PIV measurements of the flow through an intake port using refractive index matching

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Abstract The design and operation of a test bench to measure the flow inside the model of an intake port of an automotive combustion engine by means of optical methods is presented. In the test bench the refractive index of an acrylic model material is matched with a special working fluid—a solution of 62.5% sodium iodine in deionized water. Different model materials and matching fluids are discussed with respect to their ability to be used in the test bench. The main requirements for the combination of fluid and model material are to match the refractive index, offer the ability to manufacture the very complex shape of the flow channels of the intake port and maintain Reynolds-number identity. The model is machined from acrylic by means of 5-axis CNC milling. Sodium iodine is chosen as the working liquid, because the refractive index of acrylic can be matched with a sufficient solution in water, while the viscosity is not too high to be able to reach sufficiently high Reynolds numbers with a full-scale 1:1 model of the cylinder head channels and the cylinder. The required test bench is designed to enable optical access from several different sides; exemplary PIV measurements of the flow through the intake ports are presented to highlight the success of the test bench design. The results from two different measurements are presented and compared: A simple 2C2D-PIV measurement in a specific plane as well as section-wise scanning of the whole flow field by means of a 3C2D-Stereo-PIV setup. The first one was found to give very convincing results, the latter one suffered from some problems in distinct areas, e.g. around the valves. Still the data that was acquired offers a more than valuable database for the validation of numerical tools, giving detailed insight into the flow fields inside the intake ports and the cylinder.

1. Introduction

The fuel efficiency and pollutant emission of modern combustion engines is, from a fluid mechanical point of view, closely connected to the flow state in the cylinder, e.g. swirl, tumble and/or level of turbulence. This flow state in turn is dominated by the shape of the intake port(s) and the interaction of the intake flow with the valves and the valve seats. Typically, during the initial design process, the transients are neglected (e.g. the movement of the piston and the compression process) and steady-state numerical design calculations are carried out and compared with experiments on test-benches. These test-benches typically determine the time-averaged, integral values for swirl, tumble and/or pressure loss/flow rate, most often by electro-mechanical means such as impeller anemometers or straighteners mounted on a balance.

Since such approach only delivers one or two single, integral values it is not very suitable to validate numerical computations—more detailed data is desired that highlights the spatially resolved development of the flow and gives a thorough inside into the phenomena of flow structures. Such data can only be acquired by PIV methods.

Detailed flow measurements inside a cylinder have been conducted before, e.g. by Dannemann et al. (2010), Dingel et al. (2002) or Imberdis et al. (2007). All are able to measure not only the flow structures inside the cylinder, but some also to trigger on the movement of the piston and thus resolve the compression (and probably the ignition) process. However, their procedures cannot be
applied to the flow in the intake ports. Here the major challenge is to enable optical access into the very complex shaped channels without allowing for geometrical simplifications, while maintaining Reynolds-number identity.

To meet these requirements only an approach with matching refractive index is feasible since it allows (almost) unlimited optical access to howsoever complex shaped intake ports. The drawback is that the medium to be used is necessarily fluid/liquid and thus incompressible. Therefore it cannot reproduce phenomena related to the movement of the piston and the accompanying compression. This drawback seems not significant for the application discussed here, since the state-of-the-art test-benches for qualification of intake ports (e.g. AVL Tippelmann benches\(^1\)) do neither reproduce the piston movement as described above. For the steady-state flow through the intake port compressibility of the fluid does not have a dominant influence on the phenomena of the flow, as accompanying numerical studies have shown.

Several publications report successful and convincing approaches for refractive index matching:

For the use with Polymethyl methacrylate (PMMA, acrylic) several different matching fluids were found: The use of a solution of zinc-iodine (ZnI\(_2\)) in water has been reported by Hendriks & Aviram (1982). They apply this combination to measure the flow inside the model of an ink jet aspirator—at very low flow velocities. Liu et al. (1990) perform LDV measurements inside the (very complex) cooling passages of a cylinder head. Their model is manufactured by embedding a fusible core into a special castable acrylic (Transpalite SS). The matching fluid is a mixture of turpentine and 1,2,3,4-tetrahydronaphtalene (Tetraline, C\(_{10}\)H\(_{12}\)). Uzol et al. (2002) use a solution of 64 % sodium iodine (NaI) in deionized water as a matching fluid. They measure the flow inside an axial turbo-pump, but also report some valuable experiences and problems about the use of NaI-solutions. And, last but not least, Wulff (2006) reports about the usage of an oil with high refractive index (Shell GRAVEX 917) that naturally matches that one of acrylic - at least at a specific temperature of approx. 23°C.

Also, more recently, biologically inspired flow problems have been addressed with a refractive index matching approach. Kim et al. (2004) use a setup with glycerin/water as a fluid and silicone as a model material. One of the very convincing elements in their publication is that they actually use a very complex model shape based on a CT-scan of a nasal cavity, built by using rapid prototyping procedure - specifically a 3D-printer from Z Corps. Also Burgmann et al. (2009) use a very similar approach where they measure the flow through elastic vessels (simulating a blood vessel) with a specific focus on fluid-structure interaction. They also use a solution of 61 % glycerin in water as a working fluid and a special two-component rubber RTV615 (presumably quite similar to silicone) as a model material.

To summarize, a number of different approaches have been developed to enable optical measurement with matching index of refraction. Budwig (1994) gives a comprehensive overview over different matching fluids and model materials (although this reference is older than some of the above discussed papers). Beside the refractive index he assesses construction methods and scratch resistance for the model materials and density and viscosity for the matching fluids, and cites a number of further references.

2. Model Material and Liquid Selection

The object of interest here is the intake-region and cylinder of a four valve engine. The design of the shape inside the intake region is governed by engineering constraints for the cylinder head (e.g. oil or water cooling channels, space for glow plug or spark plug, eventually fuel injector, valve driving mechanisms) and is thus typically very complex, consisting of several undercuts/back tapered regions and three-dimensional surface shapes.

The core question for the given problem is to choose a suited combination of model material and liquid. This question must be addressed with respect to the three main requirements for the experiment:

- Match the refractive index (RI)
- Enable manufacture of the very complex shape of an intake port
- Maintain Reynolds-number identity, e.g. low kinematic viscosity of the fluid

For a quick glance some pre-chosen (transparent and machinable) materials are presented in Table 1. Table 2 lists possible liquids in a similar style as presented by Budwig (1994). Beside the above mentioned main requirements the cost of the liquid is a certain issue, since the test-bench needs a quite significant volume (approx. 30 liters) to be filled. Furthermore the practical tests have been limited to liquids that do not require significant effort to be operated safely.

<table>
<thead>
<tr>
<th>Type</th>
<th>n</th>
<th>Possible Manufacture Method, Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cured Epoxy Resin</td>
<td>1.51 - 1.56</td>
<td>stereolithography</td>
</tr>
<tr>
<td>PMMA (Acrylic)</td>
<td>1.49</td>
<td>milling, bondable</td>
</tr>
<tr>
<td>Cured Polyurethane Resin</td>
<td>1.49</td>
<td>casting, significant shrinkage during curing</td>
</tr>
<tr>
<td>Silicone</td>
<td>1.4 - 1.43</td>
<td>casting, elastic</td>
</tr>
</tbody>
</table>

Table 1: List of possible materials to match the liquids listed in Table 2.

2.1 Choice of the Model Material and Manufacture Method

The natural choice for the model material was cured Epoxy resin, as this is the outcome of a Stereolithography process. Stereolithography (STL) offers easy and fast manufacture of nearly arbitrary shapes (including almost unlimited undercuts and hollow spaces) and has been the most promising candidate from a manufacture point of view. Recently resins have been developed that allow the printing of transparent pieces, e.g. DSM Somos WaterClear® Ultra 10122 or RenShape® SL 7870. Practical tests have been done with the DSM Somos WaterClear-Material, two valves and a slice representing the cylinder head were printed, see Fig. 1.

Although promising, the Epoxy resin did not turn out to be the best choice: The STL-printing leaves a surface which is matt—the clear transparency appears only if the model is painted with a special sprayable transparent coating. The paint rounds off the details of the piece such as fine bevels for the valve seats. Although tiny details, they are known to have a significant influence on the
production of swirl and turbulence in the cylinder.

Furthermore none of the tested liquids was able to be matched to the high refractive index of the epoxy pieces (a mixture of tetraline and turpentine was actually not tested here, because of strong reserves due to its noxious nature). With a sufficient solution of zinc iodine (ZnI2) in water the refractive index can be increased to match that of the epoxy resin. This approach however resulted in a very strong and non-reversible discoloration of the solution into red color. On the other hand a solution of sodium iodine (NaI) in water is limited to a refractive index of approximately 1.495, since this is at the solution limit.

In order to maintain the advantages of rapid prototyping a process similar to the ones described by Liu et al. (1990) or Kim et al. (2004) was also tested for model building: A disassamblable intake port (the geometry split into four pieces) was printed on a rapid prototyping machine. Afterwards this “positive model” was filled with a water soluble model material (AeroConsultants Aquapour 4015), cured and demolded to receive a water soluble core representing the intake ports. Intention was to cover this core with a transparent polyurethane resin or to “embed” it into a castable PMMA-material. Already at that point the process was withdrawn, because the core model repeatedly broke during the demolding due to the large number of undercuts – further splitting of the positive model is required which makes the whole process inefficient for complicated geometries.

Conventional 5-axis milling of the model from PMMA turned out to be the most efficient solution. The upper region (channels inside the cylinder head) was divided into four parts and these are milled into solid PMMA-blocks. The blocks are then glued together with UV-cured acrylic cement and in the final step the outer contour was milled. The outer contour was designed such that every region has approximately the same wall thickness. The cylinder, the valves and also the fittings to adjust the valves are all milled from PMMA. Fig. 2 shows some impressions from the building process. Some basic testing has been done with very thick acrylic blocks to learn whether it would be feasible to skip the milling of the outer contour and mill the flow channels into a large “block” of PMMA. This procedure also seemed feasible. However, it must be taken into account that excessive wall thickness will lead to larger spatial error if the RI is not exactly matched, therefore the more complicated model with approximately constant wall thickness was built.
The index of refraction of PMMA at 532 nm and 20°C is \( n = 1.4947 \), based on Kasarova et al. (2006); no attempt was made to directly measure the RI.

### 2.2. Choice of the Liquid

As can be seen from the list of possible materials in Table 1, a refractive index of at least 1.49 is required. Only silicone materials could be matched with less RI, they are however elastic and not able to represent a solid shape if significant forces act on the surfaces. The combination of Tetraline and Turpentine was not tested in practice because of strong reserves due to its noxious nature.

<table>
<thead>
<tr>
<th>Type</th>
<th>( n )</th>
<th>( v/v_0 )</th>
<th>Cost (^2)</th>
<th>Hazards, Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tetraline + Turpentine</td>
<td>1.47 - 1.54</td>
<td>1 - 1.5</td>
<td>600 €</td>
<td>flammable, noxious</td>
</tr>
<tr>
<td>Aqueous solution of Zinc Iodine (ZnI(_2))</td>
<td>1 - 1.6</td>
<td>1 - 10</td>
<td>3'200 €</td>
<td>strong discoloration</td>
</tr>
<tr>
<td>Aqueous solution of Sodium Iodine (NaI)</td>
<td>1 - 1.5</td>
<td>≈ 1</td>
<td>800 €</td>
<td>discoloration</td>
</tr>
<tr>
<td>Glycerin/water</td>
<td>1.3 - 1.47</td>
<td>1 - 1000</td>
<td>insignificant</td>
<td>very high viscosity</td>
</tr>
<tr>
<td>Oil (Shell Gravex)</td>
<td>1.491</td>
<td>≈ 12</td>
<td>insignificant</td>
<td>high visc., not adaptable</td>
</tr>
</tbody>
</table>

\(^2\) The listed prices are taken from quotes of different suppliers, where the amount of quoted chemical was sufficient to fill the test-bench described below. The prices might not be fully representative, because significant scatter has been experienced for most of the chemicals (sometimes in the extent of 500 %).

With glycerin/water mixes as well as with the Shell Gravex oil the required Reynolds number cannot be matched, due to their high viscosity (and also high density), which requires large flow velocities. Large flow velocities combined with high density in turn leads to very high forces during operation, which was not found to be feasible. The two salty mixtures of ZnI\(_2\) or NaI were tested into detail.

![Fig. 3: (a) PMMA-matched solution of NaI (left) and ZnI\(_2\) (right) after three hours; (b) PMMA-valve in (almost) RI-matched NaI-solution](image)

Both solutions tend to discolorate into yellow-red when exposed to UV-light and/or oxygen. This is particular disadvantageous for PIV, since the red color is not transmissive for the green emission from frequency-doubled Nd:YAG-lasers. ZnI\(_2\) discolorates significantly more than NaI (for a given RI). Fig. 3 shows two solutions, both with RI to match PMMA, after three hours. For both solutions other chemicals can abrogate the discoloring: Sodium tetraborate decahydrate (Borax, \( \text{Na}_2\text{B}_4\text{O}_7\cdot10\text{H}_2\text{O} \)) for ZnI\(_2\) and sodium thiosulfate (Antichlor, \( \text{N}_2\text{S}_2\text{O}_3 \)) for NaI. The chemical
discoloring was more efficient for the NaI-solution. Furthermore, whereas NaI is deemed to be harmless, ZnI₂ is slightly irritant to the skin. One advantage of the ZnI₂ solution would be the larger range of possible RI, mainly because of the better solubility in water. In our case this advantage turned out to be not usable, because the stronger discoloration required much more “maintenance” of the solution. Also, last but not least, ZnI₂ is significantly more expensive than NaI. As a conclusion, the NaI-solution seemed more feasible.

During the experiments the initial discoloration of the NaI was prevented by adding a small amount of antichlor. In the test-bench the liquid is not exposed to the oxygen of the air—it is held under nitrogen atmosphere, which successfully prevents any further discoloration. This maintenance is rather easy to handle and parts of the first solution of NaI were still used after more than one year. It was found advantageous to filter the liquid from time to time by means of a commercial fish tank filter (<1µm), also to clear the solution from old, conglomerated seeding particles and other dirt particles.

The NaI-solution has however some unpleasant properties that became evident during the work and are worthwhile to note: It is highly corrosive to ferrous metals, even to stainless steels (V4A). E.g. nickel-plated screws are rusted and inoperative after less than two days. We found NaI to be usable with aluminum, PMMA (including the acrylic adhesive), copper (pump) and plastic materials, unless elastic. The use of elastic materials (silicones, polyurethane foam or fillers, soft rubbers) should be avoided, because NaI quickly embrittles these materials. This is especially a problem for sealings. Later we used rather hard rubber sealings, which had a much longer life- and seal-time than soft rubbers. Last but not least the NaI-solution slowly colors everything that gets contact. This is not critical from a measurement point of view, but after some weeks a lot of items in the near field of the test-bench started to become brown/red: floors, doors, handles, boxes, etc. Therefore it is strongly recommended to follow some procedure to ensure that the liquid is not slowly distributed unnoticed. This is not particularly easy, because the liquid itself is colorless and “feels” like water. It slowly penetrates through sealings, drops off the test-bench and—if no care is taken—is distributed by wetting hands, shoes, tools, etc.

3. Experimental Setup

3.1 Test-bench Design and Operation

The test-bench was designed to be very similar to commercial test-benches for air in terms of operation: The flow state is held constant at a given differential pressure measured upstream of the cylinder head and downstream of the cylinder. The relevant differential pressure for the NaI-solution is 39’000 Pa—it is held constant by means of a WILO TOP-Z65/10 RG circulation pump (1.15 kW). The setup is fully symmetrical (with the exception of the cylinder head flow box itself). The total volume to be filled with the liquid is almost exactly 30 l.

The test bench consists of a transparent tank in the upper part, made from PMMA sheet material. The flow model is located in the center of this tank. The shape is chosen—refer to Fig. 5(a) —such that optical access can be established orthogonally through the walls from six sideward directions (plus through the “cover plate”). The size is chosen such that each sidewall is as wide as the orthogonal projection of the flow model. This leads to the minimum volume (to prevent inflationary costs for the liquid) while still remaining all options for PIV—up to tomographic PIV.
The cover plate of the tank can be removed for easier filling. It has a vertical “buffer pipe” attached, when fully filled the liquid surface is in the middle of the “buffer pipe”. After filling the system with the liquid, the remaining space in the buffer pipe is flooded with gaseous nitrogen to separate the liquid from the oxygen in the air. During operation the liquid heats up due to the power that the pump introduces into the system. Typically uninterrupted measurements are possible for approximately 3 hrs. The liquid level in the buffer pipe slowly rises when the liquid heats up, so it can be recognized easily even without a thermometer—the level indicated to us if the liquid becomes too warm (>40°C).

The RI was adjusted by means of an Abbe-Zeiss refractometer during the setup of the liquid before the test-bench is closed. Further monitoring of the RI is not possible, since this would disturb the nitrogen buffer. During mixing of the liquid the RI can be set with an accuracy of approximately Δn=0.005. Variations of the RI due to thermal influence (specifically the heat up of the test-bench during operation) can be estimated with the regression analysis of Narrow et al. (2000): At 20°C and λ=532 nm a mass-based concentration of 62.5 % NaI in 37.5 % water gives n=1.4947. Heating this mixture to 40°C increases the RI of the solution by Δn≈0.007. An analysis based on very simple geometrical optics revealed, that a RI mismatch of this order of magnitude will result in a spatial error of less than 0.02 mm for most regions of the flow box.

It should be noted that the fluid in the test bench is in any case incompressible, while the air in the real cylinder is compressible. Accompanying numerical results show that the influence of compressibility is not dominant for the flow state in the cylinder (e.g. much less difference than what will be presented in section 4). However, to establish the full advantage of such experiments accompanying numerical computations that resolve the difference of compressible vs. incompressible flow are useful, if not obligatory.
3.2 Cavitation and Outgassing

Since the solution of NaI is fluidic it can be subject to cavitation. For deionized water at 25°C the vapor pressure is approximately 31.7 mbar. The recirculation test-bench is driven atmospherically, hence water will cavitate if local flow velocity exceeds 10.4 m/s. For solutions the vapor pressure is slightly higher (following Raoult's law), therefore cavitation occurs at slightly lower local velocity at the order of magnitude of 0.2 m/s less than for deionized water. For the current test object these local velocities are not expected.

Although cavitation is not an issue, outgassing has been observed in the test-bench at local velocities significantly lower than the above described cavitation velocity. During filling of the test-bench the fluid is whirled and thus the liquid dissolves the surrounding air, which then outgases at the point of lowest pressure or highest velocity, respectively. However, this phenomenon occurs only if the fluid has recently been filled into the test-bench and a stable operation without local outgassing can be ensured by simply waiting for a few days after the test-bench has been filled. It was found advantageous to turn on the pump from time to time during these days to circulate the fluid. Actively heating the fluid and/or decreasing static pressure would significantly shorten the time for outgassing.

3.3 PIV setup

Once almost unlimited optical access is established, the PIV setup is rather straightforward. The coordinate system for the following explanations is shown in Fig. 6. Results from two different setups will be shown here: A 2C2D-setup and a 3C3D-setup.

The first 2C2D-setup is a slice parallel to the y-z-plane through the axis of one of the two inlet valves. The Laser sheet illuminated the plane in negative z-direction, the camera was observing the scene pointing in positive x-direction – refer to Fig. 4(b) for a sketch of the setup. The spatial resolution is approximately 2 mm. The data was averaged over 20 instantaneous snapshots—since this is a rather low number it must be expected that the averaged velocity field is not converged, but the data is still valuable for comparison.

The 3C2D-experiments use the setup sketched in Fig. 4(c), see also Fig. 7(b). The laser, the light-
sheet optics as well as the cameras are mounted on a common frame which is connected to a large
traverse, the whole setup can be moved accurately in z-direction without the need for re-calibration.
To reach high spatial resolution the flow field was measured in four steps: for each step a certain
area of interest (AoA) in the x-y-plane was observed (in-plane spatial resolution ≈0.5 mm) while
scanning several slices in the z-direction by means of the traverse with steps of 2 mm. This
procedure was repeated four times with different AoA, resulting in a total of approximately 160
individual 3C2D planes. For each of these planes 500 individual snapshots (for the flow channels in
the cylinder head) or 1000 snapshots (cylinder region) were averaged. After evaluation the data was
merged into a volume by linear inverse-distance interpolation onto a cartesian grid. The spatial
resolution of the destination grid was chosen to be similar to the average spatial resolution of the
different source datasets.

For all experimental setups
the system was calibrated
with either a 2D- or a 3D-
calibration target: The test-
bench main tank was filled
with open cover plate. Then
the calibration target was
inserted into the NaI-
solution and calibration was
done. After removal of the
calibration target the flow
model was installed in the
tank, the cover plate was
closed and the test-bench
was fully filled. Silver-
coated hollow glass spheres were used as seeding material, illuminated with frequency-doubled,
double-pulse Nd:YAG-lasers: Either 150 mJ/Puls Brilliant Twins B (2C2D-experiments) or 180
mJ/Puls Litron Nano T PIV (3C2D-experiments). In neither case the full laser power was actually
needed, based on the Laser-power-adjuster around 20 mJ are needed to illuminate the tracers
sufficiently. The images were recorded with (either one or two) 1 kPxs CCD cameras (LaVision
Flowmaster series) and evaluated using the LaVision DaVis 7 Software—each of the 160 3C2D-
planes required an individual mask for evaluation. After image acquisition the average background
was subtracted to increase the signal-to-noise ratio and to filter remaining reflections.

Some experiences should be noted here: Care was taken during model manufacture, and especially
during bonding the individual parts of the model, but the interfaces between the different pieces
remained visible, although they have been polished. Comprehensive testing of the bonding
procedure (e.g. to bond in a vacuum chamber) did not show any better procedure than the one
used—inevitably small bubbles remain in the bonding layers. For most of the interfaces this is not a
problem, because the bonding layer is very thin. For the connection of the flowbox with the
cylinder, however, the bond is very complicated and very unfortunately the whole bonding is in one
line of sight for the cameras. Therefore especially in the level of the cylinder-head (refer to Fig.
2(e)) reflections and optical disturbances cannot be avoided. This is not so dramatic in the case of
the 2C2D-experiments, because of the easier optical access. In the case of the 3C2D-experiments
however at least one of the cameras has a long optical path through this bond, thus the Stereo-
algorithm produced many spurious vectors in this regime. Finally it was unavoidable to mask parts
of this area and dispense the information. Fluorescent tracer particles along with optical filters will
be used in future experiments to completely avoid influence from reflections.
4. Exemplary Results

The following section highlights some exemplary results. At first the two 2C2D-experiments are compared with the data of the 3C2D-experiments to show the repeatability of the setup. It must be noted that the 3C2D-measurements were conducted more than half a year later, after completely disassembling the whole setup. Also a (partially) new mixture of the liquid with “fresh” NaI was used.

Also data from RANS computations is shown here. Details of the numerical setup are beyond the scope of this paper—it is a carefully planned, incompressible computation representing the current state-of-the-art with the use of a two-equation eddy-viscosity model. It should be noted that the same computation was repeated with a compressible solver in order to evaluate the difference between compressible and incompressible flow. As stated above, this difference is much smaller than the one that is shown in Fig. 9.

Fig. 9 shows the resulting vector fields in the y-z-plane. For better visualization the 3D-data from the volume reconstruction (3C2D-data) and the RANS-data have been interpolated onto the mesh of the 2D-PIV-experiments using a linear algorithm. The actual spatial in-plane resolution of the 3C2D-experiments is approximately four times higher. All contours are colored with the normalized in-plane vector length of the respective view; vectors represent the in-plane velocity components.

The reproducibility of the flow is satisfactorily: Most details of the flow in the intake port are consistent between Fig. 9 (a) and (b) regarding velocity direction as well as magnitude. Some details are slightly different, e.g. the position of the clockwise vortex underneath the valve as well as the “high-speed plume” emanating on the left hand side of the valve into the cylinder.

A comparison with the RANS computation yields, however, that the reproducibility of the experimental setup is far better than typical deviation between computation and experiment: While the flow in the intake ports, again, compares quite well between experiment and RANS method, the flow structure in the cylinder shows some inconsistent features: The eddy underneath the valves is much weaker and the “high-speed plume” is much more pronounced. The origin of this significant
deviation seems to be the separation point of the flow along the convex surface on the right hand side of the channel: while the RANS-computation predicts a early separation and a rather strong shear layer, the experiments highlight that the flow can follow the curvature a bit longer, thus introducing stronger flow turning towards the right hand side of this view and strengthening the vortex while weakening the “high-speed plume”, respectively.

Finally, Fig. 10 demonstrates typical visualizations that can be done with the volume reconstructed data. E.g. streamlines can be traced from the inflow to the outflow or iso-surface studies based on velocity components and/or total velocity magnitude can give valuable inside into important flow field structures. Only time-averaged velocity fields are presented here—the magnitude of the fluctuation components is not fully converged with a statistical database of “only” 1000 snapshots. It must be noted that the level of turbulence inside the cylinder is very high: The standard deviation of the velocity components is typically up to twice as large as the respective mean component, which is—by it’s order of magnitude—comparable to the results of Dannemann et al. (2010) or Imberdis et al. (2007).

![Fig. 10](image)

Fig. 10: Exemplary flow field visualization of the volume reconstructed data; (a) contours on the outer “shell”; (b) volume streamlines; (c) iso-surfaces based on total velocity

The compilation of the 3C2D-data into a volume-based dataset also allows integration of “classical” assessment factors, most important mean mass-flow, swirl and tumble. These are the three most important values that are measured on standard, mechanical test benches and important factors for the design of the intake ports of modern combustion engines.

5. Summary

The design and operation of a test bench to measure the flow inside the model of an intake port of an automotive combustion engine by means of optical methods was presented along with exemplary results of 2C2D- and 3C2D-PIV-experiments on that bench.

A model CNC-milled from transparent acrylic was chosen in combination with a solution of 62.5 % sodium iodine in 37.5 % deionized water. This setup turned out to be the most advantageous: The viscosity of the solution is low enough to enable Reynolds-number identity with a feasible mass-flow. Furthermore it consists only of harmless materials and is affordable. However, typical disadvantage is the need to maintain the solution and to operate it under a nitrogen atmosphere.
The design of the test bench has been described in detail and exemplary results were presented. The data highlight interesting details of the flow field: Some flow features have significant effect on the further development, e.g. it was shown that the position of a separation point within the flow box channel has a very important spinoff-effect for the downstream flow. The whole flow field has been scanned progressively with several 3C2D-PIV-planes and the results were compiled into a volume-dataset. This dataset offers the ability to do full 3D-analysis, similar to what can be done with numerical data, which is particularly useful for comparisons and validation.

References


