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Measuring Turbulence in Wall-Flow Filters using Compressed Sensing Gas-Phase Magnetic Resonance Imaging

Jonathan Cooper[1], Andrew York[2], Andrew Sederman[1], Lynn Gladden[1]*

1 Department of Chemical Engineering and Biotechnology, University of Cambridge, Philippa Fawcett Drive, Cambridge, CB3 0AS, UK;
2 Johnson Matthey Technology Centre, Blounts Court, Sonning Common, Reading, RG4 9NH, UK

**Corresponding author: lfg1@cam.ac.uk*

Highlights

- First reported experimental observation of turbulent flows in a wall-flow filter
- Velocity- and diffusion-encoded MRI used to visualize flow fields in filters
- 2D gas velocity images acquired in under 14 min at 140 μm × 390 μm resolution
- 3D diffusion-weighted images acquired in under 1 h

1. Introduction

Wall-flow filters are an important technology used to reduce the particulate emissions of internal combustion engines [1] and are often combined with catalysts to create improved emission control systems. They require both high filtration efficiency to meet strict emission regulations and low pressure drop to maintain fuel economy and safe engine operation. Understanding the origins of pressure drop in filters is necessary to optimize their geometry and operating conditions. However, measurement of flow fields in these systems is challenging due to their optical opacity; hence studies have focused on *ex situ* measurements and numerical simulations. In particular, flow phenomena at the entrance and exit of filters is a significant contributor to pressure drop [2], yet few studies have been focused on these regions. It is well known that the sudden contraction and expansion of gas creates pressure losses [3], as caused by the filter geometry. Computational Fluid Dynamics has also predicted turbulent flows in these regions [4,5] that would contribute to pressure losses as well as influencing mass transfer of particulates. This study reports Nuclear Magnetic Resonance (NMR) measurements of these flow fields and their turbulent phenomena for the first time. These methods are non-invasive, applicable to opaque systems, allow sub-millimeter resolution and can encode diffusive and advective motion. In particular, MRI can resolve turbulent flow directly [6] and indirectly through turbulent diffusivity measurements [7].

2. Methods

All magnetic resonance experiments were performed using a 9.4 T superconducting magnet controlled by a Bruker AV400 spectrometer tuned to 376.6 MHz. A 25 mm birdcage coil was used for excitation and signal detection. Spatial encoding was provided by thee orthogonal magnetic field gradients with a maximum strength of 146 G cm^{-1}. Sulfur hexafluoride gas was used due to its high NMR sensitivity and favourable physical and chemical properties [8]. A spin-echo single point imaging sequence was implemented, using pulsed field gradients to provide velocity and diffusion encoding [9]. 2D axial velocity-encoded images were acquired in both the transverse and axial planes in under 14 min, while 3D diffusion-weighted images were acquired in 1 h per image, both at sub-millimeter resolution. Turbulent diffusivity maps were obtained using the method of Kuethe [10], using the equation

$$D_{turb} \propto \log s_s - \log s_f$$

where D_{turb} is the turbulent diffusivity map, and s_s and s_f are diffusion weighted images of the stationary and flowing gas respectively, and the proportionality constant is determined by the experimental parameters [7]. Compressed sensing under-sampled acquisition and reconstruction methods were implemented, allowing a reduction in acquisition time of up to 5 times. A cylindrical sample of an aluminium titanate diesel particulate filter (DPF) was held in a specially designed flow cell inside the spectrometer and connected to a recirculating gas rig, allowing pressurized sulfur hexafluoride to be flowed through the sample. The Reynolds numbers of flow in the channels, based on the channel diameter, were matched to those expected in a real filter during normal driving conditions (between 100 and 2000).

3. Results and discussion

2D images of the gas axial velocity were acquired at both the filter entrance and exit. The contraction of gas into the entrance appeared smooth and well behaved, while expansion at the exit took the form of parallel jets with regions of recirculating flows between them (Figure 1a). 3D maps allowed the microscopic turbulence distribution to be measured in addition to its relationship with the macroscopic flow field (Figure 1b). Further regions of high diffusivity were observed inside the filter channels, possibly arising from transverse flows through the filter walls. The images revealed a substantial level of non-uniformity in flow between the individual channels.

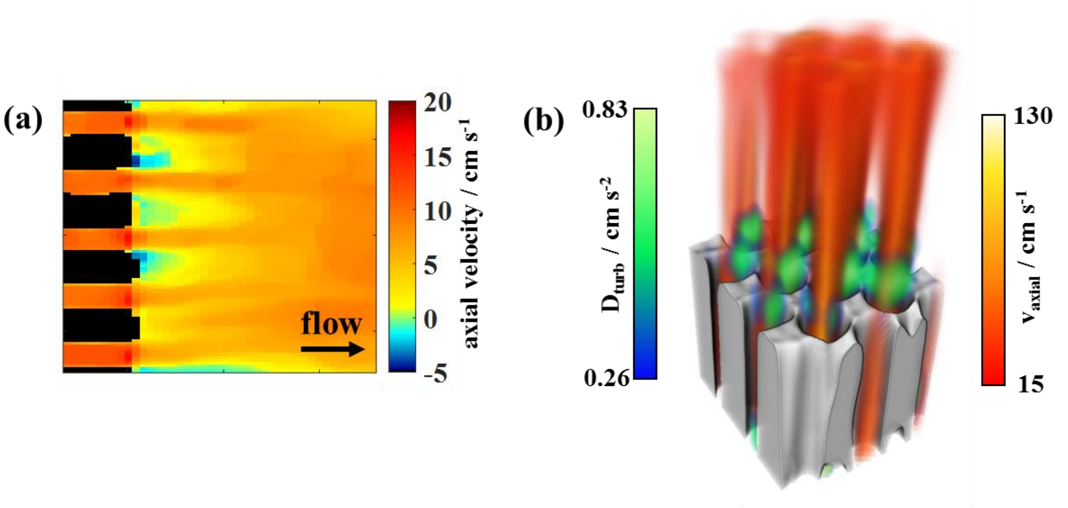

Figure 1. (a) Axial velocity distributions at the exit region of a DPF sample at Re = 360. (b) 3D axial velocity (red/orange) and turbulent diffusivity (green/blue) distributions at a DPF exit at Re = 1190.

4. Conclusions

Using state-of-the-art MRI methods, the velocity and turbulence distributions have been measured in a wall-flow filter for the first time. This has allowed direct observation of the flow phenomena present at the entrance and exit regions that contribute to the pressure drop of the system. These measurements provide data for both input to, and comparison with, numerical simulations.

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Keywords
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