# Application of Earth's Field Nuclear Magnetic Resonance to Multiphase Flow Metering

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**Abstract**

Multiphase flow metering has significant potential in a number of industries; particularly in the oil and gas industry in terms of 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 magnetic field NMR detection coil. The application of appropriate 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 are verified using superficial velocity measurements obtained from an in-line rotameter. The ability to quantify multi-modal velocity distributions via regularisation is also demonstrated by applying the measurement methodology to a two pipe system. The flow metering system has also 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.

## 1. 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 relevant 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 arguably due to a lack of trust in the reliability of commercial instruments [3].

The potential for using nuclear magnetic resonance (NMR) for flow measurements 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 non-invasive measurement and the ability to readily interpret multicomponent systems) [4]. Furthermore, in principle NMR will be able measure flow independent of the fluid pressure and temperature. 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.

A recent and promising development in NMR flow metering is the commercial MPFM (the M-Phase 5000) produced from a collaboration between Shell, Krohne and Spinlock [6]. The system (which operates at a $^1$H resonant frequency of 8 MHz) applies a combination of Carr-Purcell-Meiboom-Gill NMR pulse sequences with varying pre-polarisation conditions and MRI-based spin density profiling in order to quantify multiphase flowrates [7, 8].

Here we present a NMR flow metering system which makes use of the Earth's magnetic field [9]. In this study we demonstrate how appropriate NMR signal analysis (using Tikhonov regularisation) enables the determination of the velocity distribution for a flowing stream. We further demonstrate the application of the measurement protocol in order to interpret multi-modal (two pipe) velocity distributions. 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, reduce the lifetime of various process equipment.

## 2. Equipment and Methodology

### *2.1 Experimental setup*

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.

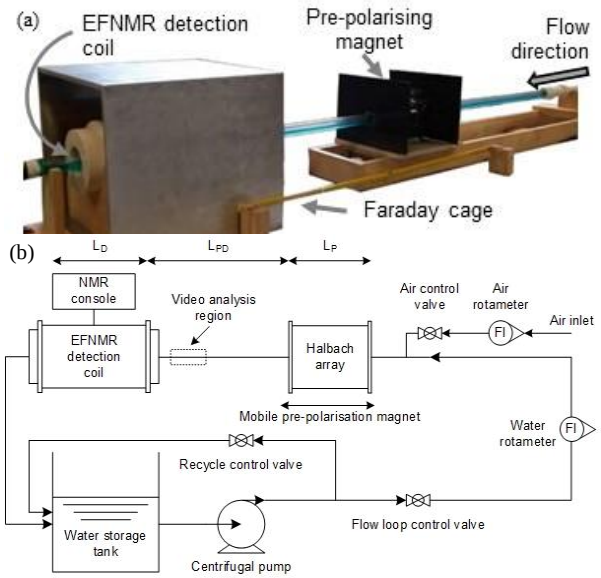



**Figure 1. (a)** Photo of the measurement section of the flow loop with the flow direction indicated. The detection coil is protected by a Faraday cage. **(b)** Schematic of the flow metering apparatus; the individual air and water flowrates may be measured using rotameters prior to mixing. The distances 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, 50 scans ($N_{avg}$) are acquired and signal analysis is applied to the final signal averaged FID. In two phase experiments, 100 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 determine the liquid holdup.

Further experiments were conducted using a modified flow loop containing two separate pipes (both with independent flow control and rotameters). The purpose of these experiments was to demonstrate the capability of regularisation in obtaining multi-modal velocity distributions. The adjusted flow loop configuration is illustrated with a photo shown in Figure 2(a) and a schematic in Figure 2(b).

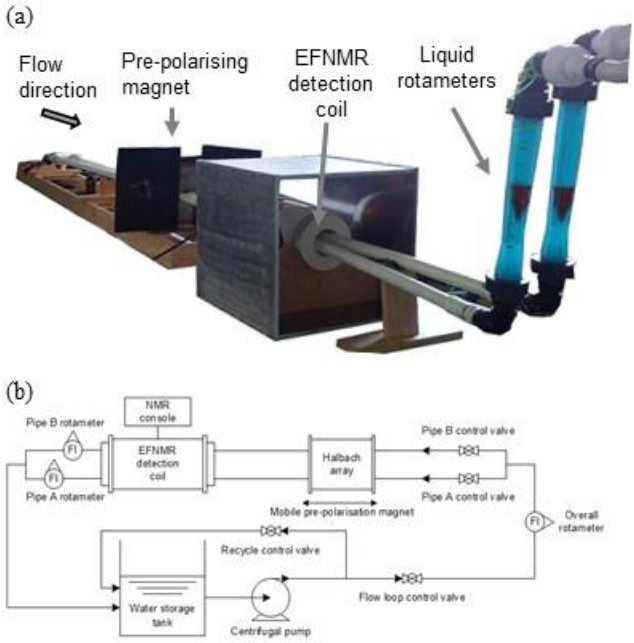



**Figure 2. (a)** Photo of two pipe flow loop. Ball valves are located after the pipe split in order to control the flowrate in each pipe. **(b)** Schematic of the two pipe system with flow direction indicated.

*2.2 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 [9]. 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 [10]. 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:

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

$$S_P = 1 - e^{-\frac{L_P}{vT_1}} \quad (2)$$

$$S_{PD} = e^{-\frac{L_{PD}}{vT_1}} \quad (3)$$

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

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 [11]. 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);

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

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 $\lambda$ 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 [11]. 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 [12]. This is repeated for all experimental data points in **S**, and a GCV score is determined as a function of λ [11]. 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 [13];

$$h_L=\frac{S_{0,i}}{S_{0,ref}} \quad (6)$$

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 oil, gas (methane) and water NMR signal will be differentiated based on their different NMR relaxation ($T_1$, $T_2$*) characteristics.

## 3. Results

### *3.1 Single Pipe Results*

Single phase (water) experimental data was acquired at mean velocities ($\bar{v}$) of 0.11 m/s to 1.10 m/s (corresponding to water flowrates of 5 to 50 l/min respectively, as measured using the in-line water rotameter). Figure 3(a) shows sample NMR signal data as a function of $t_a$ (i.e. the FID) for mean velocities ranging from 0.22 to 1.10 m/s. The regularised fit of Equation 1 to the experimental data for each mean velocity is also shown. Figure 3(b) shows the resultant velocity probability distributions, P($v$).

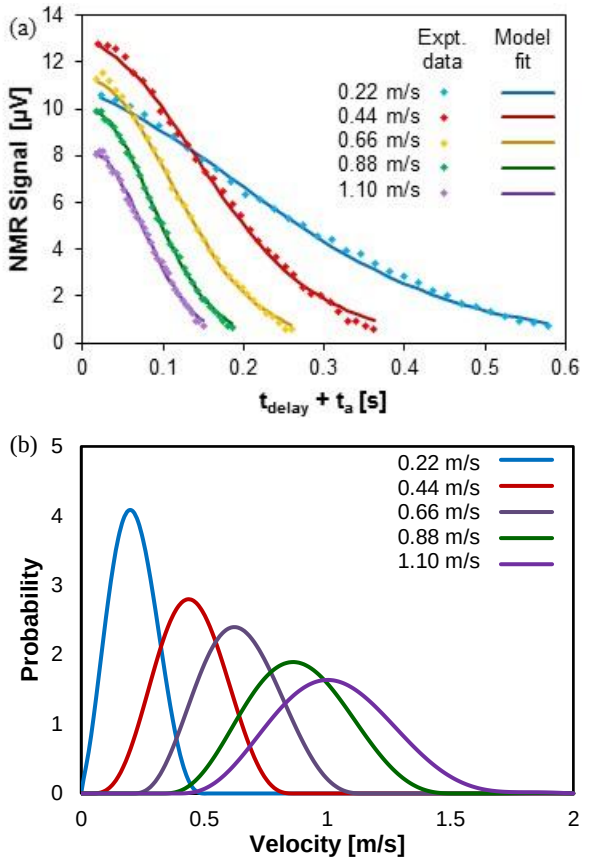



**Figure 3. (a)** Equation 1 fit to experimentally acquired FID data at mean velocities ranging from 0.22 to 1.10 m/s. **(b)** The corresponding velocity probability distributions returned by regularisation signal analysis.

Figure 4 shows the expected mean velocity value obtained from the experimental probability distributions (as shown in Figure 3(b)) compared to the superficial mean velocity determined from the in-line water rotameter. The NMR predicted velocity measurements show excellent agreement with the superficial velocity measurements from the in-line rotameter. The mean absolute error or difference for the ten velocity measurements is 4.3%

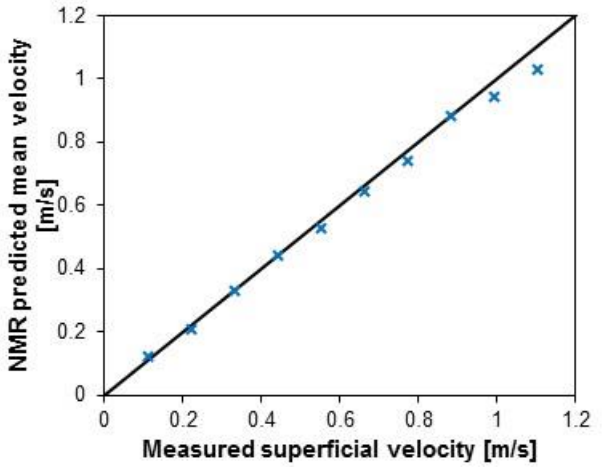


**Figure 4.** Comparison of the mean velocity predicted using regularisation of NMR data (predicted velocity) to the measured superficial velocity from in-line rotameter data (measured velocity).

*3.2 Two Pipe Results*

The two pipe experiments (conducted using the flow loop configuration shown in Figure 2) is used to test the measurement methodology using an artificially created bimodal velocity distribution. The flow rates were controlled (via ball valves) such that the velocity in pipe A was 33% of the velocity in pipe B.

Experiments were conducted with total water flowrates through the pipes of 15 to 50 l/min (with 5 l/min steps). Figure 5(a) shows the experimentally acquired FID signal fit (via regularisation) with Equation 1 for overall flowrates of 30, 40 and 50 l/min respectively. Figure 5(b) shows the corresponding velocity probability distributions returned from the analysis.

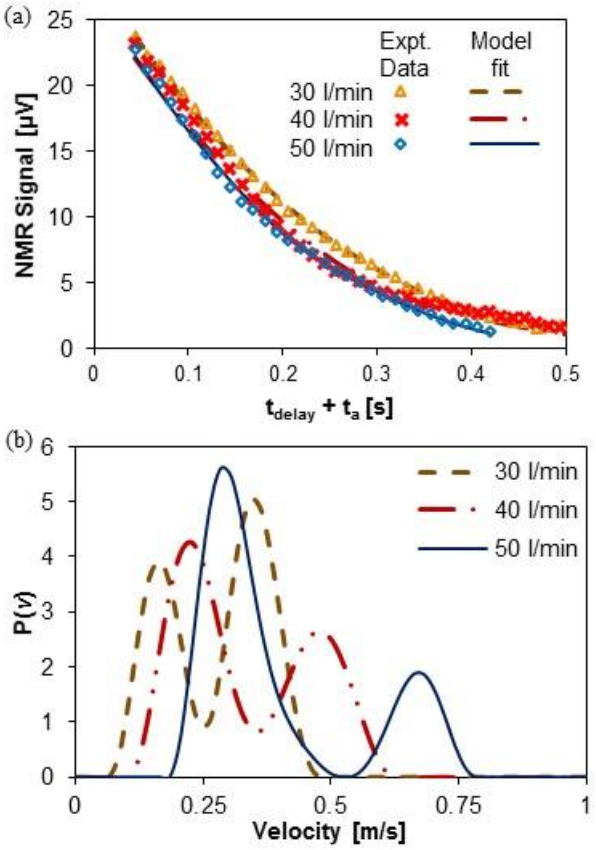



**Figure 5. (a)** The model fit of Equation 1 to experimentally obtained FID for the two-pipe experiments with total flowrates of 30 l/min, 40 l/min and 50 l/min. **(b)** The resultant velocity probability distributions returned by regularisation analysis of the two-pipe NMR data.

The resulting velocity probability distributions show two clear peaks, with each peak representative of the signal contribution from the respective pipe (i.e. the lower velocity peak is from pipe A and the higher velocity peak is from pipe B). The overall probability distributions were split into the respective two peaks (using the minimum between them) and the expected value of the separate velocity probability distributions was determined. The calculated mean velocities from NMR data analysis is compared to the superficial velocity measured by the respective rotameters in Figure 6.

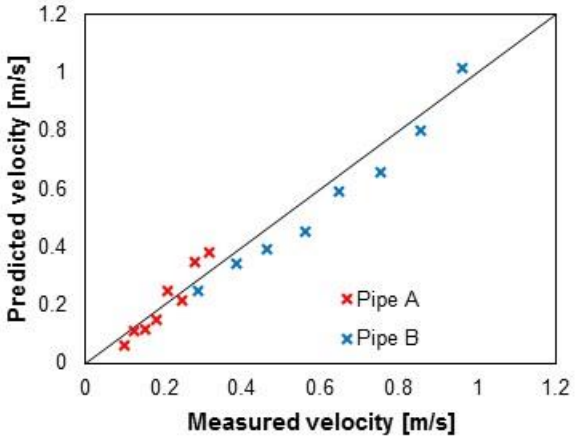



**Figure 6.** Comparison of the NMR predicted velocities of Pipes A and B (following velocity peak splitting) to the measured superficial velocities at the respective rotameters. Overall flowrates of 15 l/min to 50 l/min (in 5 l/min intervals) were used.

There is reasonable agreement between the NMR predicted velocities and the rotameter measured velocities for pipe's A and B respectively. The mean absolute error (or difference) is 20.1 % for pipe A and 11.5 % for pipe B. It can be observed that the velocity peaks of the probability distributions (in Figure 5(b)) are not equal in magnitude, despite the pipes being of equal diameter, with the relative magnitude of the velocity peak of pipe B (the faster velocity pipe) reducing with higher flowrates. We have discerned that this is partially a result of being unable to acquire signal data for $t<t_{delay}$, i.e. the initial 40 ms after signal excitation. This proportion of the FID signal ($t$ < 40 ms) becomes more influential on the relative signal contribution for pipe B on the velocity distribution as the overall flowrate increases. We are currently incorporating a Q-switch into the NMR hardware to reduce $t_{delay}$ in order to alleviate this problem.

*3.3 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 100 instantaneous scans ($N_{scans}$) obtained at 1.25 Hz (for a total experimental time of 80 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 [14].

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 7 shows the instantaneous mean liquid velocity tracked over 30 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).

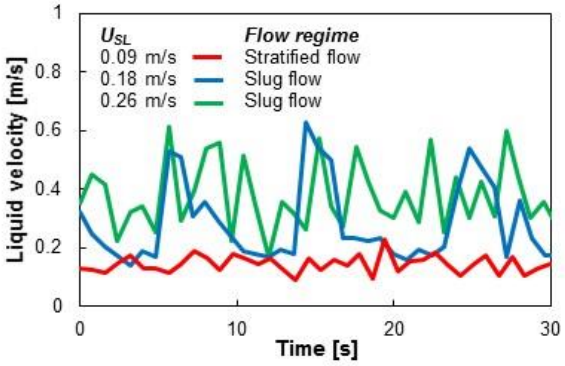
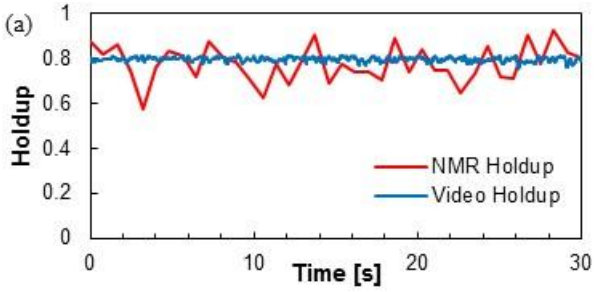



**Figure 7.** Tracking the instantaneous liquid velocity over time at superficial liquid velocities of 0.09, 0.18 and 0.26 m/s respectively and at a gas superficial velocity of 0.44 m/s. The visually observed flow regime is indicated for each superficial liquid velocity.

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 100 scans was 0.03 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 30 s experiment. Figure 8 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.



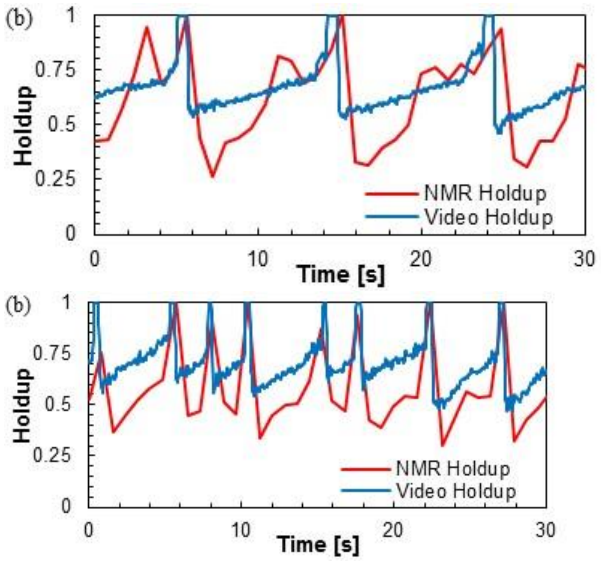




**Figure 8.** Tracking the instantaneous liquid holdup over time at superficial liquid velocities of; (a) 0.09 m/s (stratified flow), (b) 0.18 m/s (slug flow) and (c) 0.26 m/s (slug flow). The liquid holdup as determined by NMR signal analysis is compared to the holdup estimated from video analysis.

The 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.

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 $N_{scans}$ = 100 scans) is determined by:

$$\overline{U_{SL}} = \frac{\sum_{i=1}^{N_{scans}} h_{L,i} v_{L,i}}{N_{scans}} \quad (7)$$

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 9 compares the NMR predicted superficial velocity to the measured superficial velocity from the in-line water rotameter.

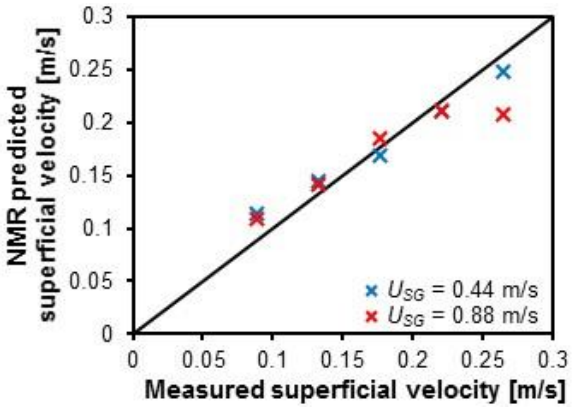



**Figure 9.** Comparison of NMR predicted superficial velocity to the measured superficial velocity from the in-line rotameter. Measurements were conducted at superficial liquid velocities of 0.09 – 0.26 m/s and superficial gas velocities of 0.44 and 0.88 m/s.

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.

## 4. Conclusion

In this work, we have presented an Earth's field NMR flow meter which can be used to accurately determine the velocity distribution for turbulent flowing streams. The velocity distributions returned by the system have been shown to be accurate when compared to the measured superficial velocity from an in-line rotameter. 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. NMR provides the ability to determine phase composition via $T_1$ differentiation [15]. Such changes, along with further investigations of gas/liquid flows will assist in developing the system towards a capable three-phase flow metering platform.

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