Density Profiles of a Draining Foam by Nuclear Magnetic Resonance Imaging

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Aqueous foams are used as drilling fluids in the petroleum industry and as fire fighting agents. In many applications, the effectiveness of a foam is related to its stability. A common method of characterizing stability is to measure the flow of liquid from the foam as a function of time. Foam drainage has recently been the subject of a detailed theoretical analysis by A. Kraynik (1983). In addition to predicting the drainage rate, the analysis modeled the density profile of the foam as a function of time. Such profiles are expected to be a fundamental measure of a draining foam's structure as well as a sensitive test of the theoretical drainage models. In this communication, we describe initial efforts to measure the density profiles of a draining foam by nuclear magnetic resonance imaging (NMRI) techniques.

NMRI, which is widely used in the medical field, is a relatively recent variation of nuclear magnetic resonance (NMR). The basic concepts of NMR theory have been discussed in a number of publications (Abragam, 1973; Slichter, 1978; Fukushima and Roeder, 1981), and that of NMRI in Morris (1986). NMR experiments are based on the absorption of RF (radio frequency) electromagnetic energy by certain atomic nuclei having nonzero nuclear spin angular momenta and, therefore, behaving as magnetic dipoles in a strong static magnetic field. In a uniform magnetic field B_o, each nuclear spin tends to align itself with B_o and gives rise to a macroscopic magnetization M_o along B_o which, by convention, is called the Z axis. An RF magnetic field of angular frequency

$$\omega_o = \gamma B_o$$

applied orthogonal to B_o will cause M_o to tip away from the Z axis. The gyromagnetic ratio γ is characteristic of the nuclei being studied, and $2\pi\omega_o$ is called the Larmor frequency. After the RF field is removed, M_o precesses around B_o with an angular frequency ω_o and induces a voltage in a surrounding RF coil. For the majority of NMR experiments, this signal is Fourier transformed to yield a frequency domain signal called the spectrum.

An imaging experiment employs linear magnetic field gradients of the static magnetic field in the desired directions (Morris, 1986). If the magnetic field B in the Z direction is

$$B = B_o + Gy$$

where $G = dB_z/dy$ is a gradient in the Y direction, then the precession frequency is given by $\omega = \gamma\ (B_o + Gy)$, which varies linearly with distance y. Thus, the spatial position y is linearly encoded with frequency, and the intensity of the frequency domain signal at any given frequency will be proportional to the number of spins present at that frequency or at that position y. This is the basic one-dimensional imaging experiment, which we have performed in this study.

Experimental

The foam studied was a stabilized aqueous foam (Rand, 1984) consisting of 97.8% water, 0.8% alpha olefin sulfonate surfactant, 0.2% polyacrylic acid-type polymer (Carbopol 941, manufactured by B. F. Goodrich), 0.2% *n*-dodcyl alcohol used as a stabilizer, and 1.0% *n*-propanol solvent. The glass sample tube was 1.8 cm inside diameter by 4.5 cm high with a polyethylene cap, and 25% of its volume was filled with the foamable liquid.

The experiment was performed on a Nalorac imager/spectrometer with a 1.89 T Oxford magnet. The pulse sequence is shown in Figure 1. The RF pulses were phase-cycled to remove the effect of ghosts and to cancel the FID's caused by imperfect pulses. The phase cycling consisted of $\pi/2(x) - \tau - \pi(y) -$ acq, $\pi/2(y) - \tau - \pi(-x) -$ acq, $\pi/2(x) - \tau - \pi(-y) -$ acq, $\pi/2(y) - \tau - \pi(x) -$ acq, with the data being added appropri-

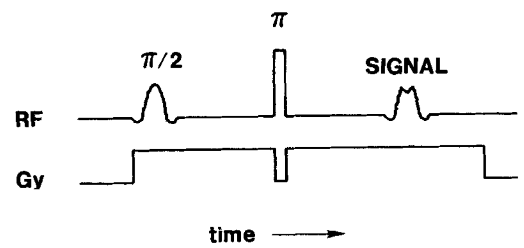

Figure 1. RF and magnetic field gradient pulse sequences used to image the draining foam.

ately. The value of τ was 4 ms, and a gradient of 1.25 G/cm was used for spatial encoding.

The foam was prepared by vigorously shaking the sample for 60 s. The tube was then placed in the horizontal bore of the magnet. Thus, the gradient of the static magnetic field is along the vertical direction and is perpendicular to the direction of the static field. The identical sample tube filled with water was used to calibrate the response of the RF coil. The density profile of the water sample is shown in Figure 2. If the reference spectrum of water is s_i, $i = 1, N$, and that of foam is f_i, $i = 1, N$, then the normalized spectrum for the foam is calculated as $F_i = f_i/s_i$ for $s_i \geq \theta$ and $F_i = f_i/s_m$, for $s_i < \theta$ where s_m is the average value of the reference spectrum and θ, an adjustable parameter, was set equal to $s_m/3$. In this way, each element of the foam spectrum is *normalized* to the response of the RF coil to that element except in the region of transition from zero to the full spectrum height at the edges of the reference spectrum. In these regions, the response of the RF coil is set equal to its average response over the sample volume.

Results and Discussion

The density profiles of the foam at various times are shown in Figures 3a–e. The earliest time at which the foam could be profiled was 20 after the agitation of the foam, and the density profile at 20 s evolved smoothly into the profiles recorded at longer times. The density at the top of the sample shows a significant departure from the step function expected for a uniform distribution of foam. The oscillating nature of the density is a combination of two opposing effects. First, a significant amount of liquid appears to adhere to the upper surface of the sample tube. This effect was observed when the sample tube was in the normal position, where the liquid was in contact with the polyethylene cap and when the sample tube was inverted, where the liquid was in contact with the bottom of the glass tube. Second, the density of the foam is quite low just below the upper surface of the sample. The extent of this area decreased somewhat as the tube was agitated more vigorously, but the low density could never be entirely eliminated by the manual procedure by which the foams were produced in this study. Visually the low density was found to consist of foam cells, which were much larger than the cells in the rest of foam.

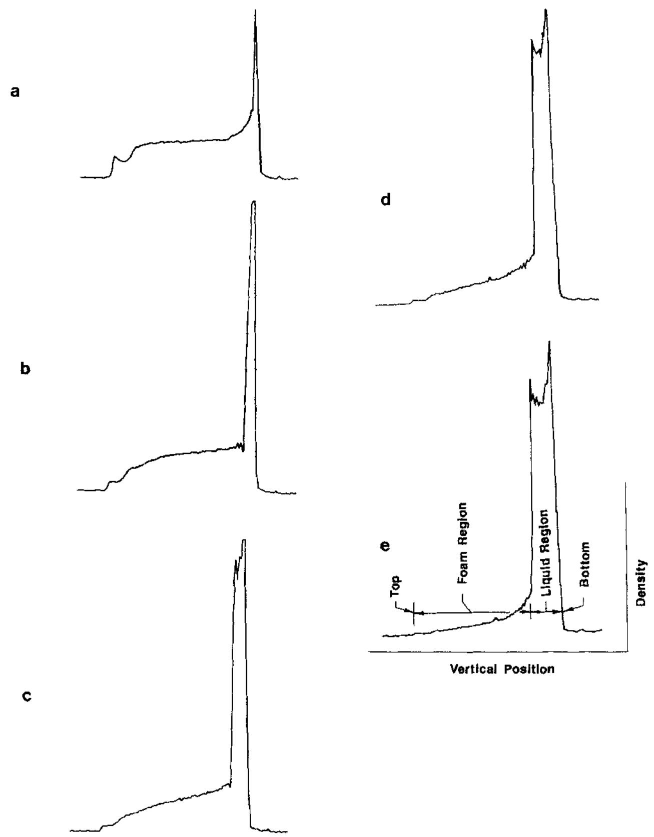

Figure 3. Complete density profiles of a draining aqueous foam for drainage times of: a) 20 s; b) 15 min; c) 30 min; d) 50 min; and e) 90 min.

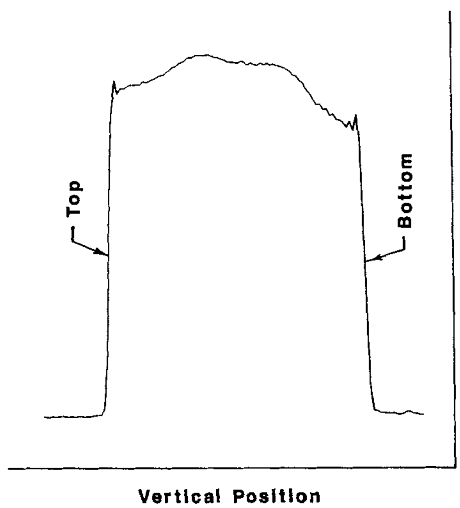

Figure 2. Density profile of the sample tube filled with water used to calibrate the response of the RF coil.

The experimental profiles were compared to a basic foam model developed by A. Kraynik (1983). The basic foam model treats the gravity-driven flow of liquid through a network of Plateau borders by assuming rigid gas-liquid interfaces, a uniform initial liquid volume fraction distribution and negligible liquid holdup in the films. Obviously, the assumption of a uniform initial liquid volume fraction distribution is not rigorously true for this system, particularly near the top of the sample. The model can be used to predict the density profiles of a draining foam as a function of time if t_o, a time scale of the experiment, is known. In principle, t_o can be calculated from properties of the foam and foam container. For the basic model, however, t_o corresponds to

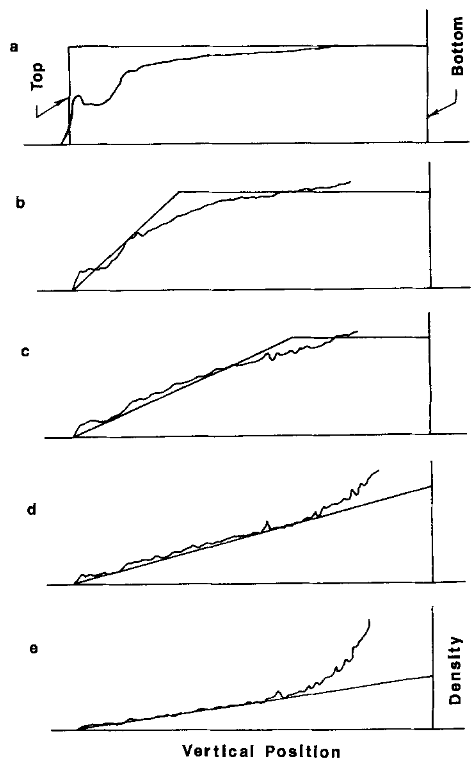

Figure 4. Experimental density profiles of a draining foam vs. those predicted by a basic foam model for drainage times of: a) 20 s; b) 15 min; c) 30 min; d) 50 min; and e) 90 min.

the time for half of the original liquid to drain. The model profile where $t = t_o$ was compared to several experimental profiles. The experimental density profile recorded at 50 min provided the best agreement between the model and experiment, and thus fixed t_o for the experimental conditions. A comparison between the experimental and basic model density profiles for several drainage times are shown in Figure 4.

The greatest deviation between the experimental density profiles and those predicted by the model occur at short drainage times. For short drainage times, i.e., $t = 0.3\ t_o$, the profile of the upper portion of the sample shows considerable curvature compared to the linear dependence of foam density vs. position predicted by the basic foam model. The effect of this curvature is to cause a reduction in density in the lower portion of the sample sooner than is predicted by the basic model. For long drainage times, $t = 1.8\ t_o$, the profile of the upper 60% of the sample is fit very well by the basic model but the experimental foam density just above the liquid portion of the sample increases smoothly compared to that predicted by the basic foam model.

Since the purpose of this work was to demonstrate the feasibility of profiling foam density by magnetic resonance imaging, an analysis of the factors causing these deviations is not appropriate at this time. Two changes in the experimental procedure should be made before a detailed comparison with the basic model can be attempted. First, changes in the preparation of foam must be made so that the system begins with a more uniform foam density. Second, in the experimental arrangement employed in this work, the liquid was allowed to accumulate in space originally occupied by the foam which differs from the model in which the liquid exits from the space originally occupied by the foam.

Acknowledgments

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