INVESTIGATIONS OF
ENGINE FLOW FIELDS AND COMBUSTION
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ABSTRACT

This paper is a summary of four year project of in cylinder flow fields in diesel engines. The project ended at 2008. The objective of the project was to study mixing of fuel and air in diesel combustion to achieve controlled combustion with low emissions. The project consisted of both computational and experimental work. Much of effort was paid on fuel sprays and mixing and the other main subject was in-cylinder swirl which was both simulated and measured.

Fuel spray measurements were done both at non evaporating conditions and in large bore medium speed research engine at real operating conditions. Optical fuel spray measurements were started at pressurized injection test rig and at the second stage of the project measurements were extended to real engine. Similar spray cases were also simulated and the results of experimental work were compared to computational values.

In-cylinder flow fields and swirl were measured with particle image velocimetry (PIV) and paddlewheel at a static flow rig. The results of different measurement methods were found to be very similar. Measured cases were also modelled with Computational Fluid Dynamics (CFD) for comparison and to evaluate accuracy of modelling. In-cylinder swirl measurements were started with a static flow rigs where engine intake flow has a strong swirl and turbulence, which is a difficult case for CFD.

The near future of combustion studies will be carried out with laser based techniques (LIF and LII) which give information of flame propagation and soot production. These techniques will have a major role on the diesel engine combustion research where the reduction of soot production and NOx emissions are in focus. Preliminary studies have been done and results are shown.

Keywords:
Engine, flow field, swirl, CFD, Combustion, spray, PIV, LIF, LII
INTRODUCTION

In-cylinder flow fields, and especially the fuel sprays, play major role in controlling diesel combustion. The aim of the project was to increase the understanding of the dominating physical phenomena which are important to engine combustion. Understanding of combustion process is important at the common effort towards environmentally friendly diesel engines.

For the proper engine process it is important to have a even cylinder charge. And for proper combustion it is extremely important to have adequate turbulence and initial swirl of in-cylinder gas. The swirl and turbulence enhance mixing of air and fuel and therefore enable better control of combustion.

Fuel spray studies are especially important for diesel engine combustion. Spray combustion has a major role at the formation of particulate emissions and NOx emissions at direct injection diesel engines. These emissions are both local environmental problem and have high effect at air quality. Many of the new after treatment techniques for emission reduction affect the overall efficiency of engine process, which will lead to higher consumption of fuels which will thereby cause elevated CO₂ emissions. The best way to contribute to flue gas emissions is to get the initial emission production to lower level.

The results of fuel spray studies can often be quickly and easily applied to practice. The problem has been the extremely high turbulence and high velocities of fuel spray which are challenging for measurements and simulations. Simulations and engine test runs are a time consuming and often inaccurate way of describing the fuel spray related issues. Optical measurement techniques have shown to give new and valuable information on the understanding of fuel sprays. This is a way to guide the simulations to the right direction and to get boundary conditions to spray and engine design. At the near future also laser induced fluorescence (LIF) and laser induced incandescence (LII) will be applied to practice. Those techniques show intermediate species of combustion and can track the formation of soot. These techniques have high expectations on the field of combustion studies.
FLOW FIELD ANALYSIS

In cylinder flows were both simulated and measured in a test rig that consisted of a cylinder head assembly through which air was blown. Different static valve lifts were used in both the measurements and simulations. The experimental and numerical setup is detailed in a publication (Kaario et al., 2007). The velocities with different valve lifts and different pressure differences over the valves were measured with laser based particle image velocimetry technique (PIV). The swirl of high speed engine was also measured with PIV and paddle wheel. PIV measurements can be considered to be reliable in terms of accuracy of the results obtained.

The computational mesh can be seen in the Fig. 1. Air was blown from the top part of the mesh through the cylinder head from which the detailed mesh insert is shown. Right after the cylinder head there was a glass liner from which the experimental and numerical results were gathered. The outlet of the model is in bottom of the geometry shown.

Even though the simulated case consisted of very high turbulence and high velocity gradients, the simulations showed to be a valuable tool for regular engine design work. In the Fig. 2 there is shown a measured flow field after the cylinder head and the equivalent numerical solution from the same plane. Both cases represented static flow at test rig with 2500 Pa pressure difference over the system. It is seen that the experimental and numerical flow fields have many similarities.

Figure 1. The computational geometry used with some details of the mesh consisting a total of 1.7 million cells.
Swirl measurements and simulations were made at 1.8 cylinder diameters from the valves. In this case different valve lifts and pressure differences were also tested. There has been discussion about the reliability of paddle wheel measurements. The regular assumption is that paddle wheel measurements underestimate the swirl. In the Fig. 3 there is shown swirl measurements with both PIV and paddle wheel some 190mm after the cylinder head. It is seen that both types of measurement techniques give roughly the same result. Accordingly, these results support to use of paddle wheel in engine swirl measurements. The pressure difference over the cylinder head has a minor effect on the swirl ratio, as was expected. This can be also seen from the Fig. 3.

In the Fig. 4 is shown the measured and simulated swirl level 1.8 cylinder diameters after the cylinder head. The swirl level is shown with different static valve lifts and with two different turbulence models. It is seen that the numerical result captures well the trend observed in the experimental data. The quantitative level of the results is also very good. With higher valve lifts the flow behavior in the cylinder starts to be increasingly turbulent. The results in the Fig. 4 indicate that the rng k-e turbulence model performs better with higher valve lifts than the standard k-e model.
Figure 3. Swirl measurements with paddle wheel and PIV right after the cylinder head with different valve lifts.

Figure 4. Measured and computed swirl ratio with different valve lifts and turbulence models. Swirl ratio is the ratio of the paddle wheel rotational speed to the vertical velocity component of air.
FUEL SPRAY STUDIES

Part of the fuel spray studies was done at pressurized measurement chambers. At the latter part of project fuel sprays were also measured at combustible environment (running large bore medium speed engine). Similar cases were also simulated, and the results of measurements and simulations were compared to existing data. It is very important to combine computational and experimental work to understand the in-cylinder phenomena and to get new information and to understand correlations between different parameters. The cold chamber measurements can be used to evaluate fuel spray simulations and theories.

Test chambers (Fig. 5) are an important tool for fuel spray validation. At measurement chambers the ambient conditions and fuel injection can be varied. At very accurately known system the effect of e.g. injection pressure and ambient density to spray structure and geometry (Fig. 5) can be validated.

The injection tests were performed at pressurized test rig with 3, 6, 12, 20 and 35 kg/m$^3$ ambient gas densities and with 700, 1000 and 1300 bar injection pressures. This resulted in 15 different combinations of injection conditions and gave a good base for further studies of spray penetration and geometry. Also PIV (Particle Image Velocimetry) measurements of fuel spray were made and the results were promising. During the project it was proven that also the optically very dense diesel fuel sprays can be accurately measured with PIV. The main results of the fuel spray flow field measurements were published (Hillamo & Kaario & Larmi, 2008).

Figure 5 Spray test rig for investigations of non evaporating fuel sprays. Photographing and PIV measurements of fuel injection were performed. A back-light image of diesel spray is shown at middle and at right hand side a laser sheet image of non-evaporating diesel spray at pressurized gas.
Fuel spray measurements in a running large bore engine

Figure 6 At left hand side the measurement system and at the right hand side there are fuel spray images from running engine.

Fuel spray penetration and velocity measurements were performed at running large bore (200mm) medium speed engine (Sarjovaara et al., 2008). The measurements took advantage of laser sheet imaging and produced data for PIV. The imaging was done with a high resolution (4 mega pixel) double frame camera. Laser sheet illumination for fuel spray was performed with 532 nm laser pulse with short duration. With a band-pass filter and a mechanical shutter it was possible to reduce flame light from the images and only scattered laser light from droplets was captured.

The optical access windows through body of a large engine were 100 mm thick. The windows were designed to endure under high pressure and temperature conditions of an internal combustion engine cylinder and to keep final compression ratio in same range than what is present at a regular engine. The peak cylinder pressure in measurements was 38 bar and there were also results from injection test bench with a close match to the same gas density. Similar injectors had been tested and optically validated by photographing (Hillamo and Sarjovaara et al., 2008). The injections had 1400 bar injection pressure and the injection duration was reduced to of 1.5 ms to keep pressures at cylinder at minimum.

The results of the fuel spray penetration measurements are in figure 7. The results are plotted to same figure with two well known empirical correlations by Hiroyasu and Dent (Heywood, 1988). It can be seen that the Dent correlation seems to be consistent with measurements. The high penetrations of Hiroyasu correlation are similar what has been found also in other studies (Hillamo & Sarjovaara et al., 2008).
Figure 7 Fuel spray penetration at running large bore engine was recorded and the penetration is compared to correlations of Hiroyasu and Dent. The nozzle hole diameter was 0.34 mm.

The results of the fuel spray PIV measurement are in figure 8. The Velocities are average values from several measurements and also the background image of fuel spray is averaged. The examples of individual raw images were presented in figure 6. The spray velocities were consistent with previous cold chamber measurement (Hillamo& Kaario& Larmi, 2008). Vectors outside the spray area were generated by background noise and post-processing algorithms, and the reliable vectors are only on the spray area.

Figure 8. Measured flow field of fuel spray at large bore medium speed engine. Measurements were done with PIV technique.
COMBUSTION STUDIES

The long term aim at engine combustion research is to get new measurement techniques to engine research. The new practical ways of measuring engine combustion consist of engines with optical access and non-intrusive laser diagnostics. The soot and NOx emissions are the most important issues with diesel engines. The combustion and soot formation can be monitored with laser induced fluorescence (LIF) and laser induced incandescence (LII). Those techniques show intermediate species of combustion and can track the formation of soot.

Preliminary combustion studies have been carried out with LIF and LII –techniques which give relative values for flame propagation and soot production. These measurements, (Fig. 9), give a good practical knowledge of capability of the laser based techniques.

CONCLUSIONS

A lot of new information was gathered during the project and new modeling issues and measurement devices were validated. This project significantly increased the understanding of engine in cylinder flows. The project also tested new experimental and modeling techniques. On some areas the measurements gathered new validation data for the simulations.

It was important to use several methods to measure the same flow phenomena. Some of the methods needed validation because there were only rough estimations how accurate these methods are. In practical engine design work a lot of relatively simple but accurate estimations are needed. Some of these estimations were shown to be good enough for initial guesses for design values, but some issues seem to need very accurate measurements to make sure that the design has been successful.
Various experimental set-ups and computational cases were studied to get new and most valuable knowledge on in-cylinder flows of diesel engines. Within the research group, experimental work is performed in close co-operation with computational fluid dynamics. This has shown to be an important issue when trying to find out and understand new issues on in-cylinder flows.

It is important to move from basic flow field studies to combustion studies. In the first place the fundamental properties of fuel jets and mixing have to be understood. The combustion process is next big thing to be studied when the emission reduction is in focus. The combustion process can be monitored with LIF and LII techniques. These techniques combine laser induced fluorescence, imaging and optical access to engines. CFD will be also used in combustion analysis. Combination of experimental and numerical approaches is strength of the research group.

**REFERENCES**


