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Measurement of an oil–water flow using magnetic resonance imaging

Susithra Lakshmanan [a,b], Wessenu A. Maru [b], Daniel J. Holland [c,*], Mick D. Mantle [a], Andy J. Sederman [a]

[a] Department of Chemical Engineering & Biotechnology, University of Cambridge, UK
[b] Oil &Gas Measurement Limited, OGH, Ely, Cambridgeshire, UK
[c] Department of Chemical and Process Engineering, University of Canterbury, Christchurch, New Zealand

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ABSTRACT

In the oil and gas industry, the current standard that is used to quantify the fraction of water (so called "water-cut") in an oil–water multiphase flow stipulates the oil–water mixture to be homogenised to ensure sampling is representative. Although there are devices that comply with the minimum requirements of the sindustry standards for custody transfer applications, our understanding of the homogenisation process is limited; where even small errors arising due to inhomogeneity could cost tens of millions of dollars annually per metering station. To that end, we have developed a flow loop and homogenisation process to study oil–water multiphase flow. Experimental investigations were carried out using magnetic resonance (MR) imaging and hence the entire flow loop has been designed to fit within a MR laboratory, with the homogenisation step itself performed within the bore of the magnet. Measurements were performed in a 2.5″ diameter Perspex pipe at stream velocities between 0.2 ms^{-1} and 1.47 ms^{-1}, to mimic typical pipeline conditions. The size of the pipe diameter used in this study is unique compared to previous studies for oil–water flow applications using MR. To facilitate experimental investigation, we have developed MR techniques to quantify the water-cut and improve our understanding of mixing in liquid–liquid flows. Chemical shift selective (CHESS) MR was used to quantify the water-cut between 2.5% and 25% for static samples. These results show a linear relationship and demonstrate that the water cut is measured with an accuracy of $\pm$0.2%. The CHESS sequence was combined with MR imaging sequences to enable visualisation of the water distribution in real time in one-dimension, or as a time-averaged measurement in two dimensions. MR measurements were also performed on an oil–water multiphase flow at a stream velocity of 0.2 ms^{-1} and for water cuts between 1% and 7.5%. Local measurements of the water cut are performed with an error of less than 1%.

1. Introduction

In most oil fields, production pipeline flows could contain up to 10% (v/v) water and it is therefore crucial to get accurate measurement of the quantity of water during custody transfer from up-stream producers to mid-stream operators. Accurate measurement requires the extraction of samples of the fluid from a section of the pipe where the flow composition is homogeneously distributed. Such homogeneity is usually achieved through efficient mixing. However, creating a homogeneously distributed oil–water mixture without causing emulsification is a challenge. Although turbulence due to fast moving fluid streams enhances mixing and also may promote the suspension of the water droplets, the difference in density between oil and water can still lead to stratification and hence poor mixing of the flow at typical pipeline flow conditions [1]. Even in macroscopically well-mixed systems, there may be significant variations in local composition of the mixture due to the interaction of the water or oil droplets as they travel downstream of the pipe. Inhomogeneity due to such poor mixing will introduce errors and could cost both industry and government millions of dollars a day in operational costs, as well as lost tax and revenue. In order to produce the required homogeneously distributed flow, various types of mixing systems are used by the oil and gas industry. Static mixers are common but they are only able to provide homogenisation over a relatively narrow range of operating conditions. Furthermore, the pressure drop across the mixers is large and undesirable. An alternative arrangement is to inject a flow of fluid perpendicular to the primary direction of flow. Jet mixers such as these are able to produce a homogeneous distribution over a wide range of operating conditions, however, the effect of a cross flow of fluid on the mixing is

* Corresponding author.
E-mail address: daniel.holland@canterbury.ac.nz (D.J. Holland).

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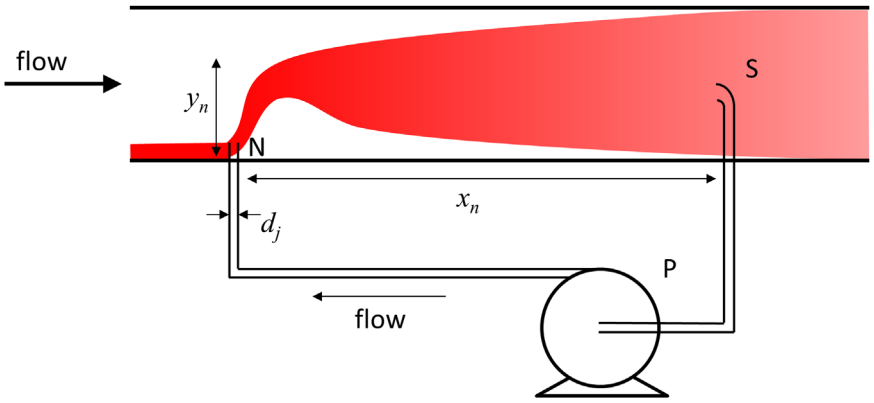

Fig. 1. Schematic diagram of the liquid jet in cross flow arrangement. Homogenisation of the mixture is achieved by withdrawing fluid from the main flow through the "scoop" (S) using a pump (P). The withdrawn fluid is re-injected into the flow using a nozzle (N) located upstream of the scoop. The resulting liquid jet mixes inhomogeneously distributed oil–water to produce a homogeneous two-phase mixture.

not well understood – particularly for the case of liquid–liquid flows. It is therefore crucial to get a better understanding of the homogenisation process in order to measure the flow rate and phase distribution more accurately and efficiently.

Oil–water homogenisers for custody transfer applications typically use jet mixing via a liquid jet in cross flow (LJICF), often using multiple jets [2]. A LJICF is illustrated schematically in Fig. 1. However, LJICF are also used in many other applications. For example, in scramjets, liquid fuels are injected into a high speed gas stream, where the complex turbulence and vortex structures produce an efficient method of mixture preparation of the fuel spray [3–6]. Smokestacks, volcanic plumes, atmospheric dispersion and oil spills are also common examples of applications that use LJICF [6]. Most studies of LJICF focus on gaining an understanding of the jet trajectory. However, the subsequent break-up of the jet in to droplets and their dispersion in the cross flow remain complex while the case of multiple jets adds further challenges [5,6].

The trajectory of a single jet describes the extent to which the jet penetrates into the crossflow, and the complex vortex structure that gives rise to the mixing. There are various ways of defining and scaling this trajectory, mainly depending on the maxima of the local velocity, scalar mixing, or vorticity [6–8]. Many studies have focused on single jets, however multiple jets ensure better mixing and decrease power requirements [2,9]. While previous investigations on LJICF have concentrated on gas-liquid systems; relatively little effort has been applied to study liquid–liquid flows,

Techniques that have been used to study oil–water flows include visual observation, impedance probes, conductivity probes, particle imaging velocimetry (PIV), γ-ray CT, x-ray CT, wire mesh sensors and hot-wire anemometers [10–13]. Invasive techniques, such as hot wire anemometry, can give information about local velocities and void fractions. However the probe used will interfere with the flow [13]. Fernando and Lenn [2] used laser Doppler anemometry (LDA) to study the flow fields produced by single- and multi-nozzle mixers in single-phase pipe flow. In liquid–liquid systems, Galinat et al. [14] used high-speed trajectography to study the drop break-up probability in an oil–water system. Drop size distribution measurements were obtained using a video recording technique by Angeli and Hewitt [1]. The flow structure of oil–water flow in horizontal and slightly inclined pipes was studied by particle imaging velocimetry [15]. However, quantitative measurements with these optical techniques are difficult in two phase flows as the flow is often opaque. Cross sectional phase distribution was measured using a traversable gamma densitometer [2]. Electrical capacitance tomography (ECT) and electrical resistance tomography (ERT) are suitable for opaque systems with high temporal resolution, but they are restricted to low spatial resolution [13]. X-ray and γ-ray techniques are fast and accurate but require the use of ionising radiation and do not measure the velocity of the fluid.

Magnetic resonance (MR) imaging is also proving to be a useful tool for characterising single- and two-phase flow in pipes [16–18]. MR has several advantages over the above techniques; it is completely non-invasive, can image optically opaque systems and can measure parameters including concentration, velocity, and diffusion. It is also possible to resolve each of these parameters spatially in one-, two- or three-dimensions. However, there are some limitations of MR including a restricted sample geometry which is imposed by the need for a strong and homogeneous magnetic field, an inability to image magnetic materials and difficulties associated with very heterogeneous materials [16]. MR techniques to study two phase flow include fast imaging techniques such as FLASH [19], RARE [20], SPRITE [21] and spiral EPI [22]. These techniques can be combined with velocity encoding to resolve the flow field [23]. However, these techniques can be difficult to apply to the LJICF arrangement. SPRITE is the most robust of these techniques but it is too slow to study LJICF, with typical imaging times >1 s. FLASH is fast and robust, but has an inherently low signal-to-noise ratio. RARE and spiral EPI are promising but EPI is sensitive to the variations in the magnetic field that arise when fluids of differing magnetic susceptibility travel down the pipe and RARE is sensitive to image artefacts due to flow at these velocities. Furthermore, when imaging liquid–liquid flow, it is important to resolve the signal from each phase independently. In this situation, chemical shift imaging [24] and chemical shift selective imaging (CHESS) [25] are often used. The acquisition time of images obtained from all of these techniques can be reduced using advanced signal processing techniques like compressed sensing [26]. Such an approach has previously been used to acquire two-dimensional images of two phase flow in as little as 10 ms [27]. However, that approach is complicated to implement and requires very fast switching of the gradients in the magnetic field that are used to resolve the distribution of species in the coil and encode for the flow and so is not applicable to the present study.

In this paper, we develop MR techniques that can be used to characterise the mixing of a multiphase flow. The multiphase flow loop itself has been designed such that it can be used in a MR laboratory, and have the homogenisation section located within the bore of the magnet. The nozzle used to inject fluid and produce a homogeneous flow is replaceable and can produce either single or multiple jets, depending on the specific nozzle design used. The flow loop developed used a 2.5″ pipe and so was of a relatively large scale for laboratory investigations, especially those using MR

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