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The Effect of Pulsations in Conditions related to Catalytic Converters

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ABSTRACT

The effect of pulsations in a catalyst converter is investigated with the aim of determining if a steady flow captures the same physical phenomena as the pulsating flow. For this specific case, guide vanes are mounted in the sudden expansion to obtain a uniform inlet flow to the catalytic layers. The test rig is successfully validated against other similar measurements, done with a steady flow. The experiments are carried out with a Reynolds number of 10^5, a Womersley number orders of magnitude larger than 1, but with an ratio between the fluid though time and pulsation period below one. This last part results in a quasi-static boundary condition. For the present setup different amplitudes and pulsation frequencies are investigated. It is thus shown experimentally that they have no influence on the mean flow. A repeatability study has been conducted which shows an overall repeatability of around 2%. An error is observed, where unwanted fractions of the packing block parts of the catalyst dummy. These fractions influence the velocity fields by clogging the hules of the catalyst dummy, but the influence is assumed to be small. Based on the results it is concluded that the mean flow field for this case is independent of the pulsations. When air enters the system a vortex ring appears in front of the catalyst dummy.

1. Introduction

Pollution from cargo transportation is a large problem for the global environment. To restrain the growing emission, the United Nations (UN) have made regulations [1] to minimise especially SOx and NOx emission. One of the main contributors to the pollution is cargo transportation by ships powered by large diesel engines. These types of engines are forced to reduce the emission with up to 80%, if they want to enter the Northern American or main EU waters. One of the solutions to accomplish this major reduction is to use the Selective Catalytic Reduction (SCR) process. This process requires that a reductant is fully mixed into the exhaust gas before the mixture enters the catalyst. In the reactor, the mixture has to be uniformly distributed over the catalyst elements, in terms of the same velocity into the catalyst channels, which are placed immediately after the expansion. This velocity has to be lower than the velocity in the exhaust pipe to achieve the desired exposer time for the exhaust gas to the catalyst material. A common way is to expanding the volume often with an abrupt expansion and for the specific case at MAN Diesel and Turbo, the expansion factor is approximately 2.7. This leads to flow separation and detachment from the wall,

which leads to a non-uniform flow profile after the expansion. This is a known problem and described experimentally in multiple papers, where [2], [3] and [4] use Particle Image Velocimetry (PIV) to determined the velocity field in the expansion. Different solutions to the non-uniform flow profile are suggested. The automotive industry sometimes use a cone shaped monolith catalyst [5]. Other solutions could be to mount different devices in the inlet, as a honeycomb spherical arch [6] or a small cone shaped obstacle in the expansion [7]. A guide vane solution is used in the present study and is described in a previous study [8]. The guide vane based flow distributor makes the flow into the catalyst somewhat more uniform by creating a vortex ring in front of the catalyst.

The flow is pulsating with a frequency according to the number of pistons in the engine, with a positive mean offset. The flow can be described with the Womersley number

$$\text{Wo} = r \left(\frac{\omega \rho}{\mu} \right)^{0.5}$$

Where r is the pipe radius, ω is the frequency of the oscillations and ρ, μ are the properties of the fluid. If the Wo $\gg$ 1 it is assumed that the inertial forces are dominant in the center of the flow. For the specific analysed engines at MAN, the ranges of the Womersley number is Wo $\in 78 - 255$ and why the inertial forces are dominant.

The ratio between the flow through time retention and the pulsation period varies in an engine between 23 and 225. The flow through time is defined as the time for the flow to pass through the guide vanes and the first catalyst layer. The ratio is above one and the effect results in pulsation variations when passing the guide vanes and the first catalytic layer.

The current study investigates the effect of the pulsation flow on the guide vanes and with a flow straightener, acting as a catalyst dummy. The overall goal is to investigate the influence of the pulsations on the uniformity at the flow straightener, and whether an assumption of steady flow condition (no pulsations) is a reasonable model in an optimizing process done with Computational Fluid Dynamics (CFD).

Other studies have also investigate the pulsation effect on the velocity distribution, just for automotive catalyst system [9], where the pulsation frequency is higher. Here they show that for larger pulsation frequency the flow uniformity increase.

2. Setup

The experimental setup is an open loop water channel located at Technical University of Delft (TUD), Laboratory for Aero- and Hydrodynamics. The setup is illustrated in Fig. 1 and further described in [10]. The experiments are carried out at laboratory conditions with a Reynolds number of $Re_d \approx 10^5$, based on the volume flow from the flow meter and the small pipe diameter. This is chosen to be in a flow region with relatively little dependency of the Reynolds number. The volume flow is set by a gear pump, controlled with a frequency converter and measured with an Ultrasonic flowmeter UFM 500 [11]. u_{bulk} is the velocity in the inlet pipe to the converter based on the volume flow from the flowmeter. The temperature is slightly increasing due to dissipation in the system causing a maximum variation of 7 K. The effect on the viscosity and thereby the Reynolds number is assumed not to be important. The diffusor connecting the pipe and the converter abruptly expand within a length of 0.5d. The measuring area starts at the end of the expansion and cover the area around the catalyst dummy. The catalyst dummy, shown on the right in Fig. 1, is a model of a real catalyst in terms of flow area.

The guide vanes (flow distributor) is illustrated in Fig. 2. It is mounted in the sudden expansion to achieve a higher uniformity in the yz-plane before the catalyst layer. The guide vanes are joint together with three bars, creating three 'channels' for the fluid to pass though.
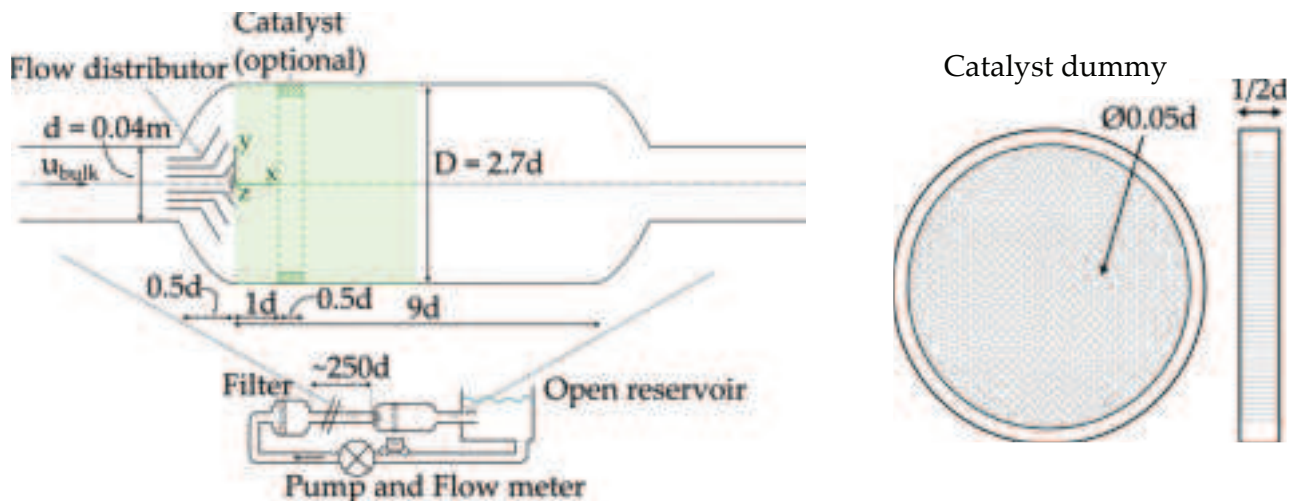
Fig. 1 Left: Schematic sketch of the setup, where all the important dimensions are shown. The coordinate system is shown on the center axis, just after the expansion. The green area shows the measurement area. Right: A model of the catalyst dummy, with the sizes of the bores shown.

Fig. 2 Flow distributor/guide vanes, where it is possible to see the tripartite guide vane construction. It is mounted in the sudden expansion.

Planar (2D2C) - PIV is used to measure the flow. Spherical hollow tracer particles [12], with a density of 1.10kg/m^3 and a mean size of 12 μm are suspended in the water. A double-cavity 572 nm Nd:YLF, New Wave Pegasus laser, with up to 10 mJ per pulse is used to create a light sheet with a thickness of 1 mm. The scatter light from the particles is recorded with one 4 MPixel CCD camera (2048 × 2048 pixel), with a 105 mm lens and a F-number of 4. The mapped area has a physical size of 0.13 × 0.13 m^2. In the PIV algorithm an interrogation area of 16 × 16px is used with a 50% overlap. An 5 × 5 outlier detection is applied.

The experiments are performed with constant flow or with pulsating flow. The pulsations are created as a sine wave, with a non-zero offset and an amplitude as a percentage of the offset. For each setting an initial delay has been applied to assure fully develop flow conditions before the measurements.

3. Results

Validation of the test rig is done by comparing two steady cases. One from the present test rig and one from a similar test rig at Technical University of Denmark (DTU) Laboratory of Fluid Mechanics. Here air is used as the fluid [13]. Both cases have a $Re_d \approx 110000$. The setup at DTU measure the velocity at a cross plane to the main flow direction with stereoscopic PIV. On Fig. 3 the validation case between the setup at DTU (air) and TUD (water) is shown. Both are with straight inlet and with the guide vanes mounted. The guide vanes are complex to manufacture and not physical mounted alike at the two test rigs. The results from the air experiment are rotated to obtain the same sampling line. The velocity profiles from the two experiments are in good agreement taking into account small geometrical differences between the two setups.

The system is set to pulsate with a constant sine wave and an example of the flow field is shown on Fig. 4. The catalyst dummy is mounted and shown as a white square. The pulsation frequency of the sine wave is 1 Hz with the amplitude of 25% of the mean flow at 2.6 l/s. It is measured with 5.25 Hz and by phase averaging accordingly to the input sine wave. 21 points resolution are obtained. Each point consist of 143 independent flow fields revealing the effect of one pulsation
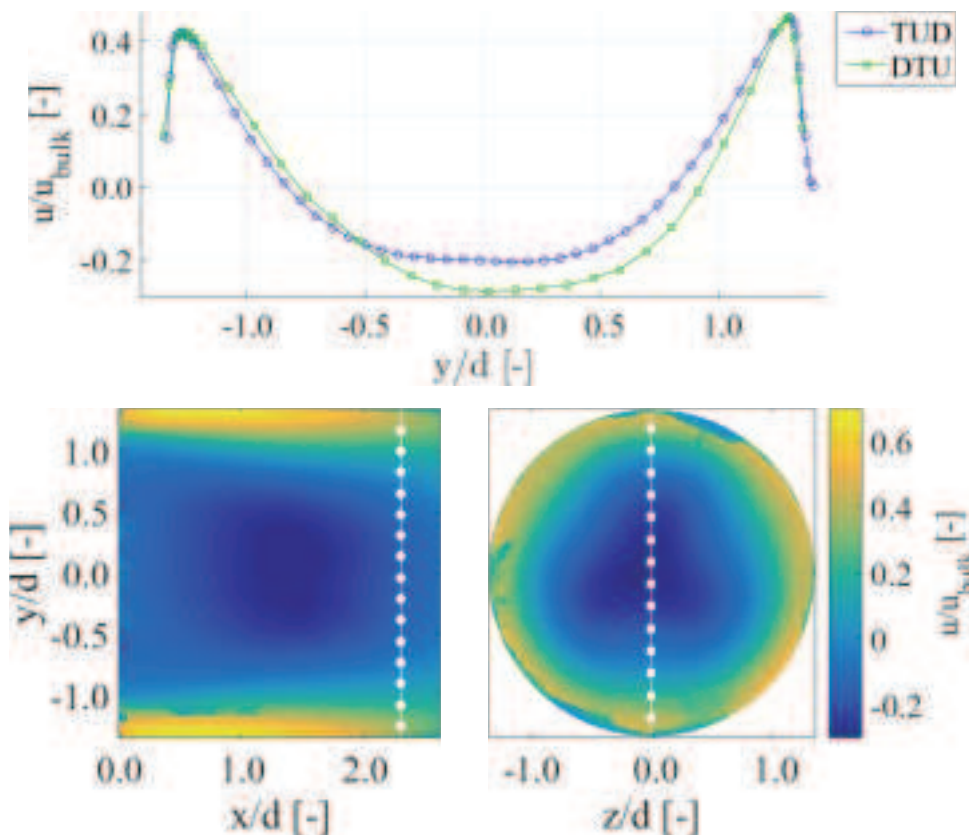
Fig. 3 Top view shows comparison between the steady cases for the setup at DTU(air) [8] and at TUD(water). Not all points are shown and the full line is used for better visualisation. At the bottom left the TUD case viewing the xy plane and right the DTU viewing the yz plane. The two cases overlap at the sample line shown on both plots as white marks.

cycle. Looking closely at the flow after the catalyst dummy one can see that the axial velocity changes over the y direction. This originate from the bores in the catalyst dummy, where some of the bores are illuminated directly by the laser sheet. Looking at the graph of the radial velocity on Fig. 4 it can be observed that it is almost zero except near the walls, where the geometry of the dummy creates a backwards facing step. The step is located at $x/d = 1.5$ and $y/d = \pm1.2$. This backwards facing step creates a burst of higher velocity at $y/d = \pm1$ and outwards for the axial velocity. This burst follows the pulsation frequency and scale with the flow magnitude and originates from the geometry of the catalyst dummy. This might have an influence on the uniformity on the next layer, but needs to be investigated further to see the effect of the geometry. The flow before the catalyst dummy is dominated by a vortex ring.
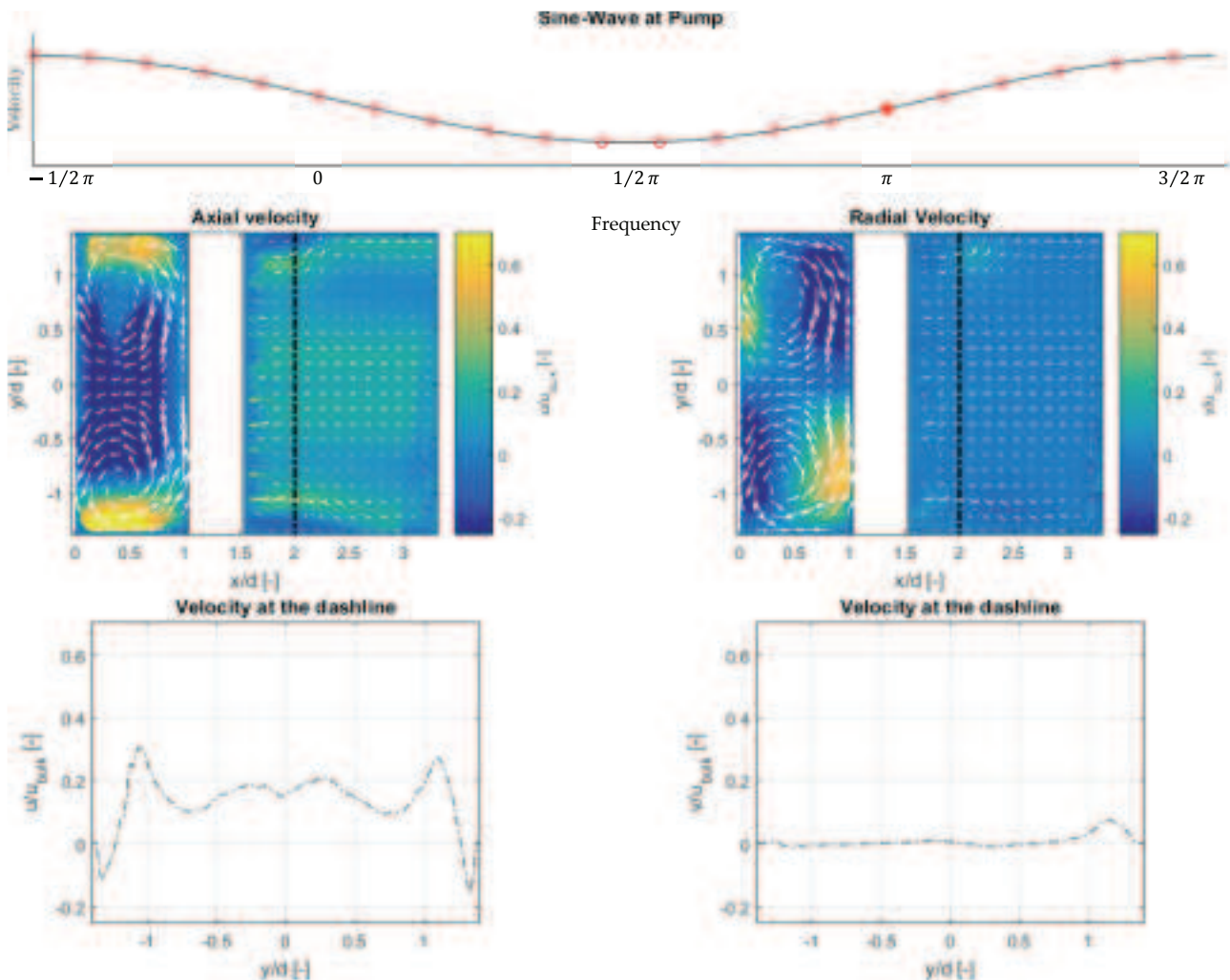

Fig. 4 Top: The sine wave prescribed to the pump, where the circles indicate the different sampling points and the full dot indicate the present case. Middle: Velocities in the measuring plane, where the white square is the catalyst dummy. The white arrows show the in-plane velocity, the colours show the magnitude of the velocity component, according to the label. Bottom: The velocity profile at the dashed line.

The phase averaging method mention above is investigated to determine if an average of the entire phase is valid. The phase average data are shown in Fig. 5, where velocity profiles at four magnitudes are plotted. It is seen that only the velocity magnitude changes as the amplitude goes from maximum to minimum, which indicates that an average of the entire phase is valid.

The influence of the pulsations are investigated with two different cases, both with and without the catalyst dummy. Both cases compare the mean flow for the entire phase, by an average of all sampled data. On Fig. 6 a mean velocity field for the steady and pulsation flow case is shown without the catalyst dummy. For the steady flow 5050 snapshots are sampled at 7.26Hz with a volume flow on 3.2 l/s. For the pulsation case 5000 snapshots are sampled at 5.25Hz. The amplitude was 25% of the mean flow of 2.6 l/s and the pulsation frequency at 0.5Hz.
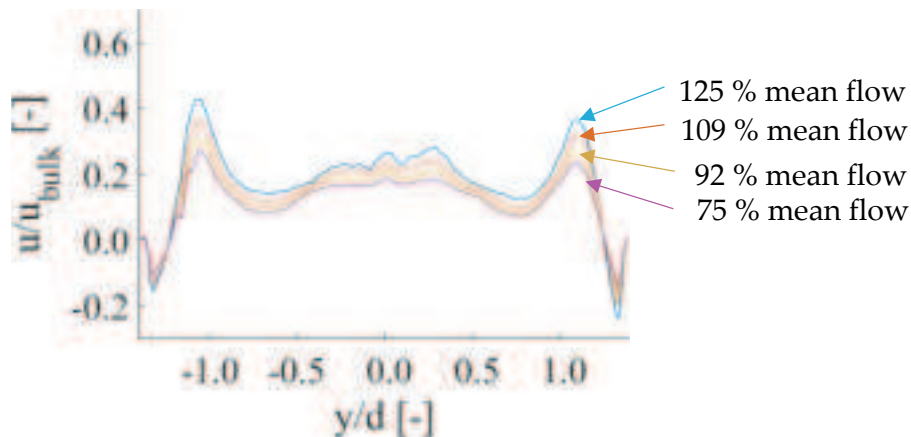

Fig. 5 Phase average velocity profiles at x/d = 2 with the catalyst dummy mounted. Only data from a half phase is shown going from maximum to minimum. The lines show the velocity at four different amplitudes.
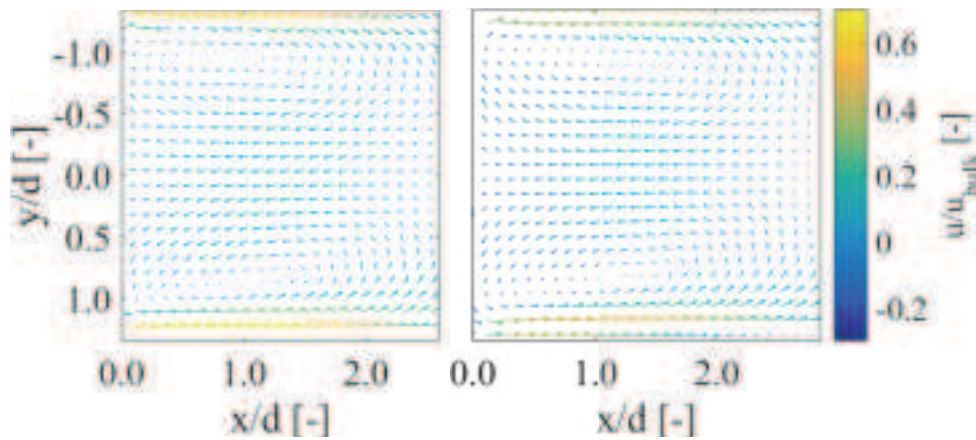

Fig. 6 Comparison between a steady case and a pulsation case, respectively. Only every 10 vector in each direction is shown. Both cases are an average of all sampled data.

In Fig. 7 the velocity field with the catalyst dummy mounted is shown. The catalyst dummy is seen as a region with no vectors. For the steady case 1000 snapshots are sampled at 5.25 Hz with a mean flow of 2.6 l/s. The pulsation case is sampled with 3000 snapshots at 5.25Hz with a mean flow of 2.6 l/s. The amplitude was 25% of the mean flow of 2.6 l/s and the pulsation frequency at 0.5Hz. Velocity profiles from both cases are sampled at x/d = 2 and the comparison is shown in Fig. 8. It is seen that for the case without a catalyst dummy the results are alike. Smaller differences in the nominal size of the velocities are observed at the center and at the peaks at the side. These differences are assumed to be insignificant. The case with the catalyst dummy mounted matches at the velocity burst and the center values fluctuate. The suggested explanation of the fluctuation between the velocities profiles is due to build up of unwanted fraction of packing at the upstream face of the catalyst dummy. These particles move between each experiment (run) as the flow changes. If the flow pulsate some of the particles observable by the eye move around. If the flow is steady the fraction of packing locks to a position.
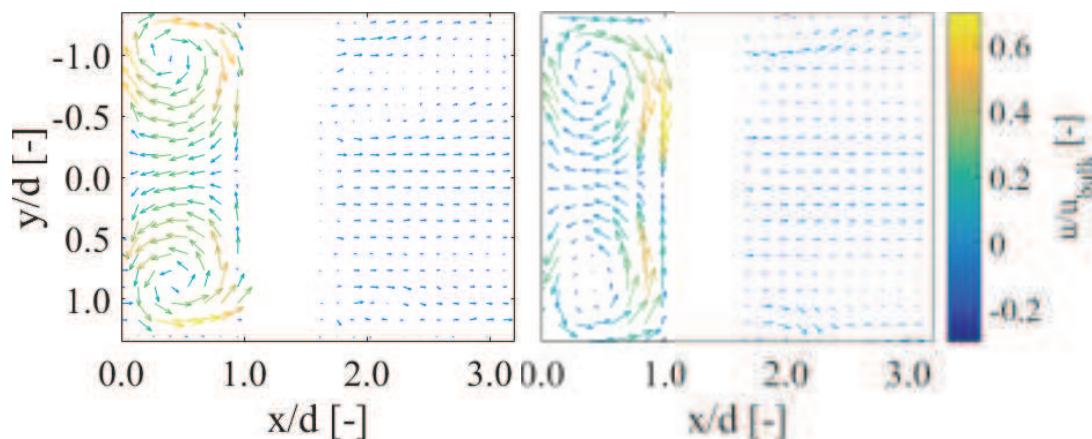

Fig. 7 Comparison between a steady case and a pulsation case, respectively. The white square is the catalytic dummy. Only every 10 vector in each direction is shown. Both cases are an averge of all sampled data.
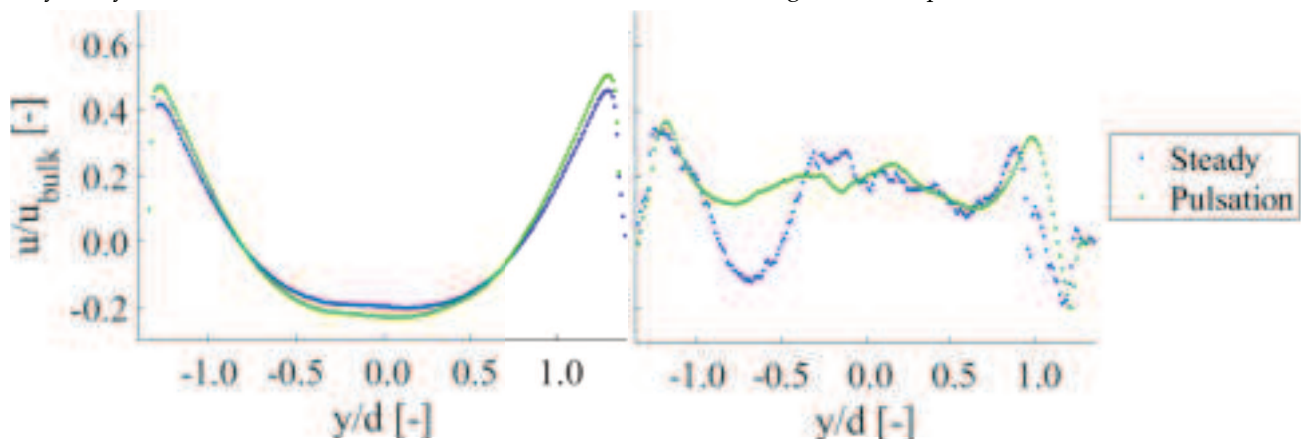

Fig. 8 Velocity profile comparison at x/d = 2. Where the left show the cases without catalyst dummy and the right show the cases with a catalyst dummy mounted. Both cases are an average of all sampled data.

A comparison of the velocity profiles before the catalyst dummy is shown on Fig. 9. The profiles are similar even though there are deviations at the upper half. These deviations could be explain by trapped air in the setup there over time remove the correlation in the areas where the vortex ring appear.

Investigation the dependencies of the pulsation amplitude and frequency is shown in Fig. 10, where the left plot shows normalised velocity profiles with change in magnitude of the amplitude from 2.5% to 25% of the mean flow. The right plot shows the change in frequency from 0.1 Hz to 7 Hz. Both cases are sampled with 315 snapshots at 7.26 Hz shown as a mean of all the snapshots. For the case where the frequency is varied the same amount of pulses are not measured. The graphs show the velocity in all interrogation areas. It is seen that nearly no change is found when changing the amplitude or frequency, only a deviation is seen at the center assumed to originate from the fractions of packing stuck in the catalyst dummy.
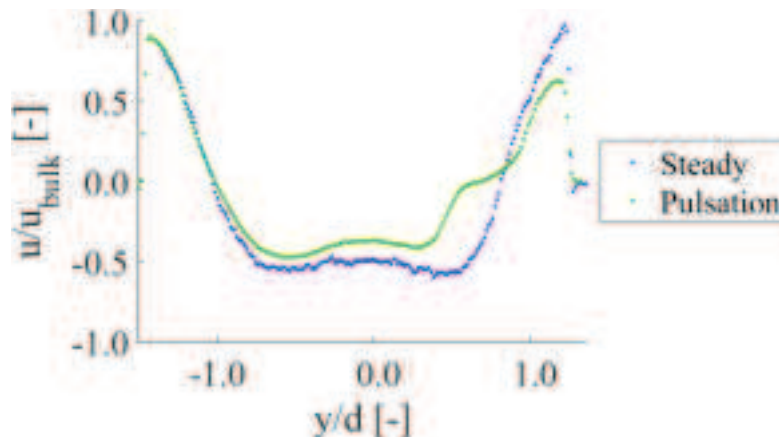

Fig. 9 Flow profile with the catalytic dummy is mounted comparison at x/d = 0.5. Both cases are an average of all sampled data.
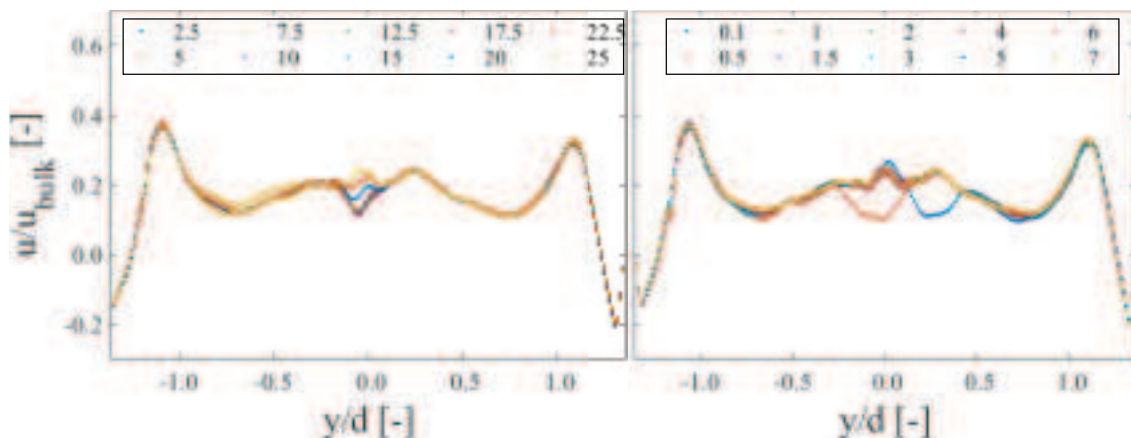

Fig. 10 Velocity profiles at x/d = 2, where the sampling frequency is at 7.26Hz and the sample size is at 315 snapshots. On the left change in amplitude from 2.5% to 25% of mean with the frequency at 1 Hz. On the right change in frequency from 0.1 – 7 Hz with amplitude 25% of mean.

The uncertainty is investigated by a repeatability study performing the same settings six times at different days. The comparison of the velocity profiles at x/d = 2 is shown on Fig. 11, where also the standard deviation for the six runs is shown. It is seen that the velocity profiles are alike and that the standard deviation is around 0.02. For the center values the standard deviation raises and confirm larger uncertainties observed.

A vortex ring was created in the inlet of the reactor, as shown on Fig. 12. The vortex ring became visible when air bubbles entered the setup through the open reservoir and subsequently got trapped in the vortex. The vortex ring was moving around and it was twisting around itself. It is possible to see that the air bubbles tend to move to the top of the vortex ring due to the effect of gravity. Thus the vortex ring appears thin in the bottom and thicker in the top.
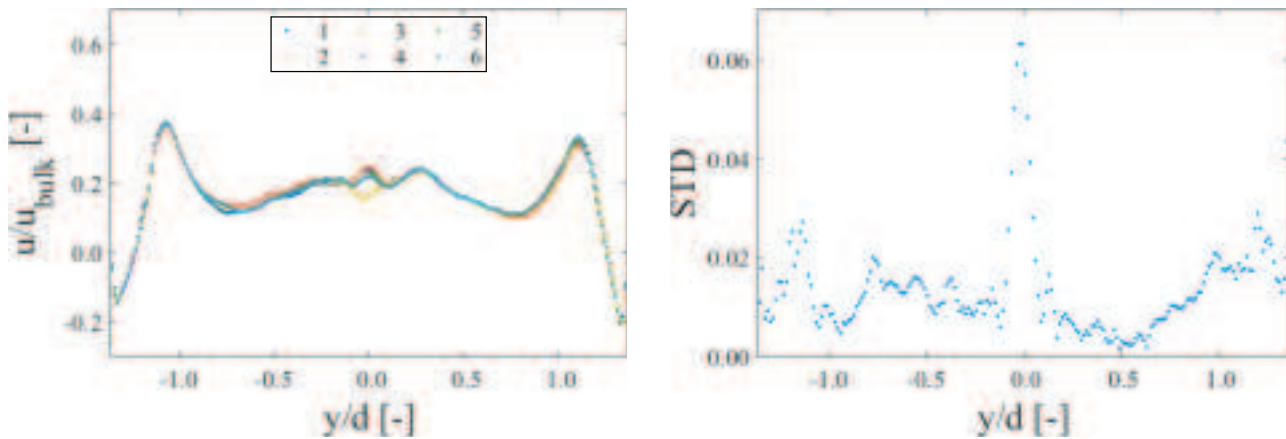
Fig. 11 Left: Velocity profiles from 6 independent run sampled at x/d = 2, where the sampling frequency is at 7.26 Hz and the sample size are at 315 snapshots. The amplitude are 25% of the mean with a frequency at 1 Hz. Right: Standard deviation (STD) of the single points.
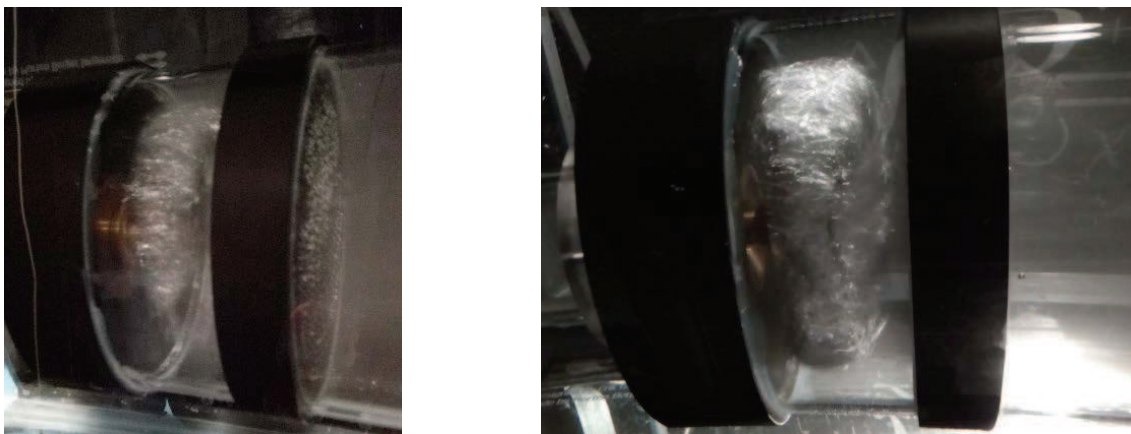
Fig. 12 Visualisation of the vortex ring between the catalyst dummy and the expansion. The flow is from left to right.

4. Discussion

The trapped fractions of packing and trapped air are the largest uncertainties for the setup. Both are attempted minimized and removed from experiment to experiment. The fractions of packing clog the catalyst dummy or move around inside the volume between the catalyst dummy and the guide vanes. Due to the geometry of the setup it was not possible to remove the particles without disassemble the entire reactor. The trapped air enters the flow at the open reservoir, where a flow guider was mounted and the problem was minimised.

The pulsations are not the same as for the large two-stroke engines. For the real exhaust gas the Womersley number is assumed to vary between $Wo = 78 - 255$ and for the test rig $Wo = 7 - 54$. Because both are above the threshold of $Wo > 2$ the inertial forces are dominant in the center of the flow and it is assumed that the same physical phenomena are dominating. For the real SCR system it is expected that the amplitudes are of the order 2-3% of the mean flow. Most test cases are done with 25%, but as concluded the amplitude is insignificant.

The ratio between the flow through time and the pulsation period vary between $0.2 - 0.4$, where the flow through time is defined as in section 1. and the velocity is u_{bulck}. The ratio is below one and the system can be defined with quasi-static boundary conditions. Comparing this ratio to the ratio for the real SCR system, one could expect different physicals phenomena such as separation at different locations. To investigate this, more experiments have to be conducted. But it was not possible to obtain the same ratio between the retention time and frequency, when keeping a Reynolds number at $Re \approx 10^5$ on this test rig.

5. Conclusion and future work

The performed PIV measurements show that an overall mean of the pulsating flow field is similar to the mean of the steady flow case. The velocity profile only changes in magnitudes at the different phase steps. Furthermore it indicates that a mean across the entire phase is valid and it is seen that no effect is observed by variation of the amplitude or pulsation frequency. The pulsation only seams to create more realistic results. This is assumed to be due to the observation that pulsation move the unwanted fractions of packing around and create a less noticeable effect on the mean of the velocity field compared to the steady case. It is concluded that a steady flow case can be used to model this setup, but that for real cases more experiments have to be conducted without quasi-static boundary conditions.

For future work, a new setup should be built to obtain a ratio between the retention time and the pulsation frequency above one, with a Reynolds number at $Re \approx 10^5$. New tests on the current test

rig are suggested to mount one more catalyst dummy in order to investigate the flow between catalyst layers and the effect of multiple catalyst layers.

6. Acknowledgements

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