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Experimental investigation of high viscosity oil–air intermittent flow

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ABSTRACT

In this work, we investigated experimentally the flow of high viscosity-oil (0.9 Pa s) and gas in a horizontal and inclined pipe providing new data-sets on high-viscosity oil multiphase pipe flows that include experimental pressure drops, bubble frequencies and lengths, holdups measured using capacitance probes. All the experimental results are compared to models or correlations present in the literature and widely used, and validated, for low-viscosity liquids multiphase flows. The main conclusion is that correlation available in literature (validated and extensively tested for the low viscosity liquid case) cannot be extended to the high viscosity case.

1. Introduction

Intermittent regime is characterized by a series of liquid plugs (slugs) separated by relatively large gas pockets; the presence of aeration in the liquid phase can lead to a further classification into slug and plug flow. The resulting flow alternates between high-liquid and high-gas composition regions and it is one of the most complex gas–liquid flow regimes since in axial direction the liquid is not distributed uniformly, leading to intrinsically unsteady conditions. When the flow is horizontal, or slightly inclined, liquid slugs fill the entire section and they are separated by stratified regions where an elongated gas bubble is located on the upper part of the pipe, while the lower part is occupied by a liquid film. Intermittent flow occurs over a wide range of liquid and gas flow rates and it is relevant to several industrial processes: oil and gas extraction and transportation, geothermal production of vapor, and emergency cooling in nuclear reactors are just few examples.

Due to their practical relevance, intermittent flows have been carefully investigated both experimentally and theoretically with special attention being paid to air–water systems, see Fabe and Liné [6]. More recently, quite some interest has arisen for high viscosity liquid multiphase flows – see Grassi et al. [9], Poesio et al. [23] and Wang et al. [29]. Very few works concerning high viscosity systems are present in literature, limiting the possibility of a systematic evaluation of old correlations and preventing the development of new ones.

Spisak and Idzik [25] were the first to investigate gas hold-up in slug flows for highly viscous liquids (viscosity from 1.3 Pa s to 4.8 Pa s). Their computational results are compared to experimental data obtained from an air-mineral oil mixture in a 25 mm inner diameter glass tube. Furukawa and Fukano [8] investigated the effects of the liquid viscosity on flow pattern using water and aqueous glycerol solutions with viscosities up to 0.015 Pa s; McNeil and Stuart [19] studied the annular flow of air and water–glycerine mixtures (viscosity up to 0.055 Pa s). The measured pressure gradients are compared with two different theoretical models, but in neither cases the agreement is satisfactory. Schmidt et al. [24] performed tests in a vertical pipe with mixtures of a gas and a liquid with viscosity up to 7 Pa s. As a result of their work, they proposed new correlations to unify the observations for low and high viscosity systems, but even in this case, the agreement between theoretical and experimental results is rather poor.

The literature available on highly viscous oil is even more limited. Colmenares et al. [3] performed experiments to study of the liquid viscosity effect on pressure drop in slug regime using oils with viscosity up to 0.48 Pa s. They found that the slug flow existence region was enlarged with increasing oil viscosity and that slug frequency and film thickness increased with increasing viscosity. Gokcal [11] performed tests with a single refined oil at four different operating temperatures, thereby changing the oil viscosity (from 0.181 to 0.587 Pa s). A recent study by Matsubara and Naito [17] focused on the effect of liquid viscosity on flow patterns of gas/liquid horizontal flow of water (or an aqueous solution of polysaccharide thickener) and air; liquid viscosity ranges from 0.001 Pa s to 11 Pa s. Most of these researches have shown that an increase of liquid viscosity has a significant impact on the

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phenomena involved and that the models developed for low-viscosity multiphase flow are not always able to predict the behavior of high viscosity liquid systems.

In this paper we present a new experimental campaign on two-phase intermittent flow with a high viscous oil. The experimental pressure drops are compared with the predictions of the Lockhart–Martinelli model, modified by Chisolm [1], and with the model developed by Orell [22]. The velocity, the frequency, and the length of elongated bubbles are measured by post-processing of capacitance signals. Slug frequency is compared with correlations by Gregory and Scott [13], Zabaras [31], Hernandez-Perez et al. [15] and Gokcal et al. [10]. Another important parameter is the average liquid holdup in the slug unit, *i.e.* the volume occupied by the liquid phase. In this work, we measured the average liquid holdup in the slug unit using the capacitance probes and we compared the values with several models, see Woldesemayat and Ghajar [30].

2. Experimental setup

All the experiments are performed in the gas–liquid flow pipe schematically represented in Fig. 1. A 9 m glass pipe (22.8 mm i.d.) mounted on a rigid frame, which can be inclined from $-10°$ (downward) to +15° (upward). A differential pressure transducer (GE Druck STX 2100), with high accuracy and sensitivity on a large range, is placed 6 m downstream the injection point and the pressure drop is measured across a 1.5 m length and the resulting accuracy is $\pm 0.1\%$ of the measured value. Capacitive sensors, to characterize the dynamics of the slug flow and to measure the gas–liquid hold-up, are placed 7 m downstream the injection device. Those probes have been developed in house and described in earlier publications, see Demori et al. [5], Strazza et al. [26], and tested for viscous oil–air flow in Foletti et al. [7]. Highly viscous oil (viscosity $\mu_o = 0.896$ Pa s, density $\rho_o = 886\ \mathrm{kg/m^3}$) and compressed air ($\mu_a = 1.77 \cdot 10^{-5}$ Pa s, density $\rho_a = 1.225\ \mathrm{kg/m^3}$) supplied directly from the University network, are used as test fluids. The superficial tension is $\sigma = 30\ \mathrm{mN/m}$. The oil is initially stored in a 1 $\mathrm{m^3}$ tank and before entering the test loop, its flow-rate is measured by a screw-spindle flow-meter, especially designed for high-viscosity liquids. The air mass flow rate is measured before entering the test section by a thermal mass flow meter and, at the same spot, air pressure is monitored. The oil–gas mixture is discharged into a receiver tank where the air is subsequently vented to the atmosphere and the oil is pumped back to the storage tank. Oil and air superficial velocities are in the ranges $u_{os} = 0.05–0.3$ m/s and $u_{as} = 0.2–1.3$ m/s, respectively. Oil and air flow rate have been measured with a 5% accuracy of their reading value. Bubble velocity is measured by processing the capacitance probe signal with Matlab. The capacitance probes (placed at distance $l_p = 200$ mm) have been built to collect two output signals, which can be cross correlated to obtain the velocity of the bubbles (u_b). It is possible to get the time interval between the signals (Δt) and, consequently, the velocity of the gaseous phase as $u_b = l_p/\Delta t$ (the accuracy of this method was estimated of being in the order of 2% with a Montecarlo like method). From the analysis of the capacitance probe signal it is possible, also, to obtain the length of the bubbles, of the slug and of the slug unit. We calculate the time needed for the bubble to transit (t_b). The length of the bubble (l_b) is calculated multiplying u_b, obtained as mentioned above, and t_b. The slug frequency was measured counting the number of slug detected by the capacitance probe over a reference time [5% accuracy].

The capacitance probe, described in Demori et al. [5] and in Strazza et al. [26], was recalibrated for the very viscous oil–air flow. The calibration curve was obtained by combining the results of simulations with COMSOL and of a series of static tests with stratified fluid (since the dynamics of the instrument and acquisition frequency is much higher than the slugs frequency, the static calibration with stratified oil is a good estimator). The static calibration is performed by placing a known quantity of oil in the pipe with sensors (closed with valves) and measuring the output value of the instrument. In Fig. 2 we can see both the data points

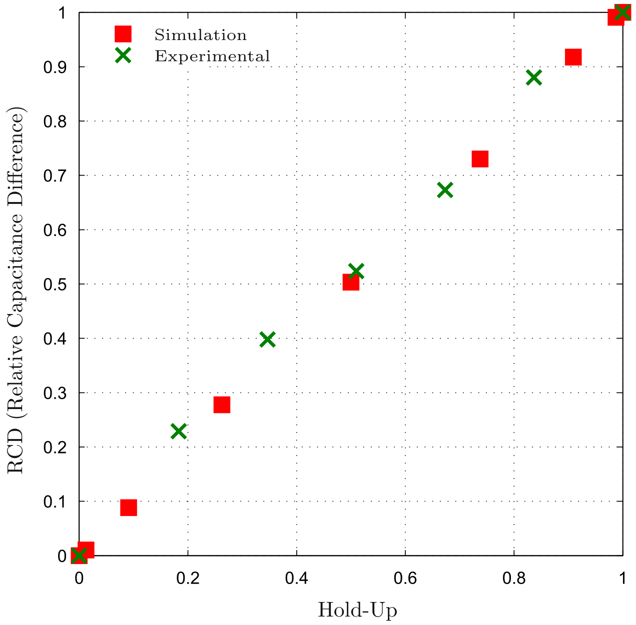

Fig. 2. Comparison between the numerical ad experimental calibration curve.

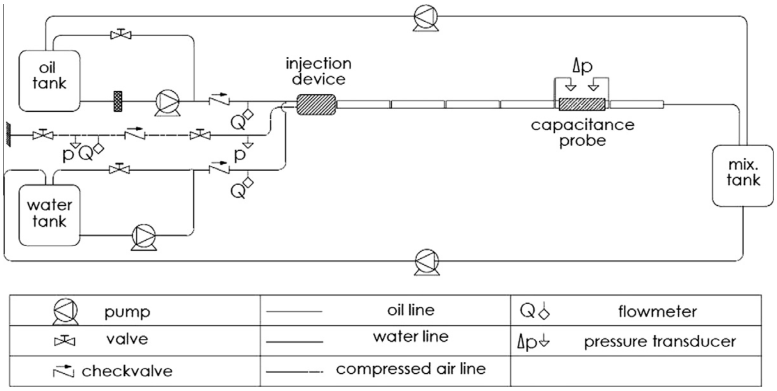

Fig. 1. Schematic of the experimental test facility.