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VISUALIZATION OF FUEL SPRAYS FOR STRATIFIED COLD STARTS IN GASOLINE DIRECT INJECTION ENGINES

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ABSTRACT
About 90% of the unburned hydrocarbons (UBHC) emissions from port-fuel injected gasoline engines are emitted during cold starts, before the catalyst reaches the light-off temperature. In Gasoline Direct Injection engines cold starts can be made much cleaner by using modern fuel injectors operating at high fuel pressures and injecting the fuel late during the compression stroke to deliver a stratified charge, thereby enhancing the fuel's rate of evaporation and reducing wall wetting. The objective of this study was to assess the relative importance of variables that influence the formation and characteristics of the sprays generated in such conditions. For this, a high-speed camera was used to acquire images and measure sprays of fuel injected by an outward-opening piezo-actuated injector into a pressurized spray chamber in which the fuel temperature could be cooled to temperatures as low as 243 K (-30 ºC). The varied parameters were fuel pressure, back-pressure, injection strategy and fuel temperature. For reliable ignition of such sprays a spark plug should be positioned in the vortex they create. The results show that if the fuel pressure is reduced to 5 MPa from the injector's design pressure of 20 MPa, as it could potentially be during a cold start, the vortex is not created and fuel will not be present at the spark. However, multiple injections and the temperature of the fuel were found to have relatively weak effects on the vortex formation.

INTRODUCTION

To be able to meet the emission standards imposed by SULEV and EURO V it is necessary to reach the light-off temperature in the catalyst within 20 seconds after a cold start [1]. During cold starts the cylinder walls, the valves, the piston and the fuel are all cold. Hence, the vaporization rate in port-fuel injected engines is poor and hence the mixture needs to be highly enriched. Cold starts of Gasoline Direct Injection engines can however potentially be very clean, with low engine-out emissions of unburned hydrocarbons, if a suitable stratified charge strategy is used. Designing a stratified charge combustion system is however a challenge. If a stratified cold start is used one can benefit from the increased vaporization rate due to the higher cylinder temperatures, and the fuel mixture does not need to be greatly enriched. Stratified cold starts also have interesting potential applicability in hybrid vehicles due to their many start/stops. In envisaged scenarios, during cold starts the engine would be operated with stratified charges for the first few cycles, in which it is most difficult for port-fuel injected engines to run free of misfires. After these stratified cycles, it would be possible to switch the mode of the engine to homogeneous operation with very late ignition so that the catalyst is heated up as quickly as possible. In addition to this it is possible to further reduce the UBHC emissions by using an early opening and closing of the exit valves [2] and to minimize the heat losses from the engine to the catalyst by using a suitable exhaust system configuration [1].

SPECIFIC OBJECTIVES

In this study sprays generated in a spray chamber were visualized and analyzed to assess the relative importance of varied parameters (including fuel pressure, injection strategy and fuel temperature) on the key characteristics of the first injected sprays of fuel required to deliver stratified combustion during cold starts.

EXPERIMENTAL SETUP

All measurements were performed in a pressurized spray chamber, with optical access, through which pressurized air is passed at sufficiently low velocity, compared to the velocity of the injected spray, to neglect in analyses of the acquired data. For this reason the environment can be regarded as quiescent. The fuel used in the tests was 95 octane gasoline. To obtain low temperature sprays a refrigeration system was designed for cooling the injector, and connected to the injector's mounting, as schematically illustrated in Figure 1.

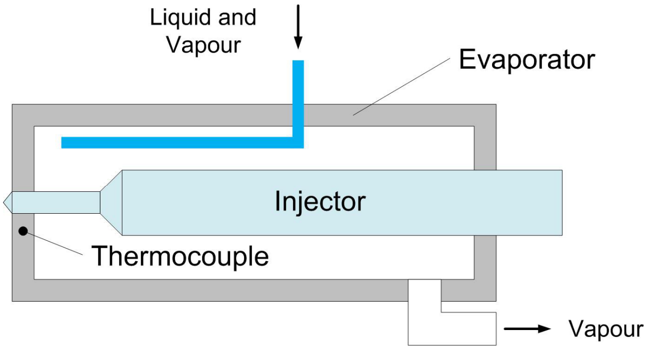

Figure 1. Schematic diagram of the system for cooling the fuel, showing the injector mounting case with evaporator tube from the refrigerator.

The temperature of the injector was thermostatically controlled using a thermocouple located in the front wall of the evaporator. It can be assumed that the fuel temperature was the same as the injector temperature since the injector was cooled for up to one hour for each tested temperature before the fuel was injected and the mass flow was very low. To confirm that the temperature of the fuel in the spray was close to the injector temperature it was estimated using a fast thermocouple positioned approximately 3 mm from the point where the fuel exited the nozzle. Although it was difficult to measure the temperature of the fuel in the spray's droplets precisely, due to the thermal inertia of the thermocouple, sufficient indications were obtained to conclude that the fuel temperature was close to the injector temperature. Shadowgraph images were acquired using a Phantom v7.3 high speed camera equipped with a Nikkor 85/1.4 lens, at a frame rate of 15900 images/s with 320×240 pixel resolution and 3 µs exposures. The view is 46 x 35 mm for all spray images throughout the paper.

RESULTS AND DISCUSSION

Test cases

When injecting fuel during warmed-up conditions in a Direct Injection Stratified Charge (DISC) engine (with wide open throttle) the cylinder pressure is around 1.8 MPa. However, during a cold start the heat losses are high, so the cylinder pressures will be much lower. The fuel pressure is also reduced during the first cycles. Reduced fuel pressure has been reported to have a great effect on the spray formation at cold starts for other types of sprays [3, 4]. Therefore, the test cases (see Table 1) were chosen to simulate these conditions. In all cases the spray chamber was at room temperature prior to the injections, so the fuel was always injected into a non-evaporating environment.

Table 1. Test cases

Fuel pressure [MPa]	Fuel temperature [K]	Injection strategy	Back pressure [kPa]
5	293, 268, 243	Single, Double, Triple	600
20	293, 268, 243	Single, Double, Triple	150
20	293, 268, 243	Single, Double, Triple	600

During warmed-up, stratified combustion, a multiple injection strategy can be used to increase the ignitibility window [5], increase the homogenization of the fuel/air mixture [6, 7] and to reduce soot [7]. Therefore, three injection strategies were applied in the experiments, with pulses and dwell times graphically defined in Figure 2 and listed in Table 2.

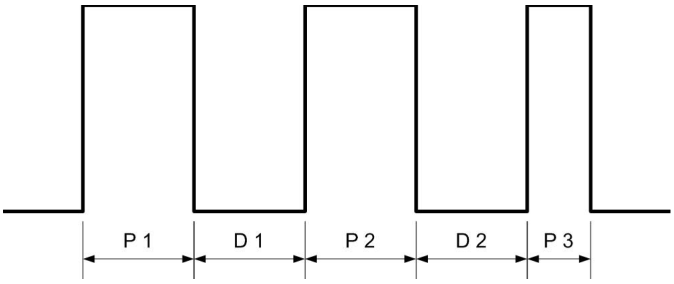

Figure 2. Graphic definition of electrical pulses to the injector driver. P is pulse width, D is dwell time (the time between pulses) and the x axis is time (arbitrary scale). Start of injection (SOI) is defined as start of pulse 1.

Table 2. Selected pulse lengths for single, double and triple injections.

Injection Strategy	P1 [µs]	D1 [µs]	P2 [µs]	D2 [µs]	P3 [µs]
Single	400	-	-	-	-
Double	250	300	150	-	-
Triple	200	300	150	200	50

This corresponds to around 13 mg fuel injected @20 MPa.

Spray formation

The outward-opening piezo-actuated injector used in the experiments is designed to operate with a fuel pressure of 20 MPa. The injector has a variable needle lift which can be used to control eg. the mass flow rate [8]. In this investigation however the needle lift was kept constant. Moreover, the injector has an annular nozzle which creates a hollow cone spray structure. The spray does not have a pre-jet like swirling type of injectors. The piezo module acts directly on the needle which results in a highly reproducible spray pattern.

Images showing the formation of a typical spray from the injector at 20 MPa fuel pressure are shown in Figure 3. Due to momentum exchange between the droplets and the air, a strong vortex of the fuel droplets is being formed, see grey arrows. This fuel droplet vortex is moving downstream with time.

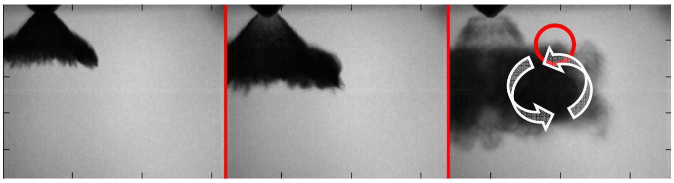

Figure 3. Images showing typical formation of the spray with fuel vortex. Fuel pressure, 20 MPa, fuel temperature, 293 K, back-pressure, 0.6 MPa.

A suitable spark plug position is within the red ring shown in the figure. In this outer edge of the fuel vortex the fuel gradient and the cycle-to-cycle variations in the fuel distribution are small, making it ideal for reliable spark ignition of the spray. A position like this is more difficult to find in a spray from a solenoid-actuated multihole injector, in which the fuel gradients and cyclic variations are higher.

The droplets exit the nozzle at high velocities and push away the air by drag forces and a spray-induced air motion is being created. It is this air motion that governs how air is entrained into the spray [9]. This paper discusses the fuel vortex but the spray-induced air motion was studied in [8]. The part of the spray-induced air motion that is directed into the spray is referred to as air entrainment. Most of the air entrained in the tested sprays come from the side, but some is entrained from below (centerflow or funnel flow), as shown in Figure 4. The spray's umbrella angle was found to be ca. 85 degrees, and very stable in all tested conditions [8].

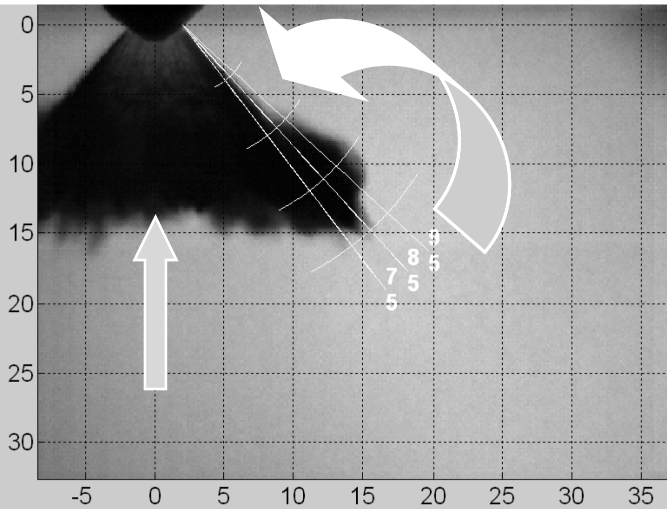

Figure 4. Image of spray showing typical umbrella angle at 0.3 ms ASOI, and white arrows indicating directions of air entrainment. Fuel pressure, 20 MPa, fuel temperature, 293 K, back-pressure, 0.6 MPa. Scales in [mm].

Influence of back-pressure

As with most types of sprays, the sprays generated in our experimental system were clearly influenced by back-pressure, which retards the spray, so the spray penetrates further at low back pressures than at higher back pressures, see Figure 5.

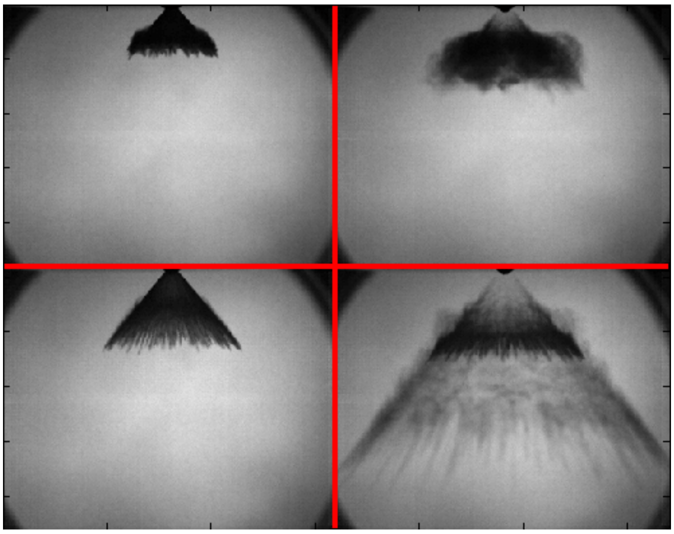

Figure 5. Images showing effects of varying the back-pressure on the sprays. Top row, 0.6 MPa back-pressure; bottom row 0.15 MPa back-pressure. Fuel pressure in both cases, 20 MPa, fuel temperature, 293 K. 0.25 ms ASOI (left panels) and close to EOI (right panels).

Streaks can typically be observed in the sprays generated at low back-pressures [10], as can be seen in the lower right image. During a stratified cold start when the back-pressure is relatively high compared to throttled conditions, there should be virtually no spray streaks. Instead, the fuel cloud should be compact by the end of the injection (EOI), as in the upper right image.

Liquid spray tip penetration

Keeping the spray liquid penetration length short can be very important to avoid wall wetting since it can have a dominating effect on cold start performance [3]. The liquid penetration is defined as the axial downstream position of the liquid spray tip, which can be obtained from the high-speed photographs. Penetration curves were calculated for the 0.6 MPa back-pressure cases, based on averaged values from 5 repetitions. Figure 6 to Figure 8 show the liquid penetration lengths obtained with 20 MPa fuel pressure.

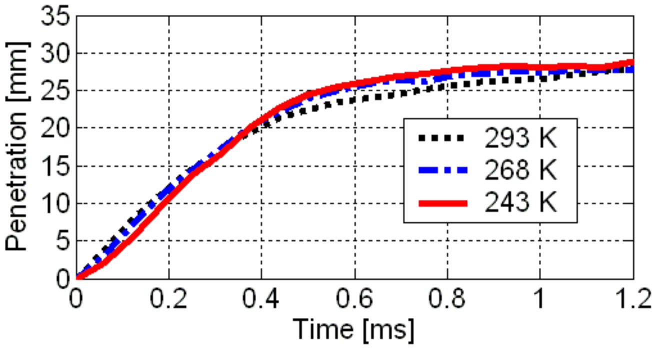

Figure 6. Liquid penetration of sprays with each of the tested fuel temperatures, triple injection, 20 MPa fuel pressure.

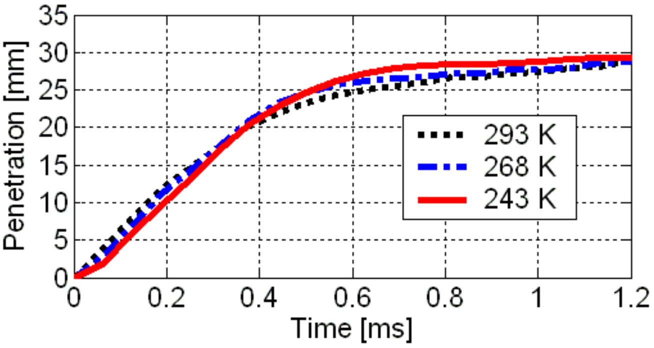

Figure 7. Liquid penetration of sprays with each of the tested fuel temperatures, double injection, 20 MPa fuel pressure.

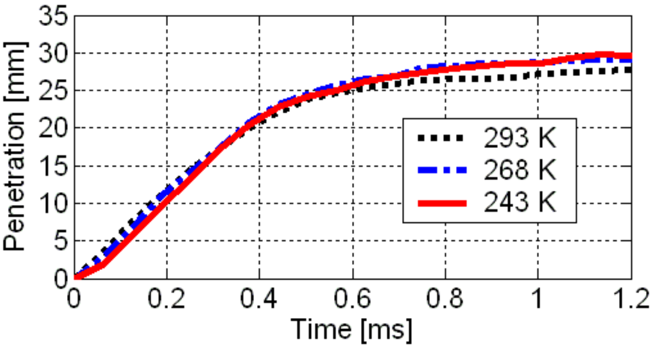

Figure 8. Liquid penetration of sprays with each of the tested fuel temperatures, single injection, 20 MPa fuel pressure.

The sprays with all of the tested fuel temperatures penetrate about 30 mm under these conditions, and their penetration curves are very similar. However, for the coldest case, 243 K, it can be seen that the spray starts slightly later, but catches up with the other curves at around 0.4 ms. Another observation is that the differences in this respect between single, double and triple injections are small, although it can be seen that the coldest sprays (243 K) from double and triple injections penetrated slightly further (ca. 3-4 mm) than the corresponding 293 K (room temperature) sprays, possibly due to associated differences in droplet sizes and velocities. Phase Doppler droplet characterization would be needed to further analyze the causes of these minor variations.

Figure 9 to Figure 11 show the penetration lengths obtained with the lower fuel pressure, 5 MPa.

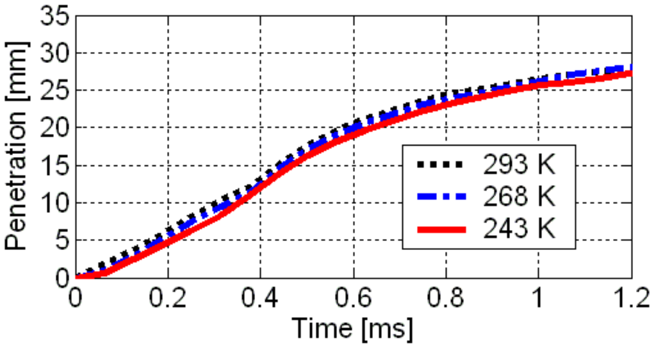

Figure 9. Liquid penetration of sprays with each of the tested fuel temperatures, triple injection, 5 MPa fuel pressure.

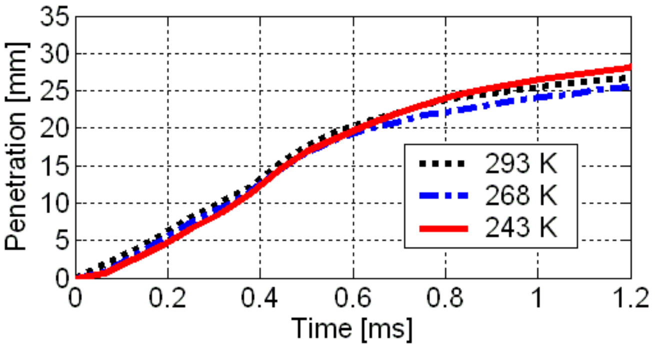

Figure 10. Liquid penetration of sprays with each of the tested fuel temperatures, double injection, 5 MPa fuel pressure.

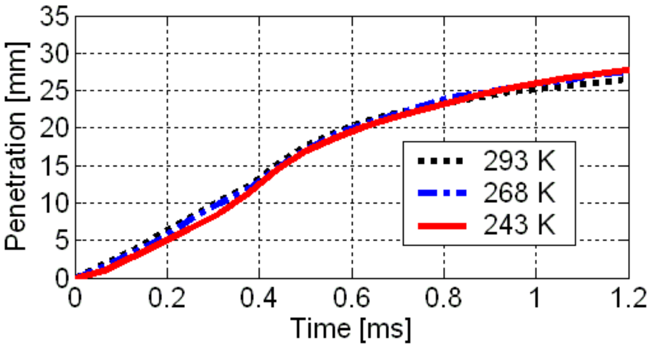

Figure 11. Liquid penetration of sprays with each of the tested fuel temperatures, single injection, 5 MPa fuel pressure.

In these cases the sprays do not penetrate as far as in the 20 MPa fuel pressure cases (see Figure 6 to Figure 8), as expected due to the reduced droplet velocities. For example, the penetration at 0.4 ms is reduced from about 20 mm (20 MPa) to 12.5 mm (5 MPa). However, as in the 20 MPa cases, the cold sprays start slightly later. The penetration curves for the triple and single injections are very similar (see Figure 9 and Figure 11). In the double injection case (Figure 10) the coldest spray, 243 K, penetrates the furthest, as in the 20 MPa fuel pressure cases. However the 268 K spray penetrates the shortest distance, unlike the trends observed in the 20 MPa cases.

Liquid spray tip velocity

Liquid spray tip velocities, calculated from the derivatives of the fitted liquid penetration curves, for the 20 MPa fuel pressure case are shown in Figure 12 to Figure 14.

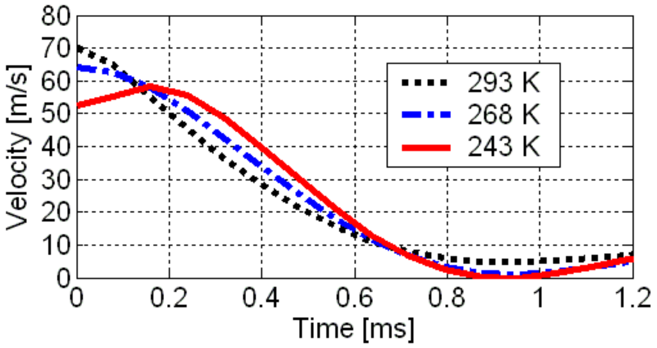

Figure 12. Spray tip velocity, for each of the tested fuel temperatures, triple injection, 20 MPa fuel pressure.

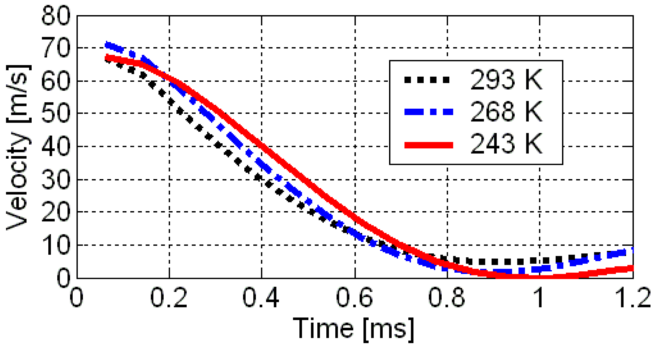

Figure 13. Spray tip velocity, for each of the tested fuel temperatures, double injection, 20 MPa fuel pressure.

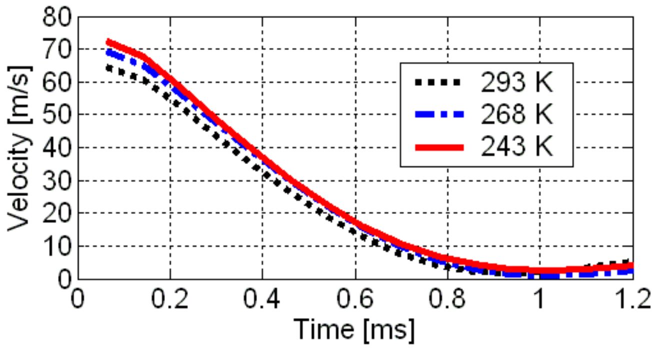

Figure 14. Spray tip velocity, for each of the tested fuel temperatures, single injection, 20 MPa fuel pressure.

The velocity from the nozzle exit is around 70 m/s for all cases. The sprays with the coldest fuel temperatures generated by single, double and triple injections had higher velocities than corresponding sprays with warmer temperatures, possibly due to differences in droplet sizes and/or vortex formation processes that promoted higher velocities at low temperature. The results obtained for the 5 MPa cases are shown in Figure 15 to Figure 17.

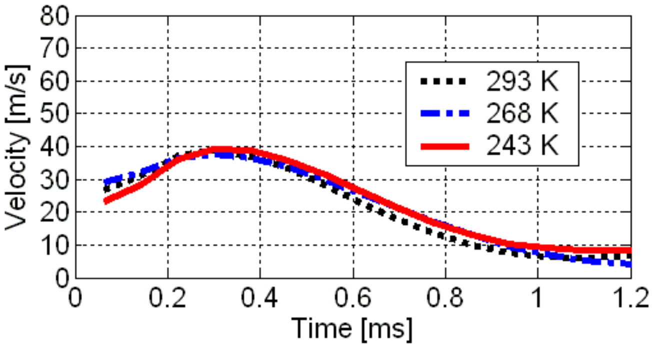

Figure 15. Spray tip velocity, for each of the tested fuel temperatures, triple injection, 5 MPa fuel pressure.

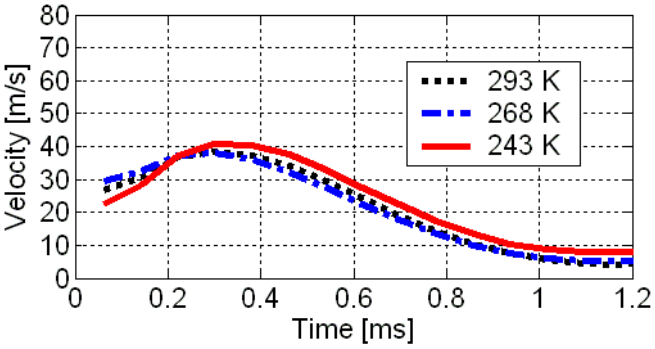

Figure 16. Spray tip velocity, for each of the tested fuel temperatures, double injection, 5 MPa fuel pressure.

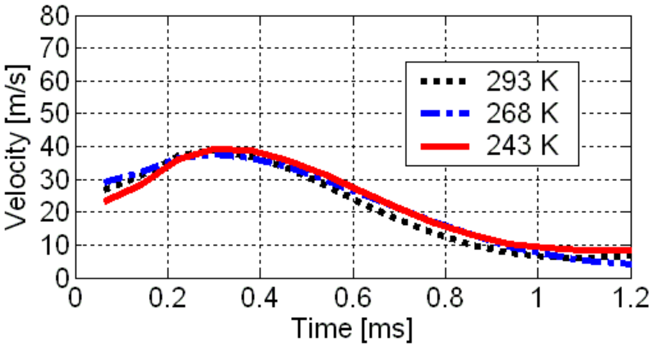

Figure 17. Spray tip velocity, for each of the tested fuel temperatures, single injection, 5 MPa fuel pressure.

The spray tip velocities are much lower than for the 20 MPa case. As for the 20 MPa fuel pressure case, the sprays with the coldest fuel temperatures generated by single, double and triple injections had slightly higher velocities than corresponding sprays with warmer temperatures. The maximum velocity is here around 40 m/s.

Influence of injection strategy

The operating condition in stratified mode of an engine can be improved by splitting the injection into multiple injections. Multiple injections will have an effect on the homogenization of the fuel/air cloud and will therefore reduce the formation of soot. It also provides a way to control the air/fuel ratio at the spark thus providing favorable ignitibility conditions [5, 6, 7].

For single, double and triple injections a fuel vortex is formed at around 0.2 ms after the start of injection (ASOI) ca. 5 mm downstream of the injector, see Figure 18. This vortex can be seen as the main vortex and moves and grows with time.

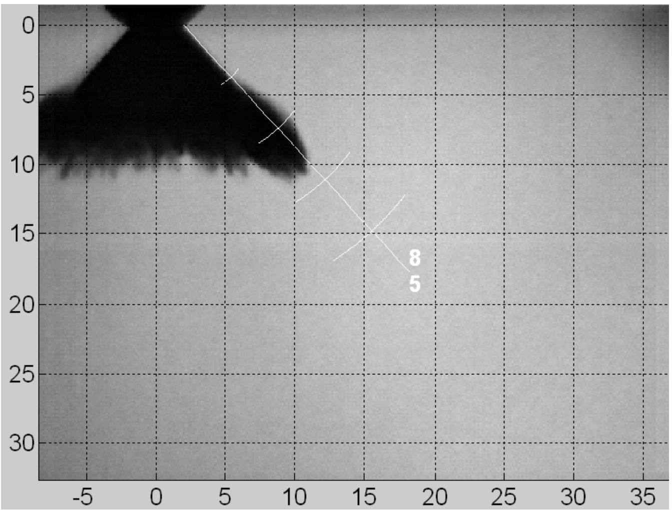

Figure 18. Image of a spray during a first pulse and a vortex being created at around 0.2 ms ASOI. Fuel pressure 20 MPa, back pressure 0.6 MPa. Fuel temperature, 293 K.

In Figure 19, the second pulse exits from the nozzle. Note that a new vortex is being formed by the second pulse close to the injector (white arrow). The main vortex has now grown and is still rotating and when the second pulse reaches the main vortex it supplies further momentum. There will be interaction between the subsequent injections since each of them supply momentum and a new vortex.

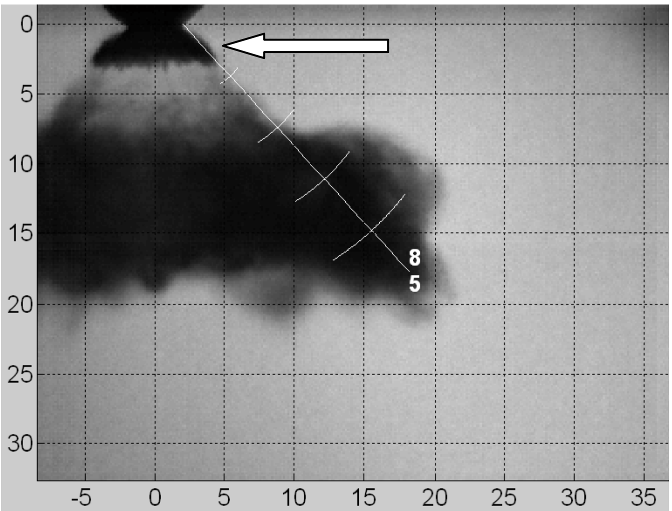

Figure 19. Image showing the start of a second pulse at 0.6 ms ASOI. Fuel pressure, 20 Mpa; back-pressure 0.6 MPa; fuel temperature, 293 K.

In triple injections this sequence of events is essentially repeated when the small amount of fuel in the third pulse is injected, see Figure 20 (white arrow). The main vortex is still rotating.

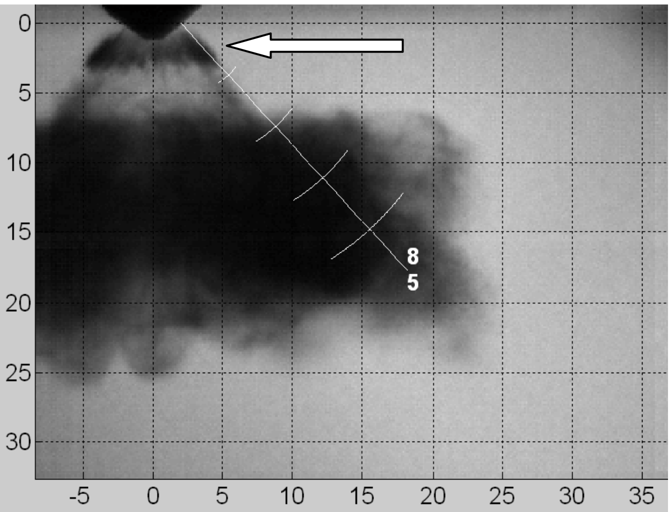

Figure 20. Image showing the beginning of a third pulse 0.93 ms ASOI. Fuel pressure 20 Mpa; back-pressure, 0.6 MPa; fuel temperature, 293 K.

The ignitibility window of a spray in an engine is dependent on the length of time the fuel is present around the spark plug. This in turn depends on how long the vortex persists, which will be longer for a double and triple injection than for a single injection. The longer vortex life-time also means a longer mixing scale which in turn means a slightly better homogenization resulting in less formation of soot.

Due to the air entrainment by the center flow, some of the droplets move up towards the nozzle during the dwell time following a second pulse (D2), which could potentially cause injector deposits in an engine. However if a third pulse is injected precisely when these upward moving droplets from pulses 1 and 2 approach the nozzle they can be decelerated by it, thus providing a possible way to control amounts of injector deposits.

In summary: dwell times between pulses (pauses) can increase the duration of the vortex, and thus the time that liquid fuel is present around the spark plug (and thus also vapor fuel). This potentially increases the ignitibility window in an engine and reduces the formation of soot.

In order to make valid comparisons of the liquid fuel distribution in sprays generated by single, double and triple injections they should be compared at times when equal amounts of fuel have been injected in each case, i.e. close to the end of the injection (EOI), which is close to the ignition. Figure 21 shows the results of a comparison of the effects of the injection strategy. At the first timing, 0.25 ms ASOI, the sprays formed by all three injection strategies are (unsurprisingly) very similar. However close to EOI (right column), the key time for such comparisons, there are several clear differences.

To ensure reliable ignitibility it is important to be able to maintain the fuel cloud close to the spark plug. With a single injection the fuel cloud moves slightly away from the spark plug position. However, with the double, and especially the triple, injection strategies it seems easier to move fuel closer to the spark plug (see dotted white lines in Figure 21). These differences may seem minor in the spray images, but in an engine they could have major effects on the duration of the ignitibility window [5]. However as will be seen, the influence of the injection strategy is relatively weak compared to those of other variables, such as fuel pressure. At warmed-up stratified charge conditions however the injection strategy can be very important.

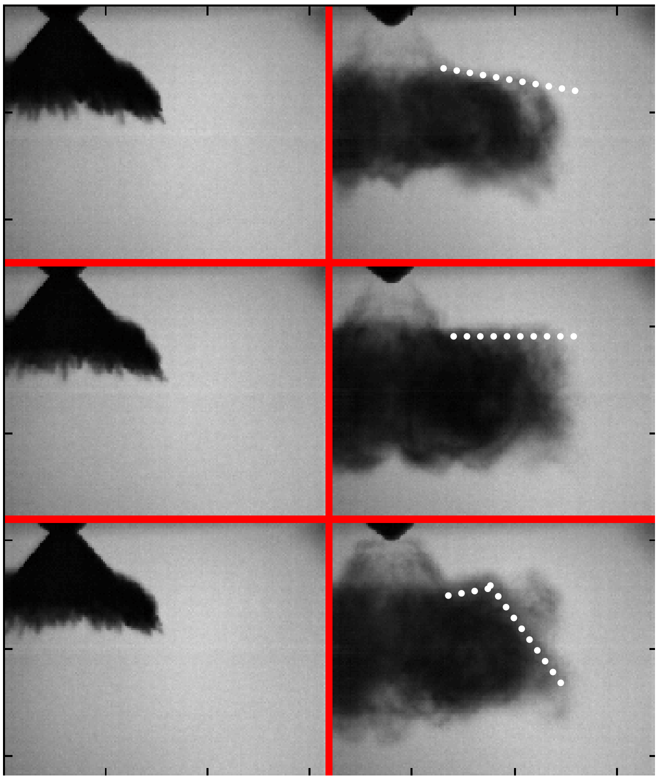

Figure 21. Images showing effects of varying the injection strategy on the sprays. First row single injection, second double injection and third row triple injection. Fuel pressure 20 Mpa; back-pressure, 0.6 MPa; fuel temperature, 293 K. 0.25 ms ASOI (left panels) and close to EOI (right panels).

Influence of fuel pressure and temperature

In an earlier investigation in an optical engine on stratified charge combustion under warmed-up conditions it was found that the triple injection strategy gave the longest ignitibility window [5]. Therefore triple injection strategy was chosen for fuel pressure comparisons. Figure 22 shows the influence of fuel temperature on the sprays for the 20 MPa fuel pressure case.

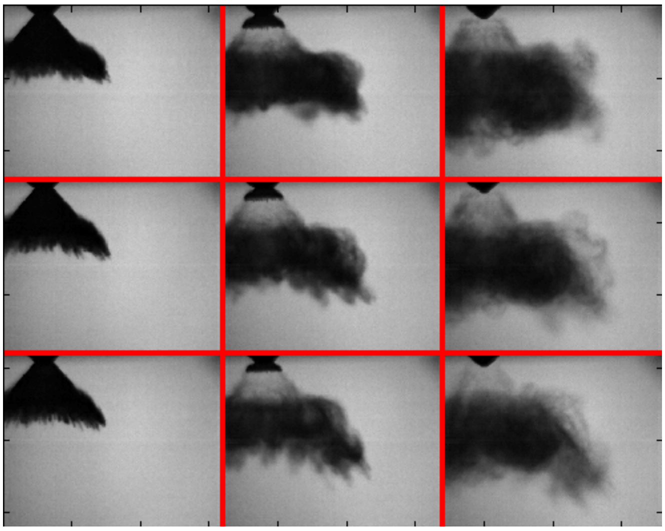

Figure 22. Images showing effects of varying the fuel temperature on the sprays. Fuel pressure, 20 Mpa; triple injection. Top row, fuel temperature 293 K; second row, 268 K, third row 243 K (-30C). Timing 0.25 ms ASOI (left panels), 0.6 ms ASOI (centre panels) and close to EOI (right panels).

There are only very small differences even between the lowest and highest fuel temperatures (243 and 293 K, respectively), and vortex formation occurs in each case, so it is not much influenced by lowering the fuel temperature. However, when the fuel temperature is decreased the surface tension increases, which might result in larger droplets and hence slower evaporation. Phase Doppler measurements of the droplets would be needed to assess this possibility.

During the very first revolutions of the fuel pump in cold starts it delivers much lower fuel pressures than the design pressure. To mimic these conditions sprays obtained with a fuel pressure of 5 MPa were examined (see Table 1), and the results are shown in Figure 23. A very important observation is that virtually no fuel vortex is formed with this fuel pressure, regardless of the fuel temperature. This means that it would be very difficult to transport fuel towards the spark plug under these conditions. Thus, sufficiently high fuel pressure is needed to form the vortex.

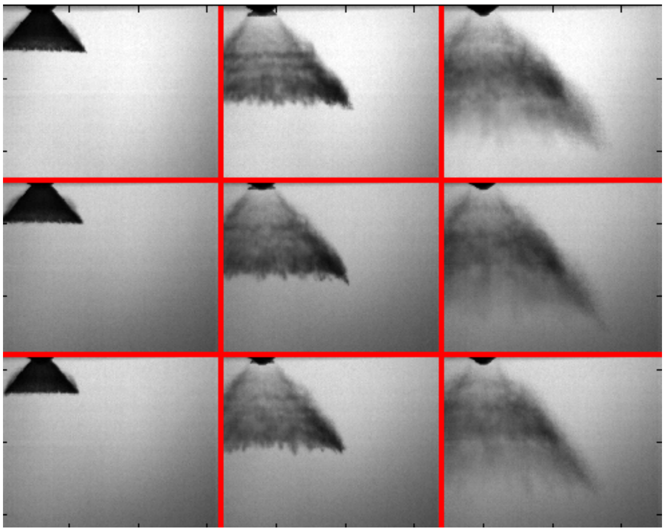

Figure 23. Images showing effects of varying the effects of varying the fuel temperature on the sprays. Fuel pressure, 5 Mpa; triple injection. Top row, fuel temperature 293 K; second row, 268 K, third row 243 K (-30C). Timing 0.25 ms ASOI (left panels), 0.6 ms ASOI (centre panels) and close to EOI (right panels).

CONCLUSIONS

Creating a vortex is crucial for ignition of these sprays during stratified operation. Within the vortices the fuel gradients and the cyclic variations of the sprays are small, which is ideal for reliable ignition. At the design fuel pressure of 20 MPa, such a vortex is always formed, regardless of the injection strategy and fuel temperature. However, during the very first cycles of a stratified cold start the fuel pressure is much lower than the design pressure. For the tested fuel pressure of 5 MPa, no clear vortex is formed, regardless of the fuel temperature and injection strategy. This would make ignition of the spray at a low fuel pressure very difficult. The fuel pressure is thus the primary parameter for creating the vortex, and other parameters like injection strategy and fuel temperature are less important. It may thus be necessary to crank the engine until sufficiently high fuel pressure is reached and then inject the fuel even, if that might take 1-2 seconds or to use another technical solution that provides sufficiently high fuel pressure faster.

Liquid penetration lengths and velocities are mainly influenced by the fuel pressure and the back pressure. The influence of the other tested variables was minor. However, the differences may be greater if the ambient temperature is increased so that vaporization has stronger effects.

ACKNOWLEDGEMENT

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