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Experiments with a Wire-Mesh Sensor for stratified and dispersed oil-brine pipe flow

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ABSTRACT

Two-phase oil–water flow was studied in a 15 m long horizontal steel pipe, with 8.28 cm internal diameter, using mineral oil (having 830 kg/m^3 density and 7.5 mPa s viscosity) and brine (1073 kg/m^3 density and of 0.8 mPa s viscosity). Measurements of the holdup and of the cross-sectional phase fraction distribution were obtained for stratified flow and for highly dispersed oil–water flows, applying a capacitive Wire-Mesh Sensor specially designed for that purpose. The applicability of this measurement technique, which uses a circuit for capacitive measurements that is adapted to conductive measurements, where one of the fluids is water with high salinity (mimicking sea water), was assessed. Values for the phase fraction values were derived from the raw data obtained by the Wire-Mesh Sensor using several mixture permittivity models. Two gamma-ray densitometers allowed the accurate measurement of the holdups, which was used to validate the data acquired with the capacitive Wire-Mesh Sensor. The measured time-averaged distribution of the phase fraction over the cross-sectional area was used to investigate the details of the observed two-phase flow patterns, including the interface shape and water height. The experiments were conducted in the multiphase-flow test facility of Shell Global International B.V. in the Netherlands.

Introduction

The flow of oil–water mixtures in directional wells and in pipelines and risers is common in oil production. Oil fields (reservoirs) frequently contain large volumes of water, which are produced together with the oil. For conventional oil and gas wells, this water production increases over field life. In order to improve the oil recovery from a reservoir additional water is often injected into the reservoirs to promote oil displacement (so called Enhanced Oil Recovery). In the oil sands industry a large amount of heated water is used to separate heavy oil from the sand. The influence of the water phase on the pressure gradient is of particular importance for the operation of the oil field. For example, water can be introduced into the well or pipeline in order to reduce the pressure drop in oil production or transportation (so called core-annular flow method).

The interest in oil–water flow started in the middle of the last century (Charles et al., 1961; Russell et al., 1959), who studied the pressure gradient for viscous oil transport in the petroleum industry when introducing water in the pipelines. Several researchers have studied the flow behavior of oil–water dispersions in laminar and turbulent flow (Cengel et al., 1962; Charles et al., 1961; Faruqui and Knudsen, 1962; Pal, 1993; Ward and Knudsen, 1967). Oil–water stratified flow has also been extensively studied since it is the flow pattern that occurs most often in a multiphase pipeline that is (nearly) horizontal. In addition to the oil–water pressure drop, several authors have also investigated phenomena like phase inversion and drag reduction in dispersed flow (Angeli and Hewitt, 1998; Arirachakaran et al., 1989; Ioannou et al., 2005; Lovick and Angeli, 2004; Lum et al., 2006; Nädler and Mewes, 1997; Rodriguez et al., 2012).

The holdup (in-situ volume fraction) is also of main interest for the design and operation of pipeline systems and facilities. There are many experimental techniques for measuring the holdup. However, the existing literature covers mainly the application of these techniques to gas–liquid flows. In liquid–liquid flows the phase distribution has been obtained by intrusive electrical methods based on the differences in conductivity or permittivity between the phases. Angeli and Hewitt (2000b) and Lovick and

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Angeli (2004) used a high-frequency needle probe to obtain the phase distribution of oil and water over the pipe cross section. Although images of the oil-fraction distribution were generated, they showed only time-averaged data. Huang et al. (2007b), proposed a capacitance probe to measure the water holdup based on the water layer thickness in kerosene-water flow in horizontal pipes. Zhao et al. (2006), applied a dual-sensor conductivity probe to obtain local oil volume-fraction distributions as well as velocity distributions in oil-in-water flows. Images of the flow were generated, though with only limited spatial resolution. Non-intrusive electrical methods are also popular. Zhao et al. (2006) and Li et al. (2005) have applied Electrical Resistance Tomography (ERT) to characterize oil–water flow. Electrical Capacitance Tomography (ECT) has been employed to investigate stratified kerosene-water flow. However, again only images with low spatial resolution were obtained (Hasan and Azzopardi, 2007).

Techniques based on gamma-ray and X-ray are also attractive for multiphase flow applications, due to their non-intrusive nature and reliability. So far these techniques (particularly gamma-ray) have been regularly used to investigate gas–liquid flows, but they were rarely applied for liquid–liquid flows. Where the gamma-ray technique has been applied to measure local phase fractions in oil–water flow systems, it shows good spatial resolution, but poor temporal resolution (Elseth, 2001; Kumara et al., 2009, 2010; Rodriguez and Oliemans, 2006). Oddie et al. (2003) measured the water holdup in two and three-phase flows while comparing three different methods: quick-closing valves, electrical with the conductive probe and nuclear densitometry. The comparison shows that the electrical method is the most popular one, due to its safety, good accuracy, and low costs.

The Wire-Mesh Sensor (WMS) is an intrusive electrical method based on capacitive or conductive measurements. So far various studies with a Wire-Mesh Sensor have been carried out in two-phase gas–liquid flows (Hampel et al., 2009; Hernandez Perez et al., 2010; Huang et al., 2007a,b; Pietruske and Prasser, 2007; Prasser et al., 2007, 1998; Silva et al., 2007, 2010; Thiele et al., 2009). Only few results with this technique exist for liquid–liquid flow (Rodriguez et al., 2011, 2012; Silva et al., 2007; Velasco Peña et al., 2013) and for three-phase flow (Silva, 2008b; Silva and Hampel, 2009). In some studies comparisons are made between the WMS and other techniques such as gamma-ray or X-ray (Beyer et al., 2010; Bieberle et al., 2009, 2010; Manera et al., 2009; Matusiak et al., 2010), Electrical Capacitance Tomography (ECT) (Azzopardi et al., 2010; Matusiak et al., 2010; Szalinski et al., 2010), or the needle probes (Manera et al., 2009). The results indicate that the Wire-Mesh Sensor is also a promising measurement technique for oil–water flow.

Recently, de Salve et al. (2012) employed a WMS to characterize the air–water interface in a horizontal pipe flow, studying stratified, slug/plug and annular flow patterns, at ambient conditions. The authors compared the void fraction measured by quick-closing valves (QCVs) with the one obtained by the WMS. They found that the void fraction with WMS shows a higher dispersion in the range of intermittent flow whereas it has a good accuracy when the flow becomes annular. Abdulkadir et al. (2011), applied a WMS in the study of air-silicone oil flow around a 90° bend showing the transition between flow patterns before and after the bend. Strubelj et al. (2010), measured the vapor volume-fraction profile during the transition from stratified flow to slug flow for condensation-induced water hammer experiments. The authors obtained a good agreement between the CFD simulations and the experimental data. Yusoff (2012), studied the transition from dispersed flow to stratified flow in oil–water flow after a sudden expansion. Our literature review shows that most of the studies with wire-mesh sensing are for gas–liquid flow or for low viscosity oil and water flow.

In the present work an experimental study on dispersed and stratified oil–water flow has been carried out in a horizontal pipe. The fluids used were oil with moderate viscosity and water with high salinity (mimicking sea water). A capacitive Wire-Mesh Sensor was specially designed and constructed to measure the holdup and phase-fraction distribution. Simultaneous accurate readings by two gamma-ray densitometers were used for the validation of the WMS holdup data.

In what follows, the Section Experiment describes the experimental set-up, the equipment and instrumentation, the measurement procedures and the test matrix. The Section Results summarizes the experimental measurements for the dispersed and stratified horizontal flow, including the mixture density, holdup and phase distribution. Results for the oil–water interface height in stratified flow are also presented. The Section Conclusions summarizes the main findings.

Experiment

Experimental set-up

The experiments were performed at the multiphase-flow test facility of Shell Global International B.V. in The Netherlands. The test facility (named the "DONAU Loop") is suited to measure a wide range of oil–water–gas flow conditions at pressures up to about 12 bars. The facility is shown in Fig. 1. The current experiments are for two-phase flow using Shell Vitrea 10 oil (887 kg/m^3 density and 7.5 mPa s viscosity) and water (brine, with 1075 kg/m^3 density and 0.8 mPa s viscosity) as test fluids. These fluids flow through a 15 m long stainless steel pipe with 82.8 mm internal diameter. A 1.15 m long transparent Perspex section is used for the flow visualization. Both water and oil are received in the same separator, which is at atmospheric pressure. The separator contains several 45°-oriented coalescence plates to accelerate the separation of the two liquid phases. Because of the difference in density, the two liquids become separated, with the oil in the upper part of the separator and water in the lower part. Each phase is displaced from the separator to the test line through its own series of pumps and pipes (Rheinhutte, RN 50/315B centrifugal pump), using and inline density meters (Schlumberger, Solartron 7835B) and flow meters (Micro Motion, Coriolis elite mass flow meters CMF 50/100/200, with ±0.1% accuracy). The mixing section is a 2 m long pipe section to which the oil and water lines are connected through independent valves (Fig. 1a). At the test section (Fig. 1b), gauge pressure meters, differential pressure transducers (Rosemount 3051C, with an accuracy of 207 Pa) and temperature meters (Metatemp Pt 100) were part of the reference measurement instrumentation. The pressure drop was measured by the differential pressure transducers with pressure taps located 6.1 m apart. A high-speed video recording camera (Olympus *i*-3) was used for the flow-pattern identification and gamma-ray densitometry (two density meters Berthold LB 444) was used for the accurate measurement of the in-situ volumetric phase fraction (holdup). At the outlet of the test section, pipes are transporting the mixture back to the separator.

Three independent computers were used to conduct the experiments and to collect the measurement data. Two of them were located in the control room and one was next to the test section. A controller based on LabView® allowed for imposing the desired inlet water and oil flow rates, the selection of the appropriate pumps and flow meters and collecting the flow data. The second computer controlled the two gamma densitometers. The third computer, with a controller also based on LabView®, was used to calibrate the Wire-Mesh Sensor and for data acquisition by means of a National Instruments PCI-6224 board. See Rodriguez and Oliemans (2006) for more details on the DONAU flow loop.