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EXPERIMENTAL CHARACTERIZATION OF HORIZONTAL PIPE SLUG FLOW OF AIR/SHEAR-THINNING FLUID

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Abstract. Experiments on slug flow were carried out with compressed air and solutions of carboxymethylcellulose (CMC) in a 44.2 mm diameter horizontal pipe. Bubble velocities and frequencies of passage were obtained through a high-speed digital camera; pressure drop was measured with a differential pressure transducer; Particle Image Velocimetry (PIV) was used to measure mean velocity profiles and turbulence statistics in the liquid film, liquid slug and along bubbles nose and tail. The flow behavior was found to be heavily influenced by the rheological properties of the continuous phase. In particular, aeration, slug frequency and pressure drop were largely increased with the CMC concentration increase.

Keywords: slug flow, shear-thinning, non-Newtonian, particle image velocimetry.

1. INTRODUCTION

Two-phase flows of gas and non-Newtonian liquids commonly occur in different industrial applications. Since the early seventies some works have focused on the investigation of pressure drops, drag reduction and flow pattern map characterization (Srivastavat and Narasimhamurty, 1973; Chhabra and Richardson, 1984; Picchi et al. 2015). However, literature dedicated to the study of the gas-non-Newtonian flow dynamics is very scarce. Sousa et al. (2007) investigates the interaction between Taylor bubbles rising in stagnant aqueous CMC and polyacrylamide (PAA) solutions, with the aid of Particle Image Velocimetry (PIV). These authors noticed marked differences on the bubble wake behavior as a function of viscoelasticity and shear viscosity.

The objective of the present work is to conduct an experimental characterization of a horizontal pipe slug flow of air/shear-thinning fluids. In addition to pressure drop and flow rate measurements, the two-phase flow properties were measured through a Shadow Sizer System; mean velocities and turbulent statistics of the liquid phase were obtained through a PIV system. The rheological characterization of the aqueous carboxymethylcellulose (CMC) were performed with the aid of a Haake Mars III rheometer.

The present experimental campaign investigated three CMC solutions and provided detailed results for the liquid velocity distributions along the film and the liquid piston. Histograms for slug frequency, bubble velocities and lengths are also furnished. This dataset allows a complete characterization of the behavior of non-Newtonian gas-liquid slug flows, which was found to be heavily dependent on the rheological properties of the continuous phase. Relevant changes were observed on the level of aeration of the liquid piston; slug frequency and pressure drop were largely increased as the CMC concentration was raised.

This database is an important tool for the development of modified slug flow models for the prediction of pressure drop and general properties of the two-phase non-Newtonian flow, as well as for validation of numerical simulations of such pipe flow problems.

2. EXPERIMENTAL PROCEDURE

For the present experiments, air and three types of aqueous solutions were tested, with CMC concentrations of 0.05, 0.1 and 0.2 (%w/w). The resulting rheological behavior of the mixtures was close to that of a power-law fluid. The properties of the fluids are shown in Tab. 1.

An overview of the horizontal multiphase flow loop is shown in Figure 1. The system is set up with a 12m long acrylic pipe with 44.2mm internal diameter. The liquid phase is transported at constant flow rate using a progressive cavity pump, minimizing the occurrence of high shear rates that would otherwise contribute to fluid degradation. The

gas was injected into the system through a T-junction at the pipe inlet. The liquid and gas flow rates were controlled through an electromagnetic and vortex flowmeters, respectively.

Table 1. Rheological properties of the liquids.

| | Concentration (% w/w) | K (Pa s ⁿ) | n (-) |
|------|--------------------------|------------------------|-------|
| CMC1 | 0.05 | 0.0263 | 0.715 |
| CMC2 | 0.1 | 0.0827 | 0.642 |
| CMC3 | 0.2 | 0.1567 | 0.619 |

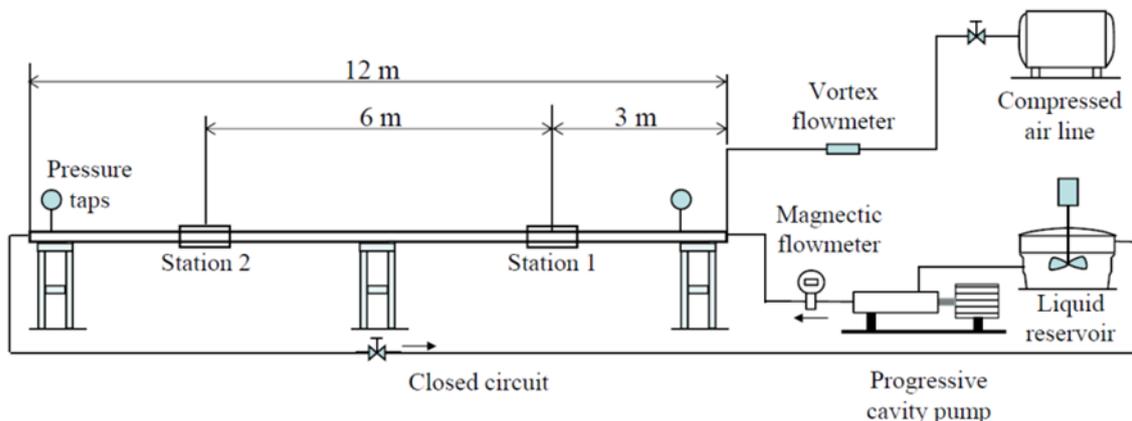


Figure 1. Diagram of the experimental apparatus and positions of measuring stations

This system provides homogeneous fluid mixtures from dispersed CMC powder in deionized water. For the present work, the test section was located 9 m away from the entrance. This section was enclosed by a square acrylic box; the space between the flat walls and the pipe was filled with deionized water to minimize optical distortions.

Bubble characteristics, including length, translational velocity and frequency, were measured with the aid of a Shadow Sizer System. A PIV system was used to measure the flow characteristics. Bubble frequency and all other flow characteristics were obtained directly from the Dynamic Studio software, through image processing and contour detection algorithms. Data presented refers to measures realized in Station 2.

3. RESULTS AND DISCUSSION

An overview of air-0.2% CMC solution is shown in Fig. 2 for different gas and liquid superficial velocities. Viscosity plays an important role on the shape of the bubble nose and the instabilities shown in the bubble contour. A comparison between Fig.2 and the air-water flow (not shown here) shows a reduction in surface distortions even for the highest liquid and gas superficial velocities.

Figure 3 shows the single-phase liquid velocity profiles for 3 different concentrations of CMC solution, with liquid flow rates of 4 and 7 m³/h. As shown, CMC concentration presents an important influence on the behavior of the velocity distributions. Special attention may be given to the 0.2% CMC solution, where a region of constant velocity appears on the pipe center due to shear-thinning effect, and consequent viscosity variation. This solution also shows the smallest velocity gradient.

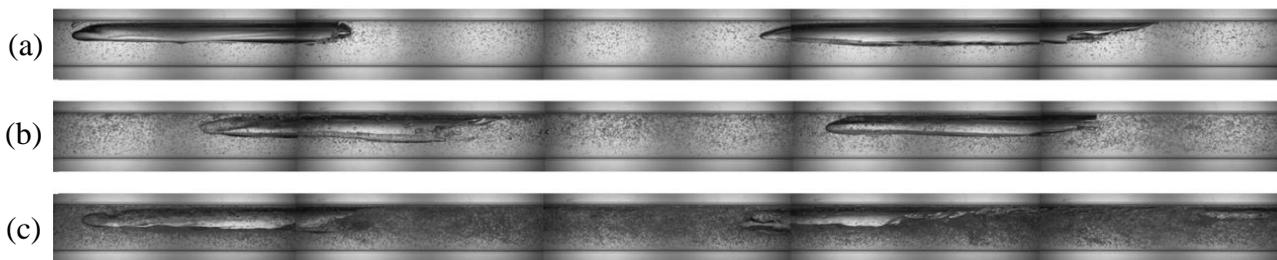


Figure 2. Air-0.2% CMC solution slug flow patterns for:
 (a) $V_{SL} = 0.72$ m/s and $V_{SG} = 0.27$ m/s, (b) $V_{SL} = 1.27$ m/s and $V_{SG} = 0.22$ m/s,
 (c) $V_{SL} = 1.81$ m/s and $V_{SG} = 0.65$ m/s.

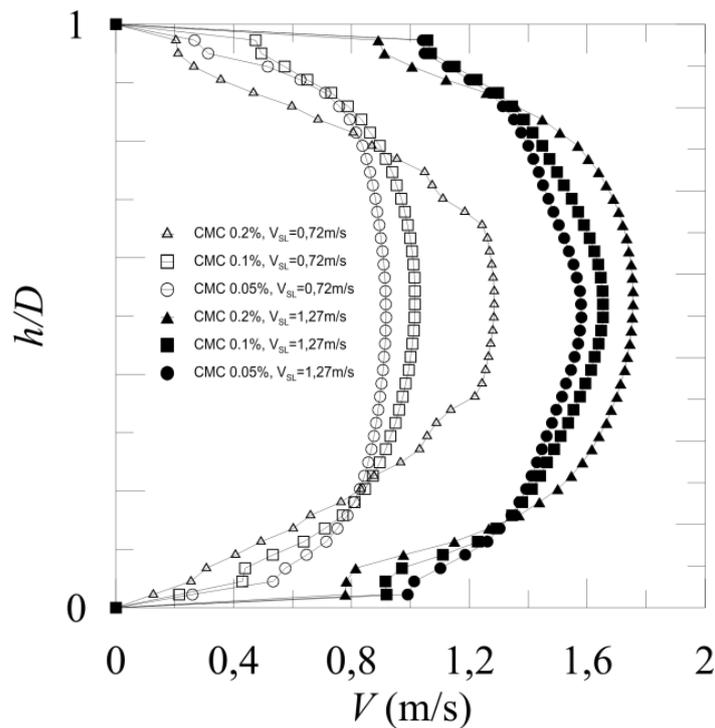


Figure 3. Liquid velocity profiles for 3 different concentrations of CMC solution and for $V_{SL} = 0.72$ m/s and $V_{SL} = 1.27$ m/s.

Figure 4 shows the velocity profiles measured in the liquid piston and in the liquid film region. As can be seen, slugs play the most important role of mass transport, since the velocity in liquid film is considerably reduced. Besides, all three liquid films presenting approximately the same velocity, it is observed an important difference in film height. PIV mean vector fields for a CMC 0.2% solution are presented in Figure 5 showing all regions of interest: liquid slug, bubble nose, liquid film and bubble tail.

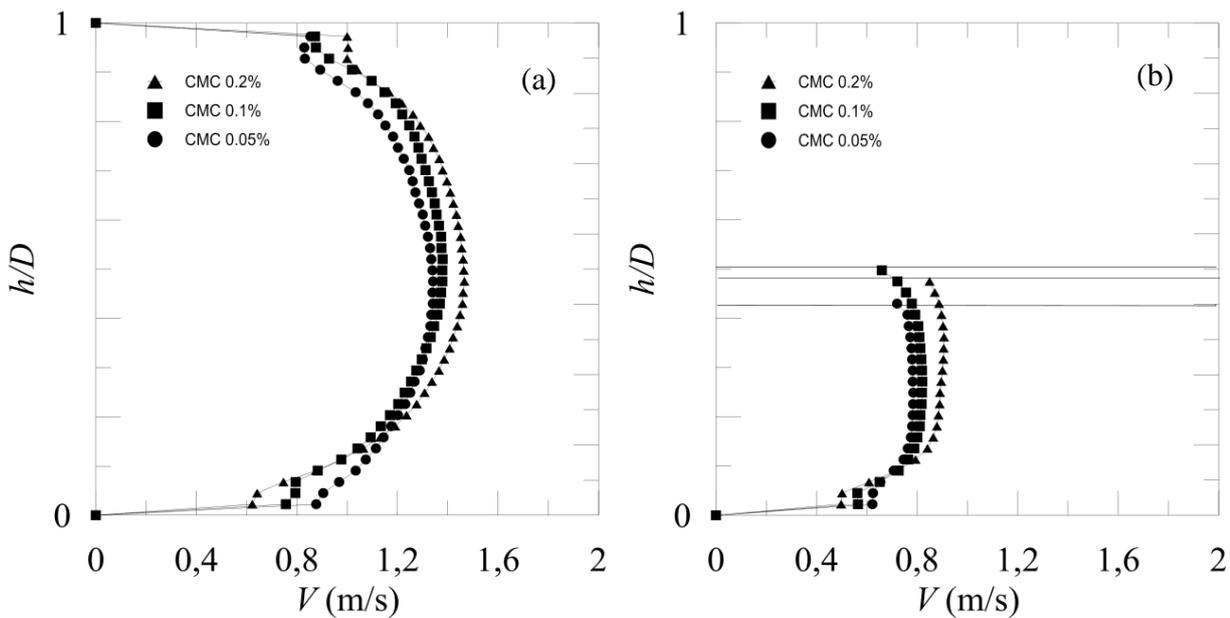


Figure 4. Velocity profiles for 3 different concentrations of CMC solution: $V_{SG} = 0.72$ m/s and $V_{SL} = 0.72$ m/s, (a) liquid piston and (b) liquid film.

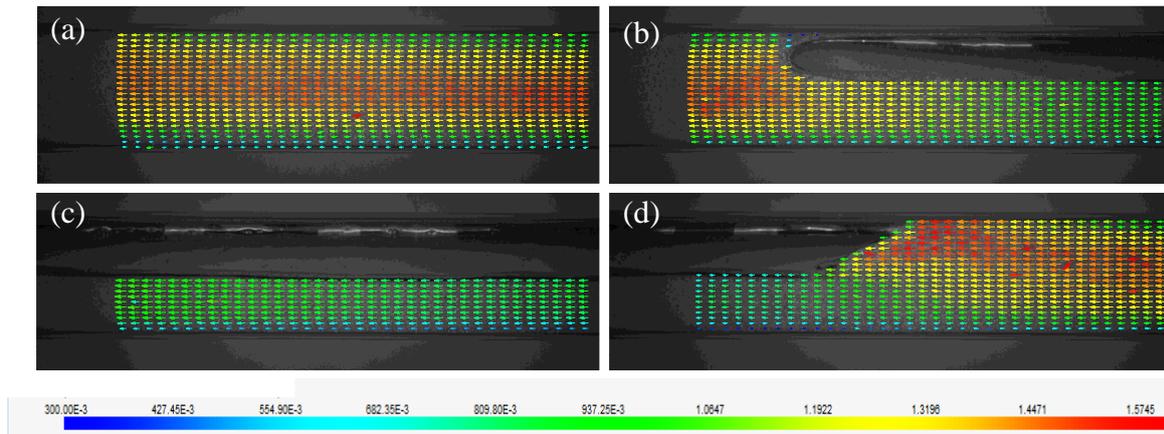


Figure 5. Mean vector field for air/CMC 0.2% solution:
 (a) liquid piston; (b) bubble nose; (c) liquid film; (d) bubble tail.

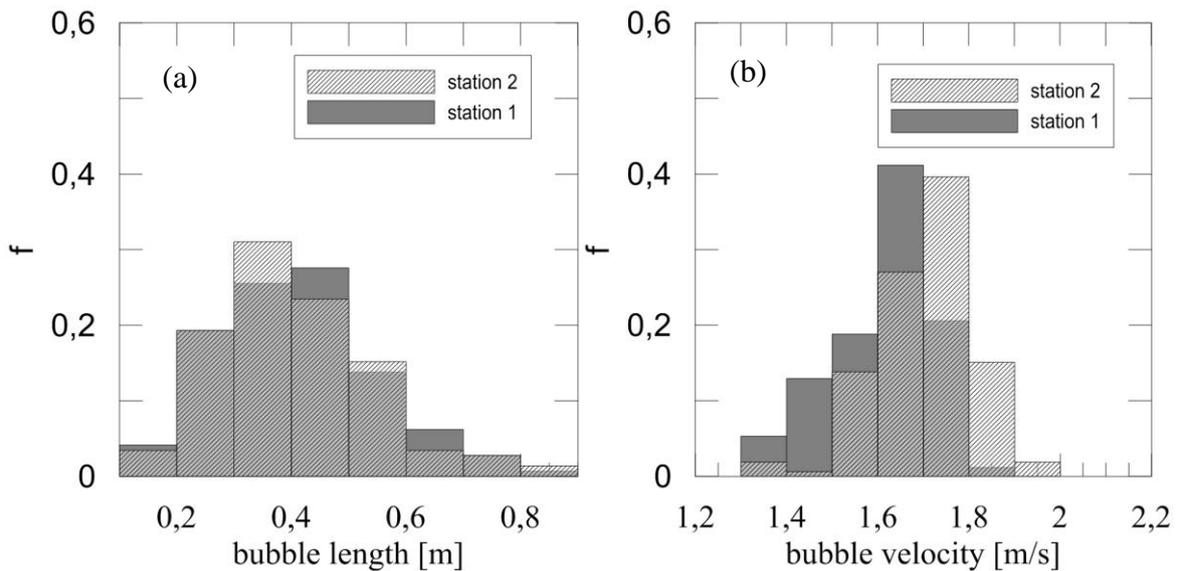


Figure 6. Histograms of bubble length and velocity for CMC 0.2% solution,
 $V_{SL} = 0.72\text{m/s}$, $V_{SG} = 0.27\text{m/s}$.

Figure 6 shows the bubble length and velocity distribution in two different pipe positions, located 6 m from each other, as shown in Figure 1. A slight increase in bubble velocity is observed. It was noticed that smaller bubbles travel slightly slower than the rest, tending to be subsumed along the flow

4. CONCLUSIONS

Experimental results for the liquid velocity distributions and histograms of bubble velocities and lengths have been presented for gas/shear-thinning horizontal slug flows. Three CMC solutions have been investigated. The frequencies of passage of bubbles and pressure drop data are shown in the full manuscript. The flow behavior was found to be heavily influenced by the rheological properties of the continuous phase. In particular, aeration, slug frequency and pressure drop were largely increased with the CMC concentration increase.

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