20th Australasian Fluid Mechanics Conference
Perth, Australia
5-8 December 2016

Online Multiphase Flow Measurement using Earth's Field Nuclear Magnetic Resonance

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Abstract

Multiphase flow metering has significant potential in a number of industries; particularly in the oil and gas industry with regards to assisting the development of marginal fields and monitoring subsea processing. We demonstrate the novel use of a nuclear magnetic resonance (NMR) multiphase flow meter consisting of a pre-polarising permanent magnet upstream of an Earth's field NMR detection coil. The application of suitable signal analysis in interpreting the ^{1}H NMR signal acquired from a flowing stream allows determination of the relevant velocity probability distribution. The accuracy of such velocity distributions is verified using superficial velocity measurements obtained from an in-line rotameter as well as comparison to theoretical turbulent velocity distributions. The flow metering system has been successfully applied to two phase air/water flows in order to simultaneously track both liquid holdup and liquid velocity with time in both the stratified and slug flow regimes.

Introduction

The development of reliable and accurate flow meters has historically presented a considerable challenge to the oil and gas industry [1, 2]. Multiphase flow meters (MPFMs) allow continuous monitoring of the composition and velocity of industrial flows (typically composed of oil, gas, condensate and water) and provide numerous benefits in terms of process safety and production management. Commercial usage of MPFMs is however currently limited, which is partly due to a lack of trust in the reliability of commercial instruments [3].

The potential for using nuclear magnetic resonance (NMR) as a flow measurement technique has previously been recognised [1, 2]. The capacity of NMR as a flow measurement technique has previously been demonstrated in a range of laboratory based high-magnetic-field applications (with advantages such as a non-invasive measurement and the ability to readily interpret multicomponent systems) [4]. The significant cost and lack of mobility of high-field NMR has previously restricted commercial applicability of NMR flow meters, however recent improvements in low-field NMR technology [e.g. 5] has aided recent development in accurate and robust NMR MPFMs.

We present a NMR flow metering system which makes use of the Earth's magnetic field [6]. In this study we demonstrate how appropriate NMR signal analysis (using Tikhonov regularisation) enables the determination of the velocity distribution for a flowing stream. The system has also been used to measure both the liquid holdup and liquid velocity of two phase air/water flows at a frequency of ~1 Hz in both stratified and slugging flow regimes. Correct interpretation of the flow regime is a crucial step in multiphase flow metering, particularly recognising slug flow which can be detrimental to production and reduce the lifetime of various process equipment.

Materials and Methods

Equipment used

A schematic of the flow metering apparatus used in this work is provided in Figure 1. The system consists of a pre-polarising permanent magnet (0.3 T Halbach array) situated upstream of an Earth's field (EF) NMR radio frequency (r.f.) detection coil. The position of the pre-polarising magnet is adjustable, however in this work a fixed polarisation-detection separation distance (L_{PD}) of 0.65 m is used. The detection coil (Magritek, New Zealand) is used to excite and detect a ~2260 Hz ^{1}H NMR signal from the flowing fluid stream. The flow loop can accommodate two phase air/water flows. The loop contains a liquid rotameter (4-60 l/min) for water and a gas rotameter (10-100 l/min) for compressed air. The individual in-line rotameters provide an accurate independent measurement of the individual component flow rates prior to mixing, in order to validate NMR measurements.

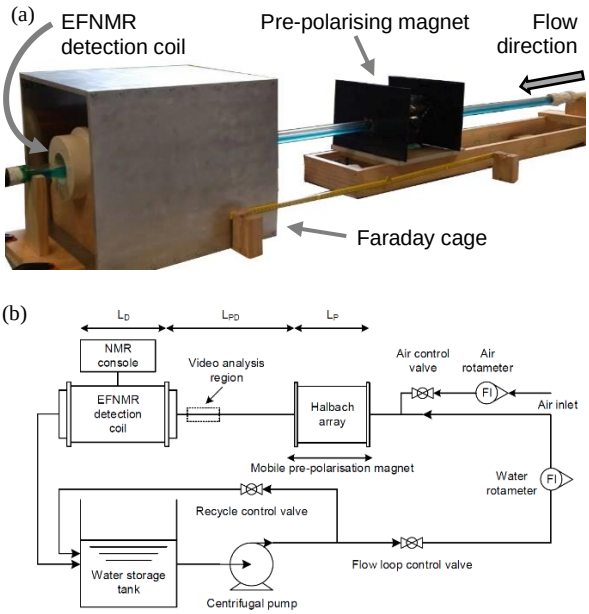

Figure 1. (a) Photo of the measurement section of the flow loop with the flow direction indicated. The detection coil is protected by a Faraday cage. (b) Schematic of the flow metering apparatus; the individual air and water flowrates may be measured using rotameters prior to mixing. The distances relevant to the model for NMR signal are indicated, i.e.; polarisation coil length (L_P), distance between polarisation and detection (L_{PD}) and the detection coil length (L_D). The transparent section of the pipe used for liquid holdup determination with video analysis is indicated.

A simple r.f. 'pulse and collect' is applied during NMR measurements in order to acquire the free induction decay (FID) signal of the flowing stream. In single phase experiments, 128 scans (N_{avg}) are acquired and signal analysis is applied to the final signal averaged FID. In two phase experiments, 128 instantaneous

scans (N_{scans}) are acquired and analysed individually, as two phase flow parameters (i.e. velocity and holdup) are time variant in slug flow.

A video analysis of two phase flows is used to obtain an independent measurement of the liquid holdup. A video (at 30 fps) of the fluid (dyed blue to assist video interpretation) flowing through a transparent section of the pipe is captured at the same time as the NMR signals are acquired. The liquid height of the flowing stream is determined by pixel colour analysis. The height is adjusted using the known cross-section of the pipe to provide the liquid holdup.

NMR Signal Analysis

A model has been developed to describe the NMR signal acquired as a function of the fluid velocity (v) and signal acquisition time (t_a) for a fluid stream flowing through the measurement system [6]. This model has been used in conjunction with Tikhonov regularisation (a mathematical inversion technique) in order to determine the velocity probability distribution of a flowing stream [7]. The measured NMR signal is a composite of three contributions: signal accumulation during polarisation (S_P), signal attenuation from intermediate decay between the polarisation magnet and the EFNMR detector (S_{PD}), and signal attenuation immediately prior to detection (S_D). When a fluid element is travelling through the flow meter with a velocity v, the NMR signal acquired at the EFNMR detection coil may hence be modelled using the following equations:

$$S(v, t_a) = S_0 S_P S_{PD} S_D \tag{1}$$

$$S_P = 1 - e^{-\frac{L_P}{vT_1}} \tag{2}$$

$$S_{PD} = e^{-\frac{L_{PD}}{vT_1}} \tag{3}$$

$$S_D = \left[1 - \frac{(t_{delay}+t_a)v}{L_D}\right] e^{-\frac{t_{delay}+t_a}{T_2^*}} \tag{4}$$

where S_0 is the NMR signal after an infinite time in the magnetic field, T_1 is the spin-lattice relaxation time and T_2^* is the effective spin-spin relaxation time, t_a is the time period during signal acquisition of the free induction decay (FID) and t_{delay} is the signal acquisition delay time. The polarisation magnet length (L_P), the polarisation-detection separation distance (L_{PD}) and the detector coil length (L_D) are defined in figure 1.

The model for the NMR signal is fit to experimentally acquired signal data using Tikhonov regularisation [8]. Regularisation is a mathematical inversion technique which has been applied in this work in order to determine the velocity distribution of the flowing fluid stream, P(v). This is achieved by minimising the following expression in order to solve for **P** (P(v) as a discretised probability distribution vector);

$$\min\{\|\mathbf{AP} - \mathbf{S}\|^2 + \lambda\|\mathbf{P}\|^2\} \tag{5}$$

where **A** is the model transfer matrix (representing signal attenuation (Equation 1) as a function of t_a and v), **S** is the signal vector obtained from experimental measurements and λ is the smoothing parameter used to achieve a compromise between finding the true solution (minimising the residual norm $\|\mathbf{AP} - \mathbf{S}\|^2$) and limiting the impact of experimental noise on the solution (minimising the penalty function $\|\mathbf{P}\|^2$). The optimal value of λ is selected using the generalised cross-validation (GCV) method [8]. The GCV method operates by sequentially removing a data point in the solution vector (**S**) and determining the value of λ which best predicts the removed point [9]. This is repeated for all experimental data points in **S**, and a GCV score is determined as a function of λ [8]. The value of λ which minimises the GCV score is the optimal smoothing parameter.

When the NMR model is applied to the analysis of two phase gas-liquid flow, only the liquid is contributing to the measurable NMR signal. Consequently; (i) the resultant velocity probability distribution is representative of the liquid velocity distribution alone, and (ii) the overall level of signal magnetisation (S_0) is directly proportional to the liquid holdup in the detector. The second observation is the principle used to estimate the liquid holdup (h_L) during two phase flow via the following equation [10];

$$h_L = \frac{S_{0,i}}{S_{0,ref}} \tag{6}$$

where $S_{0,i}$ is the overall signal magnetisation for an instantaneous NMR scan of two phase flow and $S_{0,ref}$ is a reference value for the overall signal magnetisation determined from single phase experiments with the pipe full of liquid. Note that in future gas (methane) and water signal will be differentiated based on their different relaxation (T_1, T_2*) characteristics.

Results

Single Phase Results

Single phase (water) experimental data was acquired at mean velocities (V_M) of 0.09 m/s to 1.15 m/s (corresponding to water flowrates of 4 to 52 l/min respectively, as measured using the in-line water rotameter). Figure 2(a) shows sample NMR signal data as a function of t_a (i.e. the FID) for mean velocities ranging from 0.18 to 1.06 m/s. The regularised fit of Equation 1 to the experimental data for each mean velocity is also shown. Figure 2(b) shows the resultant velocity probability distributions, P(v).

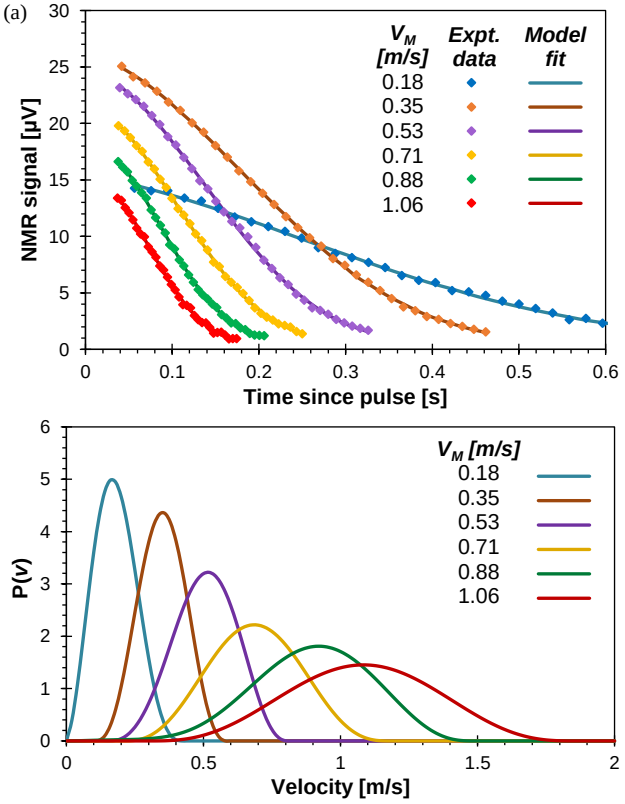

Figure 2. (a) Equation 1 fit to experimentally acquired FID data at mean velocities ranging from 0.18 to 1.06 m/s. (b) The corresponding velocity probability distributions returned by regularisation signal analysis.

Figure 3 shows the expected mean velocity value obtained from the experimental probability distributions (as shown in figure 2(b)) compared to the superficial mean velocity determined from the in-line water rotameter. The NMR predicted velocities show excellent agreement with the superficial velocity measurements from the in-line rotameter. The mean absolute error or difference for the seventeen velocity measurements is 1.9 %

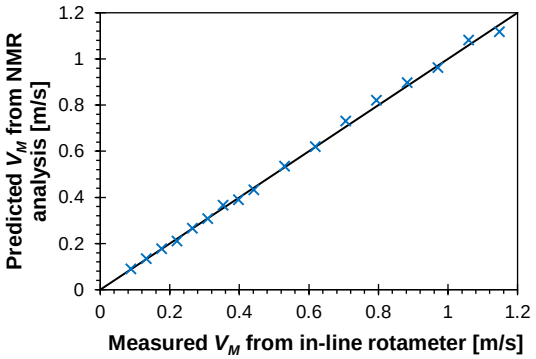

Figure 3. Comparison of the mean velocity (V_M) predicted using regularisation of NMR data to the measured mean velocity from in-line rotameter data.

Comparison to Theoretical Distributions

The experimental distributions generated from regularisation analysis of the NMR signal are comparable to theoretical turbulent velocity distributions. Turbulent velocity flows are often approximated by a power law velocity profile, where the velocity (U) at a radial position (r) in a pipe of diameter D is given by [11]:

$$U(r) = V_M \frac{n+1}{n}\left(1 - \frac{2r}{D}\right)^{\frac{1}{n}} \quad (7)$$

for a mean velocity V_M and a power law exponent n. An n value of seven is often used for fully developed turbulent flow, leading to the well-known 1/7th power law distribution [11]. Using the correlation for the power law exponent (n) as a function of Reynolds number presented in Zagarola et al. [12], water flowing at 0.44 m/s (corresponding to a Reynolds number of 13600) would be expected to have a power law distribution with n = 5.37. Figure 4 shows a comparison between the experimental velocity distribution for a mean velocity of 0.44 m/s and the theoretical velocity distribution for n = 5.37 (with n = 4 and n = 7 also shown for comparison).

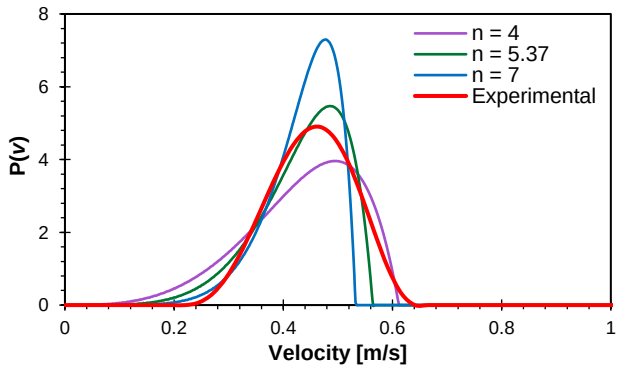

Figure 4. The experimentally obtained velocity distribution (at $\bar{v}$ = 0.44 m/s) compared to theoretical turbulent power law distributions. Power law exponents of n = 4, 5.37 and 7 are shown.

The velocity distribution returned by the regularisation analysis compares relatively well to the theoretical distribution (for a power law exponent of n = 5.37). The experimental velocity distribution has a standard deviation of 0.081 m/s relative to the theoretical standard deviation of 0.077 m/s. Exact agreement is not expected as the NMR experimental velocity distributions are obtained from a complex average of flow over the polarisation and acquisition time-frame.

Two Phase Results

Two phase air-water experiments have been conducted at superficial liquid velocities (U_{SL}) of 0.09 – 0.26 m/s (corresponding to liquid flowrates of 4 – 12 l/min) and superficial gas velocities (U_{SG}) of 0.44 and 0.88 m/s (corresponding to gas flowrates of 20 and 40 l/min). Each NMR experiment consists of 128 instantaneous scans (N_{scans}) obtained at 1.25 Hz (for a total experimental time of 102 s). The video capture of a transparent pipe section used for independent liquid holdup analysis is conducted simultaneously to NMR measurements. From visual observation, only one trial (U_{SL} = 0.09 m/s, U_{SG} = 0.44 m/s) was considered to be in the stratified flow regime, whilst all other trials were considered to be in the slug flow regime, consistent with expectation [13].

Regularisation analysis is applied to each NMR scan. The mean liquid velocities (determined from the resultant velocity probability distributions) can then be tracked over time. Figure 5 shows the instantaneous liquid velocity tracked over 40 s at superficial liquid velocities of 0.09, 0.18 and 0.26 m/s respectively, and at a superficial gas velocity of 0.44 m/s (as measured using the in-line rotameters).

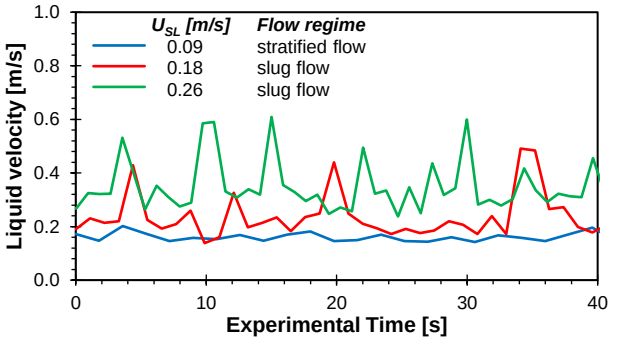

Figure 5. Tracking the instantaneous liquid velocity over time at superficial liquid velocities of 0.09, 0.18 and 0.26 m/s respectively and at a gas superficial velocity of 0.44 m/s. The visually observed flow regime is indicated for each superficial liquid velocity.

The liquid velocity track for the stratified flow experiment (U_{SL} = 0.09 m/s) can be observed to be relatively constant (the standard deviation for the 128 scans was 0.02 m/s). The slug flow experiments show much greater fluctuation in the velocity track due to the periodic presence of faster moving slugs (relative to the slower background stratified liquid film) through the detection coil. In the first slug flow experiment (at U_{SL} = 0.18 m/s) the periodic fluctuations in liquid velocity are less frequent relative to the second slug flow experiment (at U_{SL} = 0.26 m/s). This observation corresponds to longer but less frequent (~0.1 Hz) slugs occurring at lower liquid velocities whilst shorter but more frequent (~0.2 Hz) slugs occur at higher liquid velocities.

The overall signal amplitude (S_0) is extracted from each instantaneous NMR scan and used to estimate the liquid holdup over the course of the 40 s experiment. Figure 6 compares the instantaneous liquid holdup determined from NMR signal analysis to the liquid holdup estimated from the video recordings of two phase flows. Liquid holdup tracks are shown for superficial liquid velocities of (a) 0.09 m/s, (b) 0.18 m/s, and (c) 0.26 m/s, with a superficial gas velocity of 0.44 m/s for all three experiments.

The NMR determined liquid holdup shows reasonably good correlation to the video holdup estimate and is successfully able to capture the presence of slugs in the relevant experiments. The NMR signal analysis does underestimate the liquid holdup relative to the video holdup interpretation, particularly when the background liquid stratified film layer is travelling through the detection region. Two physical reasons can be attributed to this difference. Firstly, the video will capture the upper edge of a concave meniscus in the pipeline which will cause an overestimation of the liquid holdup. Furthermore, the video capture does not account for gas bubbles entrained in the liquid phase causing further overestimation of the liquid holdup in the

video analysis. Finally, perfect agreement is not expected due to the low signal to noise ratio of instantaneous NMR scans.

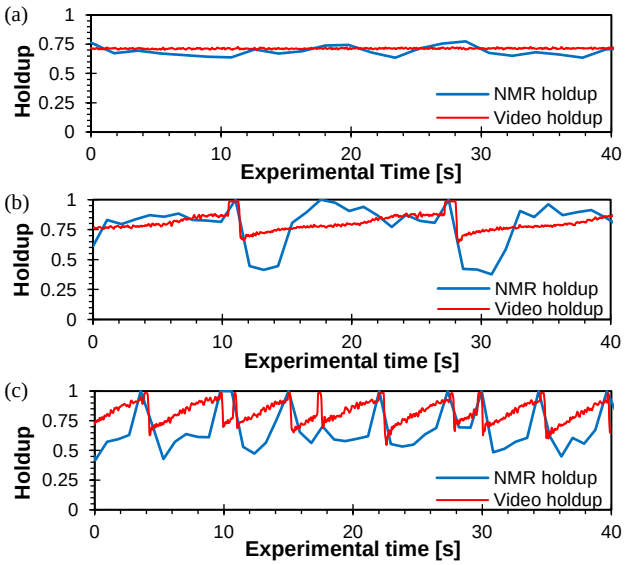

Figure 6. Tracking the instantaneous liquid holdup over time at superficial liquid velocities of; (a) 0.09 m/s (stratified flow), (b) 0.18 m/s (slug flow) and (c) 0.26 m/s (slug flow). The liquid holdup as determined by NMR signal analysis is compared to the holdup estimated from video analysis.

The accuracy of two phase velocity measurements is verified using the estimated liquid superficial velocity. The average superficial liquid velocity ($\overline{U_{SL}}$) for an entire NMR experiment (i.e. for N_{scans} = 128 scans) is determined by:

$$\overline{U_{SL}} = \frac{\sum_{i=1}^{N_{scans}} h_{L,i} v_{L,i}}{N_{scans}} \quad (8)$$

where $h_{L,i}$ is the instantaneous liquid holdup for scan 'i' and $v_{L,i}$ is the instantaneous liquid velocity for scan 'i'. Figure 7 compares The NMR predicted superficial velocity to the measured superficial velocity from the in-line water rotameter.

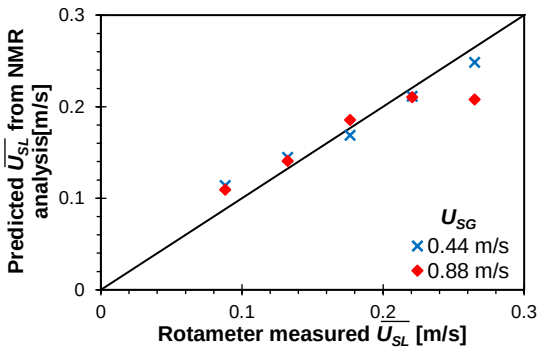

Figure 7. Comparison of NMR predicted mean superficial velocity to the measured mean superficial velocity from the in-line rotameter. Measurements were conducted at superficial liquid velocities of 0.09 – 0.26 m/s and superficial gas velocities of 0.44 and 0.88 m/s.

The NMR predicted superficial velocities show quite good agreement for the experiments conducted. At higher velocities, the frequency of slugs is too high (>0.4 Hz) for the EFNMR detection coil to correctly detect all slugs. This is evident in the results at U_{SL} = 0.26 m/s and is very evident at U_{SG} = 0.88 m/s where the liquid slugs were frequently missed. We are looking at improving the applicable velocity range for these experiments by reducing the repetition time (currently 0.8 s) for the experiments.

Conclusion

In this work, we have presented an Earth's field NMR flow meter which can be used to accurately determine the velocity probability distribution for turbulent flowing streams. The velocity distributions returned by the system have been shown to be; (i) accurate when compared to the measured superficial velocity from an in-line rotameter, and (ii) comparable to theoretical turbulent power law distributions. Furthermore, we have demonstrated that the NMR signal analysis may be extended to the analysis of two phase (air/water) flow in both the stratified and slugging flow regimes. Correct interpretation of instantaneous NMR signals acquired during two phase flow allows tracking of both the liquid holdup and velocity and subsequently interpretation of the two phase flow regime. The flow metering equipment and analysis methodology are currently being adapted to also incorporate oil. Such changes, along with further investigations of gas/liquid flows will assist in developing the system towards a capable three-phase flow metering platform.

Acknowledgements

The authors wish to acknowledge Ms Adeline Klotz and Mr Jason Collis for experimental assistance. EOF acknowledges funding from the Faculty of Engineering, Computing and Mathematics at UWA. PLS is supported by an ARC DECRA Fellowship (DE140101094).

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