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Application of cone-beam micro-CT on high-speed Diesel flows and quantitative cavitation measurements

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Abstract. X-ray computed tomography (CT) is well-known and widely used in the medical sector for diagnosis of various illnesses. The technique is based on the absorption (i.e. attenuation) of the ionising electromagnetic radiation by the object. The amount of energy to be absorbed depends on the density and its thickness; the transmitted radiation through the object is then compared to the incident radiation that leads to a reconstruction of attenuation coefficients versus spatial position in the object. Thus, the resulting three-dimensional slices of the object are used (a) to identify internal geometric features of objects, and (b) to distinguish between media of different densities, i.e. liquid and air/vapour. In this study, the geometry extraction capability has been applied on time-averaged cavitation pocket shapes, as well as, the capability of density differentiation measurements on Diesel fuel flows. Results appear promising and pose a challenge in providing quantitative measurements of cavitation vapour fraction inside an injection hole.

1. Introduction

Fuel injection systems for modern direct-injection Diesel engines play a distinct and paramount role that is well recognised as a means of controlling their performance and meeting the ever more stringent emission regulations. Cavitation phenomena become the dominant and frequently uncontrolled flow characteristics that affect the durability of the fuel system and the properties of the near-nozzle spray. Investigations over the last few years have demonstrated that Diesel injector nozzles cavitate [1, 2] under typical operating conditions, a fact that complicates further the already complex design of high-pressure Diesel injection systems. Apart from the manufacturers' quest for environmentally friendly engines, the fuel industry has recently joined this race by providing increased quality Diesel fuel, compared to previous years. The latter is primarily achieved by standardised procedures at the refinery, however, in most cases it is cost-efficient to use fuel additives in order to achieve Diesel of higher standards. Almost all diesel fuel sold commercially contains additives that are necessary to maintain efficient FIE operation, engine performance and reduce emissions. Due to their proprietary nature and relatively complex chemical structures, additives and mechanisms by which they affect injector flow and/or spray formation are not yet well-known. Detergents are one of the most important components in a diesel additive package and are used for deposit control purposes [3]. Their mechanisms include keeping new injectors clean by generating a protective film on metal surfaces and by preventing agglomeration of deposit precursors, as well as cleaning up fouled injectors by deposit removal and dispersion [4].

Chemistries used for deposit control applications are not unlike household detergents in their basic structure. Recently, a significant and unexpected increase in power was reported with the use of fuel containing specific quaternary ammonium salts [5]. PIB-based quaternary ammonium salts at a treat rate as low as 500 ppm and 1000 ppm resulted in a significant power gain compared to un-additised fuel. The mechanism by which the increase in power was achieved is not known; however, there is evidence that the flow rate through the injector is altered. Based on these findings, the present study attempts to investigate the tendency in Diesel fuel to cavitate when enriched with the above type of additives.

The success of such an experimental investigation depends on the measurement technique and the accuracy of the acquired results. X-ray computed tomography is widely spread in the medical sector, as means of measuring density variations in organs of the human body. When multiple projections are gathered at various angles, then, reconstruction of the single radiographies results in a 3-D representation of the shape of the object by means of absorption coefficients. This capability is exploited in this study in order to measure differences in density between liquid and vapour Diesel.

2. Experimental set-up

Multi-hole Diesel injector nozzles present strong flow interactions among the several orifices [2, 6]. The developed complicated flow phenomena render it impossible to study the fundamentals of cavitation inception and development and compare subtle differences for a single orifice. Therefore, a prototype nozzle was designed with certain features that enable unobstructed access to the full length of the region of interest. In detail, as illustrated in Figure 1, the nozzle comprises a single injection hole, whose axis is at an offset to the main axis of symmetry of the device. The latter, and the non-symmetric needle, ensure a flow asymmetry that causes cavitation mainly on one side of the orifice entry, enabling unobstructed view of the cavitation pocket created from any angle.

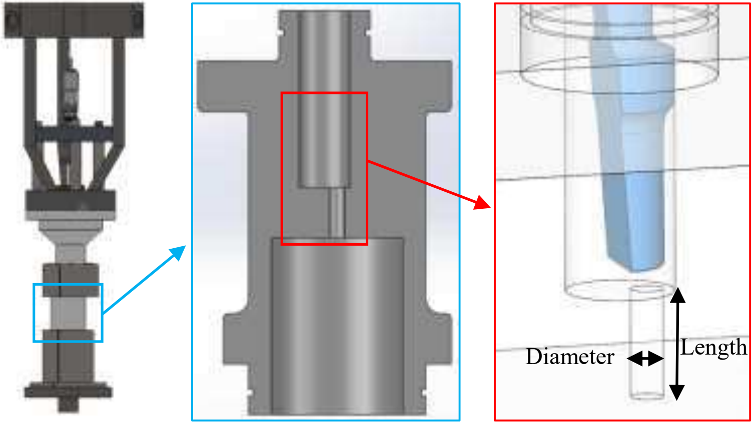

Figure 1. Schematic representation of assembled nozzle (left-most) and cut-out of the nozzle specific design parameters.

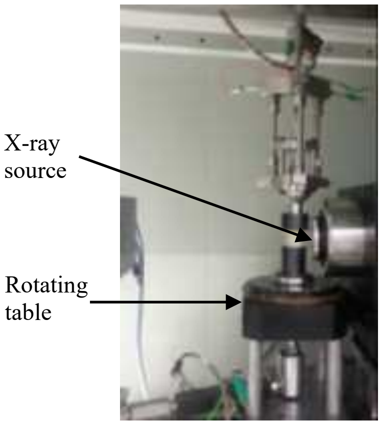

Figure 2. Test-rig inside the mCT scanner

The test-rig has been designed specifically for use inside a micro-CT scanner developed by University of Bergamo (Figure 2). The limitations in x-ray detector technology (acquisition freq. ~30Hz) and x-ray energy available from a polychromatic source, dictated the design of a steady state experiment. Therefore, the needle present in the nozzle is set at a fixed position and does not change during a complete 360° acquisition. Moreover, the hydraulic unit responsible for pressurised fuel delivery provides a maximum pressure of 140bar. The latter is not representative fuel injection pressure for common rail Diesel systems, however, the nozzle material that had to be transparent to x-rays is selected to be Peek and its strength is limited; additionally, it has been our intention to study the fundamentals of cavitation inception and development. Nevertheless, the test-rig is equipped with flow control valves, pressure transducers and a temperature control system able of controlling fuel temperature at ±1° around the set point. Finally, the nozzle has an orifice diameter of 3mm and a length of 10mm. The selection of large scale dimensions served the purpose of increased spatial resolution; the combination of a cone-beam CT scanner and the given nozzle size resulted in a voxel size of 8x8x8μm.

2.1. Measurement technique and post-processing

A cone-beam CT scanner comprises a point source that emits cone beam shaped x-rays that penetrate through the object of interest, they attenuate and the remaining energy is captured by a detector, as illustrated in *Figure 3a*. In the same *Figure 3*, images b, c and d illustrate sample single projections (radiographies) of the flow orifice under different operating conditions. The difference in radiation absorption between air and Diesel is immediately visible; the latter secures enough contrast for the reconstructed volume to enable differentiation between Diesel liquid and vapour phases.

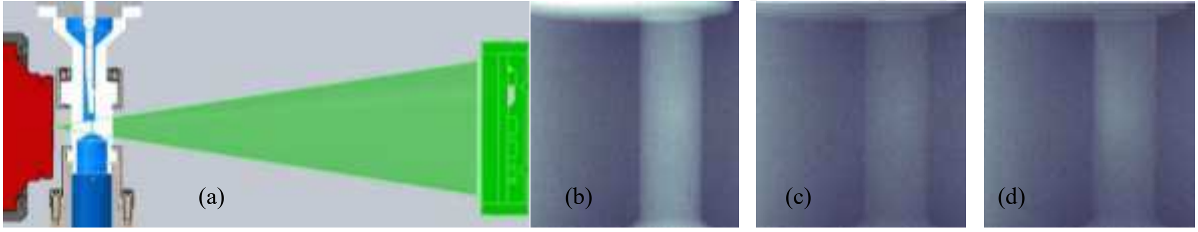

Figure 3. a. Cone beam CT setup. Projections of flow channel filled with **b.** air, **c.** Diesel and **d.** cavitating flow.

The reconstruction algorithm applied on cone-beam CT applications is the so-called back-projection algorithm of Feldkamp, Davies and Kress [7]. The algorithm is approximate but has useful properties, including errors that are relatively small in many practical instances and a form that leads to convenient computation. According to this technique, following the logarithmic normalisation and the application of a ramp filter on the raw radiographies, the image captured on the detector is back-projected to the Cartesian axis system of the object of interest and a three-dimensional density function is reconstructed. Effectively, the density function is created in terms of density slices of the object of interest normal to the rotational axis. Since the technique is based on radiation absorption comparison, it is vital for the incident cone beam to have equal energy over the whole area of interest. This is rather impossible due to the polychromatic x-ray source, a fact that potentially leads to increased calculation error. As seen in *Figure 3b,c*, along the axis of the orifice the captured intensity is not constant; it is evident that the projection is brighter at the middle. Therefore, in order to reconstruct the density map without including the error from radiation intensity differences, we devised a calibration procedure, which calibrates every voxel of the reconstructed volume against the corresponding voxel of two calibration sets, with Diesel liquid and air. Finally, the assumption that Diesel liquid and air share similar absorption properties to pressurised Diesel (at 60 bar) and Diesel vapour (at ~20 kPa) introduce relative errors of 1.2% and 2.5% for Diesel liquid and vapour respectively.

Results

The followed calibration and post-processing procedures are expected to provide results that are not affected from the spatial intensity variations of the source; an error analysis showed a relative error of ~1%. As illustrated in Figure 4, the matrix of absorption coefficients is created for every slice of the orifice for both cases, with air and Diesel. The corresponding histogram then sets the range of absorption coefficient values that represent any possible mixture of Diesel and vapour for this particular slice. Finally, the reconstructed slices of any operating condition are calibrated against these ranges, per slice.

In detail, the micro-CT technique requires approximately 2 seconds to acquire enough signal for a single angular step. This causes the acquired data to be averaged over this time period; thus, showing the mean cavitation vapour fraction of the flow. Figure 5 illustrates two slices from two different locations along the orifice length, where vapour appears darker. According to the calibration mentioned above and the corresponding colour bar one can easily extract the cavitation vapour fraction for each pixel of the slice.

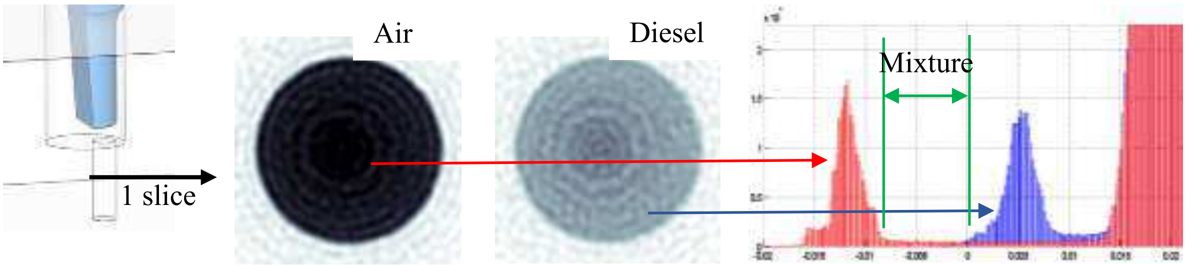

Figure 4. Calibration procedure. The super-imposed histograms of air and Diesel absorption coefficients illustrates the range of pixel values for this particular slice that represent any possible mixture other than 100% Diesel or air.

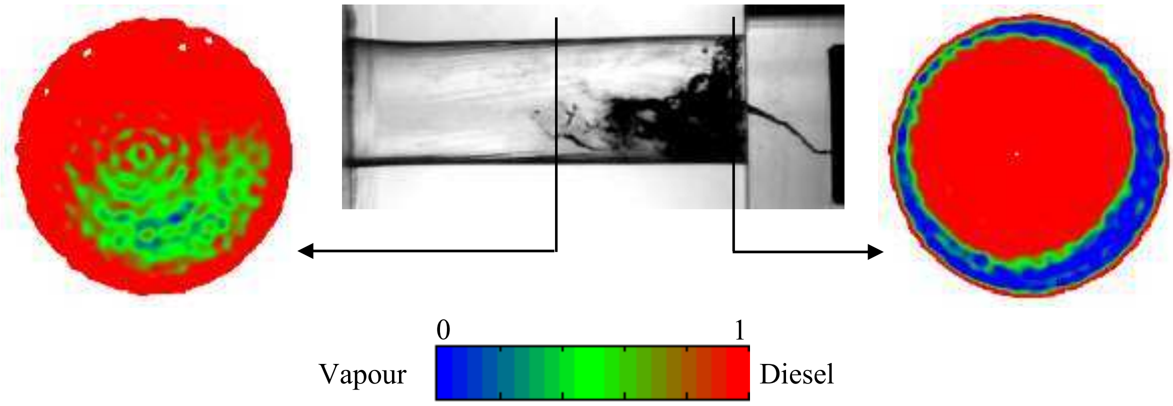

Figure 5. Quantitative measurements of vapour fraction at two different locations along the orifice.

Conclusion

The possibility of applying the micro-CT technique on highly transient cavitating Diesel fuel flows has been investigated and results appear promising in terms of time-averaged quantitative fuel vapour measurements. Since this is an ongoing investigation, we intend to keep the scientific community updated with our future findings.

Acknowledgements

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