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Experimental investigation of the effect of 90° standard elbow on horizontal gas–liquid stratified and annular flow characteristics using dual wire-mesh sensors

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

[a] *Erosion/Corrosion Research Center, The University of Tulsa, 800 South Tucker Drive, Tulsa, OK 74104, United States*
[b] *Thermal Science Department, University of Los Andes, Mérida, Mérida 5101, Venezuela*
[c] *Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Dresden, Saxony 01328, Germany*

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ABSTRACT

Fluid flowing through pipelines often encounters fittings such as elbows. Although it is true that two-phase flow patterns observed in elbows are qualitatively the same as those seen in straight pipes, the presence of a pipe elbow can modify relative positions and local velocities of the two phases as they are subjected to forces in addition to those encountered in a straight pipe. That redistribution can affect pressure drop values, chemical inhibitor concentration and distribution to the top of the pipe, as well as the erosion pattern occurring from solid particles such as sand that is entrained in oil and gas transportation pipelines. In this work, a wire-mesh sensor technique based on conductance measurements of void fraction was applied to investigate two-phase pipe flow through a standard elbow. The horizontal flow test section, consisting of a 76.2 mm ID, 18 m long pipe, was employed to generate stratified-wavy and annular flow conditions. Two 16 × 16 wire-mesh configuration sensors were positioned either 0.9 m upstream or 0.6 m downstream of the bend. The experiments were conducted at superficial liquid velocities equal to 0.03 m/s and 0.2 m/s and superficial gas velocities that ranged from 9 m/s to 34 m/s. The effects of liquid viscosity on the measured parameters are also investigated using two different viscosities of 1 and 10 cP. Stratified–slug transition, stratified wavy and annular flow patterns were observed visually in the clear section placed upstream of the wire-mesh sensors. Analysis of time series void fraction data from the dual wire-mesh sensors allows the determination of mean void fraction, local time average void fraction distribution, liquid phase distribution around the tube periphery, interfacial structure velocities, as well as probability density function characteristic signatures within the cross-section of pipe before and after the elbow. The results indicate that the distribution of gas and liquid phases and interfacial velocities are significantly altered even 20 diameters downstream of the elbow.

1. Introduction

Pipe fittings such as valves, bends, elbows and tees significantly affect multiphase flow distribution including generation of secondary flows, fluctuations in void fractions and pressure losses and velocities of gas and liquid phases. Elbows are often used in oil and gas production systems, and they cause redistribution of gas and liquid which can affect distribution of corrosion inhibitors within and downstream of the bends. Elbows are also a location susceptible to the impact of particles along the outer radius. The requirements for optimal design and evaluation of Computational Fluid Dynamics (CFD) codes and two-phase flow models such as VOF (volume of fluid) that are being developed to predict details of multiphase flows force the need for quantitative information about flow through and downstream of elbows.

Previous research available in literature concerning gas–liquid flows through elbows, only dealt with an accurate calculation of pressure drop [1,2]. However, in applications such as erosion-corrosion of pipe bends, more detailed information of multiphase flow such as velocities of liquid and gas phases and interfaces are typically required. Computational Fluid Dynamics (CFD) codes are successfully used to predict pipe erosion and even corrosion through elbows and piping systems involving a single-phase car-

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* Corresponding author.
E-mail addresses: rev87@utulsa.edu (R.E. Vieira), nrk301@utulsa.edu (N.R. Kesana), brenton-mclaury@utulsa.edu (B.S. McLaury), siamack-shirazi@utulsa.edu (S.A. Shirazi), ctorres@ula.ve (C.F. Torres), e.schleicher@hzdr.de (E. Schleicher), u.hampel@hzdr.de (U. Hampel).

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Nomenclature

A	cross-sectional area of the pipe (m^2)
B_r	systematic uncertainty or bias limit
C_{xy}, C_{xx}, C_{yy}	covariance functions between $x(t)$ and $y(t)$
c	coverage factor
D	pipe diameter (m)
$E[\,]$	expected value of []
L	pipe length (m)
N	number of samples, (−)
n	time level (−)
ID	internal diameter
P_r	precision limit
R_{xy}	cross-correlation function
StdDev	standard deviation
t	time (s)
α_g	void fraction (−)
σ_{xy}	averaged product
ρ_{xy}	correlation coefficient function
τ	temporal lag obtained from cross-correlation (s)
μ_L	liquid viscosity
μ_x	mean value of the random process $x(t)$
μ_y	mean values of the random process $y(t)$

rier fluid. Erosion is a gradual removal of the material from the pipe wall due to the repeated impacts of solid particles entrained in the production fluids. Previous investigations have proved that erosion is more prominent in pipe elbows than straight pipes [3,4]. Also, it is known that the mechanism of erosion in multiphase flows depends on the flow pattern [5,6] and distribution of gas and liquid phases.

Similarly, flowing fluids can significantly affect corrosion rates in a number of ways including accelerated mass transfer of reactants and corrosion products [7], distribution of corrosion inhibitors, fluid shear or impingement of solid particles in the fluid which disrupt protective layers [8]. Also, if CO_2 is present in the transported fluids, steel pipelines can be corroded as this process is probably enhanced by slug flow turbulence [9]. The ability to model and predict pipeline degradation processes allows service intervals to be better timed so as to reduce unnecessary checks while not being subject to costly downtime due to equipment failure. Also, modeling ability can be applied at the design stage to reduce the susceptibility of parts to wear.

The problem of determining the flow characteristics in the downstream section of an elbow also is important in design and hydrodynamic analysis of the fluid transportation systems. When flow enters the curved portion, the heavier density phase is subjected to a large centrifugal force, which causes the liquid to move away from the center of curvature. This redistribution can significantly affect erosion/corrosion processes. In order to predict complex erosion and corrosion patterns within pipe bends, predictions of gas and liquid velocities are becoming a growing target for many investigators dealing with erosion and corrosion issues. This along with relative success of CFD codes to predict details of multiphase flow, including gas and liquid velocities have motivated investigators to conduct local measurements in multiphase flow. Thus, these investigation efforts were concentrated to obtain experimental data that are required for evaluation of CFD models as they are being used to calculate details of multiphase flows. Reliable CFD calculations can help investigators to predict erosion and corrosion in multiphase flow through bends and other geometries as data and more information become available.

In this experimental study, a dual wire-mesh sensor (WMS) technique based on conductance measurements has been utilized to gather data and investigate details of two-phase flows in a pipe before and after a 90° horizontal-to-horizontal elbow. The wire-mesh sensor allows detailed measurement of the two-phase flow due to its outstanding spatial and temporal resolution. From the measurements, specific parameters of interest such as cross-section time-averaged void fraction, local time-averaged void fraction distribution, gas–liquid interfacial characteristics, probability density functions and periodic structure of interface velocities have been extracted that can be used by investigators to evaluate and improve capabilities of CFD codes to predict details of multiphase flows.

2. Background on characterization of multiphase flows in elbows

In horizontal pipes carrying gas–liquid two-phase flows, gravity introduces asymmetry to the flow regimes generated. The density difference between the phases causes the liquid to travel preferentially along the bottom of the tube. In stratified flow, the liquid travels along the bottom of the pipe while the gas passes over it. At low velocities, the interface between the gas and liquid is smooth. At higher gas velocities, the shearing action of the gas at the interface generates small two-dimensional waves (stratified-wavy flow). In stratified gas–liquid horizontal pipe flow, growing long wavelength waves may reach the top of the pipe and form slug flow or evolve into roll-waves [10]. This flow pattern subregion is called in this work stratified–slug transition and is characterized by the presence of liquid disturbances which have the appearance of slugs. These disturbances can touch the top of the tube momentarily, but do not block the entire pipe section [10]. At higher gas rates, the liquid slug is pierced by a gas core and the flow becomes essentially annular. At extremely high gas flow rate horizontal annular flows, the liquid film variation from top to bottom can be small, but at low gas flows the film is significantly thicker at the bottom of the pipe.

Investigations into the conditions of flow regimes experienced in the pipe sections upstream and downstream of bends have been restricted to single-phase flow, and only a few authors have published results for two phase gas–liquid flows. For instance, Gardner and Neller [11] carried out visual and experimental studies for bubble/slug flow using a pipe of 76 mm diameter in a vertical 90° elbow with radii of curvature of 305 and 610 mm. A traversing probe was used to measure local time average of gas (air) concentration. Various features of the flow were described and used to interpret the balance between centrifugal and gravitational forces. Usui et al. [12,13] measured the averaged void fraction over the bend using quick closing valves. Das et al. [14] and Bandyopadhyay et al. [15] reported an experimental investigation for gas-non-Newtonian liquid flow through 12.7 mm bends. They developed an empirical correlation for predicting the frictional pressure drop across the piping components. Ribeiro et al. [16] measured drop sizes upstream and downstream of a 90°, 32 mm internal diameter bend in a horizontal plane. Their results show that the downstream drop sizes are 50–75% of those upstream caused by thicker films resulting from the initial deposition and gathering of the film induced by the secondary flow in the gas phase. They concluded that the ratio of downstream/upstream entrained fraction decreases with increasing upstream entrainment fraction. The fractions of drops of different sizes which deposit on the bend have been studied by James et al. [17]. Azzi et al. [18] concluded that in a two-phase flow, there are additional effects of dissipation due to separation and remixing of the gas and liquid phases, and