SPATIALLY RESOLVED NMR RELAXATION OF GAS IN CAVITATING LIQUID

Igor Mastikhin, Benedict Newling
MRI Centre, Dept. of Physics, University of New Brunswick, Fredericton, New Brunswick, Canada, E3B 5A3
mast@unb.ca

1. INTRODUCTION

Gaseous cavitation in water begins via formation of gaseous bubbles in the body of liquid from the previously dissolved gas due to an external pressure drop. An interaction between the liquid and the gaseous phases is quite complex in case of acoustic cavitation where an external sound pressure makes the appearing bubbles oscillate, leading either to their growth and coalescence, or to their collapse and fragmentation. Gas inside the bubbles is the subject to high pressures and temperatures resulting in chemical reactions and emission of light from cavitating liquids.

Quantitative information on the behaviour of gas in multibubble cavitation is difficult to obtain with optical and acoustical methods since bubbles are excellent sound absorbers and light reflectors. Nuclear Magnetic Resonance is a promising modality for cavitation studies as its signal can be modulated by molecular environment of nuclei under study. However, a drawback of gas NMR and MRI is its inherent low sensitivity: NMR signal is proportional to the number of spins which in gaseous samples is three orders of magnitude lower than in liquid. Therefore, when doing NMR of gas in cavitating liquid, one must employ a nuclear spin different than that of hydrogen, otherwise the useful signal from gas will be swamped by the signal from water. Non-hydrogen based gases should also be soluble in water to be able to participate in formation of bubbles.

Chlorodifluoromethane, also known as Freon-22, is very soluble in water (0.78 volume/volume at 25 C). It has two atoms of fluorine that can be engaged in NMR experiments with the NMR signal distinctly different from that of water. Its NMR relaxation parameters T1 and T2 depend very dramatically on the state of this compound. When Freon-22 is in a gaseous state, it has T1 of 2.5 and T2 of 1.4 ms at 2.35 T, while for the Freon completely dissolved in water, its T1 and T2 are 2 and 1.4 s correspondingly. Thus, with NMR measurements, it will be possible to distinguish between the two states of Freon-22.

2. METHOD

All experiments were performed on 2.35 T MRI scanner (Nalorac, TX) with 20 kHz Langevin type transducer (Sensor-Tech,ON) at standing wave conditions inside the water-filled cuvette (see Fig.1). Two sets of experiments were performed: CPMG without spatial resolution and SPRITE MRI with resolution along the length of the cuvette. CPMG sequences with saturation-recovery to measure T2 at various recovery delays were designed to provide information about the amount of Freon

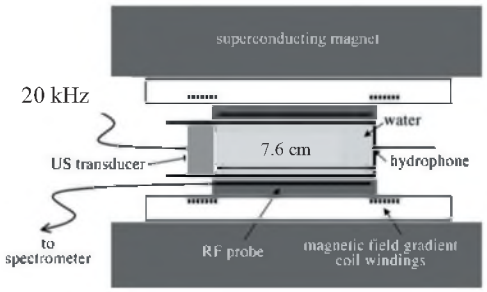

Figure 1. Experimental setup

in dissolved and free states before, during, and after cavitation. The signal intensity of the dissolved Freon was additionally saturated by a short recovery delay (1s) so that it was attenuated down to only 32% of its initial intensity. At the same time, the signal from a free gas would have no attenuation. Echo decays were fitted as bi-exponential, and the short and long components of the decays were attributed to free and dissolved states of Freon. Echo time was 300 us, with 1024 echoes and 64 scans. The saturation delay was incremented in 8 steps, from 10 ms to 1s. The total acquisition time for each series was 9 min.

SPRITE MRI (Single Point Ramped Imaging with T1-Enhancement, Balcom) was chosen for its insensitivity to presence of metal (the transducer) and its ability to detect NMR signal at short encoding times t_p. Signal intensity in SPRITE depends on the sample's T1, RF flip angle θ and repetition time TR:

$$S \propto e^{-t_p/T_2^*} \frac{1-e^{-TR/T_1}}{1-\cos\theta e^{-TR/T}} \sin\theta .$$

The imaging parameters were chosen so that the signal from the dissolved freon would be attenuated by a factor of 4 whereas the gaseous Freon would have no attenuation. With encoding time t_p of 380 μs, TR of 2 ms and 64 gradient steps, 4096 scans were accumulated with the total acquisition time for each series of 8 min.

3. RESULTS AND DISCUSSION

Before the cavitation onset, an amount of observable free gas in the cuvette was slightly above the noise level (0.86% of the total gas concentration). As soon as cavitation began, the amount of free gas increased, reaching 2.1%. After the transducer was turned off, the amount of free gas increased again and reached 5.9(3)% of the total gas concentration in the cuvette (see Fig.2). It should be pointed out that we do not necessarily detect NMR signal from all

Freon molecules that are present in the cuvette. Nuclear magnetization is sensitive to a temperature increase and local magnetic fields. If some portion of Freon is inside the cavitating bubbles, extreme conditions during the bubble collapse might destroy the freon's nuclear magnetization, thus masking the total amount of gas participating in the cavitation.

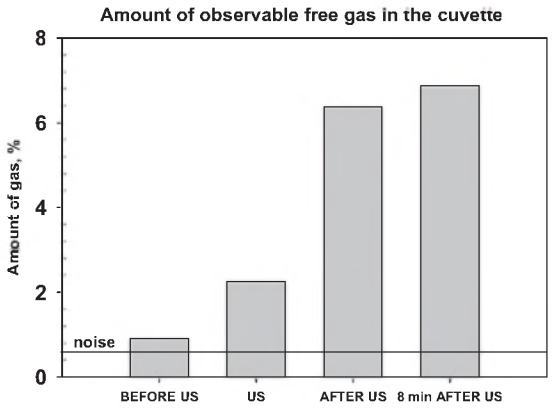

Figure 2. Amount of free gas before, during, and after cavitation.

The observed increase in the amount of free gas after the cavitation can be either due to the previously undetectable gas that has been released (which would give us information on total amount of gas inside the cavitating cloud) or due to some degassing mechanism taking place after the sound field has been switched off. Degassing power of cavitation is well-known; however, it is usually associated with the release of bubbles trapped by the sound field.

More information can extracted from a spatially-resolved data (Fig.3). Here we see a prominent increase in intensity near the centre of the cuvette, and two intensity drops on either side corresponding to a pressure node of the standing wave (the centre) and two pressure antinodes. In a standing wave, bubbles of a larger than a resonant size accumulate in a pressure node, whereas bubbles of a smaller than a resonant size accumulate in a pressure antinode (Leighton).(A resonant size radius for air bubbles in water at 20 kHz is about 0.15 mm).The signal increase in the centre indicates a presence of larger bubbles, its detection facilitated by an NMR T1 contrast mechanism that amplifies a signal from gaseous Freon by a factor of 4.

The signal decrease might mean a destruction of the nuclear magnetization by violent cavitation taking place in the antinodes: it has been argued that it is the smaller bubbles that are most chemically active, and it is from the antinodes the sonoluminescence is usually emitted in the standing wave (Leighton, Young). It is more likely, however, that smaller bubbles will cause local perturbations of the magnetic field due to a difference between magnetic permeabilities of water and gas, effectively dephasing, but not destroying, the freon's magnetization. That can be tested by repeating measurements at much shorter encoding times (50 μs vs. present 380 μs), with the subsequent conversion of the dephasing information into the bubble size distribution. We plan to perform such measurements in the near future.

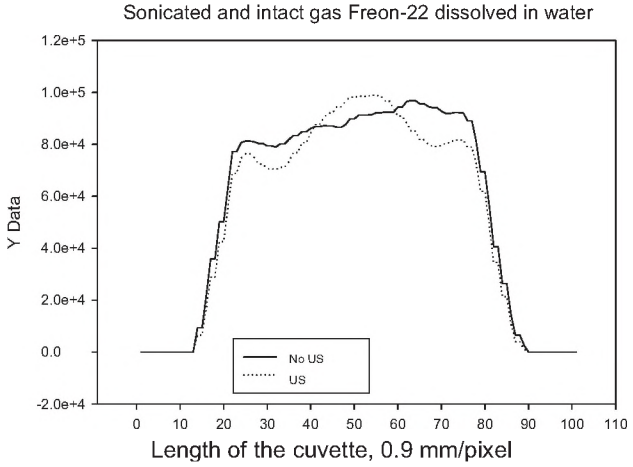

Figure 3. SPRITE profiles of Freon before and during cavitation

4. CONCLUSION

We have demonstrated, for the first time, a possibility of Magnetic Resonance Imaging of gas in cavitating fluid. MRI can provide us with unique information on the conditions inside cavitating cloud and states of both dissolved and free gas, showing great promise for a future research.

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