MAGNETIC RESONANCE IMAGING OF ACOUSTIC STREAMING IN GASES

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1. INTRODUCTION

Acoustic streaming is the motion of a fluid caused by the presence of a sound field. In the form first explained in detail by Lord Rayleigh [1], which occurs when a standing sound wave is established in an enclosure, a pattern of circulation from node to antinode is developed (Figure 1).

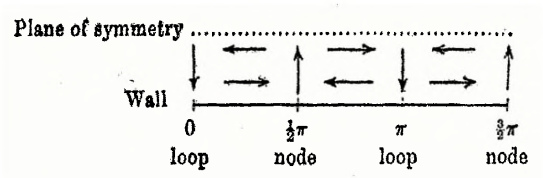

Figure 1. Illustration from Rayleigh's 1884 paper on acoustic streaming. The plane of symmetry is the centre line of an enclosing vessel.

The phenomenon of acoustic streaming has found application in cleaning, in mixing for microfluidics, and in cooling. In thermoacoustic engines, acoustic streaming is usually a parasitic effect, responsible for a reduction in efficiency. AS flows in gases are particularly delicate and quite difficult to measure, without disturbing the flow. Thus there is a need for non-invasive measurement methods in order to study important applications of AS. Laser doppler anemometry (LDA) is one possibility, but LDA cannot operate in optically opaque systems. In this paper, we demonstrate the utility of magnetic resonance imaging (MRI) as another possible measurement method for the study of AS in gases. Clinical magnetic resonance imaging (MRI) has developed at an astonishing pace in the thirty years since its inception. MRI outside the clinic is plagued by the short signal lifetimes (~ 10-4 s) of most materials, and has developed more slowly. Materials MRI has a generally lower signal-to-noise per unit time than most other imaging modalities (*e.g.* microscopies, X-ray tomography), but benefits from an extremely diverse array of possible image contrasts, which are manipulated through careful control of the spin physics during image acquisition. MR images can reflect many physical parameters including velocity and diffusivity.

2. METHOD

Both position and velocity sensitization are accomplished through the use of magnetic field gradients. The pulse sequence timing diagram of Figure 2 schematizes the history of sample manipulation during our measurement. This approach is termed the pulsed-field-gradient (PFG) spin echo [2].

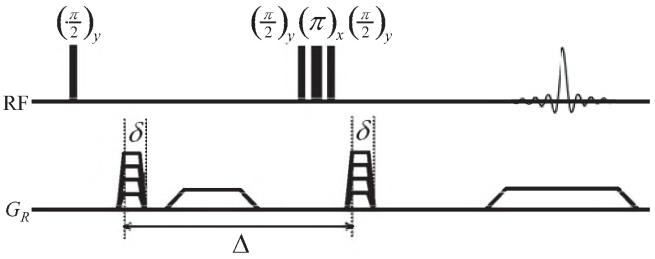

Figure 2. Pulse sequence timing diagram. On the RF axis are an excitation of the sample, an inversion of the magnetization and detection of the signal. On the G_R axis are applications of motion-sensitizing magnetic field gradient (two pulses, each of duration δ) and imaging gradient (longer, lower amplitude pulses).

3. RESULTS

The imaging sequence of figure 2 was applied at 2.4 T to a 2m-long 20-cm-diamter cylindrical tube filled with propane gas. The MRI signal from propane is long-lived for a gas (~ 10^{-2} s). One-dimensional images (profiles) of a 12-cm section near the centre of the tube are shown in the upper half of figure 3. The first data set (labeled "silent") shows 15 profiles, each acquired with a different amplitude of motion-sensitizing PFG (figure 2). The amplitude of PFG increases in the direction of the arrow. The upper row of data shows most attenuation and is most sensitized to motion. These 15 measurements were repeated five times, at roughly 15-minute intervals, before during and after the establishment of an acoustic standing wave at 835 Hz in the tube. The pattern of attenuation clearly changes in the presence of the sound field (indicating a change in the motion of the propane) and returns to its quiescent state when the sound is turned off. For quantification of this change, the 15 profiles are Fourier transformed along the dimension defined by the PFG amplitude. The resulting 5 images (lower half of figure 3) are collections of velocity spectra. Consider again the first ("silent") data set: the majority of propane appears in the central row and, therefore, has a velocity of 0 cm/s. The width of the spectrum represents the diffusivity (random motion) of the propane. The wider the velocity spectrum, the greater the

coefficient of diffusivity at that location. Before the sound field is applied, the velocity spectra along the length of the tube are identical. In the presence of the sound field ("835 Hz"), that uniformity is lost. The peak in the velocity spectrum clearly shifts towards negative velocities in the first part of the tube section, and towards positive velocities in the second part. Figure 4 shows velocity spectra extracted from figure 3 at the positions along the tube section which show the greatest difference from their quiescent counterparts. These positions are 7.27 cm apart. $\lambda/4$ calculated from literature data for the speed of sound in propane [3] is 7.25 cm (see figure 1).

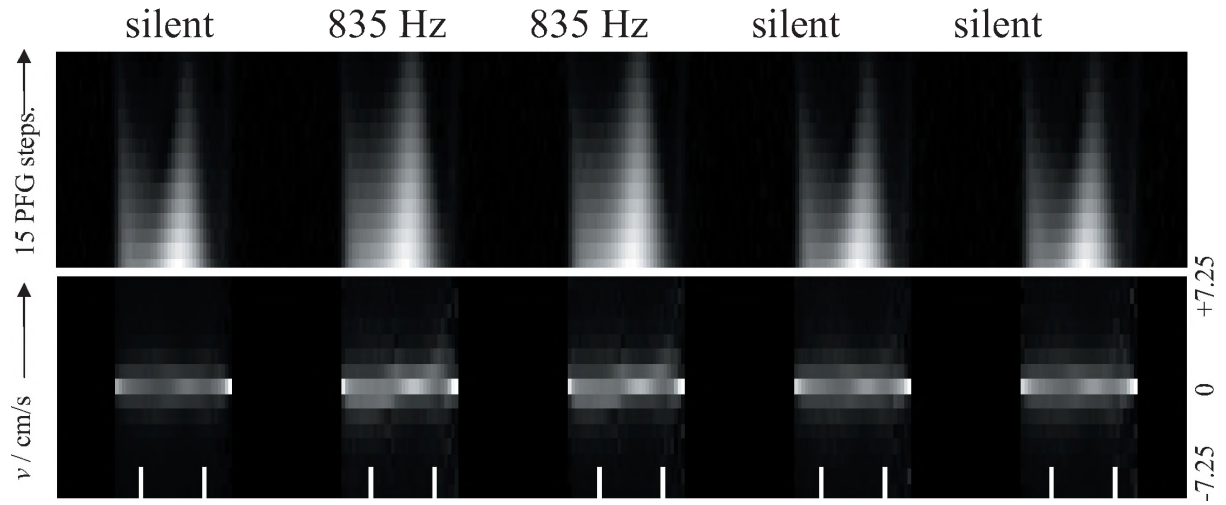

Figure 3. (Top) Five sets of profiles acquired before, during and after establishment of a standing sound wave in the tube. The section of the tube imaged is 12 cm long. Each profile is motion sensitized and 15 different profiles were acquired at each time, with increasing motion sensitization in the direction of the arrow, Fourier transformation along that dimension gives velocity spectra (Bottom), in which the horizontal axis is position along the tube, the vertical axis velocity (from –7.25 to +7.25 cm/s) and the brightness of each pixel is representative of the mass fraction of propane moving with that particular velocity at that position along the tube. Positive velocities are left to right along the tube section. The white vertical lines in each collection of velocity spectra, mark the positions of the spectra in figure 4.

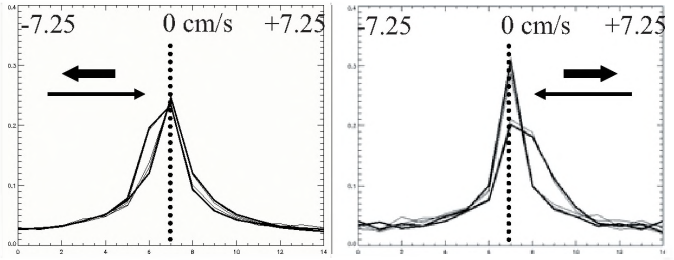

Figure 4. Velocity spectra selected from figure 3 at the positions indicated. Spectra from all 5 timepoints (before, during and after sound application) are overlaid. The profiles indicate a smaller mass fraction of faster counter flow (at the tube walls) as expected for developed Rayleigh streaming.

4. CONCLUSIONS

Magnetic resonance imaging is a completely non-invasive measurement method for the study of acoustic streaming in gases. MRI measurements will promote understanding in a variety of thermoacoustic applications.

5. REFERENCES

[1] Lord Rayleigh, *Proc. Royal Soc. of London*, **36** 10-11 (1884).
[2] P. T. Callaghan, *Principles of NMR Microscopy*, OUP (1991).
[3] Trusler & Zarari, *J. Chem. Thermodynamics* **28**, 329-335 (1996).