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Development of a CFD Model and Validation with PIV-data to Study the Fluid Motion in a Small PFI SI Engine

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Abstract. In-cylinder fluid motion has a substantial impact on air-fuel mixture formation, combustion process and emission formation. In the present paper, a simulation study of the in-cylinder fluid flow is performed using a computational fluid dynamic (CFD) model of a port-fuel-injection (PFI) engine (volume: 110 cc). First, a 1-D model is developed, and validated with the cylinder pressure traces acquired in an optical engine experimentally. The model provided the boundary conditions for multi-dimensional numerical simulations. The predicted velocity fields from CFD are then compared with the measured data obtained using particle image velocimetry (PIV) at various crank angle positions with low throttle opening condition. A good relevance is observed on comparing numerically estimated results with experimental results.

1. Introduction

In-cylinder charge motion of an IC engine is a highly complex phenomenon, and has a considerable influence on the combustion process [1]. As compared to a weaker charge motion, a strong large-scale structure may sustain the turbulent kinetic energy release to a later part of the compression stroke due to a longer duration of its breakdown [2]. Late breakdown of a large-scale flow structure can result in the increase of turbulence intensity near the TDC of compression and enhanced the mean flow at the time of spark discharge; occurrence of these events can be correlated with faster flame travel and faster combustion [1, 2]. Hence a detailed study of in-cylinder fluid dynamics is necessary for the optimization of combustion chamber geometry and ports design to improve the fuel economy and reduce the emission formation. Particle image velocimetry (PIV) is considered one of the most prevalent velocity measurement technique, as it enables simultaneous acquisition of up to three orthogonal velocity components over a two-dimensional measurement region [3]. However, it is to be noted that the experimental techniques are limited, and obtaining a comprehensive information over the entire volumetric measurement region of the engine cylinder can be burdensome or practically impossible in most cases. In addition, PIV experiments require a number of runs to ascertain a faithful result by minimizing the effects of shot-to-shot variation due to (1) out-of-plane particle motion, (2) the uncertainties involved in the correlation technique, (3) the optical aberrations, and (4) the intrinsic electronic noise associated with the camera and the synchronization devices [4]. This makes PIV a rigorous exercise which may not always be suitable. Multi-dimensional numerical simulations, instead, provide the detailed information of in-cylinder processes varying with both space and time. Therefore, in this paper, development of a CFD model for the study of in-cylinder fluid motion in a small SI engine with port-fuel-injection is discussed. The model represented to the optical version of an SI engine with port-fuel-injection and a displacement volume of 0.11 L, and utilized the boundary conditions from 1-D modeling approach. The predicted velocity fields are compared with the measured data obtained using particle image velocimetry at a low engine speed of 1200 rpm with low throttle opening of 25%. In the future, this model will be used for the investigation of various in-cylinder processes and their interactions over a broad range of operating conditions.

2. Methodology

2.1 Experimental set-up

The engine used for the study of in-cylinder flow fields is an optical version of a small (0.11 L) spark-ignition engine [5]. The detailed information of the specifications of the engine can be found in Shinde et al [16]. The engine design consists of a fully transparent liner made of quartz material with a bore of 53.5 mm, and Bowditch type extended piston [6]. The compression ratio, stroke and connecting-rod length are 9:1, 48.8 mm and 91.8 mm, respectively. In-cylinder pressure data was collected at every 0.1 crank angle degree. A piezoelectric pressure transducer was used to acquire the in-cylinder pressure data. Experiments were conducted under motoring condition at 1200 rpm with 25%, 50% and 100% throttle openings. See Figure 1 for averaged cylinder pressure traces at different throttle openings.

2.2 One-dimensional engine model using AVL BOOST

AVL BOOST is used to model the engine with available components. To accommodate the flow losses due to 3-D geometry of intake, restrictions are provided at respective locations with adequate flow coefficients (Cd). Boundary conditions are provided by ensuring less heat transfer through the quartz liner and the piston surfaces due to a lower thermal conductivity of quartz compared to its metal counterpart. As suggested by Kurniawan et al. [8], isothermal wall assumption is made while modeling. A comparative study on heat transfer correlations [9] suggested the use of Hohenberg equation [10] over other correlations. For friction modeling, SLM model is selected [11, 12]. The model developed is shown in Figure 2.

One of the major challenge in modeling the optical engine is accounting for the strong blow-by due to the larger clearance present between the piston and the quartz liner, as compared to its metal counterpart. As a consequence, the peak in-cylinder pressure reduces. This problem further enhances at lower loads. The simplest procedure in order to nullify this effect is reducing the compression ratio by a narrow margin by reducing the squish height marginally to take the effect of crevice volume on the clearance volume into consideration [13].

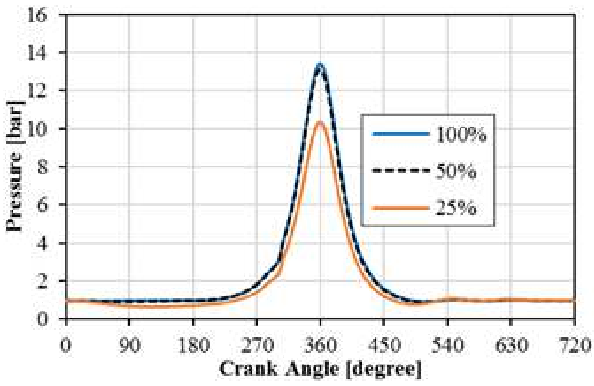

Figure 1. Averaged cylinder pressure traces at engine speed of 1200 rpm with different throttle openings

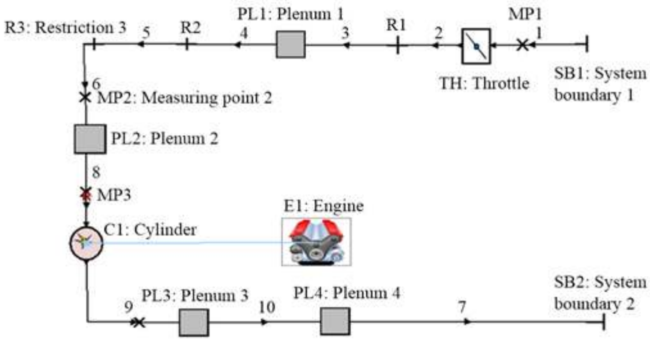

Figure 2. One-dimensional engine model usingAVL BOOST

2.3 CFD model using CONVERGE CFD

A detailed model of the optical engine is developed using CONVERGE CFD package. A second order central scheme with implicit method is used for computations as implicit methods are more stable than explicit method. RNG k-ε turbulence model was used. A complete case set-up is based on Rathinam et al. [14]. Different grid refining techniques are applied, namely, grid scaling, embedding, and adaptive mesh refinement (AMR), to improve the accuracy of the simulation results [14, 15].

- A base mesh of 4×4×4 cubic millimeters in X, Y and Z directions is used to simulate the flow in the fluid domain.
- Grid scaling technique is used to coarsen the base grid to 8 mm during first two cycles to reduce the computation time.

- Fixed embedding is done over intake port, exhaust port and cylinder region to achieve the mesh size of 1 mm. In addition to this, AMR is used to provide a refined mesh of 0.5 mm at critical regions in intake port and cylinder.
- Fixed embedding with a mesh refinement to 0.5 mm was used for all internal surface of the model.
- The total number of cells at the TDC and BDC locations were 176,951 and 428,239, respectively.

Figure 3 shows the model geometry with refined grids in different parts. The model is simulated at low engine speed and low throttle opening (as mentioned in section 2.1) for the study of in-cylinder flow patterns at various crank angle degrees (CAD). Boundary conditions at the inlet and exhaust are provided from 1-D simulated model as explained in section 2.2.

3. Results

In order to provide a quantitative measure for the comparison of the numerically estimated flow fields with the experimental data, average error, Err_average, and validation parameter, V, are introduced:

$$Err\_average = \frac{1}{k}\sum_{n=1}^{k} tanh\left|\frac{S(n) - E(n)}{E(n)}\right| \quad (1)$$

$$V = 1 - Err\_average \quad (2)$$

where k is the number of samples of cylinder pressure data acquired, $S(n)$ represents to the simulation results, and $E(n)$ represents to the experimental results. A value of V=1 means that the model output is 100% matching with the experimental data. In this work, model validation is performed based on cylinder pressure traces.

3.1 AVL BOOST modeling results

3.1.1 *Comparison of Pressure traces.* Figure 4 shows the comparison of pressure traces between 1-D simulation results and experimental results at low engine speed and low throttle opening. The comparison provided the Err_average value of 0.04, i.e. V value of 0.96, hence indicated a good correlation between model and experimental data.

*3.1.2 Inflow boundary conditions.*The intake manifold absolute pressure (IMAP) was modelled with 1-D model with a validation parameter of 0.96. Figure 5 shows the pressure and temperature profiles in the intake plenum over a complete engine cycle at low engine speed and low throttle opening.

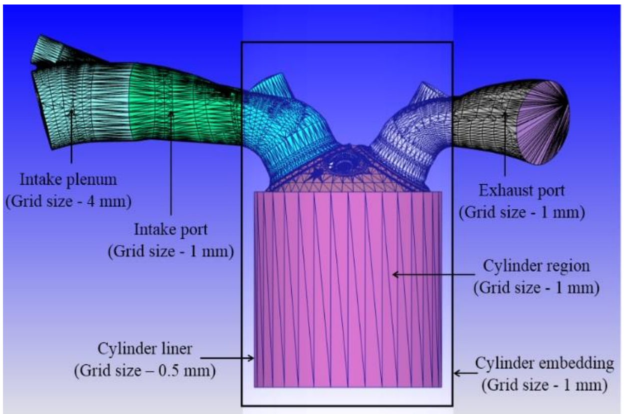

Figure 3. Computational model with grid sizes in different parts of the engine geometry.

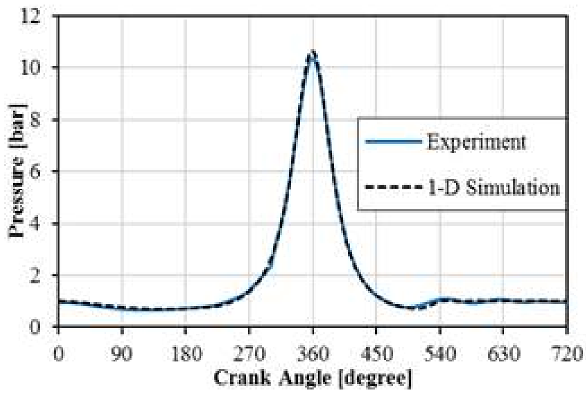

Figure 4. Comparison of cylinder pressure traces between experimental and 1-D modeling results.

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3.2 Converge Simulation results

3.2.1. Comparison of cylinder pressure traces. Figure 6 shows the comparison of cylinder pressure traces acquired from 1-D simulation with the pressure traces measured experimentally. The value obtained for the validation parameter was 0.96, with 2.9% deviation in peak pressures.

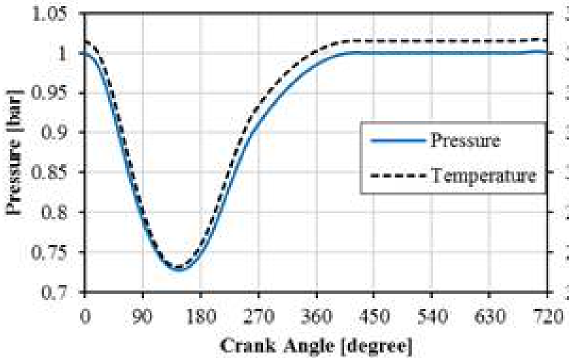


Figure 5. Intake manifold pressure and temperature.

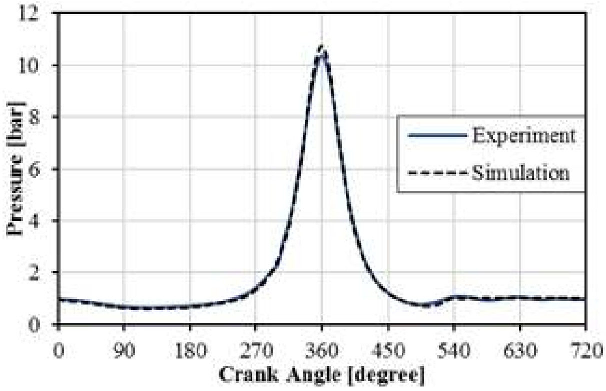
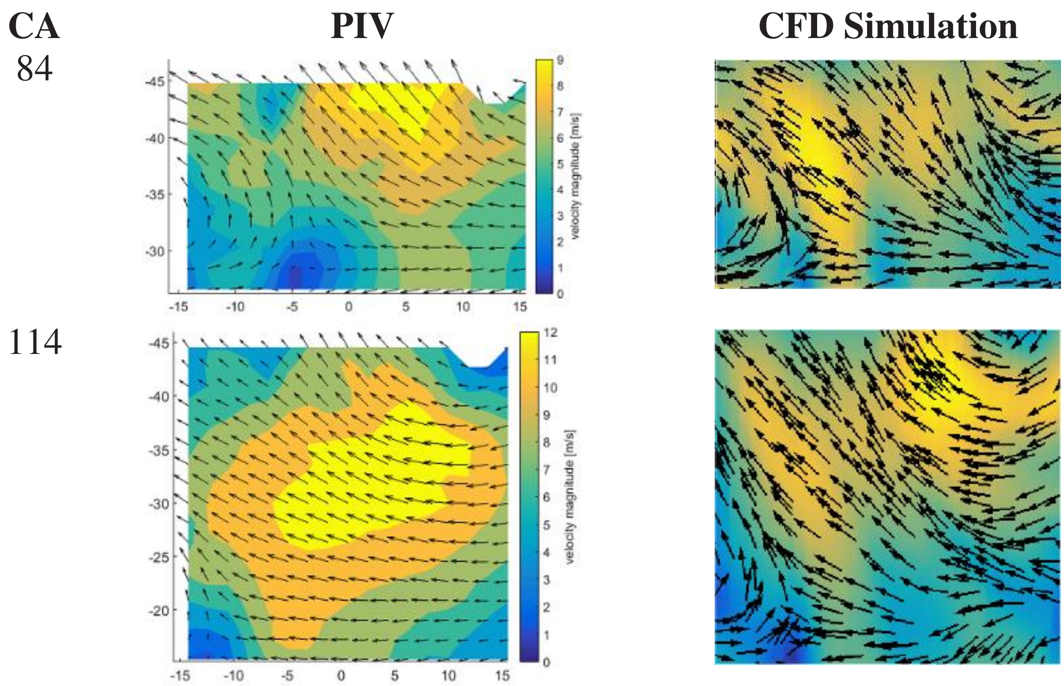


Figure 6. Comparison of cylinder pressure traces acquired from 3-D simulation with measured pressure traces.

3.2.2. Comparison of the velocity fields at various. CADs during both suction and compression strokes. The results of CFD simulation were post-processed in EnSight software. A tumble plane, same as was used for the PIV measurements [16], is clipped. Figure 7 provides the comparison of the velocity fields between CFD simulation results and ensemble-averaged experimental data obtained using PIV at various CADs. Overall, simulated velocity fields showed a good agreement with the PIV data.



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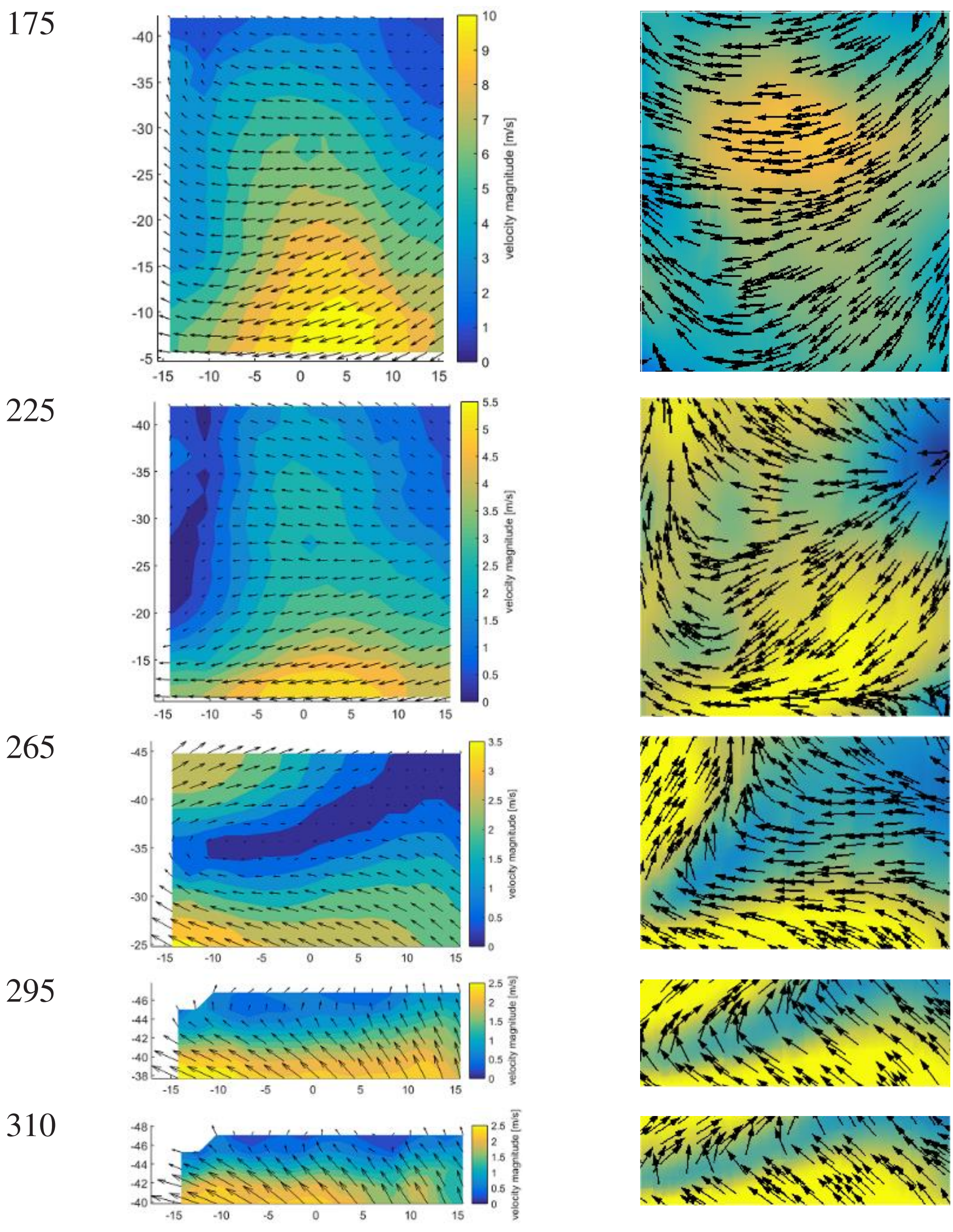

Figure 7. Comparison of in-cylinder flow fields between measured using PIV (left) (ensemble-averaged) and numerically estimated using CFD (right) over the tumble plane at various CADs.

4. Conclusion

- A one-dimensional model of a small SI engine with optical access is developed using AVL BOOST. The model was validated with the measured cylinder pressure traces at different engine operating conditions, and provided the boundary conditions for multi-dimensional numerical simulations.
- A computational (CFD) model of the engine was also developed for studying the in-cylinder fluid motion at various CADs. The velocity fields obtained through CFD showed a good agreement with the flow fields obtained by PIV for measured crank angle positions.

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5. References

[1] Heywood J.B, Fluid motion within the cylinder of internal combustion engines The Freeman Scholar Lecture 1986 *Journal of Fluids Engineering* **109** pp. 3-35.

[2] Arcoumanis C, Hu Z, Vafidis C and Whitelaw J 1990 Tumbling motion: A Mechanism for Turbulence Enhancement in Spark-Ignition Engines SAE Technical Paper 900060

[3] Reuss D, Adrian R, Landreth C, French D. et al 1989 Instantaneous planar measurements of velocity and large-scale vorticity and strain rate in an engine using particle image velocimetry *SAE Technical Paper* 890616.

[4] Reuss D.L, Megerle M and and Sick V 2002 Particle-image velocimetry measurement errors when imaging through a transparent engine cylinder *Meas. Sci. Technol.* **13** 1029

[5] Pradheep R, Mittal M, Mehta P S, Balaji V et al 2016 Imaging of Fuel Distribution in a PFI Spark-Ignition Engine Using Planar Laser-Induced Fluorescence 18th Annual Conference on Liquid Atomization and Spray Systems (ILASS–Asia 2016), Chennai, India.

[6] Bowditch F W 1961 A New Tool for Combustion Research a Quartz Piston Engine *SAE Paper* 610002

[7] http://www.avl.com, AVL boost user guide

[8] Kurniawan W H, Abdulla S and Shamsudhin A 2007 A computational fluid dynamics study of cold-flow analysis for mixture preparation in a motored four stroke direct injection engine *Journal of Applied Sciences* **7** 2710-2724

[9] Lounici M.S, Loubar K, Balistrou M and Tazerout M 2011 Investigation on heat transfer evaluation for a more efficient two-zone combustion model in the case of natural gas SI engines *Applied Thermal Engineering* **31** 319-328

[10] Hohenberg G H 1979 Advanced approaches for heat transfer calculations *SAE Technical Paper* 790825

[11] Shayler P, Leong D and Murphy M 2005 Contributions to engine friction during cold, low speed running and the dependence on oil viscosity *SAE Technical Paper* 2005-01-1654

[12] Patton K.J, Nitschke R C and Heywood J B 1989 Development and Evaluation of a Friction Model for Spark Ignition Engines *SAE Technical Paper* 890836

[13] Chryssakis C A, Assanis D N, Kook S and Bae C 2005 *Effect of multiple injections on fuel-air mixing and soot formation in diesel combustion using direct flame visualization and CFD techniques* Proceedings of ASME Internal Combustion Engine Division, Spring Technical Conference Paper number ICES2005-1016

[14] Rathinam B and Ravet F 2015 Servant C, Delahaye L. et al, Experimental and Numerical Investigations of Tumble Motion on an Optical Single Cylinder Engine *SAE Technical Paper* 2015-01-1698

[15] CONVERGE CFD user guide.

[16] Shinde G, Mittal M and Lakshminarasimhan V 2018 A Study of Cycle-to-Cycle Flow Variations in a Small Spark-Ignition Engine at Low Throttle Opening 2018 *SAE Technical Paper* 2018-32-0035