Measurement of an oil-water flow using magnetic resonance imaging

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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 industry 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 m s^{-1} and 1.47 m s^{-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 m s^{-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%.

Keywords oil-water; flow; magnetic resonance; water cut measurement; phase distribution; multiphase

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 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 Figure 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 into droplets and their dispersion in the cross flow remain complex while the case of multiple jets adds further challenges [5,6].

Figure 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.

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 (1990) 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. (2005) 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 (2000). 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 ionizing 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 [28–30]. An introduction to the relevant theory of MR is presented here and the MR techniques developed are used to explore the homogenisation of a low velocity oil-water mixture, characteristic of an oil well nearing the end of its useable life. Preliminary results are presented for the techniques developed. The paper concludes with some directions for future developments.

2 Theory

MR is a phenomena that arises when nuclei with non-zero spin quantum number is placed in a strong magnetic field. These nuclei will establish a small magnetisation. If this magnetisation is then excited using a radiofrequency pulse, the magnetisation will rotate and hence induce a current in the radiofrequency coil. This current is measured and can be used to determine the amount of material present, how fast it is moving, where it is, and more. All such nuclei within a sample contribute to the detected signal. For a detailed explanation the interested reader is referred to one of the many text books on the subject [31–34]; here a simple model of the MR experiment is used to understand some important phenomena occurring during flow imaging experiments.

After excitation and neglecting NMR relaxation effects, the equation describing the MR signal S as a function of time may be written as:

$$S(t) = \sum_k \iiint_V \rho_k(\mathbf{r}) \exp\left(-i\gamma \int_0^t \mathbf{G}(\tau) \cdot \mathbf{r}(\tau) d\tau\right) \exp(-i\omega_k t) d\mathbf{r} \quad (1)$$

Where ρ_k is the molar amount of species k at position $\mathbf{r} = \{x, y, z\}$, γ is the gyromagnetic ratio of the nuclei investigated, $\mathbf{G}$ is the strength of the magnetic field gradient as a function of time, and ω_k is the resonant frequency of species k . Note, it is not generally possible to acquire all time points, but rather measurements will be taken from times t_i to t_f , which are likely to be on the order of 1-3 ms, depending on the experiment. Furthermore, the number of spins in the system is discrete which implies that Equation (1) should strictly be defined on a discrete basis. However, even in the smallest volumes considered the number of spins is very large, $O(10^{20})$, hence the continuous approximation is reasonable.

The first point that is important to note is that the signal is influenced by the resonant frequency for each species. The resonant frequencies of oil and water differ. At a magnetic field strength of 2 T, as used in this study, a typical difference is approximately 4.5 ppm, or 400 Hz and these two components can be readily distinguished. The difference in resonant frequency is almost independent of the salt content of the water. MR is increasingly being performed using permanent magnets where the magnetic field strength is weaker and the frequency difference between oil and water becomes negligible. This frequency difference of the oil and water means that measurements performed in a strong magnetic field on such a two phase mixture will have an additional modulation of the signal owing to the contribution from the final term in Equation 1. This additional modulation of the signal can be removed by acquiring the measurements in such a way that every pixel in the image contains a complete spectrum of the different resonant frequencies in the system. Such an approach requires the

experiment to be repeated many times and is known as Chemical Shift Imaging (CSI) [24]. This approach is too slow for use on a rapidly changing system such as an oil-water flow. An alternative method is to selectively excite only the species of interest in the measurement, in this case the water. This approach is known as chemical shift selective imaging (CHESS) [25]. CHESS imaging is fast but can be sensitive to errors arising from inhomogeneity in the magnetic field. It also requires long radiofrequency pulses and so can become sensitive to flow related effects.

Secondly, although it is not obvious from Equation 1, it can be shown that the detected signal can be made sensitive to the position of the nuclei, their velocity, acceleration, etc, depending on the choice of the gradient function and the measurement times [16]. For example, a simple one-dimensional (1D) imaging measurement might consist of turning on a gradient such that the magnetic field varies linearly with position along the x-direction. After a short period of time (~ 0.5 ms) the direction of this gradient is reversed and then a series data points are acquired over a time period of ~ 1 ms. This is referred to as frequency encoding [32]. The 1D image (i.e. $\rho(x)$) is obtained from the Fourier transform of the measured data. Velocity encoding follows a similar approach but there is normally a delay inserted between the two gradients and data are acquired after the second gradient is turned off again. The important point to take away from this discussion is that both frequency encoding and velocity encoding are similar and thus every data point may be influenced by both effects. MR experiments are typically designed in such a way that only one effect is dominant but in fast moving systems such as the oil-water flow considered here, this is not always possible.

Finally, one effect not considered in Equation 1 is that of signal relaxation. During MR experiments the signal will decay following two main mechanisms known as T_1 relaxation and T_2 relaxation [32]. T_1 relaxation describes the time required to establish an equilibrium magnetisation, whilst T_2 relaxation describes how long the signal will last following excitation. During flow, T_1 is perhaps the more important relaxation mechanism and so we will not consider T_2 relaxation further here. The MR signal is obtained when nuclei are excited after being placed in a strong magnetic field. The detected signal is proportional to the magnetisation. The nuclei are not excited immediately after being placed in the magnetic field, instead some time is required in order for the nuclei to establish the magnetisation. The time taken to establish equilibrium is described by:

$$\frac{dM_z}{dt} = -\frac{M_0 - M_z}{T_1} \quad (2)$$

where M_z represents the magnetisation parallel to the applied magnetic field and M_0 represents the magnetisation parallel to the magnetic field at equilibrium. The equilibrium magnetisation is

proportional to the strength of the magnetic field. This equation has two important implications. Firstly, during flow, fluid will initially be outside the magnetic field and hence $M_z = 0$. The fluid will then enter the magnetic field and need to be present within the magnetic field for a length of time that is dictated by the relaxation time, T_1 . The signal is proportional to the magnetisation and therefore the residence time of the fluid within the magnetic field can influence the strength of the detected signal. Simplistically, if a fluid is present in the magnetic field for approximately $3T_1$, the magnetisation will be within 5% of the equilibrium magnetisation and variations in the residence time will have little effect. The length of a typical MR magnetic field will be ~ 300 mm. Thus, if fluid is travelling at 1 m s^{-1} the residence time in the magnet will be ~ 0.3 s suggesting that T_1 should be < 0.1 s for accurate measurements. Secondly, if one species has a longer relaxation time than the other species, it is possible to reduce the contribution of the slower relaxing species. The system is initially excited at a time $t = 0$, this effectively sets $M_z = 0$. Then, there is a short delay to allow the magnetisation to re-establish. The system is then excited a second time and the signal is detected. If the species of interest relaxes more quickly than other species present, the relative amount of signal associated with the species of interest can be significantly increased.

In this study, we combine the ideas of saturation of the unwanted species and selective excitation using CHESS. This approach enables us to selectively set the oil signal to zero and then selectively excite the water signal. Therefore ensuring that our measurement is sensitive to the water present in the system but not the oil.

3 Experimental

3.1 Flow loop construction and Operation

An oil-water multiphase flow loop was constructed in which the homogenisation device could be studied. The flow loop will be used to study the mixing behaviour of the homogenisation process, initially using a prototype homogeniser for liquid sampling in custody transfer as well other industrial applications. The entire loop is designed to be compatible with MR instruments, as such all piping is manufactured from Durapipe HTA® C-PVC pipework, with the exception of the section where the flow straightener is positioned and water is injected in to the main oil flow. The layout of the flow loop and associated MR instrumentation is shown in Figure 2. The majority of the piping for the flow loop is constructed out of 2" diameter, schedule 40 clear PVC tubing (inner diameter 52 mm). The section of piping that runs through the bore of the magnet is constructed from 2.5" diameter, schedule 40 clear PVC tubing (inner diameter 62 mm). The flow loop is approximately 6 m in length and 3.5 m in width. The 3.5 m width is required to enable the pumps, tanks and coalescer to be positioned

outside the 50 G line for the stray field of the magnet. The oil-water multiphase flow loop consists of the following modules:

Coalescer and Holding Tanks Module: This module takes the two phase oil-water mixture, separates it in a coalescer unit and stores the pure oil and water phases in separate tanks to be fed back to the flow conditioning module. The oil and water leaving the coalescer contains 50 ppm or less of the water and oil phases, respectively. The pure water and oil are stored in their respective tanks. The volume of water used is 200 litres, while the oil is 600 litres. The water is de-ionised with specific gravity of 1.0. Four paraffinic oils were tested, Rustlick EDM-250, VG 5, kerosene, and SAE 30. Rustlick EDM-250 was used for flow experiments as its properties resemble condensate hydrocarbons and light crudes, with a density of 810 kg m^{-3} and viscosity of 2.7 cSt at 40°C. During the flow experiments, the temperature of the oil and water is maintained at 40°C using heating coils in the respective storage tanks. For a given set temperature, the temperature is controlled to within $\pm 2^\circ\text{C}$ throughout the flow loop with this system.

Flow Conditioning and Water Injection Module: The single phase oil flow comes through the main 2" pipe, then passes through a reducing union to a 2.5" flexible tubing before it joins a 2.5" stainless steel (SST) pipe that contains a Zanker plate flow straightener designed according to ISO 5167 to ensure that the flow velocities are uniform and any swirling flow due to bends or the reducing union is eliminated. Water is injected 10 pipe diameters (10D) downstream of the Zanker plate in the same direction as the oil flow but at an angle of 23° from the bottom of the pipe. The water injection is designed to achieve the required stream velocities at the inlet of the straight pipe section with minimal disruption to the flow. The water is injected to achieve a water cut between 0.5% and 5%.

Dynamically Equilibrating Flow (Straight Pipe) Module: This section is one of the key modules where the flow is expected to achieve a fully developed multiphase flow to mimic pipeline conditions. The length of the straight line pipe was restricted to 25D by the geometry of the MR laboratory in which the experiments are to be performed. This length is short compared to what is recommended in the literature [35]. A base line test to quantify the limitations associated with the length of pipe will be carried out on the homogeniser. This will involve measuring the natural mixing without the nozzle assemblage as well as with the nozzle assemblage but without the action of LJICF. In addition, MR imaging, visual observation and high speed video imaging will be used to characterise the flow regime and compare it with published data.

Semi-Automatic Control and Data Capture Module: The loop is operated using a control panel that is driven by a programmable logic controller (PLC) and the data capture is managed using an in-house developed human-machine interface (HMI). Data from temperature transmitters, pressure transmitters, level transmitters and flow meters are captured. Except for the temperature transmitters

that have a data capture rate of 0.5 Hz all other data is captured at 5 Hz. All pumps, heaters and other equipment are operated with alarms and trips according to a standard operating procedure.

Figure 2. a) Sketch of the layout of the oil-water multiphase flow loop as it will fit within the MR laboratory. b) photograph of the assembled multiphase flow loop in the MR laboratory. The scoop for the homogenisation section is indicated in white; the MR magnet is indicated in red; the oil and water storage and separation vessels are located along the wall on the right hand side of the image.

Homogeniser Module: This module consists of a prototype homogeniser device to examine the suitability of a LJICF configuration. The module consists of the nozzle assemblage, the scoop assemblage, a pump, pressure, temperature, and flow transmitters and an oil-water mixture sampling point. During testing, a portion of the oil-water mixture is withdrawn via a scoop, designed according to ISO 3171 and API 8.2. The scoop is located a few diameters downstream of the nozzle position and is used to withdraw fluid from the flow. The nozzle is used to re-inject the withdrawn fluid into the main pipe flow to create mixing. The nozzle design and scoop location can be altered to study the effect of different arrangements on the efficiency of mixing. MR measurements were conducted between the nozzle and the scoop and used to examine the **mixing** as a function of position downstream of the nozzle, nozzle design and operating conditions. At the sample point, a volume of about 10 mL of the oil-water mixture withdrawn by the scoop is poured into a graduated cylinder every other minute to produce a volume of ~100 ml. These samples were measured for total liquid height and water height using a TOMARCH PN 31761 digital height gauge with measurement

accuracy of 0.0127 mm. The water cut was calculated by dividing the water volume by the total volume of liquid. Measurements by three operators were taken and checked for repeatability.

3.2 Magnetic Resonance

MR experiments were carried out on a Bruker Biospec (horizontal bore of diameter 300 mm) AV spectrometer operating at a ^1H frequency of 85.23 MHz. The spectrometer was equipped with a three-axis shielded gradient set capable of producing a maximum gradient strength of 10 G cm^{-1} in each direction. An 88 mm diameter radiofrequency coil was used to excite and detect the signal from the fluid. The pipe was located in the centre of the radiofrequency coil, which was in the centre of the magnetic field.

A CHESS imaging sequence was adapted to selectively image the water signal [25]. In the CHESS method, the radiofrequency pulses are designed to selectively excite the signal from the water whilst suppressing the signal from the oil phase. The pulse sequence for the CHESS excitation used in this work is shown in Figure 3. A $3000\text{ }\mu\text{s}$ Gaussian pulse was used to saturate the signal from the oil. The duration and shape of this pulse is such that a Gaussian distribution of frequencies with a full width at half maximum of approximately 500 Hz (equivalent to 6 ppm at this field strength) is excited. This first pulse saturates the oil and partially saturates the water signals. Immediately following excitation of the oil peak, crusher gradients are applied for 5 ms in all three directions at a strength of 4 G cm^{-1} to eliminate the signal from (i.e. fully dephase) any magnetisation arising from the oil excitation. A $7000\text{ }\mu\text{s}$ Gaussian pulse was then used to excite the signal from the water. This pulse will excite a frequency window approximately 200 Hz (equivalent to 2.5 ppm at this field strength) across that is centred slightly **downfield** of the water peak such that any excitation of the oil peak is negligible. Therefore, this pulse will selectively excite the signal from the water and hence the oil will not be detected. A third, $512\text{ }\mu\text{s}$ Gaussian pulse was used in conjunction with a gradient in the magnetic field to ensure that signal is only detected from a slice of fluid 2 mm thick. As will be shown, this experiment provides a quantitative measurement of the amount of water in the excited volume. The magnetic susceptibility of oil and water are different and this difference can result in inhomogeneity in the magnetic field. Inhomogeneity in the magnetic field can affect quantification of the water signal. To minimise the inhomogeneity 1.5 mM gadolinium chloride was added to the water. At this concentration, gadolinium does not influence the apparent surface tension of the water phase [22]. The addition of gadolinium also has the effect of reducing the T_1 relaxation time of the water to approximately 60 ms, which reduces the time required between measurements and enables quantitative observation of fluid at higher velocity. Furthermore, the short relaxation time of the

water will enhance the ability of the CHESS sequence to selectively detect the water signal, in preference to the oil which has a longer relaxation time (600 ms).

The CHESS method was also combined with one- and two-dimensional imaging sequences [32] to resolve the distribution of water spatially. In these experiments, the distribution of water was imaged with a field of view of 196 mm ($\times$ 196 mm) and a spatial resolution of 3 mm ($\times$ 3 mm). Both one-dimensional and two-dimensional images were obtained. The one-dimensional ‘profile’ measurements took approximately 1 ms to acquire and were repeated every 83 ms; the two dimensional measurements were acquired with 16 averages over a period of about 3 minutes. Static oil-water mixtures were prepared with fractions of water (water cut) of 2.5%, 5%, 10% and 25% measured using each of these pulse sequences. Flowing experiments were performed for water cuts of up to 7.5%.

Figure 3: Pulse sequence diagram for the CHESS sequence used for selective imaging of the water in oil-water mixtures. Shaded boxes indicate homospoil gradients; radiofrequency pulses are labelled according to the tip angle and species affected by the pulse. Imaging gradients are not shown, but when these were used they were placed on either side of the third, slice selective radiofrequency excitation.

4 Results and Discussion

4.1 Flow Loop Commissioning

The flow loop was initially commissioned and then used to study the mixing of a standard homogenisation nozzle design. During commissioning it was confirmed that the coalescer was able to achieve single phase oil and water flows that each contained less than 50 ppm of the other phase, provided the pressure at the inlet of the coalescer was maintained above 2 bar gauge.

Figure 4 shows a summary of the accuracy of the water cut for these experiments. These measurements were obtained by sampling the oil-water mixture that was withdrawn through the scoop, as illustrated in Figure 1. The oil-water samples were allowed to settle for two days before the water fraction was measured. No permanent emulsification was observed with these samples. The measured fraction of water obtained from the scoop is compared with the known fraction of water based on the measured oil and water flow rates. A relative accuracy was established and the results are shown in Figure 4. Except for three data points, the mixing achieved falls within the ISO 3171 requirement. The results demonstrate a complex behaviour with regard to the degree of mixing that can be achieved. Both the ISO 3171 and API 8.2 standards stipulate that for a horizontal pipe with stream velocity in excess of 1.2 m s^{-1} natural mixing may be achieved. The results in Figure 4 indicate that this is not the case. Furthermore, both ISO 3171 and API 8.2 recommend a scoop flow rate of between 1% and 3% of the main flow. Our results indicate that an injection of 5% is often required. This limitation of the standards is well established (Fernando et al, 1990). However, even in the worst case scenario of a stratified flow with low stream velocity ($< 1 \text{ m s}^{-1}$), with an injection of 8% of the flow it is possible to achieve homogeneous mixing. Indeed the results indicate that the extent of mixing is dependent primarily on the injection velocity, and is not very sensitive to the water cut, which was not expected.

Figure 4: Plot of the mixing accuracy of measured water cut as a function of the total flow rate into the twin nozzles grouped by velocity (identified by symbols) and water cut (identified by colour). The symbols indicate water cut (black) ~1%; (red) ~2%; (blue) ~3%; and (green) 3.5% and stream velocities (●) ~0.25 m/s; (▲) 0.35 m/s; (■) ~0.43m/s; (◆) ~0.54m/s; (▼) ~0.77m/s; (+) ~0.81 m/s; (◻) ~1.15 m/s and (×) ~1.47 m/s. The x-axis shows the injected flow rate relative to the main pipe flow. The red dashed lines indicate a level of 10% error in mixing, which is the standard required to meet ISO 3171 and API 8.2. The blue dotted lines indicate a level of 5% mixing, which is twice as good as the standard.

The results obtained using the multiphase flow loop demonstrate the need for a better understanding of the homogenisation process using the LJICF arrangement. In the next sections we develop experimental techniques that will enable us to study the homogenisation process in more detail than has hitherto been possible.

4.2 Quantification of the MR signal

Four commercial oils (Rustlick EDM-250, VG 5, kerosene, and SAE 30) with viscosities between 3 cSt and 100 cSt were tested using MR at room temperature. The spectrum of mixtures of oil and water for all four oils were similar, with the resonance of the oil peak appearing at a chemical shift approximately 400 Hz (equivalent to 4.5 ppm at this field strength) lower than the water peak in all cases. These oils are therefore essentially equivalent from the perspective of MR. Rustlick EDM-250 and VG 5 both have a high flash point and low viscosity making them safe to use at a relatively low temperature ($\sim 40^{\circ}\text{C} \pm 2^{\circ}\text{C}$) as a model for oil-water experiments.

Static oil-water mixtures were prepared with water-cuts between 2.5% and 25%. Figure 5 shows the magnetic resonance spectrum following CHESS excitation of two samples. The water peak is located at 5.5 ppm, whilst the oil peak would be located at 1 ppm. The oil peak is almost completely suppressed, meaning that the amount of water is calculated easily by integrating the signal intensity from the remaining peak.

The integral of the signal between 5 and 6 ppm, which is attributed to the water, is calculated and plotted against the known water cut, as shown in Figure 6. Each experiment was repeated between two and five times at different positions within the same static sample to provide an indication of the reproducibility of the experiments. Error bars, given by the 95% confidence interval, are shown in Figure 6 for both the measured signal intensity and the water cut. The error bars are mostly comparable in length to the size of the symbols in the plot and so are difficult to resolve. A larger error is observed for the water cut of 10% which is attributed to poor homogeneity of the magnetic field for this sample. The total signal intensity associated with each measurement had a standard deviation of about 0.1 (a.u.) for each water cut. The integrated signal intensity shows a linear relationship with the water cut. A linear fit through these data yields a slope of $0.385\%^{-1}$ with an R^2 value of 0.999. These results demonstrate that MR provides quantitative measurements of the water cut. On the basis of the calculated slope, an uncertainty in the signal intensity of 0.1 corresponds to an error in the measured water cut of approximately 0.2%, even for the poorest quality measurements obtained with the 10% water cut the uncertainty of the water cut is less than 1%.

Figure 5. MR spectra obtained from water-oil mixtures at 2.5% and 25% water. Spectra were obtained using the CHESS sequence to suppress signal from the oil peak. The water peak is located at approximately 5.5 ppm; the peak arising from the oil is largely suppressed but would be located at approximately 1 ppm.

Figure 6. Plot of the integrated signal intensity as a function of the water-cut. The solid line is a linear fit to the data passing through zero. The slope of the line is $0.385 \pm 0.005\%^{-1}$.

In order to demonstrate that the MR measurements are also quantitative under flowing conditions, the signal intensity from the spectral acquisitions was plotted for a well-mixed flow of oil and water at water cuts between 1% and 6%, as shown in Figure 7. The plot shows a linear correlation, as was seen with the static measurements shown in Figure 6. A linear fit through these data gives slopes of $(1.9 \pm 0.1) \times 10^7 \%^{-1}$ and $(2.1 \pm 0.1) \times 10^7 \%^{-1}$ for stream

velocities of 0.8 m s^{-1} and 1.2 m s^{-1} , respectively. The fact that this slope is essentially constant for changing stream velocity indicates that the effects of in-flow discussed in Section 2 are insignificant in this case. The inherent noise level in the data is $\sim 1 \times 10^6$, indicating that the water cut can be measured with an accuracy of approximately $\pm 0.2 \%$ using MR.

Figure 7. Signal intensity from MR experiments performed on a well-mixed system operating with a stream velocity of ($\circ$) 0.8 m s^{-1} and ($\times$) 1.2 m s^{-1} and for water cuts of up to 6% based on the measured volumetric flow rate of oil and water. The solid line indicates a linear fit to the data, with the dashed lines indicating the 95% confidence interval for this fit. The error bars for the measured data points indicate two standard deviations in the measured signal intensity.

4.3 MR imaging of oil-water flow

Figure 8 shows 2D MR images of a stratified oil-water flow at water cuts of 2% and 7.5%, based on the flow rate of oil and water in the system. The stream velocity of the two phase mixture for these experiments was 0.25 m s^{-1} , which corresponds to a Reynolds number of approximately 3800. The oil and water are brought together gently approximately $\sim 25D$ or $\sim 1.5 \text{ m}$ up stream of the imaging section, with the water introduced through the base of the pipe. Flow through the nozzle was turned off for these experiments. Thus, the oil and water streams travel parallel to each other and mixing was minimised in these experiments. It is clear from these images that the water remains largely confined to the base of the pipe (high signal intensity there) and little water mixes into the bulk oil flow, as expected. The interface between the water and the oil in Figure 8 is characterised by a gradual change in intensity over up to 3 voxels ($\sim 5 \text{ mm}$) from the maximum intensity (corresponding to pure water) to zero (corresponding to pure oil). This gradual change in signal intensity is due to

some flow instability at the oil-water interface that occurs even at this low velocity. In these time-averaged images, this instability manifests as a gradual change in water content from pure water to pure oil. It is possible to estimate the cross sectional area of the pipe that is filled with water. In this case the proportion of the pipe area occupied by the water at nominal water cuts of 2% and 7.5%, is $11 \pm 3\%$ and $14 \pm 2\%$, respectively. The uncertainty is calculated on the basis of the sharpness of the interface between the oil and water phases. It is clear that for these experiments, the cross sectional area of the pipe occupied by water does not scale with the water cut measured on the basis of the flow rate of oil and water through the system. This highlights the importance of performing the linearity test on the signal intensity using well-mixed system, as was done in Section 4.2.

The two dimensional images shown in Figure 8 were acquired over a period of 3 minutes and as such represent the time averaged distribution of water in the system. It is also useful to explore variations in the water distribution over much shorter time scales. To this end, one dimensional images were acquired to map the water distribution through the pipe every 80 ms.

Figure 8. 2D MR images of the distribution of water through the cross section of the pipe during stratified flow with (a) 2% and (b) 7.5% water, based on the measured volumetric flow rate.

One-dimensional profiles were acquired along the height of the pipe for a stream velocity of 0.25 m s^{-1} and water cuts of between 1% and 7.5 %, as shown in Figure 9. As in Figure 8, there was no flow through the nozzle during these experiments. These images provide a quantitative measurement of the amount of water present at each vertical position, integrated across the width of the pipe. These profiles show a similar result to the images in Figure 8 with the water collecting along the bottom of the pipe. As a guide, the profile that would be expected if the pipe were filled with water is given by the solid line in Figure 9. As the water cut increases, it is clear that the fraction of the pipe filled with water increases, as expected. All four profiles have a similar shape on the left hand side of the figure,

indicating that the pipe is filled with water at the bottom, and giving us confidence that these data are quantitative. The data for a water cut of 1% shows that a small fraction of the cross section is filled with water, and that the time-averaged interface extends over ~ 5 mm. The gradual change in intensity of the signal over this interface is indicative that at a water cut of 1%, the water travels down the pipe in waves, with the height of water changing over time. The experiments with water cuts of 2%, 5% and 7.5% all show very similar profiles and indicate that in all three cases the cross section of the pipe that is filled with water remains approximately the same. The measured flow rate of water tells us that at 7.5%, the pipe should contain almost four times as much water as at 2%. It is clear from Figures 8 and 9 that this is not the case. In fact, the measurements in Figures 8 and 9 suggest that $5 \pm 3\%$, $9 \pm 3\%$, $10 \pm 2\%$ and $13 \pm 2\%$ of the cross sectional area is filled with water for water cuts of 1%, 2%, 5% and 7.5%, respectively. Therefore, continuity requires that the velocity of the water through the pipe must be significantly less than the velocity of oil through the pipe, and that as the water cut increases, the slip velocity between the two phases is reduced. The stream velocity used here is typical of oil fields with end of production expectancy. These results demonstrate the need for homogenisation devices to ensure that samples withdrawn from the flow accurately represent the water content in the pipeline.

Figure 9. Profiles of the amount of water at each vertical position during stratified flow for water cuts of (●) 1%, (■) 2%, (◆) 5% and (▲) 7.5%. The solid line shows the profile that would be expected if the pipe were filled with water. The expected water cut is calculated from the measured flow rate of the oil and water at each condition.

To test the effect of the mixing device, one-dimensional profiles were acquired along the height of the pipe for stream velocities of 0.2 m s^{-1} and 0.8 m s^{-1} and water cuts of between 1% and 6 %, but this time with the ratio of the nozzle flow velocity to the stream flow velocity approaching 30. The resulting time averaged profiles are shown in Figure 10. These plots provide an indication of the

amount of water present at each vertical position, integrated across the width of the pipe. For perfect mixing, the curves would be expected to be shaped like a hemi-circle, as this is the projection of the cross section of the pipe. It is clear that the profiles do not conform to this ideal shape for any of the results shown. The discrepancy is due to some settling of the water into a base layer along the bottom of the pipe, and to inhomogeneity of the radiofrequency field.

Figure 10. Uncorrected profiles of the average water distribution in the pipe 330 mm downstream of the injection nozzle with stream velocities of (a) 0.2 m s^{-1} and (b) 0.8 m s^{-1} . The lines correspond to water cuts of (—) 1 %, (—) 2 %, (—) 4 % and (—) 6 %.

In order to better visualise the mixing process, it is desirable to convert these profiles into local water cut measurements by removing the effect of the inhomogeneity and the shape of the pipe cross section on the measured signal. This is achieved by measuring the signal intensity for a pure sample and dividing the signal intensity image shown in Figure 10 by this calibration profile. Figure 11 shows an example of the profile measured for a static measurement of pure oil in this system. This profile is somewhat hemicircular, however there are significant deviations particularly on the left hand side of the profile (which corresponds to the region near the base of the pipe). These deviations will also be present in the data shown in Figures 9 and 10. The effect is not obvious in Figure 9 as the fraction of the pipe that contains water is so small, however the effect is more apparent in Figure 10. The profile shown in Figure 11 can therefore be used to remove the deviations from the hemicycle seen in Figure 10 by dividing these profiles by the profile for the static oil. The intensity of the resulting profiles will be proportional to the average quantity of water at each cross-section of the pipe. Therefore, a quantitative estimate of the water cut can be obtained from a linear fit to these data, in a similar manner to the fit shown in Figures 6 and 7. Figure 12 shows the resulting normalised profiles displayed as the local average water cut. From Figure 12, it is clear that as the water cut increases, the fraction of the pipe filled with water increases, as expected. The profiles are flat over most of the cross section of the pipe, indicating that most of the pipe is mixed homogeneously. However, for the

data in Figure 12(a) at a stream velocity of 0.2 m s^{-1} , a high signal is obtained from the bottom of the pipe, indicating the presence of a relatively high concentration of water along the base of the pipe – a sign of stratification of the flow. It is instructive to observe that in this case the minimum requirement of the *APS standards* could be met by the so called C1/C2 ratio, which is obtained by taking samples above and below the centre-line of the pipe at say $\pm 0.5 \times R$, where R is the radius of the pipe. The profile is approximately symmetric for up to $2/3^{\text{rd}}$ of the pipe radius, therefore the C1/C2 ratio will be close to one, and hence will exceed the minimum requirement of the standard. However, what is demonstrated here is that the C1/C2 ratio alone is not a good measure of **mixing** as it does not account for the stratification of the flow seen.

Figure 11. One-dimensional profile acquired for a static pure oil sample. The ideal profile is a hemicircle indicating the integration across a circular pipe. The profile shown has significant deviations from the ideal profile owing to imperfections in the radiofrequency field used to excite and detect the sample.

It is also worth considering the accuracy of the data shown in Figure 12. At a stream velocity of 0.2 m s^{-1} , the time averaged profiles indicate that the local water cut can be measured with an accuracy of $\pm 1\%$, or better. However, the accuracy of the measurement is strongly dependent on the stream velocity. In this system, a stream velocity of 0.2 m s^{-1} corresponds to a Reynolds number of 3000 and hence is at the transition between laminar and turbulent flow, and the stability of the flow indicates it is closer to laminar. By contrast, a stream velocity of 0.8 m s^{-1} corresponds to fully developed turbulent flow ($Re = 12000$). It appears that during turbulent flow, the selective excitation of the water signal is not as robust as it is at lower stream velocities and some residual signal from the oil phase is observed. It is our belief that much of the variation in water cut seen in Figure 12(b) arises from the effects of turbulence, rather than from inhomogeneity of the mixing. Further work is required to confirm this. The effects of turbulence could be reduced by decreasing the spatial

resolution or through the use of phase encoding, both these are avenues for future development of the measurement technique. For the present analysis, we restrict further discussion to the laminar flow case.

Figure 12: Profiles of the average water cut at each height for water cuts between 1% and 6% at stream velocities of (a) 0.2 m s^{-1} and (b) 0.8 m s^{-1} . These profiles were obtained by normalising the profiles shown in Figure 10 using the profile shown in Figure 11. The lines correspond to water cuts of (—) 1 %, (—) 2 %, (—) 4 % and (—) 6 %.

In addition to the time averaged profiles, we acquired a series of 640 profiles at 83 ms intervals to characterise temporal fluctuations in the oil-water distribution. Figure 13 shows examples of these time resolved profiles of the water distribution in the pipe for water cuts between 1% and 6%. For all three cases, the flow is observed to be relatively stable with most of the pipe showing homogeneous distribution of water, though some stratification is evident towards the base of the pipe, especially in the high water cut experiment. However, there are some exceptions to this. At a water cut of 2%, several instances of high water concentrations immediately above the main oil-water interface were observed. These regions correspond to large droplets of water travelling down the pipe. Similar examples of droplets of water were visible to the naked eye through the transparent wall of the pipe in the absence of mixing. At a water cut of 6%, fluctuations in the level of the interface between the stratified water and the main pipe flow were observed. The variation in the interface level was up to 6 mm in height. This fluctuation in height corresponds to the area occupied by water increasing from $\sim 5\%$ up to 14% of the cross-section of the pipe. These fluctuations in the flow represent a significant deviation from ideal mixing.

Figure 13. Instantaneous measurements of the local water cut in the pipe for a stream velocity of 0.2 m s^{-1} and water cuts of (a) 1%, (b) 2% and (c) 6%. Each profile was acquired in $< 1 \text{ ms}$, and the profiles were measured at intervals of 83 ms. In each graph 64 profiles out of the total time series of 640 profiles are shown.

5 Conclusion

We have commissioned a multiphase flow loop with the LJICF configuration to study liquid-liquid flows using MR. The flow loop has been designed to fit inside an MR laboratory with the key homogenisation section designed to fit within the bore of the spectrometer. Experimental data acquired using a CHESS based imaging sequence show the static oil-water composition is quantified to within 0.2%. In addition, by combining the CHESS sequence with imaging, one- and two-dimensional images of the water distribution throughout the cross-section of the pipe were obtained. These results were also extended to flow measurements, where it was found that the water cut could be determined with an accuracy of $\pm 0.5\%$. Time averaged one-dimensional profiles of the flow were acquired and demonstrate that significant segregation can exist at the low stream velocities characteristic of oil wells nearing the end of their life. These measurements permit quantitative mapping of the local water cut with an accuracy of $\pm 1\%$ or better, provided that the flow is not very turbulent. Time resolved measurements were also obtained for these conditions with a temporal resolution of 83 ms. The time resolved measurements demonstrate that even during relatively stable flow, fluctuations of up to 10% of the cross-sectional area of the pipe can be observed. In the future, the measurement techniques described in this paper will be used to characterise mixing and the homogenisation process for oil-water flows. The experimental results will also be used to validate the CFD simulation tool, such that it can be used to produce accurate correlations.

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7 References

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