

The Influence of Cylinder Head Geometry Variations on the Volumetric Intake Flow Captured by Magnetic Resonance Velocimetry

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ABSTRACT

Magnetic Resonance Velocimetry (MRV) measurements are performed in 1:1 scale models of a single-cylinder optical engine to investigate the differences in the inlet flow due to geometrical changes of the cylinder head. The models are steady flow water-analogue of the optical IC engine with a fixed valve lift of 9.21 mm to simulate the induction flow at 270° bTDC. The applicability of MRV to engine flows despite the differences in experimental operating parameters between the steady flow model and the optical IC engine are demonstrated and well addressed in this manuscript and in a previous work [1]. To provide trust into the MRV measurements, the data is validated with phase-averaged particle image velocimetry (PIV) measurements performed within the optical engine.

The main geometrical changes between the cylinder heads include a variation of intake valve diameter and slight modifications to the exit of the intake port. The MRV measurements reveal significant changes in the velocity distribution within the overflow and underflow region of the intake valves for the two cylinder head designs. These changes produce contrasting flow entrainment patterns into the cylinder, which support evidence of different flow generated patterns captured by PIV during the intake and compression stroke.

The model generation, performed using selective laser sintering, allows easy geometrical variations and the MR-scanner enables low acquisition time and automated post-processing. MRV is revealed to be a suitable diagnostic tool to understand the volumetric induction flow within engine geometries and to evaluate flow changes due to geometrical variations of the engine.

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1. INTRODUCTION

Within automotive research and design, efforts are often focused on the engine geometry design for optimization of performance and efficiency. Within spark-ignition (SI) engines, the intake system and engine geometry play an important role in defining the in-cylinder flow, which is regarded as a key parameter influencing charge-filling, mixture preparation, and combustion [2]. An efficient optimization of the intake- and in-cylinder geometry requires knowledge of the three-dimensional flow in the entire volumetric domain.

Traditional velocimetry techniques such as laser Doppler anemometry (LDA), hot-wire anemometry, particle image velocimetry (PIV) have provided valuable information about developing in-cylinder flows [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19] and have demonstrated that the annular intake flow has large implications on

developing the in-cylinder flow motion. Such techniques however, are limited to point-wise or planar measurements and are often not capable of providing information of the annular flow within the entire intake system due to limited optical access for such complex geometries. It is beneficial to understand the flow evolution from the intake system into the cylinder to optimize engine geometries with regards to space and performance [2]. Furthermore, it is crucial to understand potential changes of the in-cylinder flow due to small geometrical modifications of the intake system or cylinder components.

Magnetic Resonance Velocimetry (MRV) is an advanced diagnostic tool to investigate average 3D flow topology within the entire measurement domain in a fast and cost-efficient way. Since optical access is not needed for data acquisition, the use of MRV is convenient in highly complex geometries for which traditional

velocimetry techniques are often limited. Recently, Freudenhammer et al. [1] applied MRV as a steady flow water-analog model to study volumetric flows within the intake and cylinder geometry of an IC engine. Measurements were performed in a 1: 1 scale model of a single-cylinder optical engine [20]. The intake valves were fixed with a .21 mm valve lift to simulate the induction flow at crank-angle 270° bTDC. MRV measurements within the symmetry plane of the cylinder domain were validated with phase-averaged PIV measurements performed within the optical engine. A detailed comparison of the flow captured from MRV and PIV concluded that MRV flow measurements conducted with water provided reliable flow data that is applicable to investigate the 3D inlet flow. Flow features such as the annular jet-like flow extending into the cylinder, its influence on large-scale flow motion, as well as flow recirculation zones were identified in 3D space. Freudenhammer et al. [1] additionally revealed the uniqueness of the MRV to analyze radial velocities exiting and entering the periphery of the valve curtain to quantify the flow rate entering the cylinder.

In this work, MRV measurements are performed to investigate the changes in in-cylinder flow details due to modifications to the intake and cylinder head geometry. Measurements are performed in two separate 1: 1 scale models of the same optical engine that is capable of housing two separate cylinder head geometries. The main differences in the cylinder head geometries are slight changes to the flow channel of the intake port as well as intake valve diameter. MRV measurements are validated with phase-averaged PIV measurements performed in the symmetry plane of the optical engines for both cylinder heads. The MRV measurements reveal significant changes in the velocity distribution within the overflow and underflow region of the intake valves for the two cylinder head designs. These changes produce contrasting flow entrainment patterns into the cylinder, which support evidence of different flow generated patterns captured by PIV during the intake and compression stroke.

2. EXPERIMENTAL SETUP

2.1. Optical Engine and PIV Measurements

The engine under investigation is an optically accessible single-cylinder direct-injection spark-ignition engine embedded in a test rig with well-defined and controlled boundary conditions [20]. The engine features 55 mm quartz-glass cylinder liner with 8 mm window extension into the pent-roof and a Bowditch piston arrangement with flat quartz-glass piston-crown window (75 mm diameter). The engine's bore and stroke are 86 mm with a displacement volume of 499.6 cm³. The engine can be equipped with one of two twin-cam, overhead valve pent-roof cylinder heads. The design of the first cylinder head is intended for wall-guided (WG) direct-injection engine operation. The WG cylinder head is equipped with a side-mounted fuel injector, a centrally located spark plug, and dual intake valves (33 mm diameter) and exhaust valves (29 mm diameter) located on opposite sides of the spark plug. The design of the second cylinder head is intended for spray-guided (SG) direct-injection engine operation. The SG cylinder head is equipped with a centrally mounted fuel injector, centrally located spark plug, and dual intake valves (29 mm diameter) and exhaust valves (29 mm) in the same arrangement as the WG configuration.

The geometrical differences of the two cylinder head geometries are highlighted in Fig. 1. The placement of the fuel injector (side-mounted or centrally-mounted) results in the following key geometrical changes. First, the empty volume on the left of the cylinder head around the injector of the WG geometry is filled in the SG geometry thus reducing the clearance volume and increasing the geometric compression ratio from 8.5 to 8.7. Second, the central position of the injector reduces the available space for the intake valves. Therefore the intake valve diameter is reduced from 33 mm for the WG geometry to 29 mm for the SG geometry. Lastly, slight differences in the intake port geometry exist to accommodate the different intake valve diameters. These differences are highlighted by the inserted lines representing the cross-sectional profiles of the intake port in the mid-valve plane (i.e. central-axis of a given intake valve, $z = \pm 19$ mm ($z = 19$ mm shown by colored outline in Fig. 1)). Upstream the red dotted line (Fig. 1 top right), the manifold is identical for both cylinder heads. The circled region (a) highlights an outward curved surface in the SG cylinder head, where the intake port diameter narrows down to meet the smaller intake valve diameter. On the left side of the valve, the SG geometry does not exhibit the abrupt hard edge as in the WG geometry (see circled region (b)). These geometrical changes of the intake port are highlighted again in Fig. 7 to demonstrate their influence of local changes of the intake charge motion.

Particle image velocimetry (PIV) measurements were performed in the optical engine for both the WG and SG cylinder head configuration. Measurements were performed to quantitatively measure the in-cylinder flow field within a 60x70 mm² field-of-view within the central tumble plane (i.e. symmetry plane, $z = 0$ mm). The engine was operated at 800 rpm with 950 mbar intake pressure and $21.5 \pm 1^\circ\text{C}$ intake temperature. Temperature, pressure and mass flows are measured within the intake and exhaust manifold and are controlled and monitored during engine operation. The intake mass flow rate, $\dot{m}_{\text{intake}} = 11.5 \frac{\text{kg}}{\text{h}} \pm 2\%$, was consistent for engine operation equipped with either cylinder head and was measured using a rotary piston gas meter (Aerzen). In previous work [1], PIV measurements were performed in the straight piping within the intake system and determined a Reynolds number of 38,000 within the intake piping ~ 390 mm upstream the engine (red dotted line in Fig. 2). For further information regarding these measurements, the reader is referred to [1].

The experimental setup for the PIV measurements is similar to that described in [20]. Brief details of the setup are provided here and the reader is referred to [20] for further details. The intake air was seeded with silicone oil droplets (Dow Corning 510 50-CST) of 0.5 μm average droplet diameter using an aerosol generator (Palas AGF 10.0) placed 2 m upstream the engine. An Nd:YAG laser (Edgewave, 532 nm) was used to provide a vertical laser sheet (0.8 mm thickness, 13.5 % of maximum intensity) located within the central tumble plane. The detection system consisted of a Phantom v711 (LaVision, 1280x800 pixel, 12 bit) camera equipped with a Nikon lens (50 mm f/1.2) for measurements with the WG cylinder head, while a sCMOS camera (LaVision, 2560x2160 pixel, 16 bit) equipped with a Sigma lens (60 mm f/2.8) was used for measurements with the SG cylinder

head. An optical crank-angle encoder (AVL) and programmable timing unit (LaVision) were used to synchronize the lasers and cameras to the engine operating at 800 rpm.

PIV velocity fields were calculated using a commercial software program (Davis, LaVision). Mie scattering images were cross-correlated using a decreasing-window multi-pass iteration scheme with a final interrogation window of 32×32 pixel and 75% overlap. PIV processing provided a spatial resolution of 1.8 mm and 1.12 mm for the WG and SG flow measurements, respectively. The velocity fields were post-processed in each step using a peak-ratio method (peak ratio factor of 1.8) and spurious vectors were removed using a median filter [21]. A Gaussian 3×3 filter was applied to remove noise and empty spaces were filled with interpolated values. The uncertainty in the PIV measurements is determined to be 5%. Details of the uncertainty analysis are presented in [20].

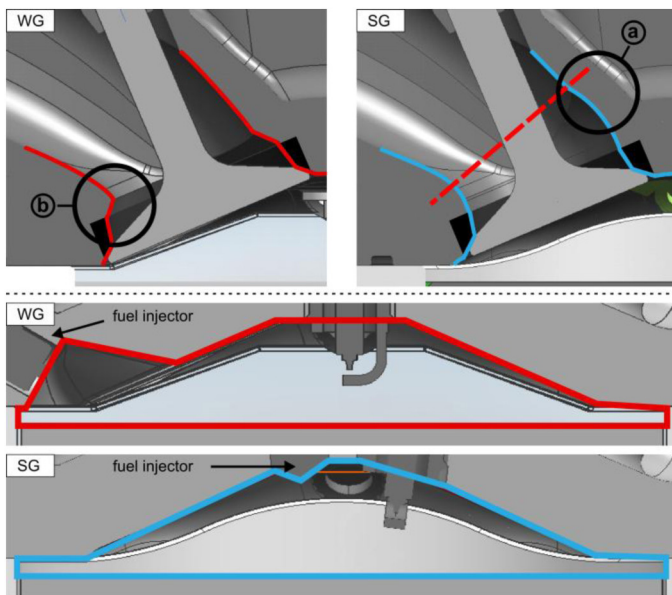


Fig. 1. (top) Cross-sectional view of the intake-valves and intake-manifold for the WG (left, red lines) and SG (right, blue lines) geometry in the mid-valve plane ($z = 19$ mm). (bottom) Cross-section of the WG (upper) and SG (lower) cylinder head in the central tumble plane at $z = 0$ mm highlight the cylinder head variations due to the modified injector position. The intake valves are on the left and the exhaust valves at the right of the spark plug, respectively, but are not visible in the $z = 0$ mm plane. The spark plug has been removed for all measurements within this work.

2.2. MRV Measurement Technique and MRV Engine Model

Magnetic Resonance Imaging (MRI) has been introduced in the early 1980s [23] primarily for clinical purposes. It is a non-invasive measurement technique and nowadays a standard tool in medical applications. Magnetic resonance velocimetry (MRV) is an advanced measurement technique that evolved from MRI and has predominantly been used to investigate blood flow inside human hearts and vessels [24, 25].

The working principle of the MR-measurement techniques is based on the quantum mechanical effect of nuclear magnetic resonance (NMR) which appears for all isotopes with a nonzero spin, such as

the element hydrogen. NMR provokes precession of the subatomic nuclides at the Larmor-frequency ω_L in the presence of a magnetic field, with the precession axis in the direction of the main magnetic field B_0 [27]. The Larmor-frequency is affected by the material-dependent gyromagnetic ratio γ and the local magnetic field strength B . The local magnetic field B again is composed of the main magnetic field strength B_0 and local magnetic field gradients $G(t)$ that can alter the local magnetic field B and thus the resonance frequency ω_L along arbitrary axes $r(t)$ within the measurement volume:

$$\omega_L(r, t) = \gamma * (B_0 + r(t) * G(t))$$

Transmitter-/receiver-coils produce radio frequency (RF) pulses that cause a tilting of the precession axis and thus the development of transverse magnetization. After the RF-pulses, the transverse magnetization starts to decay and the MR signal can be measured as an echo of the free induction decay in the receiver coils. The aforementioned magnetic field gradients $G(t)$ can be used to systematically manipulate ω_L such that the MR signal can be spatially encoded. A 2D Fourier transform can subsequently reconstruct the received MR signal to a local signal magnitude and phase angle distribution for every voxel in the measurement volume. Additionally, the magnetic field gradients can make the phase angle of the MR signal sensitive to fluid motion. This process is the key procedure of the motion-sensitive MRV-sequence and is realized via bipolar magnetic field gradients. These velocity encoding field gradients are applied such that no net phase shift is produced for stationary spins - hydrogen elements inside a voxel without fluid-motion. A net phase shift is produced however for spins that move along the gradient direction. The produced net phase shift is a direct measure for the flow-velocity along the gradient direction. Further information regarding MRI and MRV can be found in Haacke et al. [27], Elkins and Alley [29] and in [1], where MRV was first introduced as an application for engine flows.

MRV has been recognized as a beneficial tool for technical flows [26]. Since no optical access is necessary, MRV is especially beneficial for complex geometries, where optical access is often not feasible. MRV provides fully three-dimensional measurements of the flow under investigation. The acquired flow data is time-averaged over the time of data acquisition, which strongly depends on the size of the measurement volume and the chosen spatial resolution. Data acquisition for the selected measurement volume (Bifurcation and Cylinder in Fig. 2) with a spatial resolution of 1 mm in all three Cartesian coordinates took 9 min 05 seconds per scan. Four individual scans were conducted consecutively for the SG geometry model: Two flow-encoded scans and two reference-scans. The flow-encoded scans are conducted with fluid flow at the selected flow rate while the reference scans are conducted without fluid-flow. The flow-encoded scans are subtracted by the reference scans to eliminate phase-angle distortions that may result from magnetic field inhomogeneities or eddy currents. The corrected flow-encoded scans are then averaged to enhance the provided signal to noise ratio (SNR) by a factor of $\sqrt{2}$ compared the single scan [27]. The total time of measurement was less than 40 min. The MRV-measurements of the WG geometry were acquired under the same circumstances; the only

difference being the number of scans. For the WG geometry a set of 4+4 scans was acquired resulting in $\sqrt{2}$ better SNR compared to the MRV-data of the SG geometry.

Selective laser sintering was used to produce a 1: 1 scale model (MRV-model) of the optical engine previously described (Fig. 2). The MRV-model is a steady-flow water-analogue of the IC engine. The intake valves have been modeled with a steady valve lift that can be adapted via a threading mechanism. The results presented in the content of this manuscript show measurements taken at 270° bTDC, corresponding to a 9.21 mm valve lift. Exhaust valves are closed at this position. The piston is not included within the MRV model. Instead the working fluid leaves the cylinder through the bottom-part of the MRV-model, from where it is recirculated to the flow supply system. The red line in Fig. 2 indicates the location where the respective engine and MRV-model geometries became similar downstream the diffuser.



Fig. 2. Sectional side-view of the MRV-model with diffuser. The model is produced from Polyamide by selective laser-sintering.

The MRV measurements are carried out in cooperation with the Department of Radiology at the University Medical Center Freiburg. They are performed on a standard MR-Scanner (Siemens Magnetom Trio) with a 3 Tesla main magnetic field using the standard equipment for medical applications. The MRV-model is connected to a flow supply system similar to the one described in Grundmann et al. [28]. The flow supply unit is situated in the control room and consists of a 1.1 kW rotary-pump (Sondermann) that provides a flow rate up to 120 L/min, depending on the experimental setup. The flow rate is measured downstream of the pump and in the recirculating flow downstream of the MRV-model by two ultrasonic flow meters (Systec Deltawave C XUC-F). Pressure and temperature of the flow is measured at the same positions with a pressure sensor (Jumo Midas, 401001) and a Pt100 temperature sensor, respectively. The flow supply system includes a 100 L water tank in which the temperature of the water can be controlled. All parameters are monitored and controlled using a purpose made LabView program. Further information regarding the experimental setup and data-acquisition can be found in Freudenhammer et al. [1]. For the measurements presented in the context of this manuscript, the flow rate was set to 66 L/min and the working fluid was water (with a low concentration of copper sulfate) heated to 40°C to increase the Reynolds number of the flow inside the model. A Reynolds number of 38,000 inside the straight intake pipe, upstream of the engine geometry was calculated using the bulk flow velocity, the kinematic viscosity of the working fluid and the diameter of the intake pipe at the position just upstream of the bifurcation (diameter 56,3 mm, see red dotted line in Fig. 2). The parameter settings of the MRV measurements are listed in Table 1. The standard deviation of the velocity noise of the MRV measurements is 0.02 m/s. In regards to a maximum expected flow velocity (identified as the v_{enc} value), this corresponds to a maximum uncertainty of 1% in the MRV measurements.

Tab. 1. Parameter settings for MRV measurements

Fluid	de-ionized water	
Temp.	40	°C
Flow rate	66	L/min
Re-number	38,000	
Field-of-view	250 x 140 x 135	mm ³
Spatial resolution ¹	1 x 1 x 1	mm ³
v _{enc} ²	2	m/s
No. of scans SG	2 + 2	flow encoded + ref.
No. of scans WG	4 + 4	flow encoded + ref.
Acquisition time	9min 05sec	

¹ The spatial resolution of the MRV-measurements can be set prior to the measurements. Improved spatial resolution while maintaining MR data-quality can be realized yet leads to extended acquisition time and more required scan repetitions.

² v_{enc} (“encoding velocity”) is a parameter that describes the expected maximum flow-velocities that occur inside the selected Field-of-view.

3. RESULTS AND DISCUSSION

3.1. MRV Data Validation

The focus of this paper is to utilize MRV measurements to investigate the 3D inlet flow development in a single-cylinder DISI engine. This analysis is performed for two different cylinder head geometries (namely wall-guided (WG) and spray-guided (SG)) to understand differences of the inlet flow with respect to geometrical changes of each cylinder head. In order to utilize MRV measurements for this objective, it is first necessary to establish confidence that MRV data can be used to predict flow fields within operating engines. For this purpose, in this section the MRV data will be compared to PIV data performed within the operating engine. The PIV measurements consist of a well-documented, quantitative velocimetry data base that exists for the current engine [20].

For a meaningful validation, differences in operating parameters between MRV and PIV must be well addressed. This topic is discussed in detail in [1] and is summarized here for brevity. Notable differences in operating conditions are: (1) differences of working fluid (air (PIV) vs. water (MRV)), (2) moving boundaries are not considered for MRV, (3) MRV measurements exclude the piston boundary, and (4) the MRV measurement system represents a steady-state flow, while the flow within the engine inlet can be unsteady throughout induction. Freudenhammer et al. [1] evaluated the compressibility effects for air at the given operating conditions. They demonstrated that the air flow into the engine can be approximated as incompressible (i.e. $\Delta\rho \approx 1.8\%$ and $Ma < 0.3$), which is in agreement with the water used in MRV measurements. The piston surface is removed in the MRV engine model to allow the water flow to exit through the bottom of the cylinder chamber. As a result, the large-scale tumbling motion within