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Pulsating flow in a planar diffuser upstream of automotive catalyst monoliths

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ABSTRACT

The flow distribution across automotive exhaust catalysts has a significant effect on their conversion efficiency. The exhaust gas is pulsating and flow distribution is a function of engine operating condition, namely speed (frequency) and load (flow rate). This study reports on flow measurements made across catalyst monoliths placed downstream of a wide-angled planar diffuser presented with pulsating flow. Cycle-resolved particle image velocimetry (PIV) measurements were made in the diffuser and hot wire anemometry (HWA) downstream of the monoliths. The ratio of pulse period to residence time within the diffuser (defined as the J factor) characterises the flow distribution. During acceleration the flow remained attached to the diffuser walls for some distance before separating near the diffuser inlet later in the cycle. Two cases with $J \sim 3.5$ resulted in very similar flow fields with the flow able to reattach downstream of the separation bubbles. With $J = 6.8$ separation occurred earlier with the flow field resembling, at the time of deceleration, the steady flow field. Increasing J from 3.5 to 6.8 resulted in greater flow maldistribution within the monoliths; steady flow producing the highest maldistribution in all cases for the same Re.

1. Introduction

Catalysts are used extensively in the automotive industry to reduce toxic pollutants from vehicle exhausts. They are usually ceramic monolith structures, comprised of several thousand channels, often of square cross-section, of small hydraulic diameter (∼1 mm). The catalyst materials (precious metals) are embedded in a thin washcoat which is applied to the channel walls thus providing a high surface area on which exhaust pollutants can react. The size and shape of the monolith depends on vehicle size and packaging constraints. Typically a monolith for a passenger vehicle would have a circular or oval cross-section of diameter and length ∼100 to 150 mm with cell densities normally varying between 31 and 140 cells/cm^2. Space constraints dictate that wide-angled diffusers are employed to connect the exhaust pipe to the front face of the catalysts. This leads to flow separation at the inlet to the diffuser and a non-uniform distribution of flow into the channels. Fig. 1 shows a typical assembly featuring a monolith located downstream of a wide-angled diffuser along with a representation of the flow field within the diffuser with steady flow. The exhaust stream is shown separating at the diffuser inlet forming a jet which traverses the body of the diffuser before spreading rapidly as it approaches the monolith. Part of the flow recirculates and part enters the monolith. Flow separation causes maldistributed flow and non-uniform heat flux within the monolith leading to premature deactivation of the catalyst in areas of high flow. Maldistributed flow in general will cause a reduction in conversion efficiency, an increase in system pressure loss and poor utilisation of the catalyst. Many studies have been performed over the years to investigate the effect of system geometry on flow distribution and converter performance; for example Howitt and Sekella (1974), Zygourakis (1989) and Weltens et al. (1993). Indeed the degree of flow uniformity across the monolith is often used as an indicator for the acceptability of a particular design with various indices being used to quantify this, e.g. Weltens et al. (1993) and Benjamin et al. (2002). The system geometry is often complex and the exhaust is pulsating and so predicting or measuring the flow across the monolith presents serious challenges.

To simplify the situation many studies have been conducted under the assumption that the flow can be considered as non-pulsating or steady. This approximates the situation where the catalyst is located at some considerable distance downstream of the exhaust ports, so-called under-body designs. Under such conditions measurements can be made using steady flow rigs which permit a more comprehensive analysis of the flow field within the diffuser and the flow distribution across the monolith. Because the flow is unidirectional as it exits the channels hot wire anemometry (HWA) or pitot traverse at the rear of the monolith can be used to quantify flow maldistribution. Such studies can provide useful correlations between flow distribution within the monolith, system geometry and monolith resistance (Benjamin et al. (1996)). PIV measurements in the upstream diffuser have also been reported by several groups for steady flow. Shuai et al. (2001)

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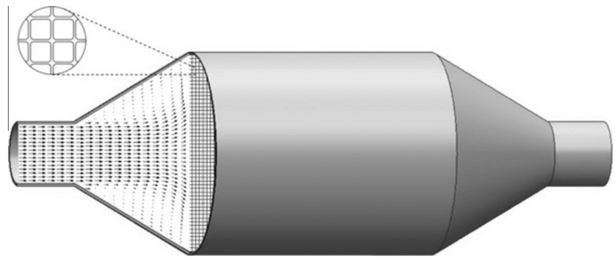

Fig. 1. Schematic showing catalyst configuration comprising a monolith in an exhaust system, catalyst channels and flow separation in the diffuser.

examined diffuser and monolith designs and compared measurements with computational fluid dynamic (CFD) predictions. In a recent study Turner et al. (2011) similarly studied the flow field upstream of a diesel particulate filter. Ilgner et al. (2001), made PIV measurements upstream of an auto-thermal gas reformer but significant image distortion due to wall curvature restricted the field of view where reliable data could be obtained. Using a planar diffuser optical distortion was minimised by Quadri et al. (2009a). By comparing the upstream flow field (PIV) with that measured downstream of the monolith using HWA it was demonstrated that the monolith radically redistributes the flow as it enters the channels.

Stricter emission legislation has meant catalysts are now located closer to the engine in order to reduce light-off times; so called close-coupled systems. For such configurations the flow is highly pulsating and a steady flow analysis is inappropriate. Pulsating flows through expanders have been the subject of limited studies. Budwig and Tavoularis (1995) measured the flow field in an open axisymmetric sudden expansion using a two-component LDV system under steady and pulsatile flows albeit at low Re ($\sim$120) and frequency ($\sim$0.2 Hz). They found that the pulsatile flow recirculation zone lengths revealed a dramatic departure from quasi-steady prediction; the instantaneous lengths correlating with the acceleration of the flow rather than the instantaneous Re. Under more representative flow conditions oscillating and pulsating PIV measurements have been obtained in open planar diffusers, Smith and King (2007) and King and Smith (2011). Their flow rig is capable of velocity oscillation amplitudes up to 50 m/s at frequencies of 7–120 Hz and steady flows up to 40 m/s. These are flow conditions more closely representative of engine exhausts. In Smith and King (2007) PIV measurements were made on diffusers with included angles up to 30°. With oscillating flow, during the acceleration part of the cycle, the flow remained attached in spite of very large adverse pressure gradients. During deceleration the flow was more prone to separation. Oscillating and pulsating flows at the same point of the cycle (start of deceleration) were also compared. For both cases flow is shown separating near the diffuser inlet but is able to reattach in the former case. In a recent study King and Smith (2011) reported on further observations made under oscillating conditions. Separation was found to begin high in the diffuser and propagated downward; the flow was able to remain attached further into the diffuser with larger Re, small displacement amplitudes and smaller diffuser angles. They also showed that the extent of flow separation grows with a non-dimensional displacement amplitude, a function of the maximum velocity and pulsation frequency. Conditions associated with exhaust after-treatment systems are however somewhat different in several key aspects; the flow is essentially pulsating and the proximity of the monolith will have a significant effect on flow development in the diffuser. Such studies that have been performed for these systems have been made using either rigs or running engines, e.g. Hwang et al. (1995), Bressler et al. (1996), Zhao et al. (1997), Park et al. (1998) and Benjamin et al. (2006). Whilst of great practical importance they most often feature "production type" exhausts which are geometrically complex providing limited access for flow measurements. A number of pulsating flow rig studies has also been reported using simpler axisymmetric geometries. Benjamin et al. (2001) measured the effect of flow pulsations on the flow distribution within ceramic contoured monoliths by measuring the cycle-averaged flow distribution at the exit to the monoliths using HWA. Contoured monoliths were shown to be less sensitive to changes in flow rate and pulsation frequency when compared to a standard monolith. Liu et al. (2003) investigated the effect of pulse shapes. Pulses with higher peak/mean ratio produced less maldistributed flow at all frequencies. Benjamin et al. (2002) studied the effect of pulse frequency (16–100 Hz) and Re (2×10^4–8×10^4) on the flow distribution within monoliths of different lengths with 60° and 180° diffusers. Both cycle-averaged and phase-averaged velocity profiles were presented. Flow maldistribution within the monolith was defined as a non-uniformity index ψ; the mass weighted standard deviation of the axial velocity across the monolith normalised to the average velocity. This index was shown to be determined by a non-dimensional parameter J (reciprocal of the Strouhal number) defined as the ratio of pulse period to residence time within the diffuser; as J increased ψ also increased. J is similar to the non-dimensional displacement amplitude introduced by King and Smith (2011). Persoons et al. (2003) found a similar correlation between their measure of flow uniformity and a scavenging ratio S (defined in a very similar way to J) for the case of a more complex system geometry.

Whilst these studies were able to derive useful correlations between flow maldistribution and system parameters it is often difficult to interpret the findings in terms of processes within the diffuser itself. This paper begins to address this issue by presenting measurements of the flow field both within a diffuser and downstream of the monolith in the presence of pulsating flow. The first objective of the study was to provide insight into the development of the pulsating flow field for a relatively simple yet representative after-treatment configuration. A second objective was to provide experimental data against which computational fluid dynamics (CFD) predictions could be assessed. Both objectives are seen as useful starting points before consideration of more complex, production-type systems.

2. Experimental method

Experiments were conducted under isothermal conditions at ambient temperature and similarity with hot engine exhaust was based on Re. For this study a planar wide-angled diffuser was chosen to enable maximum optical access and simplify measurement as the flow is approximately two-dimensional. Whilst idealised it is expected to show many of the flow features common to more complex systems and, to a first approximation, may be thought of as representative of oval or elliptical designs. Fig. 2 shows a schematic of the rig. It was supplied with compressed air via a plenum (2) incorporating a flow straightener (3) placed upstream of an axisymmetric nozzle (4). Pulsations are generated by a pulse generator (5) placed downstream of the nozzle as used in previous studies (Benjamin et al., 2002). A 12 mm aluminium housing contains a cast iron plate with four regularly spaced openings. A DC motor rotates the plate which periodically interrupts the flow. Timing signals and rotational speed are obtained from an optical-electrical transducer (±5 V output voltage) within the rotor assembly. Non-pulsating flow was achieved by fixing the rotor in one of its fully open positions. A flow straightener (6) was placed downstream of the rotor and a resonator box (7) was installed in order to shape the pulses. The plenum (8) mixes seeding particles