Cavitating Flow in a Model Diesel Injector Return Valve

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Abstract

In modern magnetic solenoid actuated diesel injection equipment, the injection cycle process is regulated by the action of the ball spill valve. This connects the high-pressure region of the needle valve and the low-pressure region of the fuel tank. The precision in timing and hydrodynamic forces determines the amount injected and the amount of the fuel returned back for the following cycle. The sequence of inlet and outlet throttle, through which the high pressure diesel flows whilst the solenoid is actuated, are expected to enhance cavitation due to their microscopic size. In the long-term this may cause the accumulation of damaging internal deposits. Two acrylic models of the spill valve reproducing the geometrical features with different outlet throttle diameters were constructed to allow an optical access of three different fuels – a paraffinic rich model diesel, a 95% - 5% hexadecane-octane mixture and a 80% - 20% hexadecane-octane mixture. Variation of the upstream pressure up to 40 bar and downstream pressures up to 10 bar and manual control of the ball valve lift height were the key elements controlling and producing the flow conditions. Experimental results show the pronounced effect of the upstream pressure on the characterisation of cavitation inception occurring at the throttle entrance. It was concluded that there is a linear relationship between upstream and downstream pressures that control cavitation inception. Moreover the ball valve height plays a significant role in cavitation inception at the beginning of the ball valve lift, where higher upstream-to-downstream pressure ratios were necessary to initiate cavitation. The highest-pressure ratio was obtained with the highest fuel viscosity and largest outlet nozzle diameter, and it consistently decreased as the viscosity and diameter decreased. No cavitation was observed in the inlet throttle passage, but the change in pressure ratio between the two acrylic blocks suggests a change in pressure in the intermediate region; thus it is possible to control the cavitation occurring in the region above the injector needle in spill valves. A high-speed, high-resolution imaging system was utilised to acquire images for inception, partially and fully cavitated flows. The results obtained are presented.

Keywords: spill valve; injector; cavitation

Introduction

A significant body of research involving the chemistry underlying the formation of soot in diesel pumps and injectors, has been published. The presence and significance of cavitation has been noted in various experiments, which may have been responsible for the alteration of diesel fuel properties during operation [1]. The high diesel fuel pressures occurring in injectors (up to 2000 bar), along with the small passages, cause an increase in the dynamic pressure, large pressure gradients and local decreases in static pressure. Locally, the static pressure may fall below the saturated vapour pressure, resulting in local boiling (hydrodynamic cavitation). As the pressure recovers, the previously generated vapour pockets collapse due to the work done by the surrounding liquid, thereby generating large vapour pressures and temperatures during collapse. The collapse of the bubbles, cloud or sheet generates a series of reactions that reflect pyrolytic degradation and dehydrogenation; eventually small particles are formed, that are carbonaceous in structure, and have a mixed amorphous and graphitic-like carbon composition [2].

Ultrasonic cavitation has proved to be resourceful in understanding the correlation between cavitation and soot formation. Suslick *et al*. [3] demonstrated that *n*-alkanes can be broken down to lower alkanes and alkenes by sonication with similar characteristics to high-temperature pyrolysis. Price and McCollom followed this with an assessment of testing diesel fuel stability using ultrasonic excitation [4, 5].

Apart from the metered injection side of a diesel injector (where forms of cavitation were identified in the recirculation zones of the injector [6]), there are other areas throughout the common rail mechanism that present similar flow characteristics. One of these is the metered side of the high pressure fuel that is returned to the low pressure fuel tank. Cavitation may occur across both return valves in injectors and return valves in high-pressure pumps.

An acrylic model of a modern diesel injector return valve was designed and manufactured in order to study the occurrence of cavitation through the low pressure side at low upstream pressures for different fuels.

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Experimental setup

A customized mechanical flow rig developed by Lockett *et al.* [7] was employed to investigate the cavitating flow occurring inside an acrylic replica model diesel injector return valve. The rig and model valve assembly is shown in Figure 1. Initially, the high pressure nitrogen cylinder was employed to fill the three high pressure cylinders (10.5l) with the fuel sample to be tested – as shown with the red arrows. Once the fuel cylinders were filled and the storage tank had been depressurised, the nitrogen cylinder was employed to pressurise the fuel in the three bottles to the required pressure for the experiment. Hence, the blue arrows in the diagram indicate the higher pressure line directions all the way to the acrylic model, where the flow cavitated as it passed through the microscopic channels of the return valve, with the downstream pressure regulated manually with a needle valve. Pressure gauges were located upstream and downstream of the acrylic model in order to control the pressure ratio occurring before and after the nozzles comprising the return valve. The upstream pressure gauge was set by manually adjusting the nitrogen bottle pressure regulator supplying nitrogen to the fuel bottles, while the downstream pressure gauge was regulated manually to a maximum pressure of 11.0 bar. The advantage of this arrangement was that it enabled manual control of the pressure difference established between the inlet and the outlet of the model return valve, hence permitting the alteration of the location and the intensity of the cavitating flow occurring across the valve.

A scaled side and isometric view of the acrylic model and housing is shown in Figure 2. The dimensions of the acrylic block were 400mm x 400mm x 300mm. The side passage represented the high pressure inlet of the fuel flow, with a Ø10mm bore, the lower channel represented the intermediate valve control chamber that was sealed to avoid leaking, and the upper passage represented the outlet of the fuel flow, with a Ø20mm bore. The functionality of the return valve was dependent on the micro passages indicated in Figure 2, comprised of the inlet throttle on the side connecting the inlet passage to the valve control chamber, and the stepped outlet throttle connecting the valve control chamber to the outlet passage. The inlet throttle was manufactured with Ø210μm, while the outlet throttle with a Ø225μm and a step of Ø450μm. The two throttles make it possible to separate the fuel lines reaching the nozzle holes at high pressure and the fuel lines returning to the fuel tank at low pressure.

Experimental Methodology

A stainless steel needle sealed the outlet throttle to allow the fuel entering to gather in the valve control chamber after passing through the inlet throttle. A rotation of the valve control elevated the stainless steel needle (shown in Figure 2); every fifth of a rotation corresponded to a 50μm needle lift. Hence, the needle is raised from its seal position to allow the fuel to flow through the outlet passage.

The upstream pressure was set by the nitrogen bottle regulator valve, beginning from as low as 10bar absolute pressure, and increased in 5 bar steps. Ball valves attached to the high pressure pipe were employed to control the fuel flow to the model return valve assembly. Once the pressurised fuel entered the acrylic model through the inlet passage, it filled the passages of the model return valve all the way to the sealed needle at the outlet throttle. When the needle was lifted (needle lift settings were 50μm and 100μm), the pressurised fuel escaped through the outlet passage and returned to the ambient pressure fuel storage tank, via the downstream pressure gauge and needle valve.

A Photron APX-RS video camera operating at 15 kHz and 3.64x optical magnification captured white light scattering obtained from the fuel flow passing through the acrylic throttle passages. This camera-lens-model arrangement achieved a spatial resolution of 5.5μm/pixel. As stated earlier, the downstream fuel pressure was adjusted to determine the onset of cavitation (inception), and the intensity of the nozzle cavitation through control of the nozzle flow velocity.

The experiment was conducted using three different fuels, a paraffinic rich model diesel (distillation profile and saturated vapour pressure similar to diesel), and mixtures of n-hexadecane and n-octane in 95:5 v/v and 80:20 v/v proportions. For each fuel and upstream pressure setting, 25 separate readings of downstream pressures for cavitation inception were obtained for a fixed needle lift. The incipient cavitation pressure ratio was recorded *'from below'* meaning that the downstream pressure was increased until the cavitation disappeared, or *'from above'* meaning that the downstream pressure was reduced until the cavitation appeared. The mean and standard deviation for each set of measurements was then determined. Table 1 summarises the properties of the different fuels.

Results & Discussion

The results showed that the fuel flow would always cavitate in the same position (at the entrance to the outlet throttle). The inlet throttle on the other hand never presented any form of cavitation, regardless of the pressure ratios, fuel types or acrylic model.

Figure 3 shows single-shot images obtained of cavitation inception (bottom of image) and fully developed cavitating flow for the paraffinic rich model diesel at 40 bar upstream and 50 µm needle lift taken at 15,000 frames/s and an exposure of 10 µs. The cavitating flow shown in

Figure 3 is characterized by regions of white light scattering obtained from discontinuous liquid/vapour surfaces formed in the multi-phase flow. The pressure measurements 'from below' were found to be more repeatable compared to the ones measured 'from above' due to flow-induced hysteresis, i.e. less stable cavitation inception when reducing the downstream pressure 'from above'. This effect was found to produce larger standard deviations in the measurement of critical downstream pressure for lower upstream pressures.

Readings for downstream pressure, i.e. pressure at the exit of the outlet throttle, were taken for a set of upstream pressures ranging from 10 to 40 bar – due to equipment limitation – for both 50 and 100µm needle lift setting, using the three different fuel types. Plots are shown in

Figure *4*, where the needle lift in the return valve is seen to have a significant effect on the pressure ratio producing cavitation inception. Comparing the two plots in

Figure *4*, the pressure ratio $\frac{P_u}{P_d}$ is larger for the 50µm lift setting, reducing for 100µm, and then remaining invariable thereafter. This phenomenon is consistent for the different fuels, meaning that the lower the needle lift, the larger is the pressure ratio required to produce cavitation inception. This occurs due to the low needle lift producing a pressure gradient across the annulus formed between the needle and the diverging conical passage, thereby reducing the pressure gradient forming across the nozzle holes.

A noteworthy finding is obtained from the variation of fuel type. From Table 1, it is possible to determine the cavitation number for the different fuels, using the following definition:[8]

$$C_N = \frac{P_u - P_d}{P_d - P_v} \qquad \text{Equation 1}$$

where P_u is the upstream pressure, P_d is the downstream pressure and P_v is the vapour pressure. Cavitation inception obtained from the paraffinic rich model diesel occurs at the largest cavitation number and lowest saturation vapour pressure when compared with the 2 hexadecane-octane mixtures (as shown in

Figure 5), therefore indicating a reduced inclination to cavitate compared to mixture 2 (95:5 v/v C_{16}:C_8), which in turn shows a reduced inclination to cavitate compared with mixture 1 (80:20 v/v C_{16}:C_8), which exhibits cavitation inception at lower critical cavitation number and the largest saturated vapour pressure.

Figures & Tables:

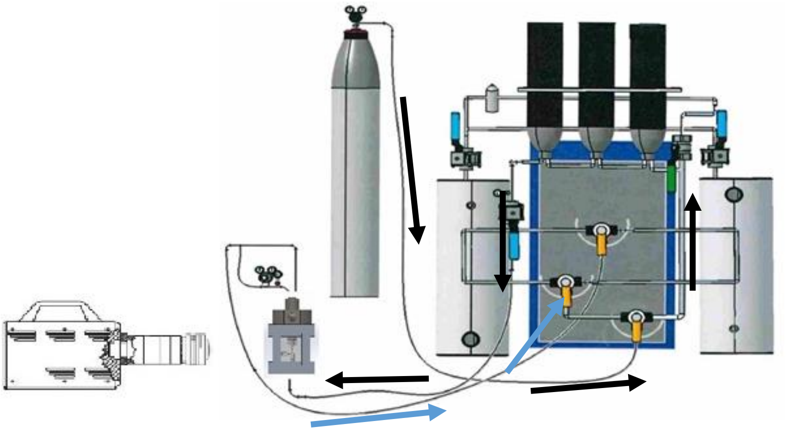

Figure 1 Schematic diagram of the test rig utilised for cavitation experiment in the acrylic model

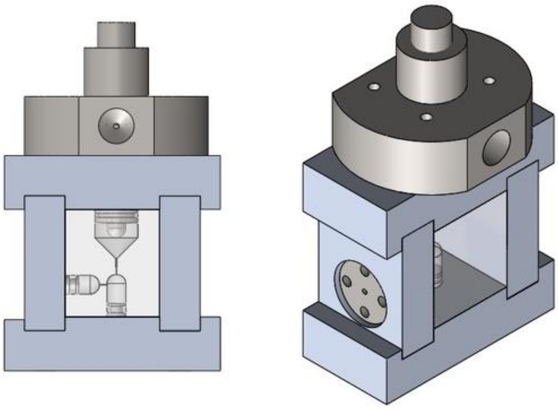

Figure 2 Front and isometric view of the acrylic model return valve assembly

Fuel	Saturated Vapour Pressure (Pa)	Viscosity (Ns/m^2)
Paraffinic Model Diesel	~ 100	0.00153
Mixture 1 (80% C_{16}, 20% C_8)	470	0.0027
Mixture 2 (95% C_{16}, 5% C_8)	150	0.00323

Table 1 Fuel properties

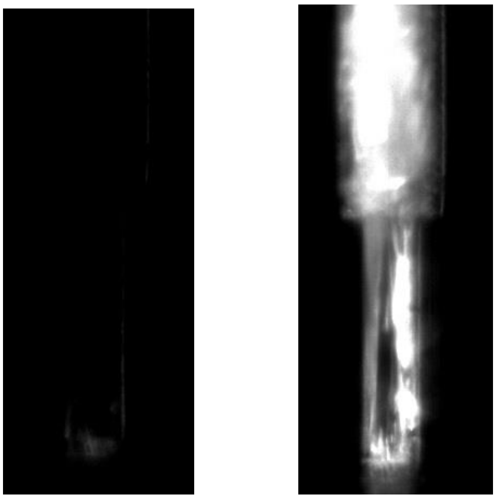

Figure 3 Incipient (left) and fully cavitated flow (right) through outlet throttle with GTL, 40bar and 50µm needle lift

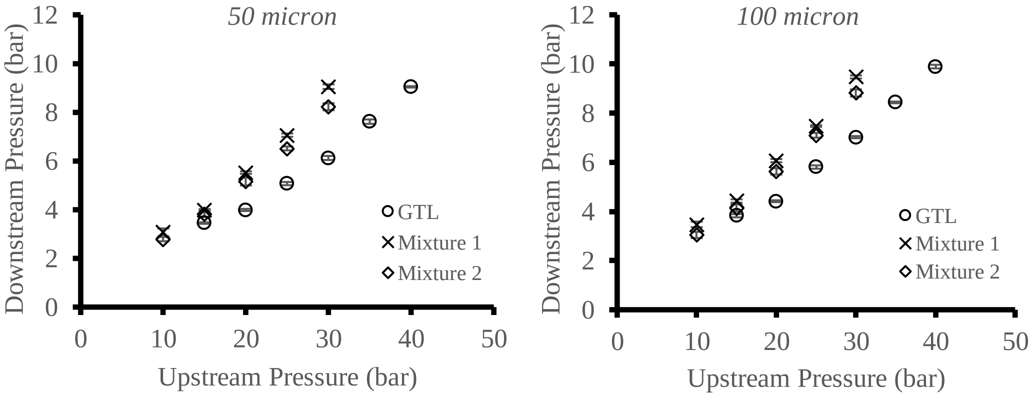

Figure 4 Upstream/Downstream pressure ratios for 50µm and 100µm needle lift

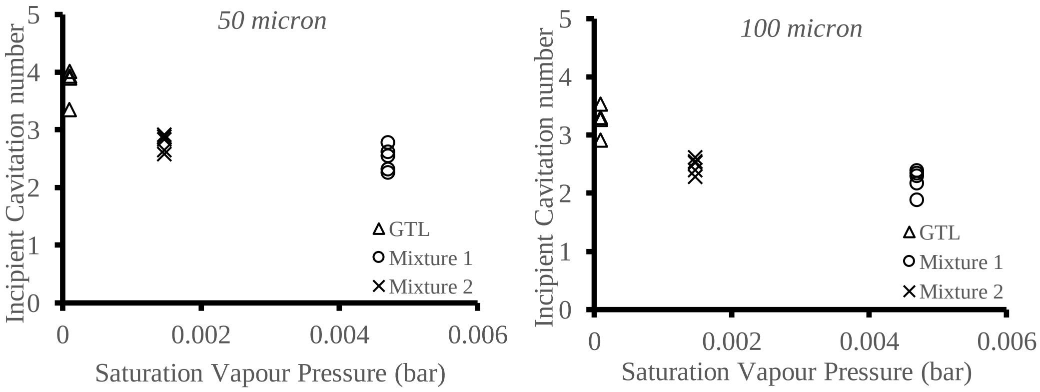

Figure 5 Incipient cavitation number for 50µm and 100µm needle lift

Conclusions

The acrylic model diesel return valve assembly enabled the determination of the flow characteristics arising from the flow developing in the pressure control system. The conclusions may be summarised as follows:

1. Cavitating flow was observed to begin at the entrance to the low pressure throttle, independently of fuel type and cavitation number (above the critical cavitation number for cavitation inception).

2. Cavitation inception was observed to depend on fuel type, cavitation number, saturated vapour pressure, and needle lift. Cavitation inception in the paraffinic model diesel occurred at the largest cavitation numbers and smallest saturated vapour pressures, as expected. This was followed by mixture 2, and then followed in turn by mixture 1, again as expected.

3. Consistently larger pressure ratios were required to produce cavitation inception for lower needle lift. This occurs because the low needle lift produces a pressure gradient in the annulus around the needle, thereby reducing the pressure gradient developing across the nozzles. Hence a larger pressure difference across the nozzles is required to produce cavitation inception. This effect is significant for the cavitating flow developing in real diesel injector return valves during needle actuation.

References

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