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DIRECT MEASUREMENT OF THE VOID FRACTION OF A TWO-PHASE FLUID BY NUCLEAR MAGNETIC RESONANCE

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Abstract—Application of nuclear magnetic resonance (NMR) to the direct measurement of void fractions of two-phase fluids has been studied. With this technique, the effective density of the fluid is determined by monitoring the NMR signal strength from a particular nuclear species in the liquid. The results, from experiments on both static and flowing systems, establish the linearity of the method for the full range ($0 \rightarrow 1$) of void fractions, independent of the mass distribution of the liquid, and demonstrate the feasibility of using NMR as a direct method for void-fraction measurements in two-phase systems.

NOMENCLATURE

ΔE,	energy separation of the two nuclear spin states;
H,	static magnetic field;
H_0,	static magnetic field at resonance;
I,	NMR signal strength;
I_0,	NMR signal strength from water;
k,	Boltzmann constant;
l_0,	length of water column;
l_1,	length of water column containing air bubbles;
l_2,	length of water column with bubble head;
l_3,	length of bubble head;
n,	number of magnetic field scans;
N_1,	number of nuclear spins in the antiparallel state;
N_2,	number of nuclear spins in the parallel state;
Q_l,	volume flow rate of liquid;
Q_g,	volume flow rate of gas;
t_0,	time spent by sample in magnetic field prior to entering spectrometer coil;
T,	absolute temperature;
T_1,	spin-lattice relaxation time.

Greek symbols

α,	void fraction;
γ,	gyromagnetic ratio;
μ_g,	dynamic viscosity of the gas;
μ_l,	dynamic viscosity of the liquid;
ρ_g,	density of the gas;
ρ_l,	density of the liquid;
χ,	quality of the two-phase mixture;
ω_0,	angular frequency at resonance.

INTRODUCTION

THE CHARACTERISTICS of fluid flow in pipes have been described by numerous theoretical models and correlations [1]. Unfortunately, there are only a few measurement techniques available to the experimenter to enable him to verify any particular model, and many of these perturb the system under investigation so that interpretation of the results is often questionable.

One area in which measurements are particularly difficult, but which is currently of considerable practical interest, is that of two-phase (liquid–gas) flow. Whether the system is steam–water, air–water, or some other combination, many problems face the experimenter when he attempts to get meaningful results from measurements on two-phase systems. The pioneering work of Singer and co-workers [2–4] has demonstrated the application of the nuclear magnetic resonance (NMR) technique to flow and velocity-profile measurements in single-phase systems, but we are unaware of its application to two-phase fluids. This report deals with the use of NMR techniques for the determination of void fraction in two-phase flow and indicates its potential for other applications.

The literature contains many reports on various methods that have been used in an attempt to determine void fractions for two-phase mixtures, and a few of the notable approaches that have a negligible effect on the flow regime are discussed below along with their applicability and limitations.

The use of electromagnetic attenuation is limited by the enclosing pipe and by the distribution of the components of the two-phase fluid. In the optical range, sharp wave profiles and the presence of spray have been found to introduce gross refraction and scattering effects, which swamp the desired signals [5]. For X-rays and low-energy γ-rays, absorption occurs in the pipe wall and depending on the material and wall thickness, this can provide a greater effect than the absorption by the fluid itself [6, 7]. Thus, the experimenter is often faced with making reliable measurements of small signals superimposed on a relatively large background signal. Another limitation of this technique is that only chordal lines through the pipe are sampled and azimuthal symmetry must be assumed to determine an average void fraction for the whole pipe. Although the possibility of scanning and mathematically unfolding exists, this is done at the expense of dynamic response.

The use of scattered electromagnetic radiation has also been attempted. In the optical region, the limitations are the same as for the attenuation method [5]. For higher-energy radiation, a well-collimated beam of monochromatic γ-rays can be used to sample the effective density of a small region within the pipe by detecting, in a narrow energy band, those γ-rays that are Compton-scattered through $\pi/2$ rad [8]. Problems arise for total void-fraction measurements, since the accuracy deteriorates as the sampled volume approaches the pipe wall. This puts severe limitations on the method when, for example, the flow regime is annular. Scattering of an intense beam of high energy γ-rays (> 1 MeV) which irradiates a short length of the whole pipe appears promising, but this technique has yet to be proven in practice.

Particle-flux attenuation and scattering techniques have also been investigated [9, 10]. Perhaps the most promising of these uses neutrons, particularly where it is possible to choose materials such that the liquid is much more absorbant than the surrounding pipework. The applications of neutron-scattering and attenuation techniques are still in their infancy and more work needs to be done before the full extent of their applicability can be realistically assessed. However, it is anticipated that signal interpretation will be one of the dominant problems.

On the electromagnetic methods, the most widely used is the capacitance gauge [11]. This technique relies on the relatively high dielectric constant of water to allow determination of changes in the effective capacitance (or impedance) between a set of plates located in the flowing fluid. The major difficulty with this approach is the dependence of the signal on void distribution [12, 13].

Of the various approaches that produce a major perturbation on the flowing fluid, the most definitive appears to be the holdup technique [14], which rapidly seals off a section of pipe, thus allowing absolute measurement of the trapped liquid and gas volumes. However, this technique cannot be used for dynamic measurements or on a system where flow cannot be interrupted. The major use of the method would appear to be in the calibration of other measurement techniques.

In this paper, we present some preliminary results that indicate the feasibility of using nuclear magnetic resonance (NMR) to determine the void fraction of a two-phase fluid. The experiments were performed for two different conditions. In the first, air was bubbled through a static column of liquid, to determine the linearity of the response of the NMR spectrometer to void fraction. The second set of experiments, on a flowing system, indicated the signal size and noise to be expected in a practical system and was the major test of the feasibility of the method.

NUCLEAR MAGNETIC RESONANCE

Most nuclei (except those with an even number of protons and of neutrons) possess a spin angular momentum and associated magnetic dipole moment. When such nuclei are introduced into a magnetic field they take up specific orientations, and NMR experiments measure the energy required to reorient the nuclear spins in the magnetic field. When a sample of interest is simultaneously subjected to a homogeneous DC magnetic field and radio-frequency (r.f.) energy with an appropriate frequency, the nuclear spins absorb the r.f. energy and change from one spin state to another. The relationship between the static magnetic field, H_0, and the angular frequency of the r.f. radiation, ω_0, at resonance, is given by

$$\omega_0 = \gamma H_0 \tag{1}$$

where γ is the gyromagnetic ratio and depends on the nuclear species present.

For hydrogen nuclei, ^{1}H, with $\gamma/2\pi$ having a value of 4.2578 MHz/kG, there are two allowed orientations for the nuclear spins, parallel and antiparallel to the static magnetic field. For a macroscopic assembly of ^{1}H nuclei the populations of these two states is given by the Maxwell–Boltzmann expression,

$$\frac{N_1}{N_2} = \exp\left(-\frac{\Delta E}{kT}\right) \tag{2}$$

where N_1, N_2 are the populations of the antiparallel and parallel states, respectively, ΔE is the energy separation of the two states, k is the Boltzmann constant, and T is the absolute temperature of the sample.

Since the transition probabilities for stimulated emission and absorption between the two states are equal, absorption of energy by the ^{1}H nuclei will occur only if $N_2 > N_1$. Hence, immediately after the r.f. field is applied, a net absorption of energy will result. The r.f. field disturbs the thermal equilibrium of the spins, as expressed by equation (2), and the levels would become equally populated if it were not for a mechanism of thermal equilibration. This is a relaxation mechanism, by which nuclei in the upper energy state decay to the lower state, by a radiationless transition, to restore thermal equilibrium. The nature of this relaxation process, by which the absorbed energy is dissipated, will not be discussed further here since it is outside the scope of this work. It is sufficient to note that this relaxation process exists, since it is essential for the continuous absorption of energy, and that there is a characteristic time, called the spin-lattice relaxation time, T_1, associated with it.

For practical reasons, the absorption of energy by the spin system is recorded at a fixed frequency, by scanning the magnetic field through the resonance condition described by equation (1). This leads to a resonance absorption peak, as shown in Fig. 1. The position of this peak for a particular nucleus in a magnetic field is a fundamental property of the nucleus. Each nucleus has a particular value of the gyromagnetic ratio, γ, so that for a fixed frequency of the r.f. field, each nucleus will exhibit a resonance at a particular

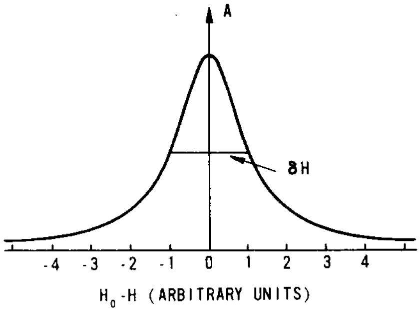

FIG. 1. Absorption of energy vs magnetic field, obtained by sweeping the magnetic field through the resonance condition.

value of the applied magnetic field. This allows a positive identification of the nucleus, with the strength of the resonance giving a measure of the number of such nuclei present in the sample. This method of measuring the concentration of the nuclear species is what we wish to use to determine the density of a two-phase mixture. Provided the resonance is not saturated by too much r.f. power, the intensity of the absorption signal is proportional to the area under the curve shown in Fig. 1. This area represents the total number of nuclei of a particular species enclosed by the r.f. coil in the magnetic field. Since this is a fixed volume, any changes in signal strength are due to changes in the effective density of the fluid. This is essentially a relative measurement and for the absolute determination of density, a normalization procedure is required.

For a more detailed description of NMR spectroscopy the reader is referred to standard texts, such as those by Abragam [15] and Carrington and McLachlan [16].

EXPERIMENTAL ARRANGEMENT

The NMR spectrometer used in these experiments was a broad-line induction spectrometer first described by Bloch *et al.* [17]. Its design [18] is similar to a basic Varian system, which is commercially available, and uses Varian probes, in the frequency range 2.5–25 MHz. The magnet was a Magnion electromagnet, with a 38.2 cm pole cap which was tapered to 20.3 cm and was capable of producing fields up to 22 kG in the 6.4 cm gap. Since the magnetic field was essentially homogeneous over a relatively large volume, the volume that the spectrometer sampled was defined by the coil in the probe, which was 5 mm long and could take pipes up to about 16 mm OD. The magnetic field within this sensitive volume was uniform to within 100 mG. For the experimental conditions that were used, the magnitude of the r.f. energy deposited in the sample was estimated to be less than 10^{-10} J.

To improve the signal-to-noise ratio, it is usually necessary to perform some signal processing to achieve an adequate output signal. The common procedure is to apply a modulating magnetic field superimposed on the scanning field and use phase-sensitive detection and lock-in amplification. However, for this work, it was found that non-adiabatic rapid passage through the resonance was more suitable [19]. In this approach, the magnetic field is continuously scanned, using a sawtooth waveform, and a multichannel analyzer, whose scans are synchronized to the magnetic field, accumulates the signals from each passage through the resonance. This continuous averaging process, developed by Klein and Barton [20], requires a total number of *n* scans, where the signals are added to produce an output whose amplitude is *n* times that of a single scan. On the other hand, the noise components add randomly, giving a noise signal $(n)^{1/2}$ times that for a single scan. Thus the signal-to-noise ratio increases as the square root of the number of scans. This is the same result that is obtained for the high-frequency components of the noise when a single, long scan is used. However, the long scan does not filter out low-frequency noise and tends to be upset by strong pulses or spikes, common in this type of application.

In this work the resonance signals produced by the hydrogen nuclei in water were fairly strong, and were visible even on a single passage through the resonance. It was thus possible to keep the number of scans to a reasonably small number and still achieve a good signal-to-noise ratio. A block diagram of the experimental arrangement is shown in Fig. 2. A Nicolet (Model 1062) digital computer, operating in the signal-average mode, was used as the multichannel analyzer. This computer employs an analogue-to-digital converter to transform the output voltage of the spectrometer to a form suitable for storage in the 1024 channels of the analyzer memory. The magnetic-field scan was driven from the channel address to set up a one-to-one correspondence between channel number and magnetic field. The memory contents of the Nicolet computer were viewed on an oscilloscope and the total accumulated spectrum recorded on an X–Y recorder.

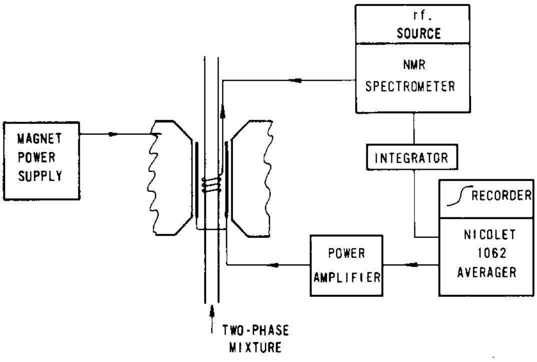

FIG. 2. Schematic diagram of NMR spectrometer.

The air supply for the experiments to be described in the following sections was tapped, via a pressure-reducing valve, from the general laboratory process air line, and the air flow was measured with a Matheson (Model 604) flow meter.

For the flow-simulation experiments, the water was driven through the spectrometer probe by a pumping system and the flow determined by a Brooks (Model 1306) flow meter. Pressure gauges were used on the air line just before the meter, and on the downstream side of the spectrometer coil, to aid in the determination of the quality of the fluid at the location of the probe.

STATIC VOID-FRACTION MEASUREMENTS

To achieve a system that would provide a wide range of void fractions that could be determined by an independent method, it was decided to use an air-bubble approach. A fixed, vertical column of liquid of length l_0, determined experimentally by a ruler, was supported on a porous plug in a 12 mm ID glass tube, which was capable of being inserted into the spectrometer probe. When air was introduced into the liquid through the plug, the bubbles produced increased the void fraction of the liquid. Measurement of the new liquid level, l_1, led directly to an absolute measurement of the void fraction, α, using the expression

$$\alpha = 1 - \left(\frac{l_0}{l_1}\right). \tag{3}$$

During the course of this work, it was found that acetone, containing a trace amount of glycerol, gave a liquid capable of sustaining a high bubble density, without slug formation. Such a mixture was able to support measurable void fractions up to 0.65.

To achieve higher void fractions, a soap–water mixture was used. Again, the original liquid column height, l_0, was measured, and by slowly passing air through the porous plug, a "head" of bubbles was created on the surface of the water, with a corresponding decrease in the height of the liquid column to l_2. The water represented by the length l_0–l_2 was now present in the bubble head, of length l_3, so that the void fraction of the bubble portion was given by

$$\alpha = 1 - \left(\frac{l_0 - l_2}{l_3}\right). \tag{4}$$

By using different porous plugs, different bubble sizes were created, leading to a variety of void fractions.

The NMR signals from the ^{1}H nuclei in the fluids were recorded for the appropriate bubble conditions and also for the liquid alone, using various signal-processing techniques. The measurements with the liquid allowed normalization of the results obtained from the bubble experiments.

A series of measurements was made under fast-passage conditions, with the spectrometer operating at 24 MHz and the subsidiary coils sweeping the magnetic field through a range of 2 G, at a frequency of 25 Hz. Because of the small linewidth of the ^{1}H resonance in the liquid, it was felt that this approach encroached on the limits of magnet stability ($\pm$100 mG). This caused an irreproducible broadening of the resonance linewidth and made it impossible to use peak height as a measure of the strength of the resonance.

To overcome this problem, the signal from the spectrometer was passed through a filter with a time constant of 100 ms, to integrate the detected absorption signal before storing it in the averager. The area under the absorption curve was thus represented by the vertical height of the signal step recorded in the computer memory. This approach is intrinsically independent of magnet stability, within reasonable limits.

Void fractions less than 0.6 were produced by bubbling air through the liquid. Since such a process is inherently noisy, NMR measurements were made over a period of typically 10 s, to obtain steady average readings. The liquid column height was typically 150 mm, of which the detector coil sampled approximately 5 mm. Hence, the column height, which included end-effects, was an adequate, although not an exact measurement of the void fraction recorded by the detector coil.

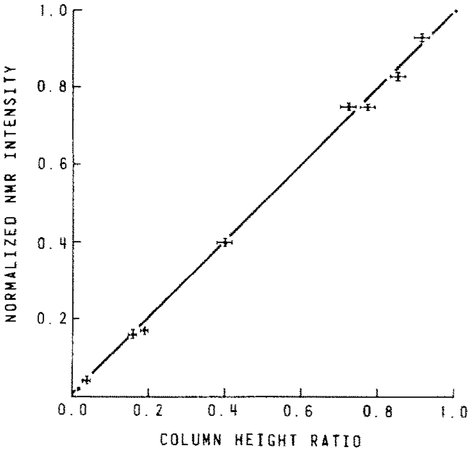

FIG. 3. Static void-fraction measurements, using a fast passage through the resonance and a signal integration process.

Figure 3 shows the results of the experiments using the integration procedure described above. The normalized absorption signal shows a linear dependence on the void fraction of the fluid, represented by the column height ratio, defined as (l_0/l_1) with the bubbles in the liquid, and $[(l_0 - l_2)/l_3]$ for the bubble-head experiments. The one-to-one correspondence between the integrated NMR signal and the absolute void-fraction of the fluid indicates that the technique is independent of the distribution of the liquid within the sensitive volume of the probe, for the liquids used in these experiments. This was further confirmed by another set of experiments in which sample tubes of various diameters were introduced into the probe. These results gave a close linear relationship between the NMR signal intensity and the cross-sectional area of the sampled water.

These results suggest that the NMR output signal is independent of the liquid distribution (and thus the flow regime) in a two-phase mixture.

VOID-FRACTION MEASUREMENTS IN FLOWING SYSTEMS

To determine the effect of spin-lattice relaxation time on the ^{1}H NMR signal intensity with a flowing fluid, preliminary experiments were performed with normal tap water flowing through a 12 mm ID tube inserted into the spectrometer probe. The integrated resonance signals from this single-phase fluid were measured for different flow rates.

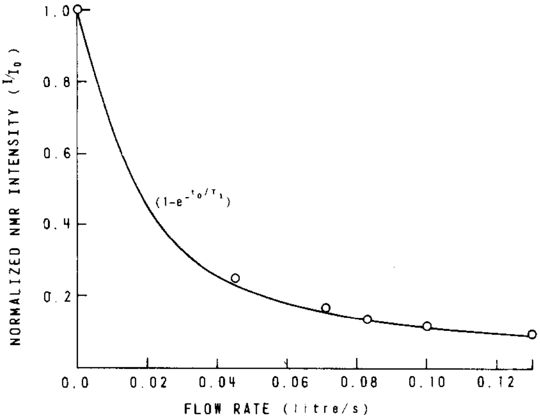

FIG. 4. Variation of the NMR signal intensity with flow rate for a single-phase water system.

The variation of the intensity of the ^1H NMR absorption signal with tap water alone, as a function of flow rate through the spectrometer probe, is shown in Fig. 4. The decrease in signal intensity with increasing flow rate is due to the relatively long spin-lattice relaxation time of the ^1H nuclei in normal tap water.

When the nuclei, flowing into the spectrometer probe, first experience the magnetic field, the populations of the two energy states are equal, since prior to entering the field the nuclear spins are randomly oriented. If the nuclei are maintained in the field, the population distribution will relax with the characteristic time, T_1, to the condition described by equation (2). The flow rate determines the time, t_0, after entering the magnetic field, when the population distribution is sampled by the spectrometer, at the centre of the magnetic field. The NMR signal intensity, I, is a function of the net nuclear magnetism of the sample and is thus a function of the time spent in the magnetic field and T_1. The variation of I with t_0 is given by

$$I = I_0\left[1-\exp\left(-\frac{t_0}{T_1}\right)\right] \qquad (5)$$

where I_0 is the maximum signal intensity, measured with zero flow. Using an effective radius of 23.9 cm for the magnetic field, to determine t_0 from the measured flow rates, and a T_1 value of 2.3 s for ^1H in water [21], gives the continuous curve shown in Fig. 4. The good agreement between the experimental results and equation (5) demonstrates one way in which NMR may be used to measure the average flow rate of a single-phase fluid without the need for pipe penetrations or other devices that could disturb the flow.

These experiments indicate that to avoid problems associated with relaxation-time effects, in interpreting results from flowing fluids, it is necessary to perform the experiments with $t_0 \gg T_1$. This may be achieved by either having low flow-rates or using a fluid with nuclei having a sufficiently short T_1. However, if this is not possible, equation (5) above shows how one can correct for such an effect, should the need arise.

Following these preliminary experiments, a complete flow system was set up so that measurable flows of air and water could be driven through the tube inserted in the spectrometer probe, thus providing two-phase mixtures with a wide range of qualities. To satisfy the condition $t_0 \gg T_1$, the water was contained in a closed-loop system and doped with the paramagnetic salt $CuSO_4 \cdot 5H_2O$ [22]. The copper sulphate was added until no difference in NMR intensity could be observed between maximum flow and stationary water conditions.

To determine the relaxation time of the ^1H nuclei in the doped solution, a separate experiment was performed, using a tone-burst sequence, as described by Look and Locker [23]. However, it was not possible to saturate the resonance and a value for T_1 of $< 500\,\mu s$ is estimated from the known limitations of the experimental technique. Chemical analysis of the solution indicated a copper-ion concentration of 3.4 ions/ml. These results are not in agreement with those of Bloembergen *et al.* [22]. However, Goldman [24] has recently shown that the technique of progressive saturation of the absorption-mode signal, as used by Bloembergen *et al* [22], leads to results for T_1 which may be almost an order of magnitude too large.

From these relaxation-time measurements on water, with a paramagnetic impurity concentration of 1 part in 10^3, and with a magnet having an effective radius of 24 cm, the water velocity can be as high as 10 m/s and still produce a signal intensity within 1% of that from stationary water. For larger velocities, it is possible to increase the impurity concentration, or to make a correction to the observed signal intensities, using equation (5). The latter approach is less accurate, because of the exponential behaviour of signal intensity with t_0, which is dependent on flow rate.

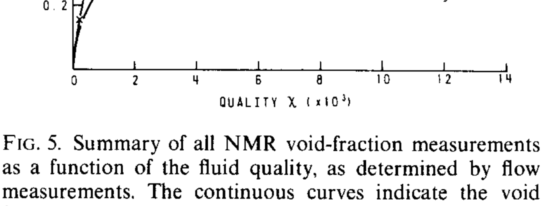

FIG. 5. Summary of all NMR void-fraction measurements as a function of the fluid quality, as determined by flow measurements. The continuous curves indicate the void fractions predicted by two different models, using the same flow measurements.

Measurements were then made under a wide variety of two-phase flow conditions in tubes of 9.3 mm and 12 mm ID, with both upward and downward co-current flows of air and water. The results are shown in Fig. 5, where the void fraction, α, determined by NMR is plotted against the quality, χ, of the two-phase mixture, determined from the liquid and air flow measurements, using the relationship,

$$\chi = \frac{Q_g \rho_g}{Q_g \rho_g + Q_l \rho_l} \tag{6}$$

where Q_g, Q_l are the volume flow rates of the gas and liquid, respectively, and ρ_p, ρ_l are the corresponding gas and liquid densities at the location of the spectrometer coil.

Also shown in Fig. 5 is the calculated relationship between void fraction and quality, assuming a homogeneous model in which no slip occurs between the liquid and gas in the two-phase system [1], and which is given by

$$\frac{1-\alpha}{\alpha} = \left(\frac{1-\chi}{\chi}\right)\frac{\rho_g}{\rho_l}. \tag{7}$$

For the case where the average velocity of the gas is different from that of the liquid, Lockhart and Martinelli [25] have derived a correlation which relates void fraction to quality, through the relevant viscosities, μ. This correlation is

$$\left(\frac{1-\alpha}{\alpha}\right) = 0.28\left(\frac{1-\chi}{\chi}\right)^{0.64}\left(\frac{\rho_g}{\rho_l}\right)^{0.36}\left(\frac{\mu_l}{\mu_g}\right)^{0.07}. \tag{8}$$

This relationship, for the conditions used in these experiments, is also shown in Fig. 5.

Under the usual condition for co-current upward flow, i.e. the average gas velocity is greater than or equal to the liquid velocity, the homogeneous model represents the upper limit of the void fraction for a particular fluid quality, whereas the Lockhart–Martinelli model is a better approximation for more annular-type flow. From Fig. 5, it can be seen that the results show that for the flow conditions of these particular experiments, homogeneous flow occurs in low-quality mixtures, for both flow directions, but as the quality increases the results tend toward the Lockhart–Martinelli correlation.

In general, these results are self-consistent and we believe that the discrepancies between the experimental results and the calculations are due to uncertainties in the flow-rate measurements, and the flow regime, rather than in the accuracy of the NMR measurements. For example, the two points at low quality with high void fractions were obtained under conditions of downward flow, with low water-flow rates. Although the air flow was also small, a pocket of gas was trapped inside the vertical tube which passed through the spectrometer probe. The gas was kept in equilibrium by the fact that its natural buoyancy was balanced by the drag force downwards due to the flowing water. This unknown negative (or zero) slip ratio leads to problems in defining void fractions from quality measurements. However, we believe the NMR results reflect the true void fraction that existed in the tube under those conditions.

The results that are summarized in Fig. 5 represent a wide range of experiments run under different conditions and some of these will now be discussed individually.

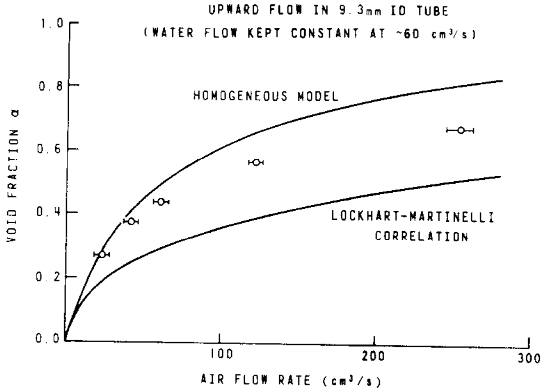

FIG. 6. Variation of the void fraction with air flow, for upward flow in a 9.3 mm ID tube, with water flow kept constant at ~60 cm³/s.

One set of measurements was performed with upward flow through the 9.3 mm ID tube. Figure 6 shows the results from those experiments, where the water flow was kept as constant as experimentally possible and the void fraction was determined as a function of the air flow. Once again, homogeneous flow is indicated for low air flows while a more annular-type flow regime became established for high air flows, corresponding to higher qualities for the fluid.

The problem of air holdup with downward flow, as described above, can be minimized by using high water flows. Figure 7 shows the results of a series of void-fraction measurements as a function of air flow for downward flow with relatively high, constant water flow. These results also indicate homogeneous flow at low void fractions and a transfer to annular flow at higher qualities.

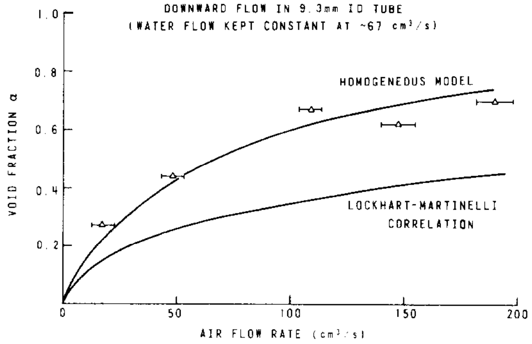

FIG. 7. Variation of void fraction with air flow, for downward flow in a 9.3 mm ID tube, with water flow kept constant at ~67 cm³/s.

Figure 8 shows similar results for the 12 mm ID tube, with upward flow and relatively low water flow. In this case a distinct change in flow behaviour is seen to occur between air-flow rates of 100 and 140 cm³/s. Visual observations confirmed this to be a change from churn to annular-type flow.

Measurements were also made in the larger tube with constant air-flow rate and varying water-flow rates. These results are shown in Fig. 9, and although there is poorer agreement with the models in this case,

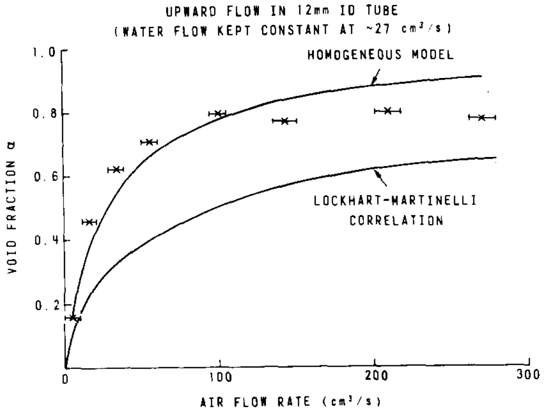

FIG. 8. Variation of void fraction with air flow, for upward flow in a 12 mm ID tube, with water flow kept constant at ~27 cm³/s.

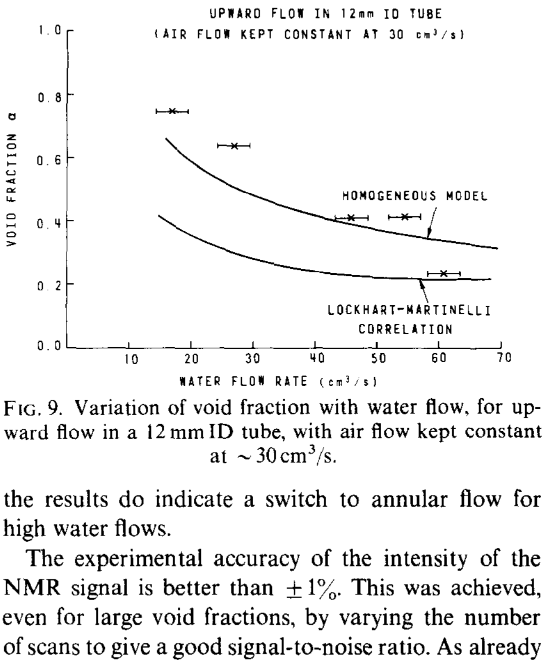

FIG. 9. Variation of void fraction with water flow, for upward flow in a 12 mm ID tube, with air flow kept constant at ~30 cm³/s.

the results do indicate a switch to annular flow for high water flows.

The experimental accuracy of the intensity of the NMR signal is better than ±1%. This was achieved, even for large void fractions, by varying the number of scans to give a good signal-to-noise ratio. As already noted, measurements were made throughout the test period on liquid only, for normalization purposes. For the twelve readings taken over a period of three days with H_2O in the 12 mm ID tube, the reproducibility was also better than ±1%.

For the flow-rate measurements, both flow meters had an accuracy of ±3% of full scale. This is the main source of inaccuracy in the quality measurements and the corresponding void fractions derived from the two theoretical models. The uncertainties in the flow-rate measurements are shown in Fig. 6–9.

As far as systematic errors are concerned, this is still uncertain. The flow measurements did not always agree with the void-fraction measurements as determined by NMR and it is suggested that this is due to the relative crudeness of the flow system and to limitations in the correlations.

SUMMARY AND CONCLUSIONS

The results obtained in this study indicate the feasibility of using NMR techniques for measuring void-fractions in two-phase systems, by measuring the nuclear magnetic resonance absorption in the liquid portion of the two-phase mixture.

Static experiments confirmed the linearity of the NMR signal intensity with void fraction of the fluid, and indicated independence of sensitivity to the mass distribution that may exist in the tube. This is not unexpected since the skin depth for the penetration of r.f. radiation into pure water is the order of several meters. This is of prime importance when cross-sectional averages, rather than point or local measurements of void fraction, are required.

Various data-handling procedures were investigated to find the most suitable method of determining the NMR signal intensity. It was found that the rapid-passage method was best, with the signal being integrated to yield the true resonance absorption strength.

Experiments on a flowing system have shown that relaxation-time problems can be overcome by doping the water with paramagnetic impurities. They also indicate that accurate measurements of void fraction are possible under a wide variety of flow conditions and adequate accuracy can be achieved by using signal-averaging techniques.

The experiments described have been limited to air–water mixtures in glass pipes. For application in steam–water systems, it should be borne in mind that the observed signal is a measure of the total hydrogen content, both in the steam and in the water. There is no reasonable upper limit for sample temperature. NMR experiments with identical configurations have been performed up to 1000°C. For low-pressure systems, provided the void fraction is not close to 1.0, the component of the signal from the steam is negligible compared to that from the liquid.

It is also possible to use the signal from hydrogen nuclei in liquids other than water. Freon, for example, is used in many heat-transfer experiments and has hydrogen as one of its major constituents. However, the technique is not limited to hydrogen-containing liquids since any nuclear resonance may be used. For example, it might be convenient to look at nuclei such as sodium or lithium, which could be introduced into water as a fixed concentration dopant.

The major limitation of the technique is the requirement for a non-metallic pipe section in the vicinity of the probe, to allow penetration of the r.f. field into the fluid under study. This could present problems for high-pressure, high-temperature systems. The use of hydrogen-containing pipes, such as lucite, is possible, provided allowance is made for the background signal arising from the pipe wall. However, perhaps the most important result of this study is that it appears possible to use NMR to accurately calibrate other devices suitable for use in high-pressure, high-temperature systems.

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MESURE DIRECTE DE LA FRACTION INERTE D'UN FLUIDE BIPHASIQUE PAR RESONANCE MAGNETIQUE NUCLEAIRE

Résumé—On a étudié l'application de la résonance magnétique nucléaire (RMN) à la mesure directe des fractions inertes dans les fluides biphasiques. Dans cette technique, la densité effective du fluide est déterminée en agissant sur l'intensité du signal RMN provenant d'une espèce nucléaire particulière présente dans le liquide. Les résultats provenant d'expériences effectuées à la fois sur des systèmes au repos et des systèmes en mouvement ont établi la linéarité de la méthode dans tout le domaine (0 → 1) de fractions de vide, indépendamment de la distribution des masses dans le liquide. Se trouve ainsi démontrée la possibilité d'utiliser la RMN comme méthode directe de mesure des fractions de vide dans les systèmes biphasiques.

DIREKTE MESSUNG DES GASVOLUMENANTEILS EINER ZWEIPHASENSTRÖMUNG MIT HILFE DER KERNMAGNETISCHEN RESONANZ

Zusammenfassung—Es wurde die Anwendung der kernmagnetischen Resonanz (NMR) zur direkten Messung des Gasvolumenanteils von Zweiphasenströmungen untersucht. Mit dieser Technik wird die effektive Dichte des Fluids bestimmt, indem die kernmagnetische Resonanz-Signalstärke einer bestimmten Kernspezies in der Flüssigkeit aufgezeichnet wird. Die Ergebnisse aus sowohl ruhenden wie strömenden Systemen zeigen die Linearität der Methode über den gesamten Bereich des Gasvolumenanteils (0 → 1), unabhängig von der Massenverteilung der Flüssigkeit und beweisen die Eignung der kernmagnetischen Resonanz-Methode zur direkten Messung des Gasvolumenanteils von Zweiphasensystemen.

ПРЯМОЕ ИЗМЕРЕНИЕ ПАРОСОДЕРЖАНИЯ В ДВУХФАЗНОЙ СРЕДЕ С ПОМОЩЬЮ ЯДЕРНОГО МАГНИТНОГО РЕЗОНАНСА

Аннотация — Изучалась возможность применения ядерного магнитного резонанса (ЯМР) для прямого измерения паросодержания двухфазных жидкостей. С помощью этого метода определялась эффективная плотность жидкости путем наблюдения за интенсивностью сигнала ЯМР от определенного вида ядер, находящихся в жидкости. Результаты экспериментов как для статических, так и для текучих систем позволяют сделать вывод о линейности метода для всего диапазона (0 → 1) паросодержаний независимо от распределения массы жидкости, а также показывают возможности применения ЯМР как метода прямого измерения паросодержания в двухфазных системах.