Experimental Study of High Pressure Gas Injection Using Optical Methods

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Problem

The high-pressure dual-fuel (HPDF) marine engine is considered a promising concept based on potentially higher efficiency, independence of fuel quality and absence of methane slip. Despite this it has still not been implemented in serial engines due to quite limited research effort related to the study of high-pressure gas injection. In the current study, the injection processes of high-pressure gas was experimentally studied in a constant volume combustion chamber (CVCC) using a prototype gas injector. The effect of injection pressure, chamber pressure and nozzle geometry was evaluated. The study was conducted using a number of optical methods such as Schlieren and Background-Oriented Schlieren (BOS) with corresponding numerical analysis.

Gas Jet Characteristics

In direct injection engines there is short time for mixing of fuel and air. Therefore an understanding of the characteristics of the gas jet is crucial in order to facilitate good combustion conditions. Accurate determination of macroscopic characteristics such as the jet tip penetration, speed and angle for representative pressure ratios is invaluable. Larger penetration can increase the jet volume and with this also increase air utilization, while a short jet tip penetration can be necessary if wall impingement has to be avoided[1].

Optical Methods

In order to assess the characteristics of the injected fluid an optical analysis was conducted.

Optical analysis processes are beneficial as they are non-intrusive and have high temporal and spatial resolution. For the experiments performed in this thesis, Schlieren and Background-oriented schlieren was utilized. Both of these techniques takes advantage of the phenomenon of light refracting as it passes through media of different density. As the light is refracted the image will be distorted depending on the density of the medium the light passes through, allowing for a visualization of the density gradients. The light refraction follows the Gladstone-Dale relation. [2]

$$n - 1 = k\rho \tag{1}$$

where k is the Gladstone-Dale coefficient, n is the refractive index and ρ is the fluid density.

Acknowledgements

References

[1] Hajialimohammadi, Alireza ; Edgington-Mitchell, Daniel ; Honnery, Damon ; Montazerin, Nader ; Abdullah, Amir ; Agha Mirsalim, Mostafa: *Ultra high speed investigation of gaseous jet injected by a single-hole injector and proposing of an analytical method for pressure loss prediction during transient injection.* Fuel, 184, 2016

[2] G. S. Settles: *Schlieren and Shadowgraph Techniques.* Springer, 2001

[3] Thielicke, W. and Stamhuis, E.J. :*PIVLAB-Towards User-friendly, Affordable and Accurate Digital Particle Image Velocimetry in MATLAB.* Journal of Open Research Software, 30, 2014

Test Procedures and Analysis

The entirety of the testing was conducted at SINTEF Ocean's combustion laboratory at the Center of Marine Technology in Trondheim, where extensive modifications have been made to the laboratory in order to perform gas injection testing. All injections were captured using a high speed camera at 40 000FPS and the optical methods mentioned were applied to yield material for further analysis. For the optical analysis, a total of 200 test injections were performed. 100 injections for each imaging technique. Five different nozzles with different geometric shapes and sizes were investigated. Injection pressures of approx. 220bar and 380 bar and chamber pressures of 1bar and 20bar were used.

The background-oriented schlieren images were analyzed using a particle imaging-velocimetry (PIV) script[3] to create a displacement vector field, this field then was integrated numerically by use of the Poisson equation, Eq. (2), to create a refractive index field which was then converted to a density field by using Eq. (1).

$$\nabla^2 n = f(x, y) \tag{2}$$

The conventional schlieren images were analyzed using a custom script made by co-supervisor Vladimir Krivopolianskii. This script converts each image to a black-and white image based on a user-defined threshold, locates the boundaries of the jet and measures penetration length and cone angle.
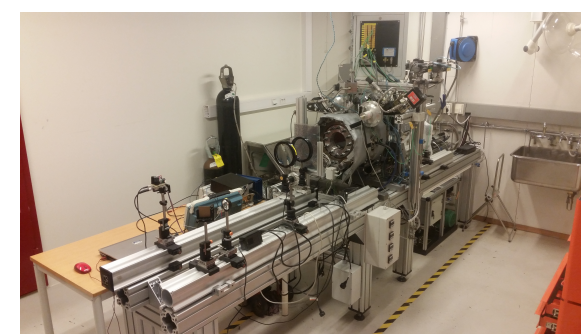

Experimental Results

The figure below shows the steps in the BOS analysis. A displacement vector field was created from the distortion in the image by way of PIV, this was then integrated and converted to a density field. Unfortunately the results proved to be highly inaccurate due to difficulties setting proper boundary conditions for the numerical solver. The interrogation area was to small and there were to many stochastic effects due to the dynamic and turbulent nature of the jet. Despite unsatisfactory results, a foundation for further work utilizing this technique for similar studies have been laid.
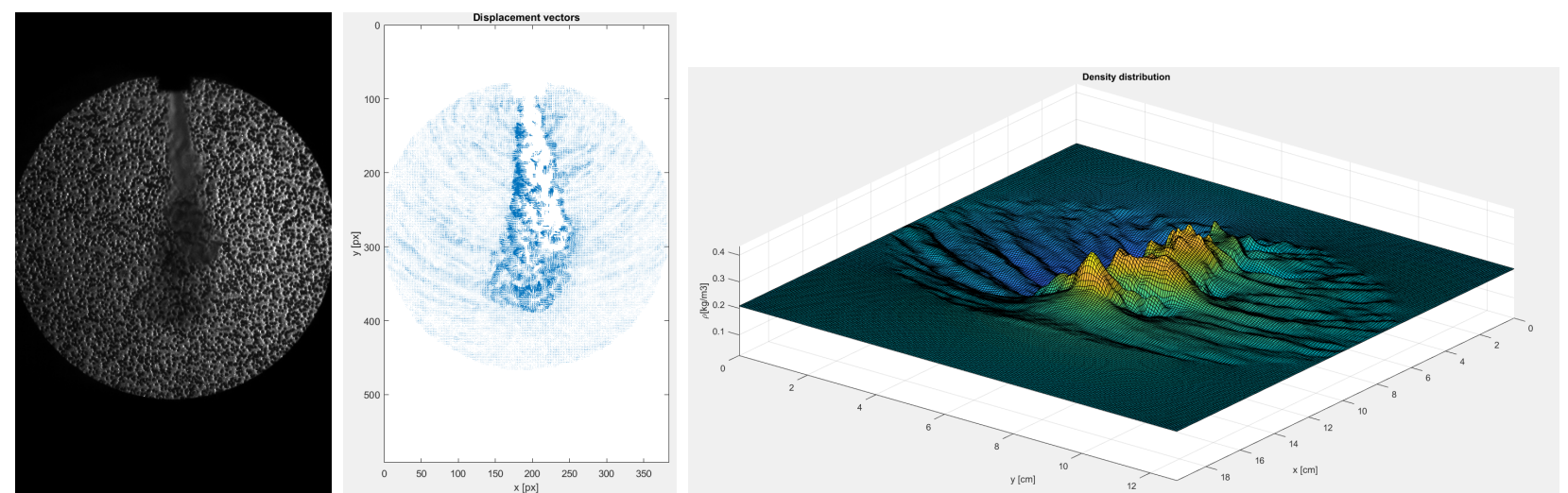
Examples of fully developed gas jets from three different nozzles with the same injection pressure and chamber pressure captured using the schlieren technique can be seen below.
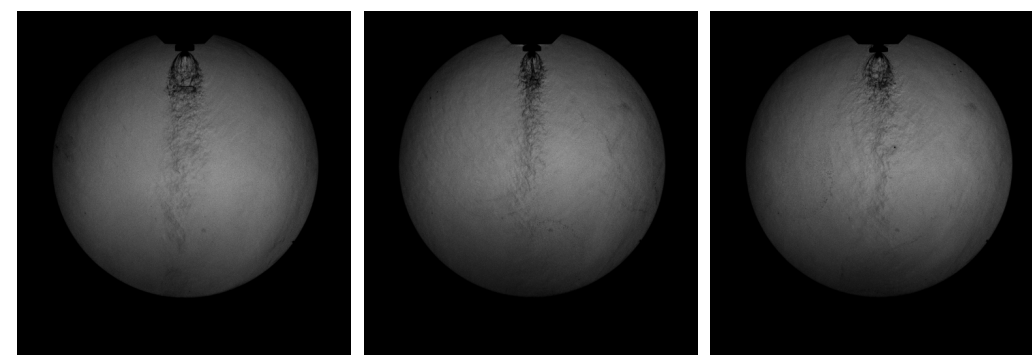
In the figure below, jet propagation and average cone angle can be seen for different combinations of chamber and injection pressure using the same nozzle.
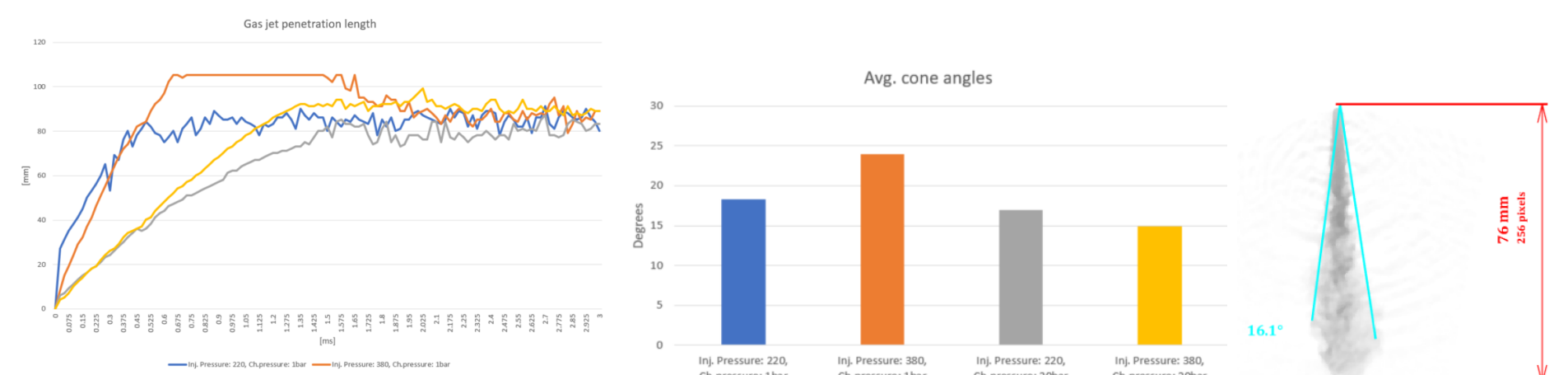
Conclusion

As there is still work left to be done, no definitive conclusions can be drawn, but some trends can be pointed out. The maximum gas jet penetration length was quite similar for all combinations of injection- and chamber pressure but the gas jet velocity was affected significantly, as the time to obtain maximum penetration varied widely. The cone angle decreased as the chamber pressure increased, but injection pressure increase had opposite effects on cone angle at the different chamber pressures.

The effect of nozzle geometry proved difficult to measure quantitatively, but interesting phenomena could be observed by manual visual inspection.