Experimental cavitation and spray measurement in real-size Diesel injection nozzles with high-resolution neutron imaging

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Abstract

The development of internal combustion engines is challenged by increasingly stringent emission limits. This challenge can only be solved by a deeper knowledge of the combustion process itself. However, the combustion is strongly influenced by the processes inside the injector nozzle. This begins with the internal flow of the injector, which significantly influences the spray formation. One of the key parameters here is the appearance of cavitation caused by the nozzle geometry, needle lift and injection pressure up to 3000 bar. However, there is lack of knowledge about the real flow inside injectors at these high pressure conditions. The cavitation effects in the injection port area destabilize the emergent fuel jet and improve the jet break-up. Therefore internal flow, the jet break-up, the atomization and the mixture formation are closely connected in the combustion chamber and therefore have a direct impact on emissions, fuel consumption and performance of an engine.
In this work, the flow in a nozzle of a real diesel fuel injector is analyzed with high-resolution neutron imaging. Due to the different mechanisms of interactions between neutrons and the material, the steel structure of the nozzle is relatively transparent to neutrons, while the fuel possesses high neutron attenuation [1]. This distinguishes the neutron imaging from x-ray measurements, in which the fuel is of a very low contrast. Thanks to these advantages of the neutron imaging in comparison with other methods (e.g visible light microscopy with glass structures [2]), the nozzle can be investigated under realistic pressure and flow conditions.
Recently, the high resolution neutron imaging instrument (`Neutron Microscope') has been developed at Paul Scherrer Institut (PSI) [3]. This allows the acquisition of neutron radiographies with the spatial resolution down to 5 micrometers [4]. An injection nozzle has been enclosed in a specially tailored chamber that allowed placing the nozzle in close proximity of the detector and tested in-situ Neutron Microscope.
The injector was operated under steady state condition at lowered injection pressures up to 170 bar. In this pilot high resolution investigation water, with gadolinium salt as a tracer, was used to optimize the contrast of the images. The nozzle was modified to a single hole nozzle due to an easier observation. First examinations show various cavitation phenomena. Different characteristics of cavitation in the spray hole were detected, and its influence on the spray formation was clearly visualized simultaneously.

Keywords

Injector, Nozzle flow, Radiography, Cavitation, Neutron imaging, Neutron microscope

Introduction

The coupled process of the internal nozzle flow and the primary break up is important for combustion. These processes are very complex, such as momentum exchange between liquid phase and gas phase, turbulence in the liquid phase and in the gas phase, transient heat transfer, boiling behaviour, surface tension effects, cavitation etc. (Figure 1) [5].

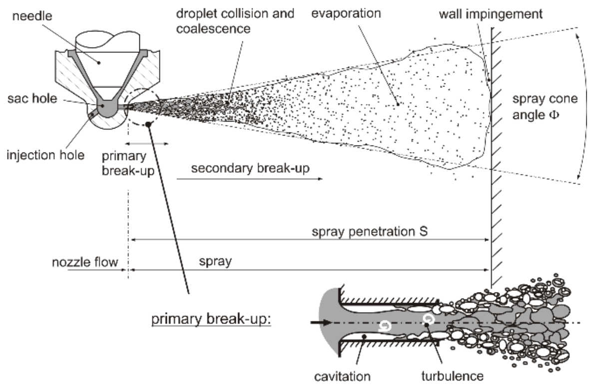

Figure 1. Features during the spray formation in the Diesel injection nozzle [5]

In modern Diesel injectors, an injection pressure up to 3000 bar is used. The liquid fuel is injected through the injection ports with speeds exceeding 500 m/s. In the spray holes cavitation and prevailing turbulence are the main departure mechanisms for the jet break-up at the spray hole outlet [2]. After leaving the spray hole the liquid jet breaks into drops and ligaments, which form a dense spray in the vicinity of the nozzle. This first part of the spray break-up is called primary break-up. It is followed by the so-called secondary break-up, where larger droplets desintegrate into smaller droplets. In these areas, droplets are colliding and associating. The secondary break-up is caused essentially due to aerodynamic forces,until the relative speed between droplets and gas phase disappears. Additionally, drops can collide and associate. In this area of the spray also the evaporation processes taking place. The resulting fuel jet is characterized by the penetration depth and the spray cone angle[6][7][8].

Figure 2 shows typical cavitation modes in the internal injector flow. These cavitation modes can also occure simultaniously. The transition of the individual cavitation modes can be merge to each other [2].

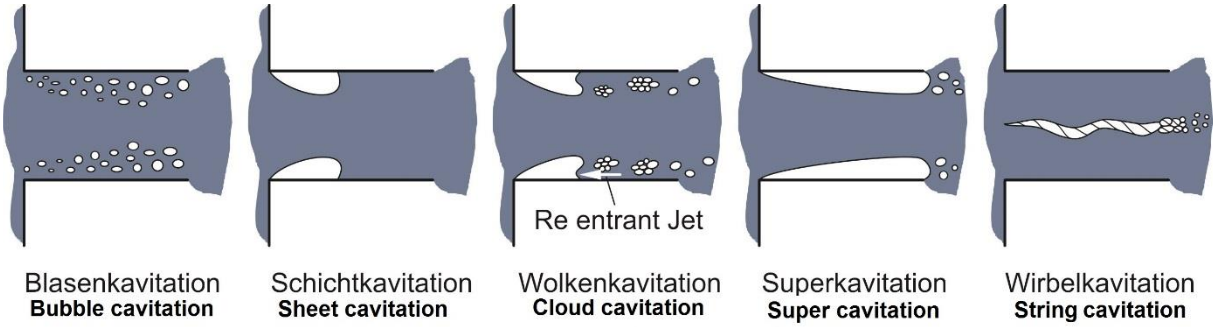

Figure 2. Display of cavitation modes [2]

Figure 3 shows the model concept of the interaction between the internal flow and the spray behaviour. The cavitation induced processes like additional turbulence are typically leading to an increased spray cone angle [9].

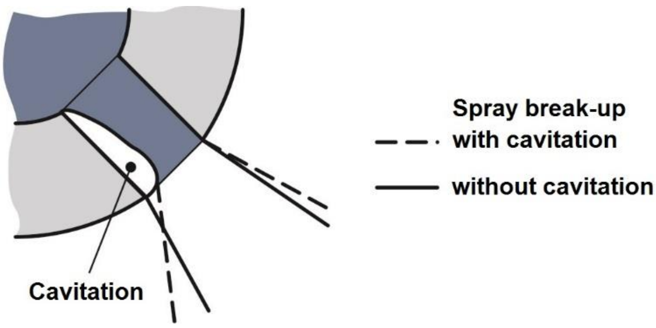

Figure 3. Model concept of the interaction between the cavitation and the spray development [2]

This change in cone angle can improve the combustion process by using more air inside the combustion chamber. On the other hand, a change or fluctuation in the spray propagation can result in an uncontrolled spray that could hit walls of the combustion chamber.

Also, cavitation is responsible for wear and destruction of nozzles. If cavitation bubbles are imploding at the wall of the spray hole, the occurring pressure peak is able to strip material out of the surface. This effect can also be usable to remove deposits inside the spray hole. [5][8]
The cavitation in the diesel injection nozzle represents one of the prime examples that are suitable for neutron imaging which provide useful information. Neutron imaging is a very appropriate tool for visualization of cavitation inside the metallic nozzle, since neutron attenuation in the fuel is much higher than that in the nozzle body made of steel. However, the investigations of cavitation processes inside the diesel injection nozzle hole are so far limited. In the early 2000s, Takenaka et al. [10][11] attempted to visualize the distribution of light oil in the realistic one-hole nozzle under used pressures of up to 20 MPa. However, even though a single nozzle hole of 380 micrometres was used, the details of cavitation were blurred by the available spatial resolution of the used neutron imaging detector with estimated resolution in the order of many tens of micrometres. Since then, the spatial resolution of the neutron imaging detectors has been developed significantly. At Paul-Scherrer-Institute, the detector for the high resolution neutron imaging has been developed recently [12][13]. This detector is called 'PSI Neutron Microscope' and delivers down to 5 micrometres spatial resolution in 2D[14].
In this paper, we present the first attempt for the high resolution imaging of the cavitation diesel injection nozzle hole with up to now unprecedented high spatial resolution.

Experimental arrangement

Diesel injection nozzle arrangement

In this experiment, a modified stock injector has been used to investigate its inside nozzle flow. The Injector was a Bosch Cri 2.1, which 8 original spray holes were closed on the outside by a welding laser. A new straight spray hole was drilled by a laser in a slight different position and angle to avoid overlapping spray holes in the line-of-sight of the neutron measurement. In this experiment, only the added spray hole was investigated. The new angle of the spray hole was set to 81.5° to the injector axis. No additional hydro erosive rounding was done to enhance the occurrence of cavitation. The radiographic images are showing a spray hole diameter of 200 µm. To ensure a continuous injection for long exposure times without powering the injector, the spring of the pilot-valve was removed.

The injector was mounted with the nozzle ending inside a compact aluminum chamber. This chamber was designed to minimize the distance between the nozzle and the scintillator screen to minimize the geometrical unsharpness. With this setting a distance of 4.5 mm between the investigated spray hole and the scintillator could be realized. The injection chamber was scavenged by pressurized air at independently adjustable flow rates and pressures. By this, undesirable wall wetting was reduced and an increased air charge density for a more realistic spray break-up was feasible. Water as surrogate injection medium with added 50 vol% glycol based anti-freeze for corrosion protection and ~8 wt% of $GdCl_3 \cdot 6H_2O$ as contrasting agent was used to optimize the contrast of the images.

Because of the emerging mixture of air and liquid, a separator was used to recirculate the injected liquid. Therefore, the scavenging air flowed through a long tube that was laid in loops before the air could expand to the ambient. Because of the still passing wet air, an automatic refill system was installed to compensate the loss of liquid in the circuit during scavenging the chamber. Assuming that the pure water evaporates, and not the solved salt, only water was refilled to the system. That was done by a second tank, which filled up the first by a floater valve.

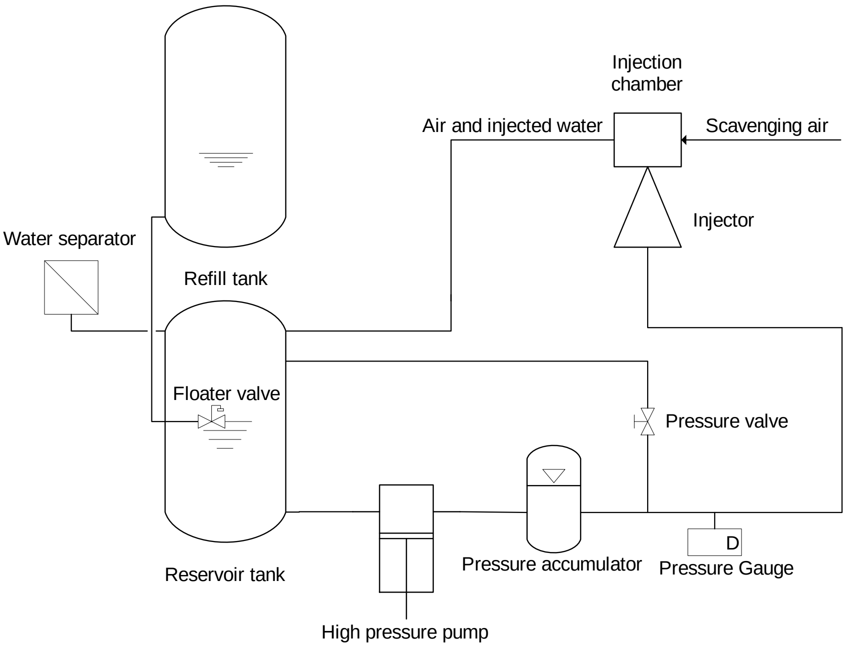

Figure 4. Experimental setup for the neutron imaging for the stock injector

The injection system was pressurized by an air-driven liquid pump. That pump applies a given air pressure to its piston surface, which is directly connected to a smaller pump plunger. Through the large area ratio between the piston and the plunger, the liquid pressure is higher than the air pressure by the factor 300.

Because of the cyclic working principle of the pump, it was necessary to use a pressure buffer to avoid fluctuations in the injection pressure. Therefore, a gas filled diaphragm accumulator was used to keep the adjusted injection pressure on a constant level.

The regulation of the injection pressure was done by a pneumatic pressure regulator at the pump and a bypass valve in the high pressure line of the injector. The injection pressure was set to 160 bar and 167 bar. The ambient pressure inside the chamber was set to 2.5 bar to ensure the scavenging of the chamber and a forced spray breakup.

High resolution neutron imaging

The 'PSI Neutron Microscope' has been installed at POLDI beamline [15]. The pulse overlap chopper of the beamline has been set to its parking position and the pairs of horizontal and vertical slits delivered a collimated thermal neutron beam (L/D = 220) on the above described injection nozzle. After traversing the sample, the attenuated neutron beam was detected by a 3.5 µm Gadox-157 [16] scintillator screen on Si-substrate with 200 nm iridium layer [17]. The light generated at the scintillator screen has been detected by CCD camera with a dedicated high numerical aperture objective (Andor iKon-L, cooling -60° C). For all the acquired images, the exposure time was set to 120 s and the isotropic pixel size equalled 2.7 micrometers.

In order to visualize the distribution of fuel inside the nozzle hole without the influence of the steel nozzle, the projection images of the nozzle with the fuel are not normalized by the open beam image without any sample but by the image of the nozzle without the fuel. Figure 5 shows an example of such neutron radiograph. In the bottom left part of the image there is the nozzle body with the needle tip surrounded by the injection medium. The spray hole is visible on the right side of the sac hole. The exit of the spray hole and the edge of the nozzle body is marked by a white line. Below the spay hole there are the closed original spray holes. They are filled with the injection medium to their dead-end. Behind the open injection hole, the exiting spray is shown as it enters the chamber.

Due to a suboptimal scavenging of the chamber, several small droplets of the injection medium appeared on the walls of the injection chamber (see the top right part of Figure 5).

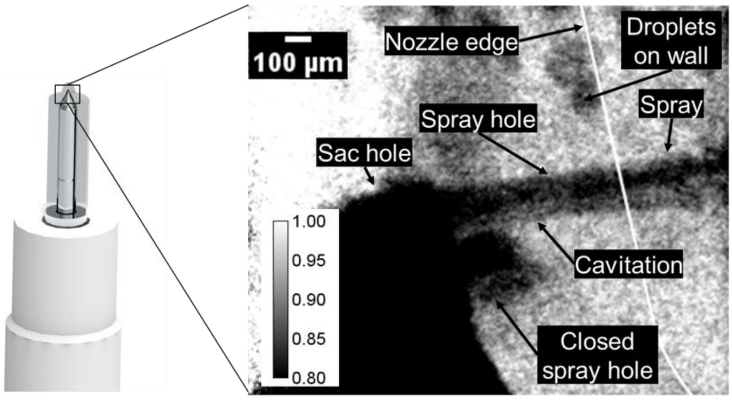

Figure 5. Neutron radiography of stock injector with the spay hole and the fluid

Results

A series of high-resolution neutron radiographs were acquired under different operating conditions. If a cavitation phenomenon appeared, the generated gaseous phase absorbs less neutrons then the liquid. Therefore, a cavitating zone inside the nozzle orifice can be detected as an area of higher neutron transmission.

Although the injection system was kept under constant boundary conditions during the entire series of neutron radiographs (up to 50 minutes), the individual radiographs in the series are showing different cavitation modes from sheet to super cavitation. The injection pressure was set by a simple needle valve and had no direct control circuit. As this regulation of the air pressure was not perfect, slight changes in the injection pressure with resulting changes for the cavitation conditions cannot be fully excluded. So, in addition to the fluctuating and highly turbulent cavitation phenomena itself, the images are probably also affected by slow change in the injection pressure of a few bar. This slight deviation couldn't be measured in the experiment.

These little changes may lead to different cavitation events inside the spray hole and different results in break-up. In Figure 6 three different images of two image series with an injection pressure of 160 bar and 167 bar are shown. The black colored flow has a grey value of 0.8 or less. That means those areas are absorbing more than 20% of the neutron flux. The images presented in Figure 6 show clearly areas of cavitation and no-cavitation within the nozzle hole. The areas showing the cavitation possess higher transmittance value than those in which the cavitation does not occurr. For example, the statistical analysis of the transmittance values of the image in Figure 6b show that differences in the mean transmission values between the corresponding cavitation and no-cavitation areas (as measured on windows of 16 x 8 pixels in size) are at least two times larger than the respective standard deviations of transmittance within these areas.

The image on the left was taken at 167 bar and shows a very low cavitation tendency, which could have been caused by a lowering of the injection pressure as outlined above. In the right image, super cavitation occurred during the capturing. It was also taken at 167 bar. The cavitating area is formed from the edge of the nozzle orifice to the exit of the nozzle hole. In the exiting spray, the influence of cavitation on the following spray formation can be observed. The spray axis and angle are changing depending on the cavitation occurring inside the injection hole.

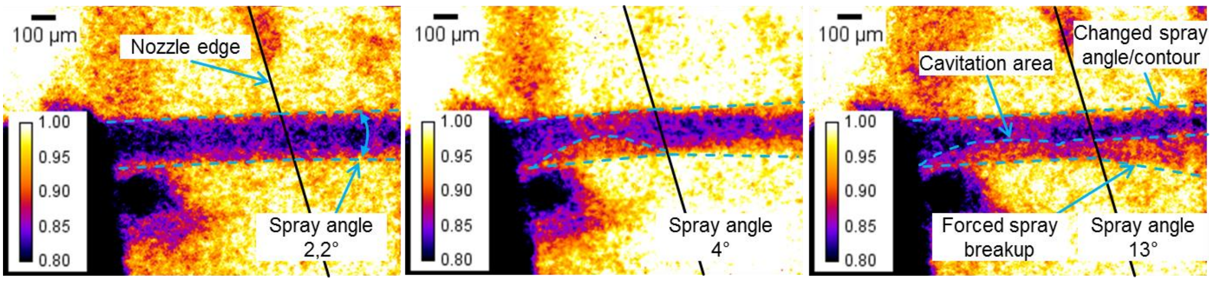

Figure 6. Cavitation phenomena in the spray hole and the influence on the spray.
Low Cavitation (left, 167 bar), Sheet cavitation (middle, 160 bar), Super cavitation (right, 167 bar)

In the example image (Figure 6 right) the influence on the spray break-up can be observed. There is a high density gradient in the spray. On the bottom part of the spray, a less dense area occurs behind the part of the injection hole, where also cavitation takes place. As a result, a highly asymmetric spray with a larger spray angle then on images with a low cavitation tendency is being formed. The spray is redirected to the bottom side and the spray angle increases from 2.2° (left) to 13° (right).

The middle image of Figure 6 was taken at 160 bar injection pressure. A wing-like sheet cavitation formed out and a change in the spray axis in comparison with the low cavitation situation in the left image was observed. A possible explanation would be an influenced flow momentum at the end of the nozzle orifice. The flow tries to rejoin the wall as the cavitation collapses inside the hole and therefore has a radial momentum when the liquid exits the nozzle. Because there is nearly no mass transport inside the cavitation area, the flow exits the nozzle in an angular way.

Conclusions and Outlook

The high-resolution neutron imaging has been applied for the in-situ assessment of the cavitation inside the spray hole of operating realistic diesel injection nozzle. A tailored in-situ sample chamber has been developed and tested for the first time in conjunction with the ‘PSI Neutron Microscope’. The injection nozzle was operating under quasi-stationary pressure conditions and utilized water gadolinium salt solution as injection medium. Thanks to the high-resolution of the neutron imaging arrangement, the different cavitation mechanisms were observed inside the realistic real-size spray hole for the first time. The cavitation type was correlated with the exit spray angle. Because of the experimental uncertainties of the injection pressure, it was not possible to explain the unexpected observation of different cavitation effects under same set of conditions completely.

In future measurements, the optimization of the sample chamber will lead to improved scavenging of the sample chamber and therefore to minimization of the occurrence of the droplets on the chamber walls. Above that, the realistic and regulated injection pressures with diesel fuel (up to 2000 bar) are foreseen to be realized by using stock steel nozzles. The synchronization of neutron imaging (in stroboscopic mode) with the operating diesel injection nozzle is also to be realized.

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