), siamack-shirazi@utulsa.edu (S.A. Shirazi), e.schleicher@hzdr.de (E. Schleicher), u.hampel@hzdr.de (U. Hampel).

http://dx.doi.org/10.1016/j.expthermflusci.2015.02.007
0894-1777/

Nomenclature

A	pipe cross-section area (m)
A_C	cross-section gas core area (m)
A_F	cross-section liquid film area (m)
$a(i,j)$	reference area matrix
d	pipe diameter (m)
d_C	hydraulic diameter of the gas core (m)
d_F	hydraulic diameter of the liquid film (m)
f	frequency (Hz)
f_C	core friction factor (–)
f_E	entrainment fraction (–)
f_I	interfacial friction factor (–)
f_L	liquid friction factor (–)
Fr_{SG}	superficial gas Freude number (–)
g	acceleration due to gravity (m/s^2)
i, j	spatial indexes (–)
k	time index (–)
k_T	number of measured frames (–)
L	pipe length (m)
PDF	probability density function
P_r	precision limit of the void fraction result (–)
p	absolute pressure (Pa)
QCV	Quick Closing Valve
Re_C	core Reynolds number (–)
Re_F	liquid film Reynolds number (–)
Re_{SL}	superficial liquid Reynolds number (–)
Re_{SG}	superficial gas Reynolds number (–)
S_I	interfacial perimeter (m)
S_L	wetted perimeter (m)
St_G	gas based Strouhal number (–)
t	measuring time (s)
V_{water}	time avg. signals with the pipe filled with water
V_{air}	time avg. of signals with the pipe filled with air
V_{SL}	superficial liquid velocity (m/s)
V_{SG}	superficial gas velocity (m/s)
v_C	gas core velocity (m/s)
v_F	liquid film velocity (m/s)
$V(i,j,k)$	output matrix of the WMS
$V^*(i,j,k)$	liquid volume fraction
We_{SG}	superficial gas Weber number (–)
X	Lockhart–Martinelli number (–)

Greek Symbols

α_T	total void fraction (–)
α_C	core void fraction (–)
$\bar{\alpha}_G(i,j)$	local time averaged void fraction (–)
$\langle\alpha_g(k)\rangle$	instantaneous cross-sectionally averaged void fraction (–)
$\langle\bar{\alpha}_g\rangle$	cross-sectionally averaged time series or mean void fraction (–)
ρ_L	liquid density (kg/m^3)
δ_L	liquid film thickness (m)
ρ_G	gas core density (kg/m^3)
ρ_L	liquid density (kg/m^3)
τ_I	interfacial shear stress (Pa/m)
τ_{WL}	wall shear stress (Pa/m)
μ_G	gas viscosity (cP)
μ_L	liquid viscosity (cP)
$\sigma_\alpha(i,j)$	standard deviation of the local time average void fraction value (–)
σ_α	standard deviation of the cross-sectionally averaged time void fraction data (–)
θ	inclination angle (radians)

an increasing restriction on gas production. At the end of the lifetime of gas wells, the gas production rate decreases strongly. Due to this decrease, the drag force of the gas phase exerted on the liquid phase may no longer be sufficient to bring all the liquid to the surface. Liquid starts to drain downward (flow reversal). In such a situation, depending on the gas reservoir conditions, the liquid could accumulate down hole, block the inflow into the production tubing and gas production could cease. This phenomenon is called liquid loading. As reported by Belfroid et al. [5] virtually all of the world's gas wells are either at risk of or suffering from liquid loading and that the modeling of liquid loading behavior is still quite immature.

Interaction between gas and liquid phases in two-phase flow provokes complex, highly deformable interfaces and configurations usually difficult to describe. The simultaneous flow of gas and liquid in a pipe for instance can produce a large number of spatial configurations of the phases due to the deformable interface between them. These spatial configurations can become periodic over time leading to chains of interrelated flow structures. The chain of these interrelated flow structures is usually referred to as phase distribution in flow assurance [4]. Examples of these periodic structures are waves in churn flow and disturbance waves in annular flow. The disturbance waves have unique characteristic velocities and frequencies which can be used to classify them into flow patterns [6]. Thus, information about this periodic structure is valuable to reconstruct the overall pressure drop in any multiphase flow system.

This study presents new, time resolved quantitative information on gas–liquid vertical flows at medium and high superficial gas velocities. Wire-Mesh Sensor (WMS) technology was used to measure local time varying void fractions. In order to identify the effect of liquid viscosity on void fraction values and periodic flow structures in pipe flows, data has been acquired for three different liquid viscosities (1, 10 and 40 cP). This work, therefore, contributes to the on-going discussions on the liquid loading problem in natural gas production and transportation by providing novel experimental information to better understand the behavior of the periodic structures in annular two-phase flow as well as the mechanisms governing exchange and transfer of momentum between the film and gas core in vertical annular two-phase flow.

2. Characterization of multiphase flows in vertical pipelines for annular and liquid loading conditions

Several experimental studies on annular flow and liquid loading in vertical pipes have been presented. For example, Alamu [7] showed that flow structure becomes more periodic as liquid viscosity increases. On the other hand, structure velocity decreased with increase in liquid viscosity due to lower liquid phase momentum.

Zangana [8] carried out several experimental runs to measure pressure drop, liquid film thickness and wall shear in 127 mm vertical pipe. No completely unidirectional upward flow was observed from the results of directional wall shear stress measurements. The change in the direction of the liquid film was also supported by the measurements of wall shear stress, local film thickness and high speed video images.