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Magnetic resonance velocity imaging of gas flow in a diesel particulate filter

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ABSTRACT

Magnetic resonance (MR) velocity imaging has been used to investigate the gas flow in a diesel particulate filter (DPF), with sulphur hexafluoride (SF_6) being used as the MR-active gas. Images of the axial velocity were acquired at ten evenly spaced positions along the length of the filter, for three flow conditions corresponding to Reynolds number of Re = 106, 254 and 428 in the filter channels. From the velocity images, averaged axial and through-wall velocity, as a function of position along the length of the filter, have been obtained. These experimentally obtained velocity profiles are analysed and a qualitative comparison with the results of previously reported numerical simulations is made. The MR measurements were used in subsequent analysis to quantify the uniformity of the through-wall velocity profiles. From this it was observed that for higher Re flows, the through-wall velocity profile became less uniform, and the implications that this has on particulate matter deposition are discussed. The MR technique demonstrated herein provides a useful method to advance our understanding of hydrodynamics and mass transfer within DPFs and also for the validation of numerical simulations used in their design and optimization.

1. Introduction

During the operation of a diesel engine, particulate matter (PM) will form during the fuel combustion process as a result of imperfect mixing at the molecular level between the fuel droplets and oxygen (van Setten et al., 2001). In recent years diesel engine design has improved to produce lower particulate emissions, however there is still a need for onboard emission control systems to reduce the PM content in the exhaust gas. The diesel particulate filter (DPF) is currently the most widely used technology to achieve compliance with government legislation such as the EURO 6 directive which currently sets the limit of PM emissions to be 5 mg km^{-1}. At their simplest level DPFs are used to physically filter PM from the exhaust gas. However, in order to meet these increasingly stringent legislated limits, multifunctional systems incorporating a catalyst, so-called catalyzed DPFs, have also been developed (Ahmadinejad et al., 2007; York et al., 2009; Watling et al., 2012).

DPFs typically take the form of a porous ceramic substrate made from cordierite, silicon carbide or aluminium titanate. These materials are chosen for automotive applications as they are suited to the harsh environments encountered in the exhaust. Typically these materials exhibit a high mechanical strength, are resistant to high temperatures and temperature shocks and possess a low thermal expansion coefficient (Lachman and Williams, 1992; Williams, 2001). DPFs are comprised of many parallel channels separated by permeable walls with opposite ends of the adjacent channels plugged in a 'checkerboard' pattern. Due to the structure of the DPF, the PM-laden exhaust gas enters the filter through the engine side inlet channels and because of the plugs, that are impermeable to the gas flow, the exhaust gas is forced to pass through the porous, permeable walls separating the channels. As the gas passes through this permeable wall, the PM is deposited on the wall of the inlet channel and the clean gas leaves through the outlet channel. To ensure that the filter operates for the lifetime of the vehicle and to avoid an excessive back-pressure on the engine, which results in a fuel penalty, the filter must be regenerated *via* a passive (continual) or active (periodic) process to remove the accumulated PM (Twigg, 2011).

It follows from the above that a good understanding of the influence of the exhaust gas flow on DPF performance is essential for the optimization of their design to achieve compliance with increasingly stringent emission legislations. To date, direct measurement of gas transport within a DPF has not been reported. Such measurements are particularly challenging because they require a non-invasive probe capable of imaging flow fields within an optically opaque medium. Instead, research has focussed on numerical modelling. The original model used to describe transport in a DPF was developed by Bissett (1984) and most subsequent models have derived in some part from this work (Koltsakis et al., 2013). Model validation has been achieved

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Nomenclature

Latin characters

d	diameter, m
D	self-diffusion coefficient, $m^2\ s^{-1}$
F	Fourier transform operator
G	magnetic field gradient vector, G cm^{-1}
g	flow-encoding magnetic field gradient vector, G cm^{-1}
g	flow-encoding magnetic field gradient, G cm^{-1}
J	regularisation functional
L	length, m
M	number of axial velocity measurements
N	number of through-wall velocity calculated values
NUI	non-uniformity index
Re	Reynolds number
S	compressed sensing under-sampling pattern
Stk	Stokes number
TV	Total Variation
t	time, s
v	velocity, m s^{-1}
w	wall thickness, m
x	matrix form of image to be reconstructed
y	matrix form of image raw data

Greek symbols

α	regularisation parameter
γ	gyromagnetic ratio, rad $s^{-1}\ T^{-1}$
Δ	difference between two values, -
Δ	flow observation time, s
δ	flow-encoding gradient encoding time, s
ε	substrate porosity, %
μ	average through-wall velocity, m s^{-1}
μ	dynamic viscosity, Pa s
ν	experimental noise
ρ	molecular density, kg m^{-3}
σ	standard deviation of through-wall velocity, m s^{-1}
σ	standard deviation of noise

Subscripts

ave	average
c	channel
flow	motion-encoding direction
min	minimum
max	maximum
ph1	first phase-encoding direction
ph2	second phase-encoding direction
p	pore
slice	slice of excited spins
w	wall
xy	through-wall direction
z	axial direction

indirectly by comparison of model predictions with measurements of pressure drop (Torregrosa et al., 2011; Piscaglia and Ferrari, 2009; Piscaglia et al., 2010). Schejbal et al. (2009) have compared predictions of pressure drop across the filter, inlet and outlet temperature of the gas, and outlet concentrations of NO_x with experimental data from the Extra-Urban Drive Cycle (EUDC). Although a good agreement has been reached between the empirical evidence and the models, in each of these different studies the system was treated as a 'black box' and it was therefore not possible to include any information on the flow behaviour within the channels.

Further notable numerical studies include the work of Sbrizzai et al. (2005), Soldati et al. (2010), Bensaid et al. (2009, 2010) and Yu et al. (2013a), who have reported numerical simulations of gas flow within DPF structures and used these to explore how the gas flow influences, most notably, filtration efficiency and formation of the PM layer along the length of the inlet channel during operation. In particular, the study reported by Bensaid et al. (2009) has suggested that the uniformity of the PM layer that forms during operation is determined by the relationship between the structure of the filter, the nature of the PM and the gas flow fields within these systems. The PM deposition profile that forms during operation is important as calculations suggest that this can have significant effects on the temperature profile during filter regeneration (Yu et al., 2013a,b). For instance, if there is an uneven distribution of the PM due to a non-uniform through-wall velocity profile, oxidation will occur at different rates depending on the local PM content. Consequently, high thermal stresses in the filter can form as a result of the temperature gradients produced during combustion of the uneven PM deposit. If the temperatures and thermal stresses are high enough, this can lead to melting or cracking of the filter substrate and deactivation of the catalyst in the catalyzed DPF systems. Therefore, the requirement for a good understanding of the gas flow fields on the channel scale of the DPF is of the utmost importance for their design and optimization for specific applications.

The present work employs magnetic resonance (MR) velocity imaging to measure directly the flow velocities along the DPF channels. MR velocity imaging is particularly well suited to such measurements because it is truly non-invasive, there is no need for tracer particles and optically opaque systems can be studied. This is not the case for other flow measurement techniques such as particle imaging velocimetry (PIV), laser Doppler velocimetry (LDV) or hot wire anemometry (HWA). Further, MR velocity imaging has the advantage that it is able to acquire one, two and three-dimensional images of the flow field depending on the nature of the system and the information required. MR velocity imaging is well-established as an experimental technique for investigating liquid flows; however, imaging studies of gas flows are relatively few. This is mainly due to challenges associated with the low signal-to-noise (SNR) ratio presented to the experimentalist; in particular due to the low molecular density of the gas phase, which is typically around three orders of magnitude lower than that of liquids. Gases also exhibit a higher self-diffusion coefficient than liquids which can result in a greater degree of diffusive attenuation of the signal and blurring of the image (Sankey et al., 2009). However despite these challenges, the importance of gas phase transport processes in a range of applications, such as reaction engineering and aerodynamics research, has been an incentive to develop the capability to implement these measurements.

Newling (2008) provides a thorough review of the gas flow measurements using nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) and a brief summary of the literature relevant to the present study is now given. Of particular relevance to the present work is the use of gas phase NMR in the study of porous materials. For example, Koptyug and co-workers have demonstrated the acquisition of two-dimensional MR velocity images of hydrocarbon gases at atmospheric pressure flowing through a cylindrical pipe and alumina monoliths of different channel geometries (Koptyug et al., 2000, 2001, 2002). In the monolith studies (Koptyug et al., 2000), the feasibility of using MR velocity imaging to investigate the flow of thermally-polarised hydrocarbon gases (acetylene, butane, propane) at ambient pressure with reasonable detection times (20–40 min) and a spatial resolution of 400 μm was successfully demonstrated. MR