Comparison of gasoline and mono-component fuels: effect of the temperature on the atomization of a GDI spray

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Abstract

A spray from a GDI multi-hole injector operated in ambient air at known conditions is used to investigate and compare the atomization results from five different fuels: two gasolines with different distillation curves, and three mono-component fuels, pentane, hexane and N-heptane. The analysis is focussed on the effect of the fuel temperatures between 30°C and 120°C.

The spray is studied with different experimental techniques to better understand the different behaviours.

The global spray behaviours, like spray penetration and spreading angle, are illustrated by photographic results. Then the atomization is accurately measured by Phase Doppler Anemometry and results are analyzed and compared. The spray droplet are measured at 45mm axial distance from the injector tip in 13 different radial positions; after data post-processing the average velocity and diameters results are plotted, both as time evolution in a fixed position, and as radial profiles during the quasi-steady injection period.

For each pure component, the temperature increase gives negligible effects up to its boiling point, above which stronger variations are observed in all the investigated parameters. The typical structure change with the spray collapse at increasing temperature is easily visible from photographic comparison. From PDA, atomization effects are more evident and easy to quantify and compare: the velocity profile clearly shifts towards the centre of the collapsing spray, while the droplet velocity and size decreases.

Both gasolines show this same behaviour too, starting from a temperature slightly above their distillation initial point, that is also very close to the boiling point of hexane. All the results from both gasolines are very similar to those from hexane at the same temperatures, thus highlighting the importance of a correct model fuel choice when evaporation phenomena become important on the spray development.

Keywords: GDI Spray, fuel temperature, distillation curve, atomization, PDA, droplet sizing.

Introduction

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

In a direct injection spark ignited engine, fuel flash boiling is often attained due to the combination of the control strategy, with the fuel injected during the induction stroke and at low load, and the evaporation characteristics of commercial gasoline, with their distillation curve starting around 40° at ambient pressure,. The fuel compositions may affect directly the spray formation at its initial stage, and consequently its mixing, combustion.

In previous works the insurgence of flash boiling, and the measure of its quantitative effect in pure components, binary mixtures and blend, has been related to different parameters: the ratio between the fluid saturation or bubble pressure and the ambient pressure [1, 2, 3, 4], the fuel superheat compared to the bubble temperature [2, 3, 5, 6,], the Jacob number [2, 3]

The use of mono component fuels, or binary mixtures, thanks to their excellent preparation repeatability, is an optimal choice for industrial testing and long term comparison of injector and sprays, and well explains the use of N-heptane and Isooctane as test fluids, thanks to their similitude in terms of density and viscosity to real gasoline at ambient conditions. However, for the tune-up of real engine, in many real operative conditions where a real gasoline would show boiling phenomena changing the spray targeting [7], these two fluids may not have such behavior and results may be misleading.

The present work is focused on the spray droplet velocity and size study at different temperatures and its aim is to highlight the conditions where the fuel composition can induce different behaviors that may be not negligible.

Experimental Set-up

A standard production injector is used, the same sample tested in recent works [2, 8]; it has a static flow rate of 13 mm^3/ms (N-heptane at 100bar), used in GDI engines with relatively small cylinder capacity. It has been chosen because in its spray pattern, composed by five jets, one jet is well separated from the others, nearly axially oriented and thus easily accessible for optical techniques. Figure 1 shows two views of the real spray at cold conditions, while Figure 2 shows the nominal spray pattern at 45 millimeters from the injector tip, the injector reference coordinates (X_{INJ} Y_{INJ}), the position of the PDA system with its reference coordinates (X_{PDA} Y_{PDA}), and the accurate centering of the studied jet obtained by velocity measurements.

The spray is directed with the injector axis oriented vertically downwards, coincident with the PDA vertical axis (Z_{INJ}=Z_{PDA}), and the electric connector direction identified as X_{INJ}. The injector is mounted in a rotating flange on the top of the closed bomb detailed in previous works [9], kept with open windows (100 mm diameter) and a slight air suction for continuous air renewal.

Spray images are visualized on a backlight telecentric photographic system, in fact a schlieren set-up used without the knife. A digital camera, a PCO Sensicam single shot fast shutter, is used to capture single images of the spray from front and side views, respectively the XZ_{INJ} and YZ_{INJ} planes. The image resolution is set at 10 pixel/mm, the exposure about 1 microsecond to use the whole dynamic range of the camera.

Droplet size is measured by a Dantec PDA configured to measure one velocity component, set vertically downstream directed as the injector axis Z, and the droplet diameter. The system includes an Ar+ laser operated at 512 nm, a fiber transmitting optic with a beam expander and a 310 millimeters focal length lens, a classic PDA receiver oriented at 70° side scattering with a 500 millimeters lens, a P80 processor, and its dedicated software. The measured velocity is set in the range -10 to 130 m/s, with the positive direction directed downward in the laboratory, coincident to the injection axis; the droplet maximum diameter is limited at 80 microns.

Measurements are performed at Z = 45 millimeters downstream of the injector tip, normally in 13 positions disposed along the axis parallel to X_{INJ} reported in red in the spray side view of Figure 1b, sometimes 16 positions are used at the highest temperature when the spray deviation is higher than usual. In the preliminary set-up, the velocity was measured also along the direction Y_{SPRAY}, the studied jet was correctly centered and the symmetry was verified.

Experimental Conditions

The fuel pressure is set at 50 bar for more accurate PDA measurements, to avoid the common problems encountered at higher, although more engine-like pressures [1]. Thanks to the relatively low injection pressure, compared to a higher one, there are less droplets, with lower velocity and larger dimensions. Thanks to the large diameter, in the order of a tenth of micron, the relative measure accuracy is increased; also there are less very small droplet, in the order of the micron, a dimension that is close to the light wavelength that limits the PDA inferior size range. The lower number of droplets decreases the probability of having two droplets at the same time in the measurement volume, thus reducing the probability of multiple signal that lead to lost measurements; and consequently reducing the bias of the PDA in favor of larger droplets.

The injector holder and the fuel line are heated up at the same temperature, set from 30 to 120 °C in steps of 10°C, sometime some value are skipped, depending on the studied parameter behavior, to focus the study where the temperature variations has more evident effect on the studied parameters.

Double injections are used, with two logic pulses of 1 millisecond separated by a pause of 0.5 milliseconds. The results reported are relative to the second spray event, which has reached a more steady condition than the first one.

Five different fuels are tested: two gasoline with sufficiently different distillation curves (same batches used in [10, 2], and three pure components. The distillation curves are reported in Figure 5.

a) Front view, YZ_{INJ} plane **b)** Side view, XZ_{INJ} plane

Figure 1 a) Front view of the spray. **b)** Side view of the spray, in red the axis for the PDA measurement (parallel to X_{INJ}, at Y_{INJ}=0, Z=45mm)

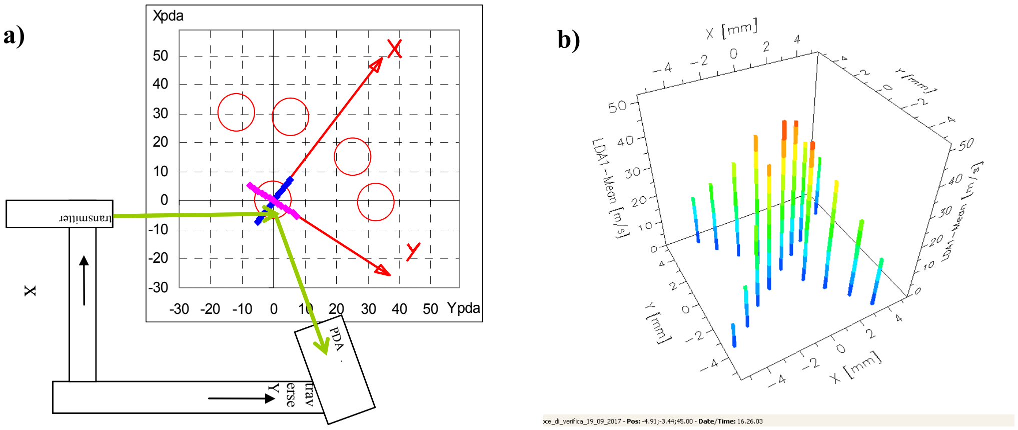

Figure 2 a) The spray nominal pattern at Z=45mm with its reference system XY_{Spray} in red. The PDA optic system is indicated (not in scale) with the laser path in green and its reference system (X_{PDA} Y_{PDA}) centred on the studied jet. **b)** Centring of the studied jet at cold conditions (quasi-steady average axial downstream velocities, XY_{PDA} coordinates).

The time evolution of the spray shape from its side view at cold conditions (Fuel04 at 30°C) is given in Figure 3; the spray timing compared to the logic pulse is influenced by the different opening and closing delays, and the closing phase is not as sharp as the opening one. The first injection lasts from 0.3 to 1.4 ms, then after the pause of about half millisecond, the second spray is injected. Note that when the injector closes, the vertical jet is suddenly attracted to the right side by the other four jets, whose momentum and consequently air entrainment are much stronger than those of the studied single jet.

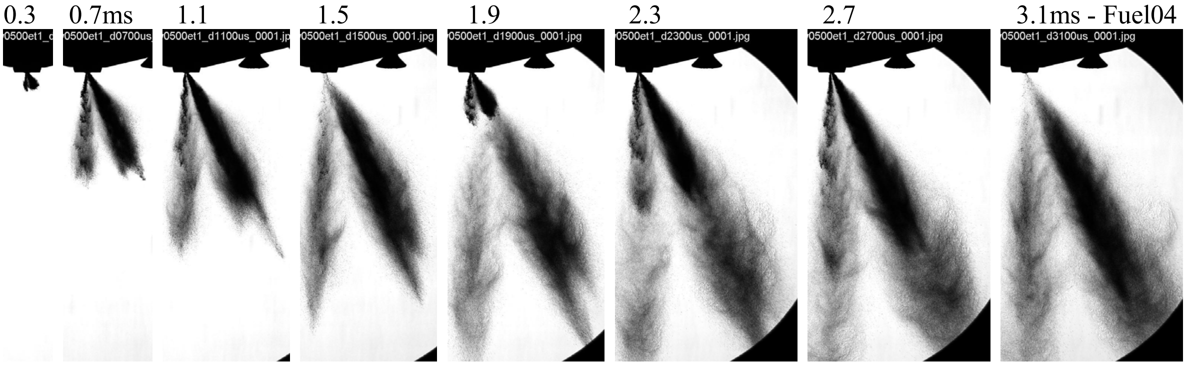

Figure 3. Time evolution of the double injection event. Fuel 04, T=30°C

Figure 4 shows the fuel temperature effect at a fixed delay (t=2.7 ms) on the same Fuel04, for temperatures ranging from 30°C up to 120°C, when the vertical jet is nearly disappearing and merging with the other jets. This temperature is also the maximum mechanically possible for the injector.

Figure 5 shows similar photos for pentane, whose test temperature is limited up to 70°C, when the vertical jet disappears. The distillation curves of the tested fuels are also reported here.

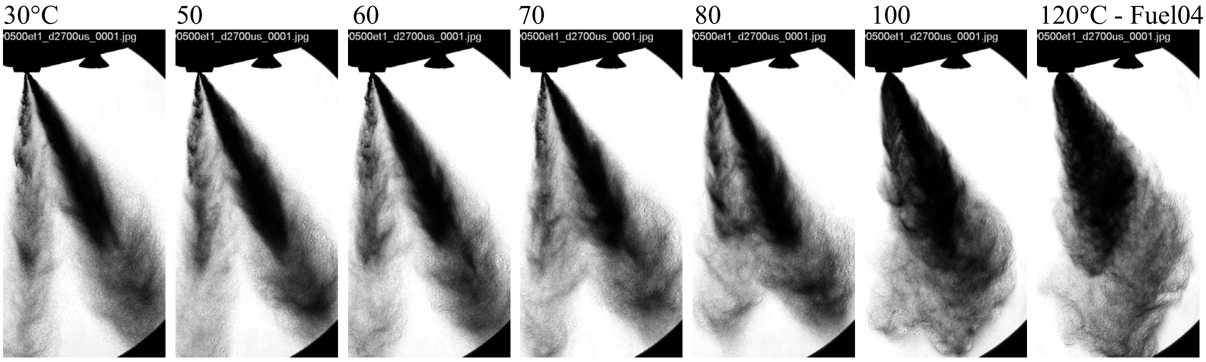

Figure 4 Fuel04: temperature effect at fixed delay 2.7 ms.

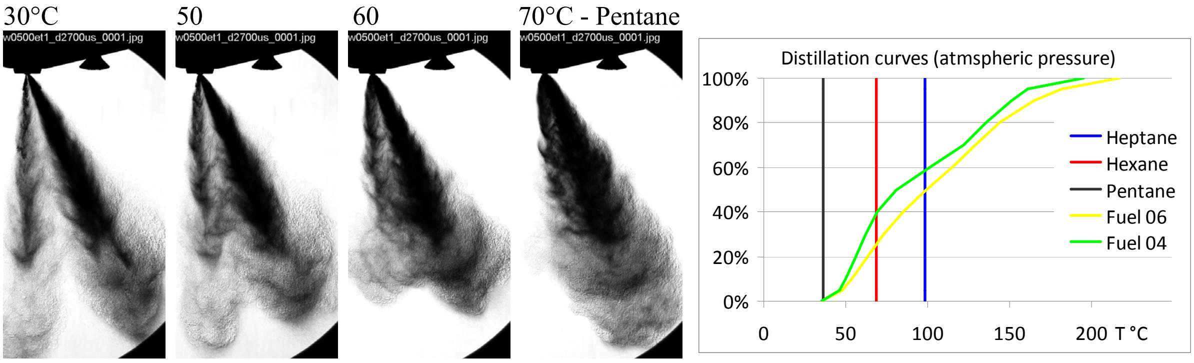

Figure 5 Pentane spray. Fuel temperature effect at fixed delay 2.7 ms.
All the distillation curves are also reported

PDA data acquisition and processing

At each measurement position injections are operated at 5 Hz for 100 seconds, to collect up to 200'000 droplets for accurate statistical results. Data are then averaged over time bins 0.1 ms long, to obtain the typical average values for droplet population. The PDA bias towards larger diameter is also evaluated and corrected for by weighting the droplet data in function of their diameter with an empirical function similar to the one used in [11]. An example of the results at cold conditions is reported in Figure 6, where per each time bin are reported the total droplet counts in that time bin over the 500 injections, the droplet average velocity and diameters D_{10}, D_{20}, D_{30} D_{32}. The logical injection pulse is also reported; the delay in the measurement is partially due to the mechanical injector delay, and partially to the convection time up to the measurement position that is 45 mm from the injector nozzle.

Figure 7 reports only the average velocity and diameters, not the counts, for two different temperature. The position of the measurement was chosen following the spray shifted towards higher X_{INJ} values due to the spray collapse at higher temperature, the criterion will be easier explained in a following paragraph.

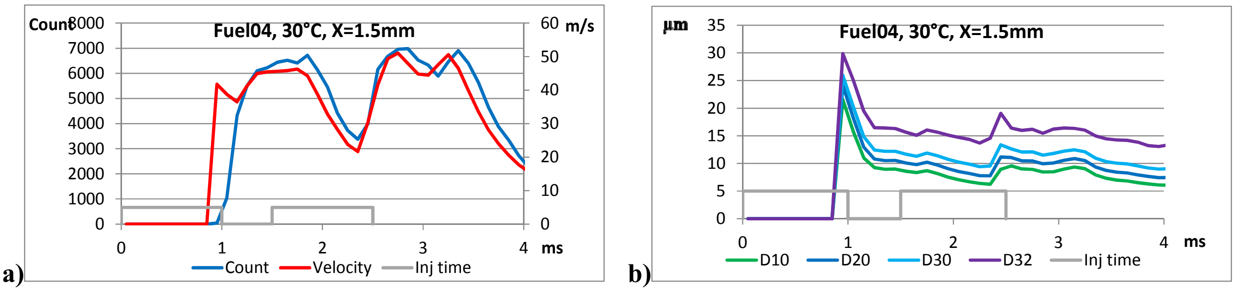

Figure 6 An example of the time evolution of the droplet statistic values at cold conditions.
Fuel 04, T= 30°C, position $(X,Y,Z)_{INJ} = (1.5, 0, 45)$ mm **a)** Droplet counts and velocity **b)** Average diameters

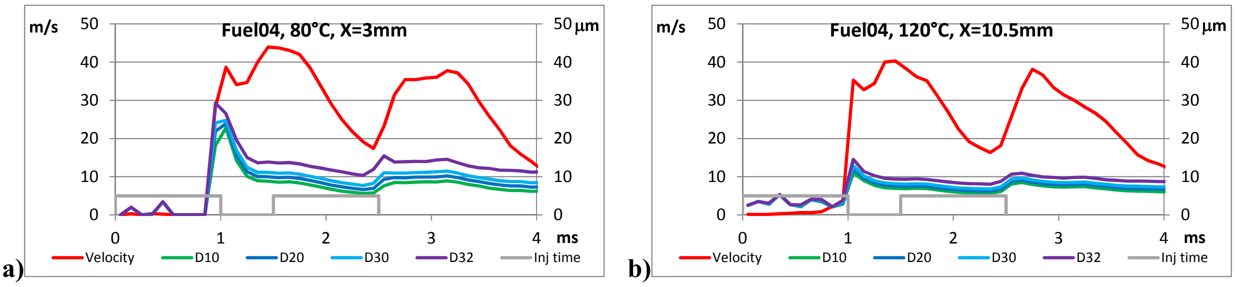

Figure 7 An example of the time evolution of the average droplet statistic values.
Fuel 04, **a)** T= 80°C, X_{INJ} = 3 mm, **b)** T= 120°C, X_{INJ} = 10.5 mm

Results and Discussion

The data of figures 6 and 7 shows some typical behaviors of GDI sprays. The first pulse at cold conditions shows the typical initial burst of fast and big droplets, that is most probably an issue of an aero-dynamical selection, where the large droplets produced by the poor atomization of the pre-jet are not efficiently slowed down by the air drag. Note that their number is very limited. This burst of large droplets is much less visible at the second pulse, probably because of the presence of the smaller droplets that reduced their statistical influence, as already speculated in a previous work [8] with wider analysis of double injections. At increasing temperatures, this burst is much reduced, and the reason may be due to different mechanisms.

- The averaging effect of time windowing: due to a slightly different timing, the few large droplets may fall in a time bin where they are averaged together with many small droplets.
- Much faster evaporation: the large droplets in the first burst are exposed to large quantity of fresh air.
- Better atomization: due to lower surface tension because of the temperature, or directly by flash boiling inside the larger droplets that causes their break up.

The latter hypothesis is supported also by the general narrowing of the average diameters dispersion at higher temperatures. In fact, a faster evaporation would lead fast disappearing of the smaller droplet, while the larger ones would stay longer, following the D^2 law [12], with a spreading of the average values. On the contrary the results show that the D_{10} keeps around 8 microns, while D_{32} falls from 15 microns at cold conditions to 13 microns at 80°C and less than 10 microns at 120°C, a behavior that is opposite to the evaporative selection, and supports the break-up mechanism explanation.

From the data used to build Figure 6, it is calculated also the quasi steady velocity value during the second pulse, by averaging the droplet velocities in a unique longer time window from 2.8 to 3.3 ms. The same values are calculated from each tested position, thus the spatial profile of the quasi steady period is built, for each fuel at each temperature; the results are reported in Figure 8 (Fuel06 is not reported since it is very similar to Fuel04).

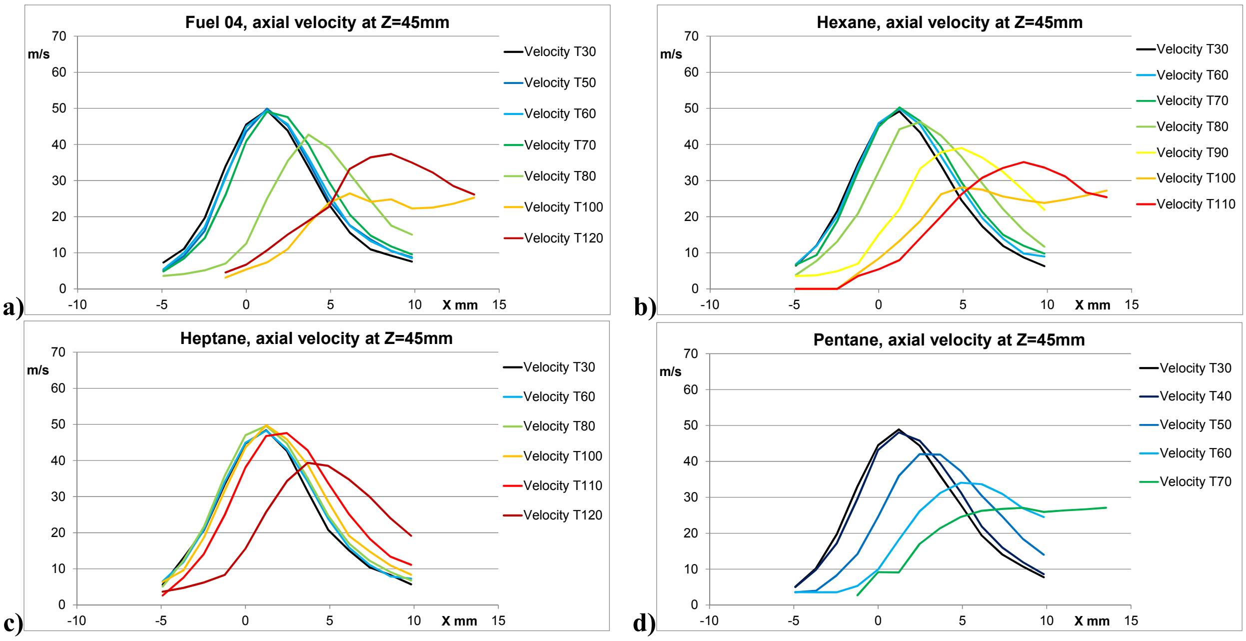

Figure 8 Spatial profiles, along X_{INJ} (Y=0, Z=45mm), of the quasi steady droplet average velocity (time window 2.8-3.3ms) for four tested fuels, at different temperatures (few value were not tested, color coding is kept).

It can be observed that the spray profile shifts towards the right side at higher temperature, typical of the conditions when the entrainment from the other four jets become stronger and the single jet studied is deviated. The deviation is seen clearly about a tenth of degrees Celsius above the pure components boiling point: at 50°C for the pentane (T_{boil} = 36°C), at 80°C for N-heptane (T_{boil} = 69°C), at 110°C for N-heptane (T_{boil} = 98°C). For the gasoline it is clearly visible at 70°C, but already at 70°C and even at 60°C a minimal shift may be indicated; a temperatures clearly above the beginning of the distillation curve, and higher if compared to pure components.

For very large deviations towards the right, the jet partially merges with the other jets and the velocity profile is deformed clearly towards a new maximum further on its right.

From the data of Figure 8, the maximum values of the velocity profiles are plotted against the corresponding temperature and reported in Figure 9a. A similar procedure is repeated for the droplet average diameters, which are chosen from the position of the velocity maximum; the results are reported in Figure 9b. For all the fuels the velocity is almost constant up to its boiling temperature, beyond which a sharp decrease is measured. Note that the segments between two measured point should be intended only as a graphical aid for better visualization purpose, they do not represent a correct result trends between real data. The two gasolines and the hexane behave very similarly among them, and quite differently from the other pure components. The average diameter also show that behaviour, but with slightly larger variations, where evaporation is for sure playing an important role, the measurement accuracy and repeatability are for sure less accurate than for the droplet velocity, and the statistical processing is more complex.

The data of Figure 9 belonging for the pure components are also plotted against the overheat degree (T-$T_{BOILING}$) in Figure 10; the data from gasolines could not be elaborated since their boiling temperature are not defined. In this last plot it is clearly evident that the velocity data are very well scaled by the superheat degree; the diameter do not scale that well, for the aforementioned reasons.

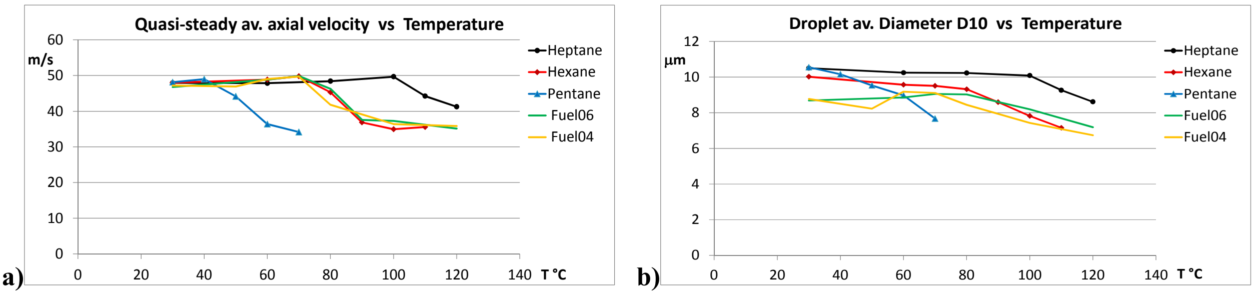

Figure 9 a) Maximum value of the quasi steady droplet average velocity (spatial profiles along X, time window 2.8-3.3ms) for the tested fuels, at different temperatures. **b)** Droplet average diameter in the same positions.

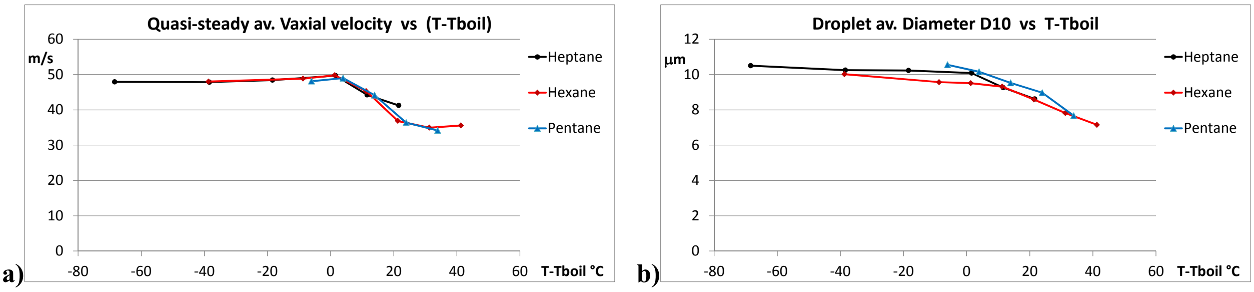

Figure 10 The same data of Figure 7 as a function of T-$T_{boiling}$, for the three pure components. **a)** quasi steady droplet average **b)** Droplet average diameter in the same positions.

Conclusions

A GDI spray was successfully used to compare the behaviors of five fuels, two gasolines and three mono-component hydrocarbons, at temperatures between 30°C and 120°C, a range where flash boiling is expected to induce a strong change in the spray shape. The droplet velocity and diameter measured by PDA are used to calculate the overall spray velocity and size profiles, that are used as indicators for the comparison.

It has been found that the temperature increase gives negligible effects on the velocity profiles up to a temperature slightly above the boiling point of pure components, or the initial distillation point of the gasolines. Above these temperatures stronger variations are observed. The spray progressive collapse is quantitavely evaluated through the measured jet displacement towards the centre of the spray pattern and the maximum velocity trend. Data reduced by the overheat degree fall all together in a very narrow band, thus confirming that the superheat degree can be used in such cases for data reduction. It is also highlighted that gasoline and N-heptane behave quite differently, because flash boiling insurgence in N-heptane is strongly delayed, compared to gasolines, by more than 30°C, in that temperature range typical of real engine. This poses serious questions on the choice of model fuel for the tune-up of real injection systems.

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