Comparison of gasolines with different distillation curves: effect of the temperature on a GDI spray opening angle

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Abstract

A GDI multi-hole injector was used to investigate the effect of the fuel composition and temperature on the spray angle. Ten different fuels were tested: three pure mono-component hydrocarbons, six different gasolines and one very light fuel with a short distillation curve. The injector and the tested fuel were heated-up at different temperatures ranging from 20 to 120 °C, then the spray was injected in a quiescent bomb. Back light photography was used to capture still images of the spray from which some geometrical parameters could be extracted.

Attention was focused on the spray spreading when quasi-steady conditions are reached: its initial and far field angles could be compared to infer information on the effect of the fuel composition on these spray macroscopic parameters. No effects are evident when the fuel temperature is below the distillation curve. Evaporation and flash boiling effects are immediately visible when the fuel temperature increases above the initial point of the distillation curve: the spray width measured close to the injector widens, while it narrows in the far field.

For the six tested gasolines the measured angles start to change at similar temperature, they show smooth variation with the temperature increase, and behave very similarly among them with slight or negligible differences. The pure components and the light fuel show a much stepper change when the temperature increases above their boiling point. The comparison put in evidence the limits and differences when using a mono-component fuel to simulate gasoline injection.

Introduction

When a liquid is injected into a gas to form a spray, flash boiling can occur if the vapour tension of the injected liquid is above the ambient gas pressure.

In a direct injection spark ignited engine, fuel flash boiling can occur easily. Due to the usual characteristics of commercial gasoline, with their initial boiling point around 40° at ambient pressure, during the induction stroke of a non turbocharged engine flash boiling conditions are often attained, and nearly always at partial load or when the engine is already warmed-up. Fuels of different compositions may affect differently the spray formation, and consequently its mixing, combustion, the engine performances and emissions.

In a previous work [1] the authors, using blends of two pure components, evidenced that the effect of flash boiling, as regard as their insurgence and quantitative effects, can be related to the ratio between the fluid bubble pressure and the ambient pressure. Other authors scaled the results to other parameters, like the fuel superheat compared to the bubble temperature [2].

In laboratory research activity, testing can be performed with different aims, with wider freedom in choosing the test conditions and parameters, among them also different fuels can be used. For reasons that are partly technical and partly historical, Normal-heptane and Iso-octane are still used as reference fluid in many applications, among them for testing injectors. The reason keeps clear form an industrial point of view: a test fluid that is a pure component can be easily restocked everywhere and keeps its properties unchanged even when managed or conserved improperly, e.g. if it evaporates partially it does not change composition, so it is a perfect reference fluid for production quality testing, comparison among different laboratories, tuning-up simplified CFD codes. For the purposes of designing and tuning-up the injection system of a real running engine, the benefit of using a constant reference fuel strikes against the fact that it can behave differently from the real gasoline available on the road, as already observed and investigated by other authors like [3].

The aim of the present study is to highlight the possible differences induced by the fuel composition on the produced spray at different temperatures in engine-like conditions, and to evidence whether these differences may be negligible.

Experimental set-up

A multi-holes GDI injector was used to inject the fuels and in a constant volume chamber.

The test chamber has an internal volume of 10 litres (internal diameter 206 mm and height 300 mm), two of its four windows with 100 mm diameter aperture were left open and used for the visualizations. The air temperature inside the chamber is monitored by means of a J type thermocouple whose tip is placed near the injector tip but out of the spray range. In the present study, to have a complete evacuation of the injected fuel during the interval between two injections, the chamber was continuously flushed with ambient air, at very low speed to avoid influencing the spray behaviour. The air was at nearly constant ambient pressure and temperature, ranging between 20 to 25°C.

The fuel was pressurized using a sac pressure accumulator in order to avoid direct contact of the fuel with the pressurizing gas. The pressure was controlled by a pressure transducer and a feedback circuit acting on the solenoid valve of the pressurizing gas circuit. The tests presented were performed at 100 bar fuel injection pressure.

The injector was placed at the center of the upper flange of the chamber using an appositely designed adapter. The injector with its holder and the fuel were heated-up at different temperatures ranging from 20 to 120 °C with 10°C steps. The injection duration was set to 3 milliseconds and the repetition rate was limited to 0.5 Hz in order to guarantee that the fuel temperature was as close as possible to that of the injector; the low injection frequency also facilitated the air renewal even at low speed.

Ten different fuels were investigated. Three were pure mono-component hydrocarbons: n-hexane, n-heptane and isooctane, whose characteristics are well known. Five were gasoline blends of known distillation curve, named in the text with simple numbers. One was a commercial gasoline (RON95) bought from a gas station, of unknown distillation curve, named “fuel 95”. One was a very light blend, with its distillation curve comprised between 23 and 38 °C, named “fuel C5” because it is mainly composed by hydrocarbons with five carbon atoms. The distillation data and curves are reported in table 1 and figure 1.

	Iinitial Boiling Point	evaporated 5% volume	Evaporated 10% volume	evaporated 95% volume	Final Boiling Point
Fuel 01	33°C	45	50	170	186
Fuel 04	35°C	46	50	161	195
Fuel 05	35°C	49	55	166	189
Fuel 06	35°C	48	54	182	217
Fuel 08	34°C	48	54	169	193
Fuel 95	Unknown	Unknown	Unknown	Unknown	Unknown
N-heptane			98.4°C		
Iso-octanel			99°C		
N-hexane			68.7°C		
Fuel C5	23	26	27	34	38

Table 1. Distillation data

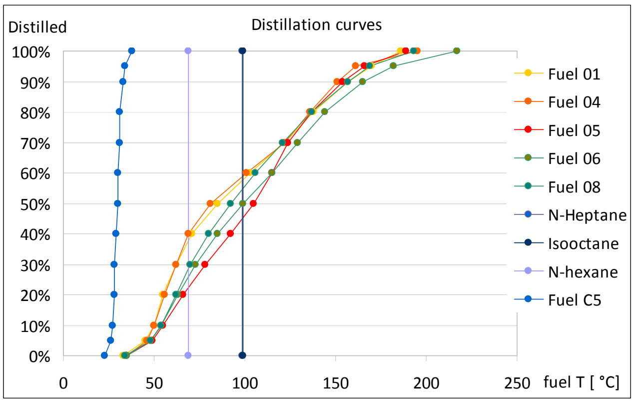

Figure 1. The distillation curves of the fuels used (Fuel 95 not available)

Figure 2. The spray pattern on a plane perpendicular to its axis

The effects of flash boiling on the spray structure were studied by comparing the images of the spray in different operative conditions. The imaging system used a backlight configuration derived from a Z-schlieren set-up, thus allowing imaging without perspective distortion. The injector is a standard production, solenoid-actuated GDI injector, with six holes whose spray pattern is shown in Figure 2. The injector was oriented to have four of the six jets nearly aligned in the visualized image plane, while the other two are slightly out of the imaging plane, along the line of sight of the optical system and are seen superimposed. The optic was adjusted to have an image spatial resolution of 0.1 millimetres per pixel, a nearly uniform background and a neat contrast with the spray edge. A stroboscopic lamp with a flash duration of few microseconds was used as light source; the images were acquired by a PCO Sensicam digital camera with its exposure time set at 3 microseconds. The injector ECU, the flash lamp and the CCD camera were controlled by a multichannel pulse generator. At each experimental condition, 30 single shot images were acquired, for statistical analysis, with a delay of 2.7 milliseconds from the injector command, thus capturing an image of the spray in its quasi-steady conditions, when the spray head has already passed away from the field of view, and the spray angle has reached a steady value.

Experimental results

The study is focused on the analysis of the spray shape reached in the above mentioned quasi-steady conditions, so that only its quasi-steady conical part is visible, and its width has reached a steady value in the measured region. The study allows to highlight two effects of the increasing fuel temperature on the spray structure: its initial widening due to flash boiling, and the coalescence of the single plumes to form a unique spray at further distance. The study purposely is focused on the spray width, and do not consider the spray penetration, since in a multi-hole spray its penetration is the complex results of two possibly contrasting phenomena, namely the initial shortening of the penetration of the single plumes, followed by their collapse and merge thus resulting in a spray that may have a much small frontal section and hence less drag and faster penetration in the far field.

Some of the images acquired are reported in the figure 5, as annexes after the text. Only eight out of the ten fuels are reported, and only six out of the eleven temperatures. It is worthy to say that for the fuel C5, additional images at the temperature levels at 25 and 35 °C were also captured, thus narrowing the temperature step within its reduced interval of distillation.

The sprays formed with the different gasolines, reported in figure 5a, do not show any visible change from 20° to 40°, then there is a smooth transition towards a shape that is narrower in the far field, but with an increased angle at the very nozzle exit. At 60°C, not too far from the distillation initial point, the six plumes are still clearly separated, then they merge together. At this level of details, no clear differences are visible among the different gasolines.

The other fuels are presented in figure 5b. Iso-octane and normal-heptane sprays show a similar behaviour but translated with the temperature: the four single plumes are still visible at 100°C, close to their boiling temperatures, respectively 98 and 99°C. The N-hexane spray, that has a boiling temperature of 68°C, is more similar to the gasolines, with its plumes well separated at 60° and still visible at 80 °C. The light fuel C5 anticipates its shape change, and at 120°C has become a very narrow jet, also much more transparent showing that the evaporation is reducing its liquid fraction.

Processing and discussion

Attention was focused on the spray spreading and was turned into quantitative observation by measuring two parameters: the spray width very close to the injector tip, and a global spray angle in the far field. These two parameters where identified and chosen among others after observing the photos reported in the annexes.

Standard procedure of image analysis were adopted to extract the information on the spray shape, with intensity normalization to correct for possible shot-to-shot fluctuations of the flash intensity, and back-ground subtraction. A threshold of 10% of the intensity decrease was chosen to identify the spray outline; the spray width or angle were considered at the external edges of the two outer plumes when still separated. In the near field, were an angle can be hardly defined, the spray width was measured between 0 to 1 millimetres from the nozzle; the position is marked by a dark gray dash in the scale of figure 3. In the far field the spray angles was derived geometrically from the spray widths between 20 and 60 millimetres of axial distance from the injector tip; such distances are also marked in darker gray on the length scale of figure 3. The width and angle results are reported as charts in the figures 3 and 4. Dispersion bars are reported as ±1 sigma around the average computed over the 30 images processed at each test condition.

Evaporation and flash boiling effects are visible when the fuel temperature increases above the initial point of the distillation curve: close to the injector the spray width widens, while in the far field it narrows.

From the spray width is reported in figure 3, no effects are evident when each fuel temperature is below its distillation curve. The six gasolines present very similar trends, their widths increasing from 70°. The vertical displacement of the results looks like an image processing effect due to a systematic error in the border detection. The image resolution used is 0.1 mm/pixel: when accounted for on both sides, added or subtracted, the uncertainty is in the order of magnitude of the dispersion among the different lines.

The results from Normal-heptane and iso-octane looks identical; their width increases already at 100°. The width of the normal-hexane spray stars to increase from 70°, and its slope seems to increase more than the other multi-component gasolines, but the tendency is week because of lack of data at higher temperatures. The light fuel C5 width seems to increase already at 25°C, but in the same order of magnitude of the data dispersion, and above 35°C its slope is clearly stepper than that of the other gasolines.

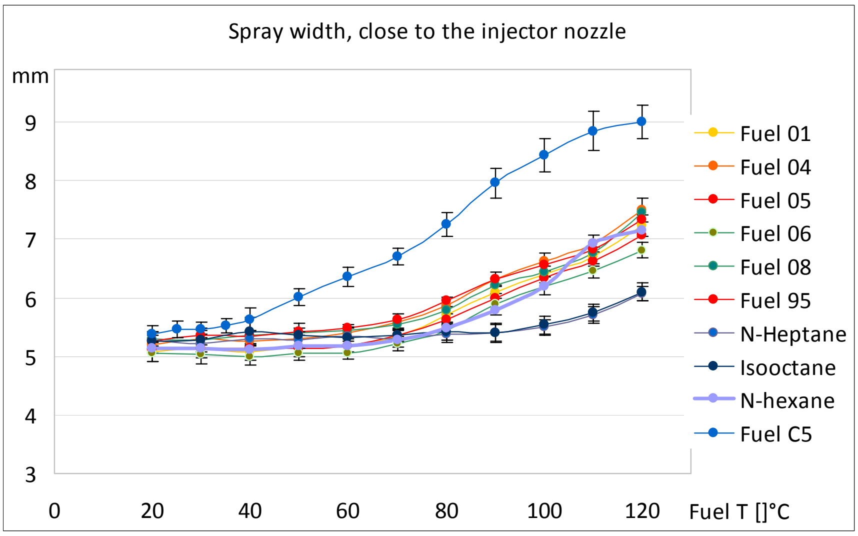

Figure 3. Spray initial width, as a function of the fuel temperature

The spray far field angle is reported In figure 4. The analysis is quite similar to that of the spray initial width, with the variations slightly delayed at higher temperatures. The data dispersion is initially reduced, probably because the systematic errors are relatively smaller compared to the larger width measured in the far field; then the dispersion increases reflecting the higher dispersion and unpredictability of this boiling phenomenon.

For the six gasolines, the angle is still constant up to 70°C, and shows the first decrease at the following temperature step 80°C. Some differences are visible: fuels 6 and 8 show an initial lower effect, that could reflect the slight differences in the initial boiling point of the different fuels, but the temperature resolution is not sufficient to give clear statements; Fuel 04, which has more light components, shows some more angle narrowing at the higher temperatures.

Normal-heptane and iso-octane looks very similar, with a slight angle decrease at 100°C, but still in the order of the data dispersion, and then clearly at 110 and 120°C. Normal-hexane starts increasing at 80°C, and there are sufficient data to state that the narrowing is steeper than that of the multi-component fuels. The light fuel C5 shows the same steep slope of the N-hexane, but starting from 35°C.

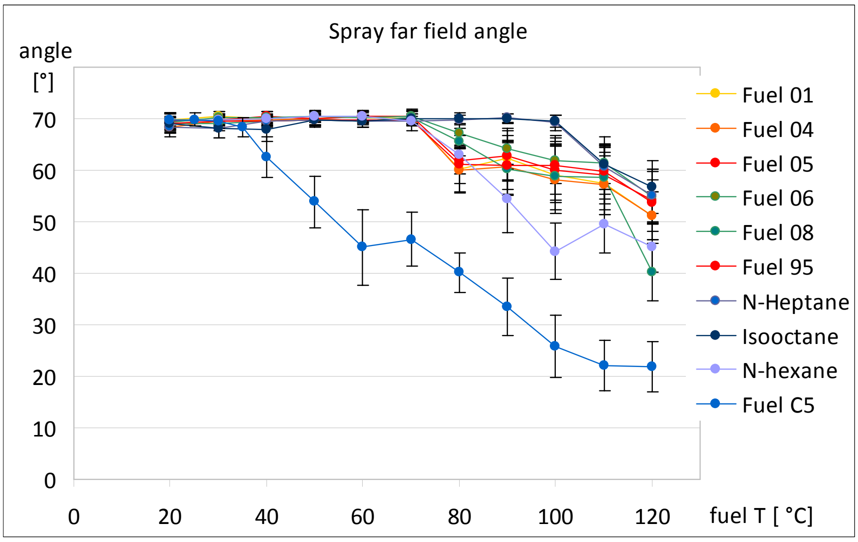

Figure 4. Spray far field angle, as a function of the fuel temperature

Conclusions

Different result can be drawn from this study.

Iso-octane and N-heptane are very similar among them, it is nearly impossible to appreciate a difference. N-hexane has a similar behavior, with similar slope of the investigated parameters curve, but starting at lower temperature.

All the normal gasolines behave very similarly among them, with slight differences. For all the tested gasolines, the spray near field width start to increase when the fuel temperature exceeds its boiling point or initial distillation curve, and shows very similar trends. The spray far field angle shows some slight differentiation also among gasolines.

The gasolines behave quite differently from pure components: the gasolines show a smother slope of their parameters variation, whose curves lays between the curves from the N-hexane and those from the heavier pure component couple.

The very light C5 fuel has a stepper parameter variation more similar to that of a pure component fuel.

The result can be summarized as follows: there is not a pure component that can simulate the spraying behaviour of a gasoline; the pure components and the light fuel, due to their univoque saturation curve or a very short distillation curve, show a stepper change with the temperature increase, while all the gasolines show smother variation, between those of N-hexane and iso-octane.

A general consideration that can be drawn is that, although pure components are appreciated to test injectors and production quality with high accuracy thanks to the reproducibility of the results, these results can be quite far from the real ones obtained with any real gasoline in real engine conditions, even thought of different composition.

Acknowledgements

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References

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[3] Aleiferis, P. G., van Romunde, Z., R., An analysis of spray development with iso-octane, n-pentane, gasoline, ethanol and n-butanol from a multi-hole injector under hot fuel conditions, Fuel 105 (2013) pp. 143–168.

ANNEXES: SPRAY PHOTOS

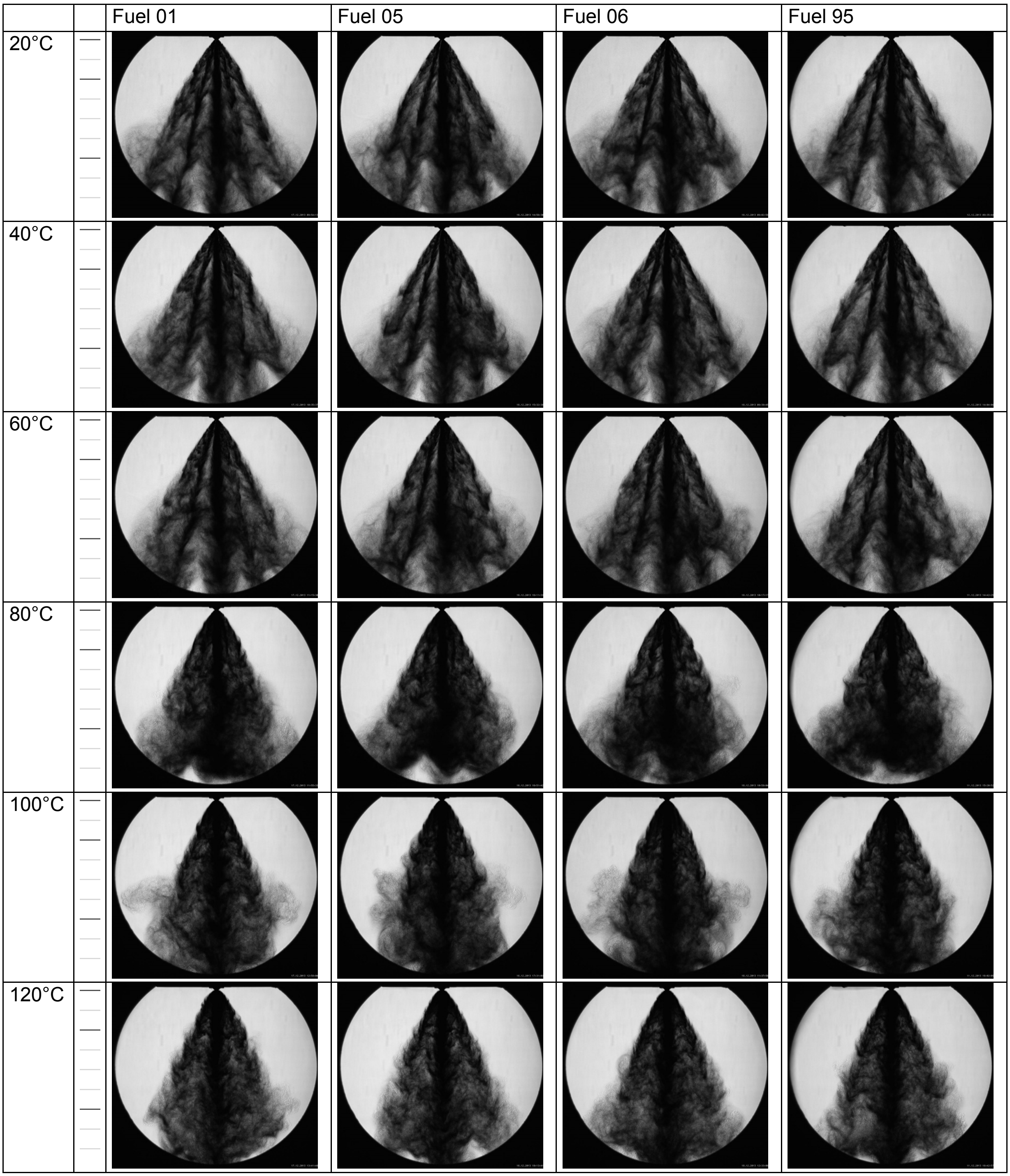


Figure 5a. Some spray images. Pfuel=100bar, Tfuel= variable, Pair=1 atm, Tair= 20-25°C, time delay= 2.7 ms from injector trigger. The scale on the left marks steps of 10mm

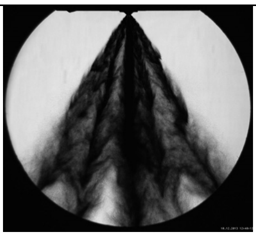
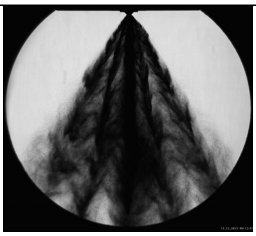
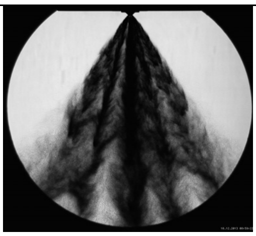
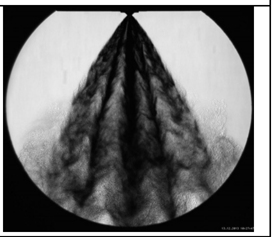
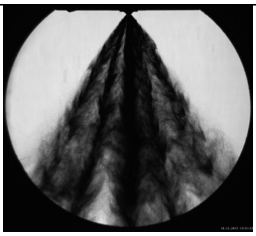
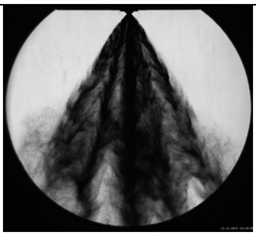
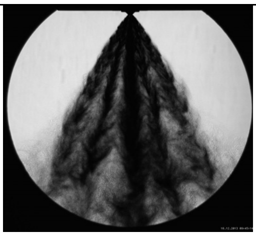
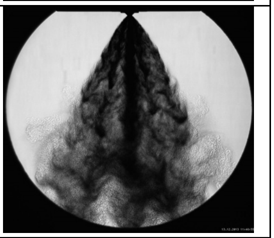
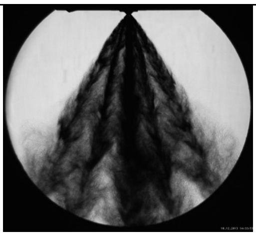
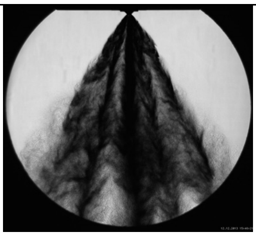
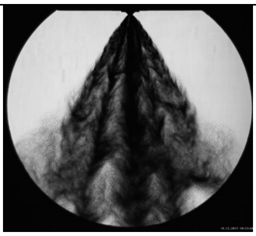
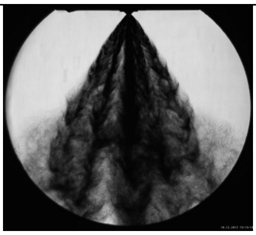
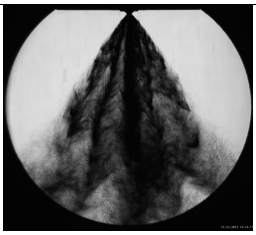
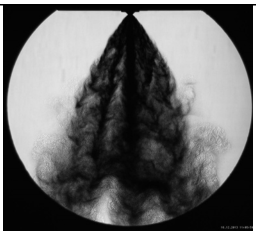
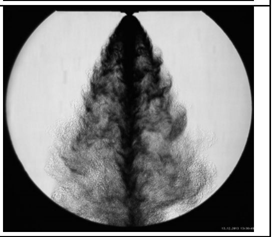
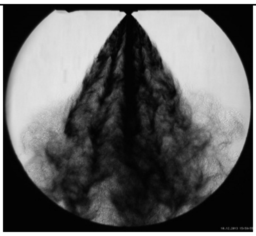
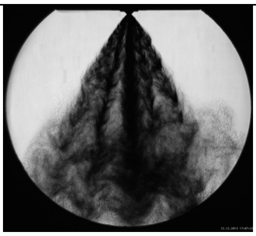
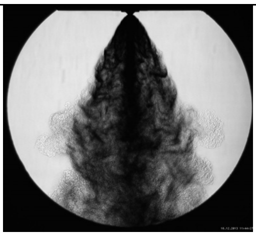
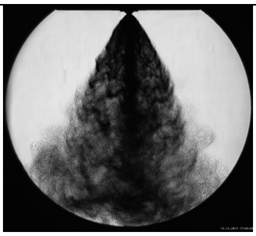
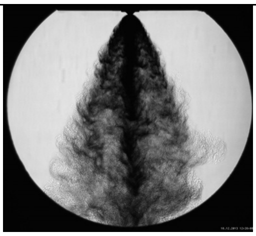
		N-ept	Iso-oct	N-exane	Fuel C5
20°C					
40°C					
60°C					
80°C					
100°C					
120°C					

Figure 5b. Some spray images (follows). Pfuel=100bar, Tfuel= variable, Pair=1 atm, Tair= 20-25°C, time delay= 2.7 ms from injector trigger. The scale on the left marks steps of 10mm

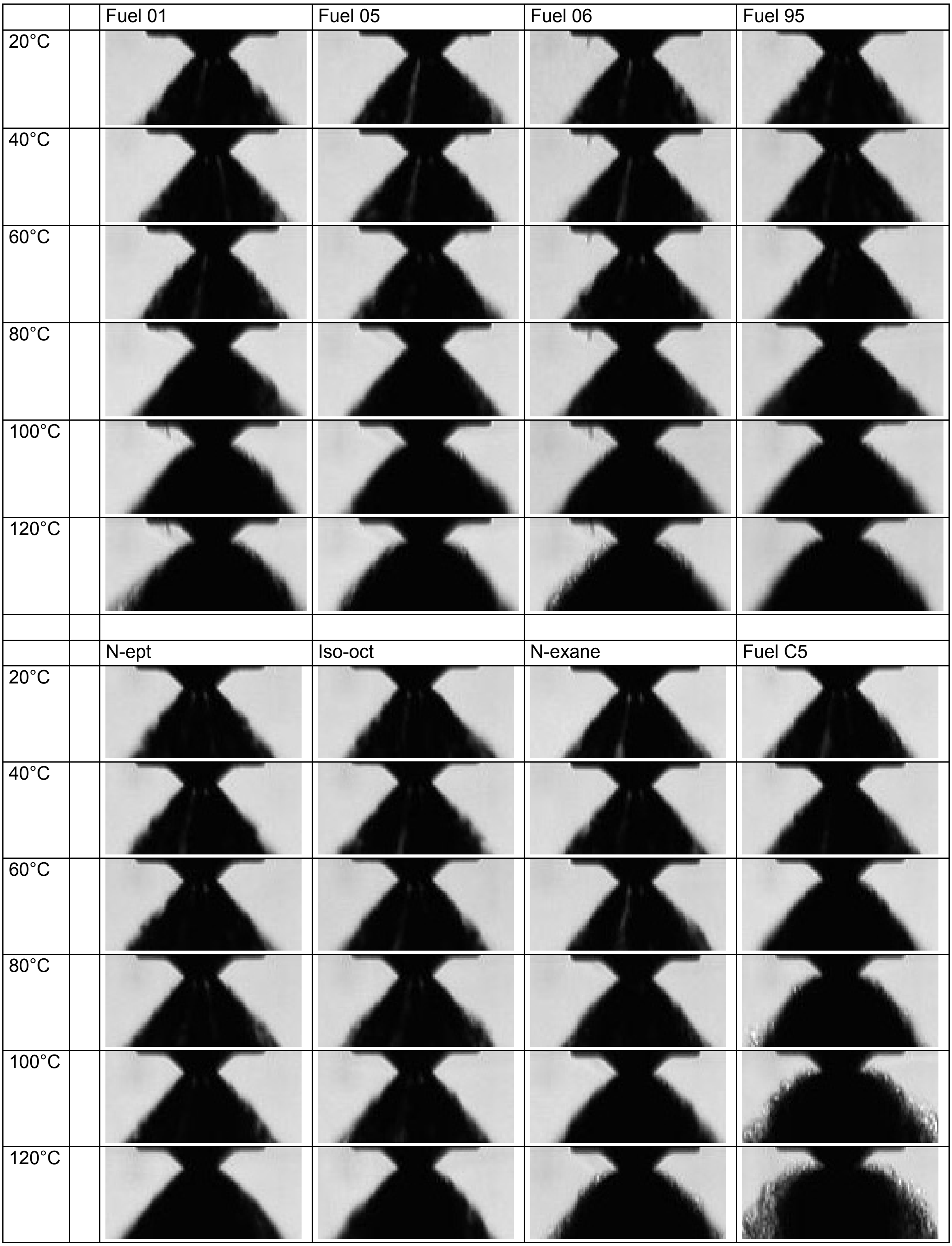


Figure 5c. Some spray images (follows). Pfuel=100bar, Tfuel= variable, Pair=1 atm, Tair= 20-25°C, time delay= 2.7 ms from injector trigger. Zoom on the injector tip region