NATIONAL HIGH MAGNETIC FIELD LABORATORY
2018 ANNUAL RESEARCH REPORT

Phase Contrast MRI of Creeping Flows using Stimulated Echo

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Introduction

Creeping flows govern many important physiological phenomena such as glymphatic flows in the brain. However, few methods exist to measure such slow flows non-invasively in optically material. Phase-contrast MRI is a velocimetry technique routinely used in the clinic to measure fast flows in biological tissues, such as blood and cerebrospinal fluid (CSF), in the order of cm/s. Use of this technique to encode slower flows is hampered by diffusion weighting and phase error introduced by gradient hardware imperfections. In this study, a new PC-MRI technique was developed using stimulated echo preparation to overcome these challenges [1]. Flows as slow as 1 lm/s are measured and validated using controlled water flow through a pipe at 4.7 T. The error in measured flow rate obtained by integrating the measured velocity over the cross-sectional area of the pipe is less than 10%. The developed method was also able to capture slow natural convection flows appearing in liquids placed inside a horizontal bore magnet. Monitoring the 4D velocity vector field revealed that the natural convection flows decay exponentially with time.

Experimental - There should be one blank line Arial, 10 pt. space before each heading.

Flow was measured [1] in the 4.7 T magnet system of the NHMFL Advanced Magnetic Resonance Imaging and Spectroscopy Facility. Measuring 3D velocity requires four acquisitions per voxel with flow-encoding gradient polarities along the imaging gradient axes (i.e. read, phase and slice) systematically varied according to Hadamard encoding [2]. A stimulated echo phase-contrast MRI pulse sequence, with flow compensated imaging gradients, measured flow. Phase encode and read de-phase gradients were placed before the flow-encoding gradient to reduce image misalignment across the flow acquisitions due to varying eddy currents generated with flow-encoding gradient polarity switching.

Results and Discussion

As expected for pipe flow, the axial velocity profile (**Fig. 1**) was parabolic with a minimum flow sensitivity of ~ 1 micron/s, and errors in flow rate less than 10%. For natural convection flow (**Fig. 2**), stronger axial flows from Hadley convection vorticities (i.e. vorticity along +x using the right-hand rule), obtained in this study with gravity along -y, indicate temperature gradients in +z along the bore length of the magnet based. The asymmetry in the vortex could be from heterogeneity in the axial temperature gradient, since our magnet is enclosed at one end and has a door at the other end.

Conclusions

The effect of diffusion weighting, which randomizes the phase, was minimized using a stimulated echo preparation, while the phase errors arising from gradient imperfections were reduced by placing a time symmetry in the pulse sequence. The method was capable of measuring flows as slow as 1 micron/s with potential applications in materials research and *in vivo* with the brain and other organs.

Acknowledgements

The National High Magnetic Field Laboratory is supported by the National Science Foundation through NSF/DMR-1157490/1644779 and the State of Florida. This work is supported in part by the NIH/NCATS Clinical and Translational Science Award UL1 TR000064.

References

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[2] N.J. Pelc, N.J. et al, Journal of Magnetic Resonance Imaging **1**, 405–413 (1991)

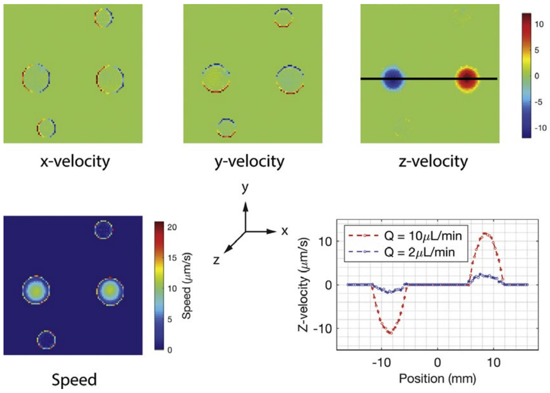

Fig.1 Measured water pipe flow. Two large tubes in the images contain flowing water, and smaller tubes contain 0.6% hydrogel as static control.

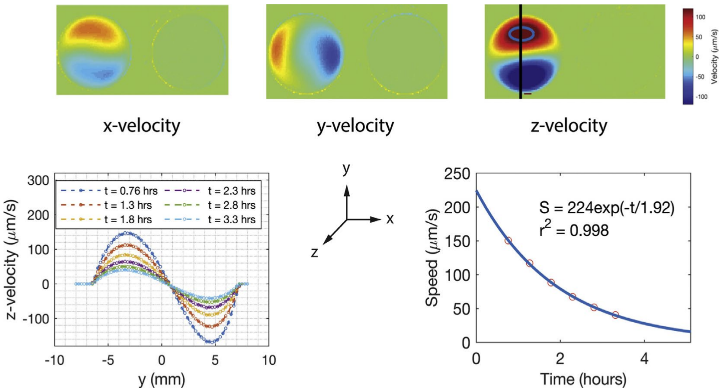

Fig.2 Measured natural convection inside a horizontal cylindrical tube filled with water and another tube filled with 0.6% hydrogel as a static control.