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# Correlation of Internal Flow and Spray Breakup for a Fuel Injector Used in Ship Engines

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Abstract: A full-scale fuel injector for a large marine engine has been studied inside an optically accessible, high pressure spray research chamber. The injector tip was made of quartz and it had two holes oriented nearly normal to the injector centerline. Realistic nozzle internal flow passages were used, but a Scania XPI injector body delivered the fuel. The injector body was mounted in the side of the high pressure and temperature spray chamber at Chalmers (one of the windows was replaced), and the jets it produced pointed downward into a spray catch facility. Commercially available Diesel fuel was provided by an accumulator at 110 bar delivery-line pressure. The spray was ejected into flowing air at room temperature and pressures of 10 bar (to achieve relevant cavitation numbers), with injection durations on the order of hundreds of ms. The steady flow portion of the injection process was studied. Internal flow was observed using white light imaging, while spray breakup dynamics were observed using a Ti:sapphire laser-based, time gated ballistic imaging system. Spray dynamics were also studied using a spray impingement measurement inside the chamber. The internal and external (near field breakup) flows seemed to be correlated. Under high levels of cavitation the spray appears to break up similar to an aerated spray, producing a dense field of large primary drops at a fairly large spray angle. Under non-cavitating conditions the spray seems to break up similar to a more classical Diesel injector; including such features as an intact core, surface waves, some bag breakup, and what appears to be air entrainment.

## 1 Introduction

Emissions regulations have been in effect for road vehicles since the early 1970's, and they have slowly grown more strict over time. Advanced technologies such as exhaust catalysts with oxygen sensors and feedback control for light-duty, spark-ignited gasoline engines; or high pressure injectors with turbocharging, exhaust gas recirculation (EGR), and selective catalytic NOx reduction (SCR) for heavy-duty Diesel engines are fairly commonplace. The marine engines in oceangoing ships, however, have not had to adapt to the same kinds of regulation until recently. The International Maritime Organization (IMO) has published emissions targets for SOx, NOx and soot. More recently they have published $CO_2$ limits in order to address global climate change concerns. There are also defined emissions control areas (e.g. ports) where even stricter levels are held.

Much of the ongoing marine engine development is focused on meeting the requirements of the IMO Tier III legislation which will be in effect in 2016. Tier III dictates an 80% reduction in NOx engine out levels. Engine manufacturers are investigating engine internal NOx reduction methods, such as Miller/Atkinson timing, water in fuel (WIF), and EGR. The advent of these methods requires that engine manufacturers have a good understanding of all internal processes - including fuel injection.

Just to orient the reader, the single cylinder engine displacement used in oceangoing two-stroke engines by MAN can range from 0.14 $m^3$ to 2.0 $m^3$, in formats from 5 to 14 cylinders and with power levels from 4,000 $kW$ to 87,000 $kW$. Oceangoing ships can burn various forms of fuel, from bunker fuel (a tar-like fuel that requires heating just to pump it) to normal Diesel fuel. The fuel of choice depends upon what is available in port and at what price, but nowadays it is not unusual to switch from the much cheaper bunker fuel to Diesel as the ship nears port. This is one big difference between road vehicles and ships; road vehicle manufacturers have been able to specify fuel properties fairly tightly whereas the necessary fuel flexibility for an oceangoing ship adds additional difficulties. These fuels can have different abrasive and cavitation behavior, for example, presenting challenges to injection system design. Moreover, the in-cylinder sprays of these fuels are different, and it is therefore imperative to know how these in-cylinder characteristics of the fuel are controlled by the fuel injection system.

It is very expensive to perform tests on such engines, although it is done. MAN Diesel and Turbo, for example, has a 4-cylinder test engine in Copenhagen where one cylinder can be rigged with an optical cover with 24 ports offering various window combinations for a given optical measurement campaign. Flame and spray visualization as well as in-cylinder flow measurements have been demonstrated with this cover. Much of the engine research and development work, however, still relies upon numerical modeling.

The challenge to computational fluid dynamics (CFD) modeling of such engines is to achieve better predictability. A weak link in that problem has been detailed understanding of the flows in the interior of the nozzle and their effect on fuel spray breakup. These injectors are much larger than what one finds in a surface transport engine. A heavy-duty truck engine can typically have from 6 to 8 holes per injector, and the holes will be on the order 100 - 150 $\mu m$ diameter. A ship injector can have perhaps 5 holes and they can be from 0.7 to 1.6 $mm$ in diameter. The spray exits on the side of the cylinder and injects fuel with the swirling flow. Typically two such injectors are used per cylinder, but on some of the larger models three injectors are employed. The spray produced by such a device can reach meters in length when ejected into atmospheric air.

It is thought that cavitation plays a large role in the development of such a spray. It can occur as "geometric cavitation" (located at the corner and wall of the nozzle hole and caused by the sudden reduction of static pressure as the flow enters the passages) or as "string cavitation" (sometimes called "vortex cavitation", appearing transiently within the core of strong vortices that can build up in these geometries, see e.g. Andriotis et al. [1]). It appears that both types of cavitation can occur in the kind of injector under study (Andriotis et al. studied the same geometry).

The goals of the work described here are twofold: 1) to perform measurements under somewhat more realistic conditions (pressure and temperature, ultimately), and 2) to correlate the interior flows with primary breakup, as revealed by ballistic imaging [2] and hence to provide experimental guidance to CFD development. We have recently completed a first experimental campaign in the Chalmers high pressure and temperature spray rig. The campaign was aimed mostly at development of the necessary hardware and techniques required for such a project, but it did yield some preliminary findings of interest. The results presented here are thus somewhat preliminary but they do reveal interesting dynamics. More detailed experiments are planned for a second campaign.

## 2 Methods

The high pressure and temperature spray chamber at Chalmers is capable of reaching 100 bar and 900 K. It uses a steady flow of air moving slowly to evacuate vapor and combustion products, but not so fast as to affect the spray. It has large quartz windows that provide optical access (see Figure 1a). The injector body for a marine engine is quite large and it would present problems for a rig such as this one. In response, a full size nozzle mimicking a realistic geometry was attached to a Scania XPI heavy-duty truck injector body. The interior of the injector (Figure 1b) was equipped with a realistic cut-off shaft to ensure that the flow was characteristic of the marine injector. Under normal operation in an engine, the cut-off shaft is closed when there is no injection (it is seated all the way to the left in Figure 1b) . At start of injection, the cut-off shaft will lift and un-cover the nozzle holes. In the current experimental set-up the cut-off shaft is geometrically fixed. However, during an injection with the original injector, the shaft is in the open position during most of the injection. It is this situation the test-set-up is mimicking. Several versions of the nozzle tip (the working section of the injector tip, with two holes, as labeled in Figure 1b) were fabricated in steel and in quartz. Hole number 1 in Figure 1b had an inner diameter of 780 $\mu m$ and it was oriented at $78°$ to the injector centerline. Hole number 2 had an inner diameter of 750 $\mu m$ and it was oriented at $58°$ to the injector centerline. The spray was ejected almost vertically downwards into slowly co-flowing air at room temperature and pressure of 10 bar (to achieve a relevant cavitation number), with injection durations on the order of hundreds of ms. The steady flow portion of the injection was studied selectively. The stainless steel honeycomb at the base of Figure 1a was located on top of a thick stainless steel wire pad. The combination was used to stop rebound of the large amount of fuel that was ejected at high velocity.

A high pressure piston-accumulator was used to transfer pressure from compressed air to the fuel supplied to the injector, and the accumulator was charged with compressed air at 110 bar. This was used instead of a pump because the injector was operated longer (100's of $ms$) than a normal Diesel injector at high flow rates but low delivery pressure. The pressure in the sac volume of the injector (around 80 bar) was lower than the pressure in the accumulator because of the head loss across the cut-off shaft.

A white light system for illumination and imaging of the quartz tip was constructed around the chamber. It relied upon front illumination as the cylindrical quartz tip, together with the long distance from the tip to the collection optics, rendered normal shadowgraphy difficult. A new design (discussed below) is planned, but for now the system allowed us to identify periods of strong cavitation.

The spray formation region was studied using ballistic imaging (BI) [2]. This technique uses a short

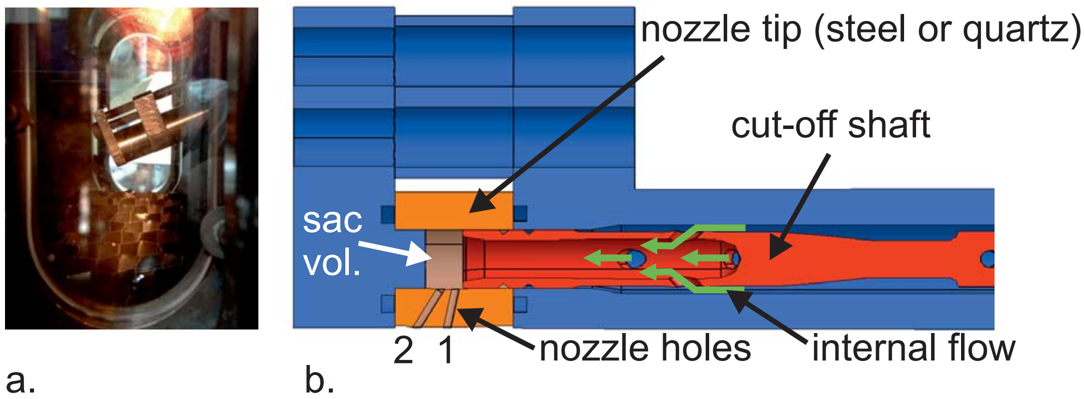


**Figure 1: a. A metal-tip version of the injector in Chalmers high pressure and temperature spray chamber, b. Diagram of injector.**

pulse laser system to illuminate the spray formation region. A very small amount of light directed into a spray passes through a dense cloud of small droplets and exits without being corrupted (it is often called ”useful imaging light”). Useful imaging light can be used to construct an image of larger liquid structures inside the spray. Such structures refract the useful imaging light similar to the way a shadowgram system can do this in an open flow. Ballistic imaging is actually a form of shadowgraphy that discriminates useful imaging light from light that was highly corrupted by multiple scattering off-axis. BI shadowgrams have somewhat limited dynamic range when compared to shadowgrams from flows without drops, owing to the small amount of light available in a single-shot image format. They usually do reveal the liquid/gas interface of intact liquid structures (when they exist) with reasonably good spatial resolution, however.

The current ballistic imaging system used light from a Spectra-Physics MaiTai mode locked Ti:sapphire oscillator that was amplified at 1 $kHz$ by a SpitfirePro chirped pulse regenerative amplifier. It generates pulses on the order of 100 $fs$ pulsewidth at 800 $nm$ wavelength, with about 4 $mJ$/pulse ($\sim$ 2 $mJ$/pulse is commonly used for experiments). The optical layout was a fairly standard single-wavelength one with a $CS_2$ optical Kerr effect (OKE) time gate [2] and using an Andor iXon EMCCD camera, acquiring images at 30 $Hz$ (triggered by the laser amplifier). The system was mounted around the Chalmers spray chamber, which can be traversed up and down.

The metal injector tip (identical design) was also studied via more classical rate-of-momentum measurements in the chamber under the same conditions, using a Kistler force transducer. Here, the actual momentum flux through the orifice is measured via impingement of the orifice flow onto a force transducer at the orifice exit. The difference between the measured momentum flux and the theoretical maximum (based on the measured pressure drop across the orifice) can be attributed in part to gas phase flow in the orifice (e.g. cavitation). An expression for the momentum coefficient ($C_m$), based on these measurements, is given by Payri et al. [3]:

$$C_m \equiv \frac{F_{imp}}{2A(P_{inj} - P_b)} \tag{1}$$

where $F_{imp}$ is the measured impingement force (momentum flux), $A$ is the geometric outlet area, $P_{inj}$ is the sac pressure in the injector, and $P_b$ is the back pressure (gas pressure in the spray chamber in our case). There are various ways to define a cavitation number, but we prefer the following [3]:

$$C_N \equiv \frac{(P_{inj} - P_v)}{(P_{inj} - P_b)} \tag{2}$$

where $P_v$ is the vapor pressure of the light end in the fuel.

## 3 Results

The injection durations lasted about 300 ms; with startup, steady flow, and shutdown periods (see Figure 2). The pressure overshoot at the start was highly reproducible (over 50 measurements) and seems to be a physical phenomenon. It can be attributed to the conversion of high momentum fluid entering an empty sac and being converted to pressure, lasting until steady flow is established. Interestingly, the peak of the pressure pulses is just above the predicted failure of quartz with stress concentrations at the inlets to the injector holes (analyzed via finite element analysis), and indeed several quartz tips fractured at exactly this location (the metal tip was used for impingement and sac pressure measurements).

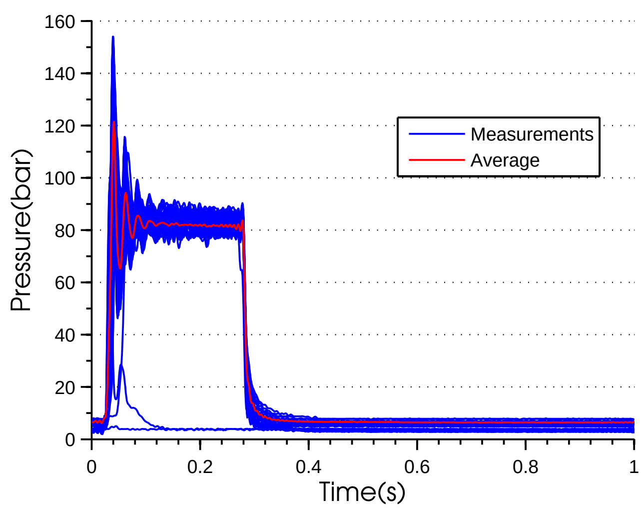


**Figure 2: Sac pressure over the duration of an injection.**

Observation of the interior flow indicated a complex buildup to the steady period, geometric cavitation at the wall of the nozzle holes during the steady period, and then a rapid conversion to low cavitation just as the fuel pressure is released and before flow has slowed significantly. Once the spray begins to shut off, the flow becomes a laminar stream with very little breakup. Because there was limited time for experimentation, only one range of cavitation numbers (around 1.2) was investigated. Figure 3a is a ballistic image for the spray under highly cavitating conditions, while

Figure 3b is for the case near the end of injection when the spray was still breaking up but nearing shut-off (e.g. $C_N$ was significantly reduced by the fall in fuel pressure).

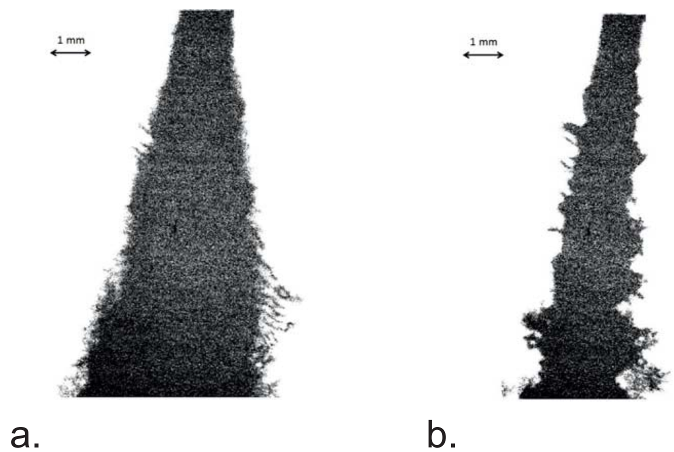


**Figure 3: Ballistic images of the near field from hole number 1 at a sac pressure of 80 bar (for image a at least), chamber pressure of 10 bar, and at room temperature; a. 135 $ms$ ASOI, in the cavitation period, b. 337 $ms$ ASOI as cavitation ceases.**

Figure 3b is very much like the ballistic images of a single hole diesel injector issuing into still air during the steady period [4] (the spray in reference [4] did not appear to be cavitating either). The liquid cores in the collection of ballistic images under these flow conditions have characteristic surface waves and ligaments, a small amount of bag breakup, and what appears to be air entrainment, although no voids in the fluid stream were imaged. Figure 3a, on the other hand, is an unusual structure with a wide spray angle. We have encountered such a structure just once before. During studies of an effervescent (internally aerated) spray, Linne et al. [5] observed the same kind of structure at very high gas to liquid ratios (GLR). In that study it was possible to vary the GLR, from a fairly weakly atomizing spray all the way up to a nearly explosively atomizing spray. At low GLR, the ballistic images included long ligaments and large primary drops. As the GLR increased, especially at high liquid flow rates, the ligaments were replaced by a dense cloud of very large drops that surged (a common occurrence with effervescent sprays) and produced waves of drops. As the flow rate and GLR increased further the cloud of very large drops blocked the useful imaging light and so the images represented just a shadowgram of the outside of the spray; much as one would get simply with a white light shadowgram. By that point ballistic imaging could not probe into the cloud because it was made up of very large drops that are more like a collection of thick round ligaments. Ligaments usually block useful imaging light, which is how ballistic imaging normally captures their images.

It is our speculation that the highly cavitating spray depicted in Figure 3a is very much like the high GLR effervescent spray. We have not been able to investigate a range of cavitation numbers to observe evolution of flowfields towards this structure to confirm the idea, but observation of the sequence of images during shutdown implies that this did happen. Because these were our first ballistic images in the chamber with this spray we did not have time to further optimize the system.

The measured momentum coefficients ($C_m$) are shown in Figure 4 as a function of $C_N$ for both nozzle holes. While the injection pressure was the same for both orifices during optical experiments (and the intention was to perform experiments at just one value of $C_N$ during this initial campaign), a range of cavitation numbers is shown in the data because the air pressure to the accumulator drifted slightly over time. $C_m$ changed very little across the range of cavitation numbers covered in this experiment. This indicates a cavitating orifice flow [3]. The operating point for ballistic imaging experiments is marked Figure 4, confirming that the spray was cavitating during the steady period. Note that $C_m$ was much higher for orifice 2, which could be related to the fact that there is a smaller angle between the central axis of the nozzle and that of the orifice 2 than that of orifice 1, and orifice 2 is larger.

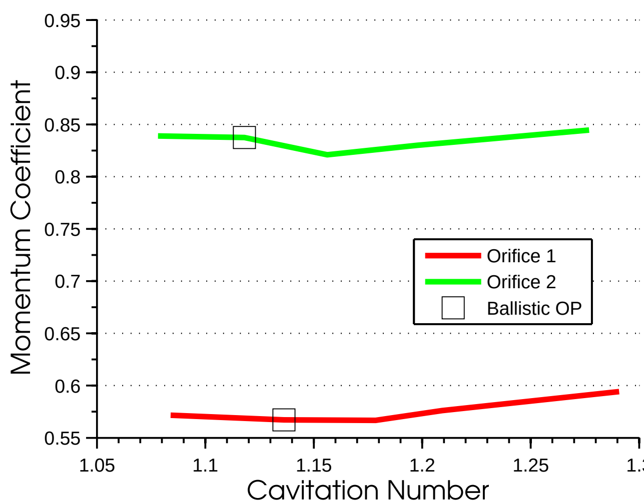


**Figure 4: $C_m$ vs. $C_N$ for both orifices, based upon pressure and impingement measurements in the spray chamber under the same conditions as the experiments represented by Figure 3.**

## 4 Future Work

The next set of experiments will take advantage of the lessons learned in the first campaign. Square cross section nozzles (with cylindrical interiors) will simplify shadowgraphy when using a long distance microscope (already confirmed using acrylic structures). Acrylic nozzle tips, which can tolerate an increase of at least 50 bar fuel pressure (by FEA), will be used during room temperature experiments in the chamber. Both acrylic and quartz have an index of refraction close to that of fuel (around 1.5), making it straightforward to identify wall cavitation via dark regions in shadowgraphy. Sapphire tips at even higher fuel pressure (and finally at high temperature) will also be evaluated, but sapphire has an index around 1.7 and so dark bands will appear at the walls even without cavitation. The magnitude of this problem remains to be investigated.

During the original experiments, low laser intensity was used for ballistic imaging simply to avoid overheating the $CS_2$ in the OKE time gate. Unfortunately, that produced low dynamic range images that are not optimum and are hard to process. The ballistic imaging system will be more carefully aligned and adjusted at higher energy. Higher image dynamic range will produce better images and perhaps reveal some interior structure even in highly cavitating flows. It will also be possible to focus down closer to the outlet to better define dynamics.

Future experiments will also cover a much broader range of cell pressures, from low $C_N$ up to high. This will allow identification of boundaries for breakup regimes, similar to the effervescent spray work.

## 5 Conclusion

The results of this study are preliminary but they indicate that these experiments can be conducted over the desired ranges of flows and pressures. Nozzle cavitation can be observed and correlated to spray breakup. Highly cavitating sprays seem to produce a vigorous type of breakup similar to an effervescent spray with high gas-to-liquid ratios. More weakly cavitating sprays seem to break up like a more normal Diesel jet. These results remain speculative, however, and are subject to further investigation.

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