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INFLUENCE OF TEMPERATURE ON THE SPRAY CHARACTERISTIC AT FUEL DIRECT INJECTION

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ABSTRACT

The influence of temperature on fuel atomization of fuel direct injection nozzles is characterized experimentally. The behaviour of n-hexane-, n-octane- and gasoline-sprays after atomization is investigated under different liquid-temperature conditions by using different injector-types: a swirl injector, designed for wall-guided gasoline fuel injection, and a multiple orifice injector for spray-guided fuel injection. To evaluate fuel temperature influence the sprays are observed macroscopically by using a high-speed-camera and microscopically by measuring droplet diameters. All experiments run under atmospheric conditions.

Fuel temperatures influence fuel atomization and spray propagation. With increasing fluid temperatures change of spray structure is observed. Changed fuel properties lead to smaller droplets and increased spray cone angles at injector tip. Further increase of fuel temperatures results in flash boiling atomization followed by spray collapse and a further reduce of droplet diameter.

INTRODUCTION

The port fuel injection in spark ignition engines has been replaced by direct fuel injection. The aim of this application is to achieve more powerful and more fuel-efficient engines. Three principles has been established: air-guided, wall-guided and spray-guided direct injection. There is particularly a demand on research for the spray-guided injection method under stratified air fuel mixture conditions. Studies of fuel direct injection identified the considerable importance of fuel temperature on atomization, propagation and evaporation of fuel sprays. The temperature dependence is caused by physical properties and transport coefficients, as density, specific heat capacity, surface tension, viscosity, thermal conductivity, etc., as well as different mechanisms of vaporization. This can especially be observed in the case of a high pressure difference between fuel and cylinder-atmosphere. Such conditions may lead to an atomization process in which flash boiling occurs [1].

In particular, during spray-guided gasoline direct injection, it is extremely important to ensure a stabile spray, that provides an ignitable fuel-air-mixture near the spark plug at ignition point under stratified charge conditions. So changed fuel spray propagation may cause ignition misses. [2]

Especially, in extreme engine operation points, like cold start or full load, atomization conditions vary from their nominal values and may lead to a change in mixture preparation. Under cold start conditions, the reduction of pollutant emission and an improved engine running could be achieved by increasing fuel temperatures [3]. In stratified mode operation and during engine warm up operation an optimum for fuel temperature have to be found. During studies concerning the direct start without starter of a direct fuel ignition engine [4] change of mixture preparation could be detected by trying to start the high tempered engine.

Other situations where operation conditions are changing may occur at automatic engine stop/start applications or during start of combustion engine operation at the use of hybrid-electric vehicles.

Aim of this work is to evaluate previous examinations, where the influence of temperature on direct fuel injection was observed, under non-engine-relevant conditions.

EXPERIMENTAL SETUP

The experimental investigation is carried out with an injection test facility consisting of a replaceable fuel injector, fuel and injector heating system, fuel pressure variation and injection control unit. Fuel and injector temperature, fuel pressure and injection time can be varied.

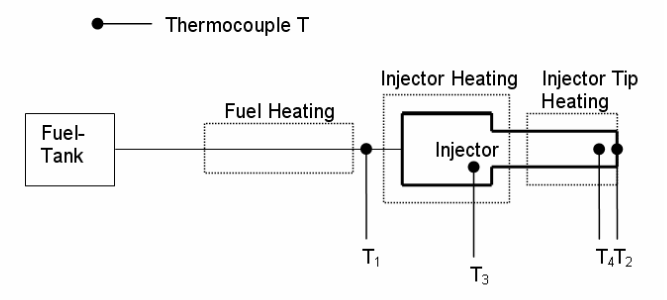


Figure 1: Temperature conditioning principle

Figure 1 shows the system of temperature conditioning. Heating elements for fuel pipe, injector body and injector tip are used. Thus, fuel, injector body and injector tip can separately be heated. Temperatures of fuel inflow and injector tip are monitored through a set of thermocouples T1 and T2. All heating elements are flown through by silicon oil AK50, that is heated by thermostats. In- and outflow temperatures of silicon oil are controlled by thermocouples, too.

Test Injectors and Fuels

The influence of the fuel temperature on atomization should experimentally be characterised. The behaviour of n-hexane-, n-octane- and gasoline-sprays (see Table 1) after atomization is investigated for different liquid-temperature conditions using different injector-types: a swirl injector, designed for wall-guided gasoline fuel injection, and a multiple orifice injector for spray-guided fuel injection

Table 1: Test fuels and physical properties (at 0.1MPa, 20°C)

Fuel	Gasoline	n-Octane	n-Hexane
Boiling Point °C	-	125	68
Surface Tension, mN/m	22.6	21.6	18.5
Density kg/m	680	720	690
Viscosity mPa s	0.65	0.71	0.38

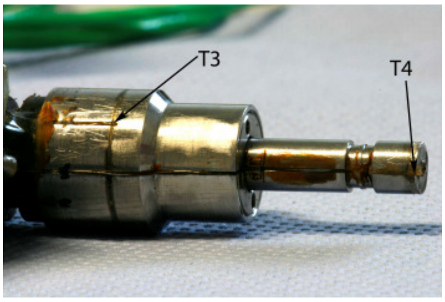


Figure 2: Swirl Injector with thermocouples T3 and T4

Figure 2 shows a picture of the used swirl injector which was fitted with two extra thermocouples, one at injector body and another one at injector tip (see Figure 2, also Figure 1: T3 and T4). The resulting spray axis is 19.5° out of injector axis and the spray cone angle is given with 30°.

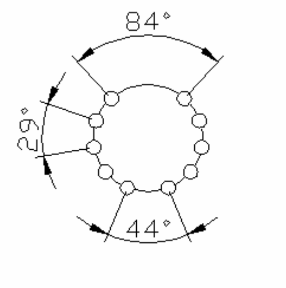


Figure 3: Hole arrangement of the multiple orifice injector

The multiple orifice injector contains 10 holes that are asymmetrically arranged. The arrangement of the holes can be seen at Figure 3. There are two larger gaps of 84° and 44° and another 8 gaps with a 29° width. The nominal spray cone angle is 90°.

PDA-Measurement-System

The scheme of the experimental setup for PDA (Phase Doppler Anemometry) investigation is presented in Figure 4.

The optical measuring system uses a 5W argon-ion laser light source and two-dimensional optics (blue λ=488 nm, green λ=514,5 nm), which enables the time resolved measurements of two velocity components and diameters of spherical, homogeneous and transparent particles .

Some PDA-setup-parameters are shown in Table 2.

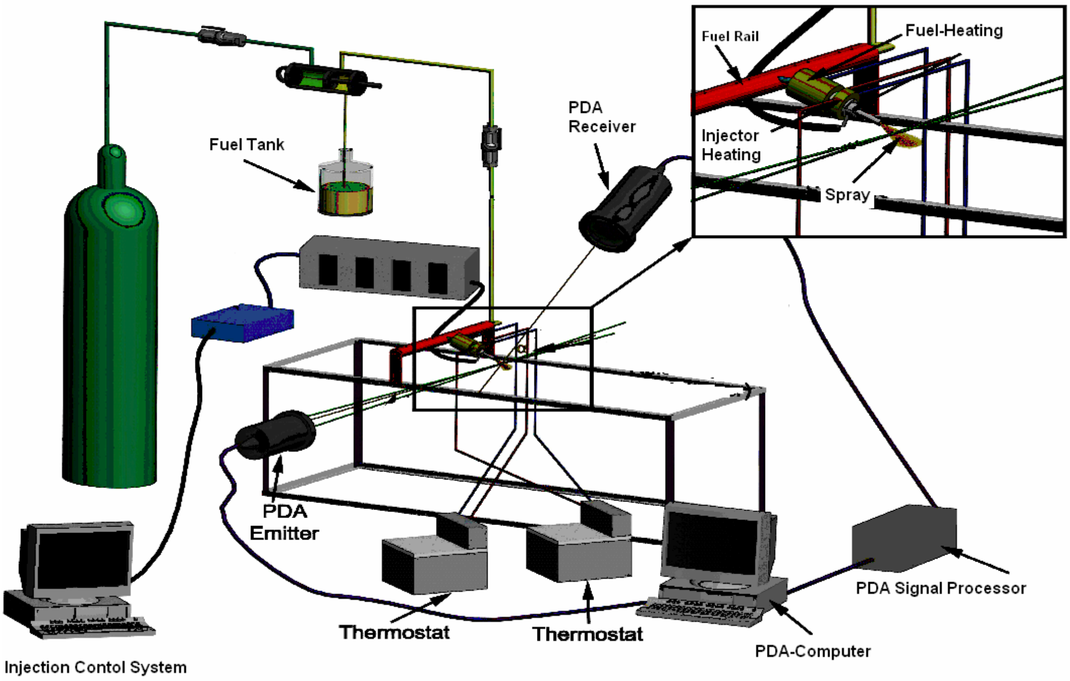


Figure 4: PDA measurement setup

Table 2: PDA-Setup and Parameter

Parameter	Value
Scattering angle	30°
Transmitter focal length	250mm
Receiver focal length	250mm
Max./Min. detectable diameter	
Gasoline	103.9µm/0.9µm
n-Octane	98.7µm/0.9µm
n-Hexane	96.4µm/0.8µm

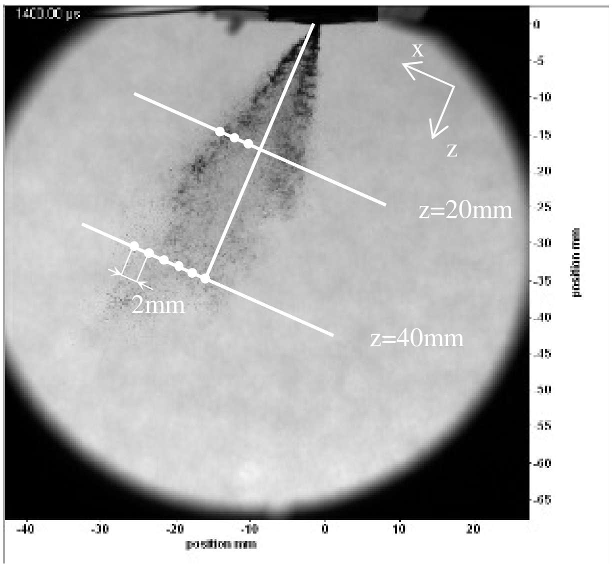


Figure 5: Measurement positions for swirl injector

Measurements are made at radial positions across the spray, at different axial distances from the injector tip. In Figure 5 the measurement positions for the swirl injector are shown. A 3D-traversing unit allows an exact positioning of the PDA-measurement volume.

The measuring process begins with PDA-instrument parameterization (see Table 2) and calibration. After this, the measurement section must be positioned exactly on the nozzle tip centre for adjusting the point of origin of the traversing unit. From that point the traverse follows the programmed measuring positions for required experiment. The number of fuel injections for every measurement point is different, because of changing data acquisition speed that is dependent on the spray structure. Spray structure is changing in dependence of temperature so not for every measurement point particles can be detected respectively the detectable amount of droplets is very low. Only points with high data acquisition rates are regarded but always at least 2 points per measurement plane. At every measurement position 3000 valid captures are made. After reaching this value the measuring section moves into next point. The single injection will be released after nozzle triggering, which also activates the PDA measuring system.

The PDA measuring time is 5ms per injection. With the time interval of about 1500ms between two injections it is ensured that the next measurements will not be affected by the previous ones. In order to secure the reproducible initial conditions, the air-fuel mixture will be sucked off continuously with velocity of less than 0,2 m/s.

High Speed Cinematography

For analysing temperature influence on spray structure and penetration, the spray is visualized with a high speed cinematography system. Furthermore the visualisation results are used for determine measurement positions for PDA investigations. For macroscopic observation, shadowgraph images and impinging light images of the fuel sprays are captured with a digital high speed camera (LaVision HighSpeedStar6). The 12bit-monochrome CMOS-sensor has a resolution 1024x1024 pixel and a frame rate of 5.4kHz. Higher frame rates up to 675kHz are possible reducing the resolution. A single pixel has a size of 20x20µm. Exposure time of the camera can be reduced to 1µs.

Light source for the shadowgraph images was a spark flash lamp (Nanolite). The flash duration last 18ns and represents the exposure time. Maximum flashing rate is 20kHz. The lens used on the camera are a 135mm, f/2.8 Nikkor camera lens with a spacers of 20 to 36mm. The diaphragm was set on 5.6. With a frame rate of 5kHz the whole camera sensor was used.

For the impinging light images a 2kW halogen lamp provides as light source. Here a 85mm f/1.8 Nikkor camera objective was used and the diaphragm was set on 2.8. The camera frame rate was 40kHz at 3.34µs exposure time and the used camera sensor area was reduced on 384x320pixel.

Camera and fuel injector are synchronistically triggered.

Advanced investigation with a laser light-section unit are possible and will be prospectively executed.

Experimental Conditions

The macroscopic and microscopic studies of the direct fuel injection sprays formed by the various injectors are carried out varying fuel temperature, fuel pressure and duration of injection. The fuel temperature was adjusted in the range between 25°C and 125°C. The experiments are performed, when the temperatures of injector tip, injector body and fuel temperature reached the desired value.

Duration of injection is varied between 1.2 and 1.8ms.

Injection pressure differs from 9MPa to 15MPa. The higher pressure of 15MPa was only used for the multiple orifice injector. For both injectors these combinations of injection duration and injection pressure present operation points of part load operation, where stratified charge conditions were achieved.

At all experiments the spray is injected into ambient air under atmospheric conditions.

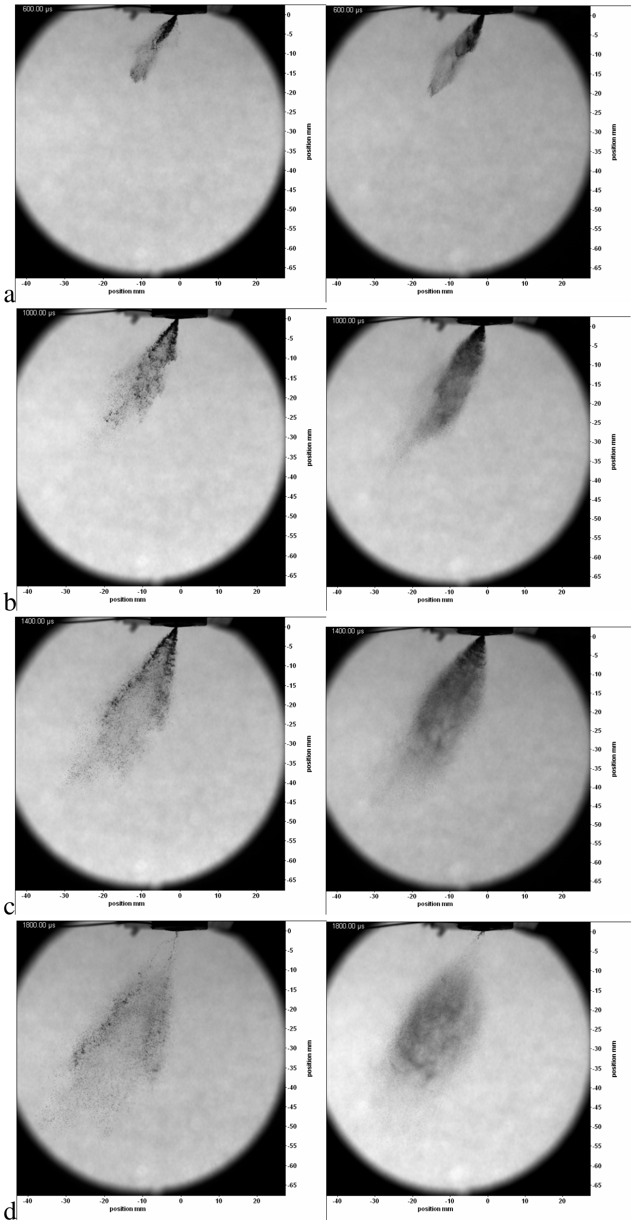
RESULTS

The presented results represent a first exemplary selection of observable trends.

Visualisations

Figures 6 and 7 shows single injection shadowgraph images of gasoline spray and its propagation formed by the swirl injector at different temperatures.

The stages of spray forming can be described as followed (see figure 6, fuel temperature 25°C): development of a pre-spray (a), start of forming conical main spray (b), fully developed main spray as hollow cone (c) and end of injection (d).

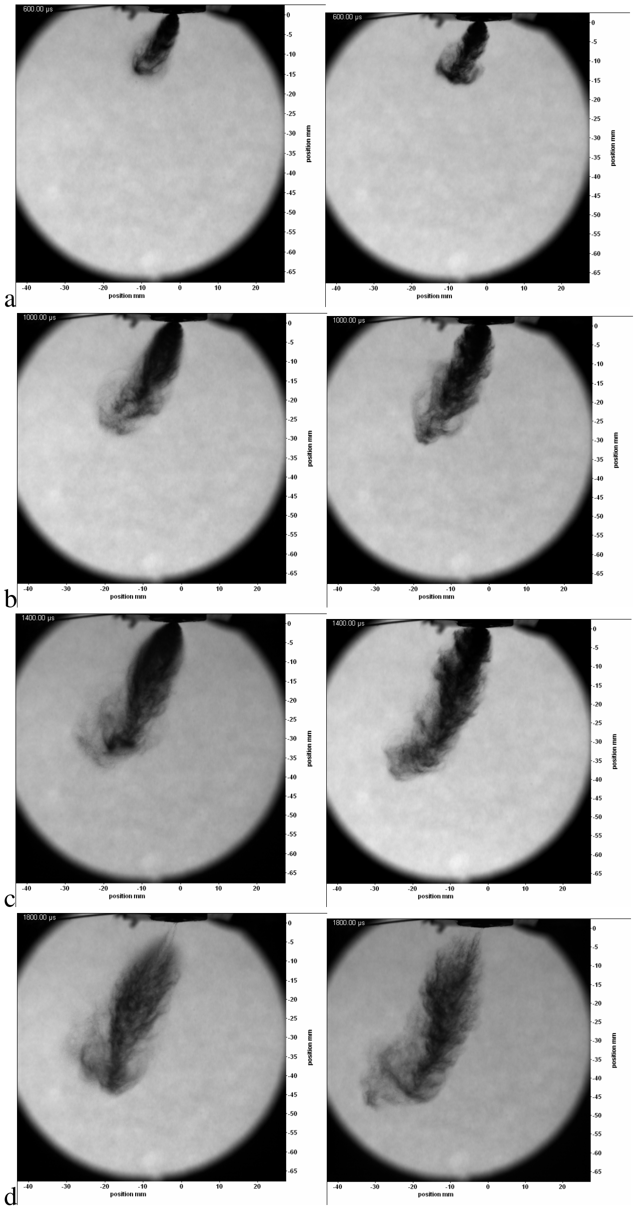


25°C 65°C

Figure 6: Shadowgraph images of swirl injector gasoline spray propagation (t_{ASOI} = 600µs(a), 1000µs(b), 1400µs(c), 1800µs(d))

This is also being seen in Figure 8, where injector tip and the begin of atomization is magnified displayed. The left column of images in Figure 8 shows the spray at a gasoline temperature of 25°C. At the first image the pre-spray is being seen. The second row shows the establishing spray, while in the third picture the fully developed, conical main spray is observable.

A pre-spray is typical for swirl injectors [5]. First row of images (Figures 6 and 7) shows this pre-spray 600µs after start of injection (ASOI).

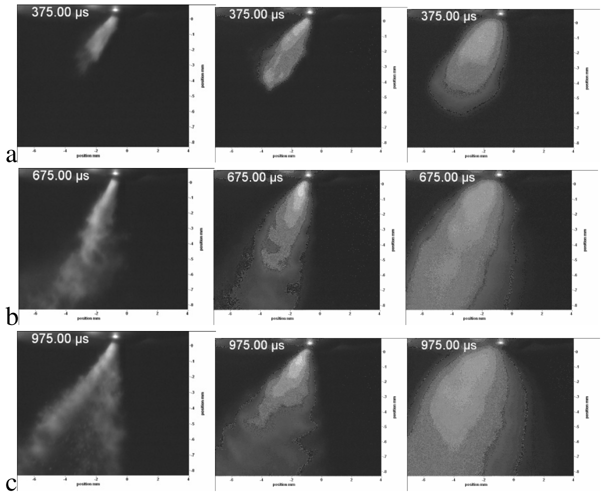


95°C 125°C

Figure 7: Shadowgraph images of swirl injector gasoline spray propagation (t_{ASOI} = 600µs(a), 1000µs(b), 1400µs(c), 1800µs(d))

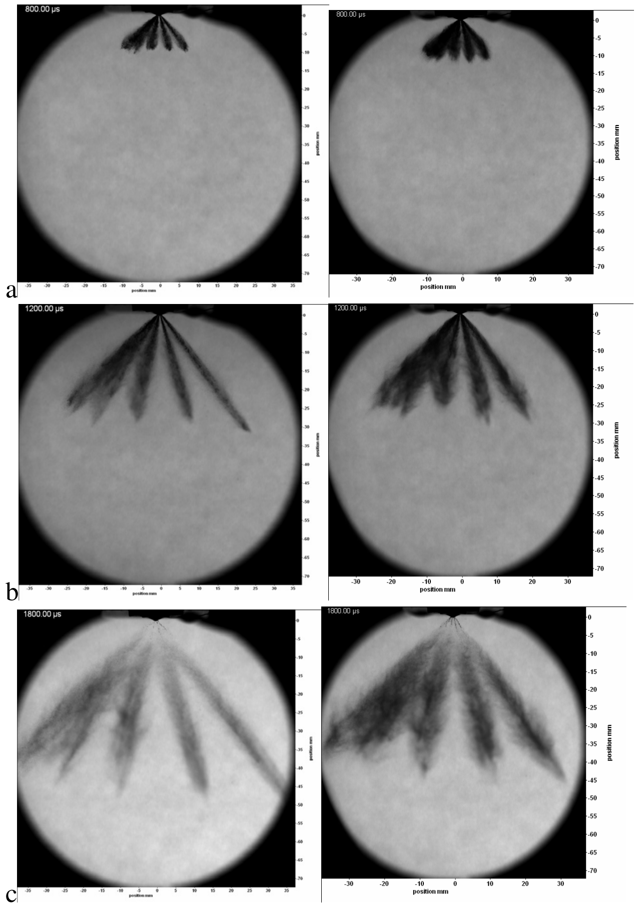
With increasing fuel temperatures, the spray structure changes. At 65°C fuel temperature (figure 6) droplets starts to expand into the initial hollow cone spray and a full cone spray is shaped. Changing fluid temperatures are accompanied by changing physical properties of fluids. Atomization is basically dependent on viscosity, density and surface tension, that are decreasing with increasing temperature. This lead to an improved atomization with smaller droplets and changes in spray structure. [5]

At higher temperatures (Figure 7) the spray looses its conical form at all and collapses. This change of spray structure is caused by evaporation of initially sub-cooled fuel components in the injector caused by the sudden decrease of pressure. This mechanism is called flash-boiling.



25°C 65°C 95°C

Figure 8: Impinging light images of the swirl injector tip and discharging fuel for different temperatures (t_{ASOI} = 375µs,(a), 675µs(b), 975µs(c))



25°C 65°C

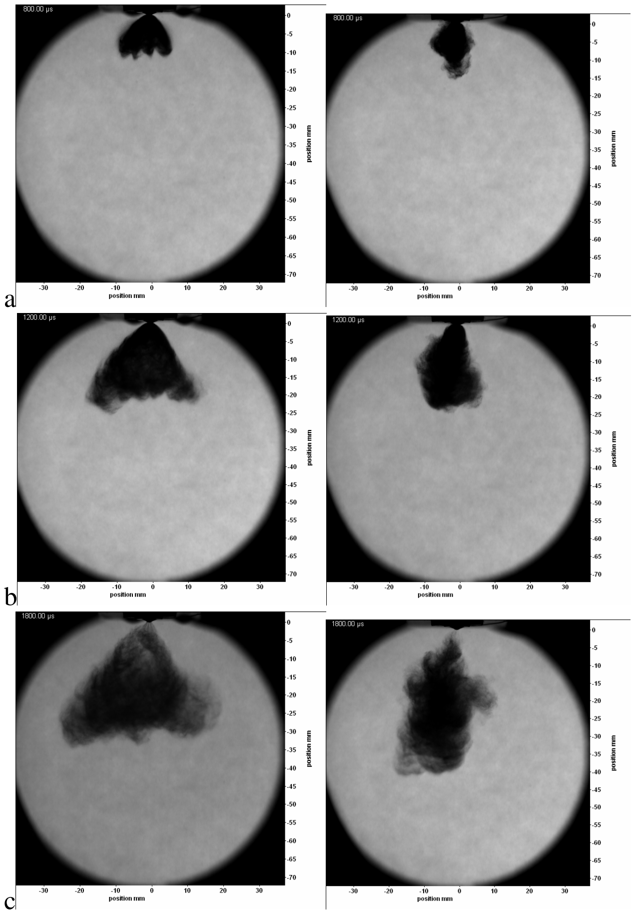
Figure 9: Shadowgraph images of multi hole injector gasoline spray propagation (t_{ASOI} = 800µs(a), 1200µs(b), 1600µs(c))

In [6], this flashing evaporation of the fluid in fuel injectors is described. Depending on the pressure ratio of injection pressure and back pressure, different spray shapes occur. The spray form, that is observed at images of Figure 7, belongs to the *spray shape of second regime* as described in [6]. This regime is characterised by large initial spray cone angles at injector orifice, that is caused by a external expansion of the two-phase flow. This large cone angles can be seen especially at Figure 8 at images for fuel temperature of 95°C.

Temperature influences the atomization of pre-spray, as well. At low temperature conditions the pre-spray consists of few, fast droplets with relatively large diameters. When temperature is raised, pre-spray changes to an optically dense spray of smaller particles.

The time from start of injection until first outflow of fuel out of the injector orifice is decreasing with increasing temperatures. This might be caused by changed fluid properties and by changed properties of electromechanical injector system, as well.

The spray propagation of the multiple orifice injector is displayed in Figures 9 and 10. The 84° gap between two of the orifices (see Figure 3) is placed on the right-hand side. The jet of the injector fore side cover the jets of the rear side, so, not all ten jets are being seen.



95°C 125°C

Figure 10: Shadowgraph images of multi hole injector gasoline spray propagation (t_{ASOI} = 800µs(a), 1200µs(b), 1600µs(c))

With increasing temperatures the spray cone angle of jets seems to widen. Droplets expand into the former gaps between the jets. Until gasoline temperatures of 85°C the single jets are clearly distinguishable. At higher temperatures the multiple jet structure blurs to a cone like shape (see Figure 10 for gasoline temperature of 95°C). Another effect of raised fuel temperature is the decrease of radial penetration. The spray contracts and the width the spray front is reduced.

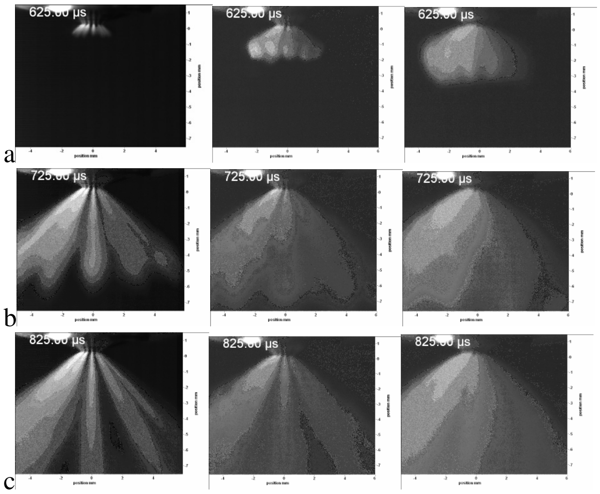


Figure 11: Impinging light images of the swirl injector tip and discharging fuel for different temperatures (t_{ASOI} = 625µs,(a), 725µs(b), 825µs(c))

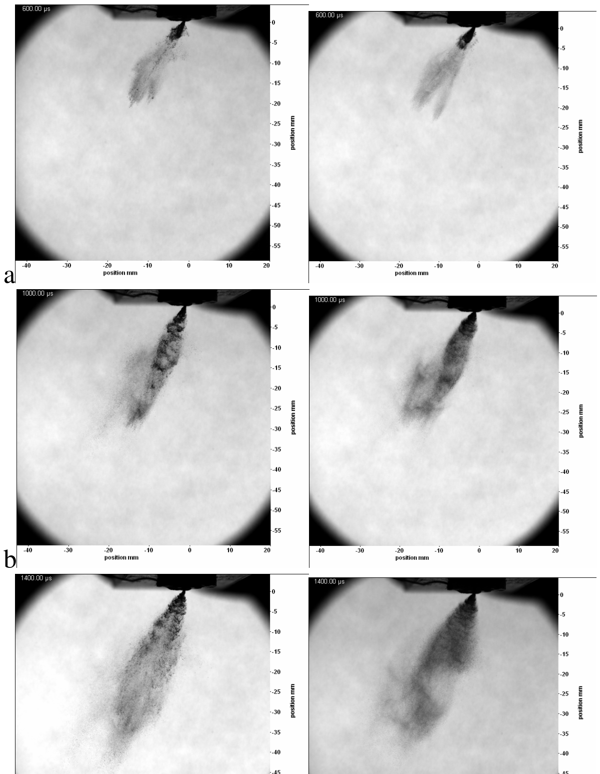


Figure 12: Shadowgraph images of swirl injector n-hexane spray propagation (t_{ASOI} = 600µs(a), 800µs(b), 1000µs(c))

Figure 11 shows the spray at close-up range of the injector tip. The time difference between start of injection and first outflow of fluid is reducing with increasing temperature at this injector, too. While for 25°C fuel temperature at t_{ASOI} = 625µs the fluid just starts to flow out of the orifices the spray already covered a distance of 2mm for 65°C and 3mm for 95°C,. Right after leaving the injector the spray starts to expand caused by flash boiling at higher temperatures (Figure 10, temperatures of 95°C).

By further increase of fluid temperature the spray collapses to an vortex cloud (Figure 10, temperature of 125°C). Spray shape is heavily contracted.

Figures 12 and 13 show the influence of fluid temperature of a n-hexane spray atomized by the swirl injector. At 25°C fluid temperature spray behaviour is quite similar to gasoline spray (Figure 6). By raising the temperature slightly under boiling temperature (68°C at 0.1MPa = back pressure), the spray still remains to its conical shape. Spray appearance seems more dense and less as hollow cone (see figure 12 65°C). At fluid temperature of 75°C flash boiling occurs. Initial cone angle at injector orifice is strongly increased and the conical spray shape is lost. The spray is contracted, and spray width of main spray front is decreased.

When atomizing n-octane by the swirl injector, same dependence on temperature can be observed. As long as fluid temperature is below boiling temperature the spray maintains conical shape, but when boiling point is passed flash boiling is initiated (see Figure 13).

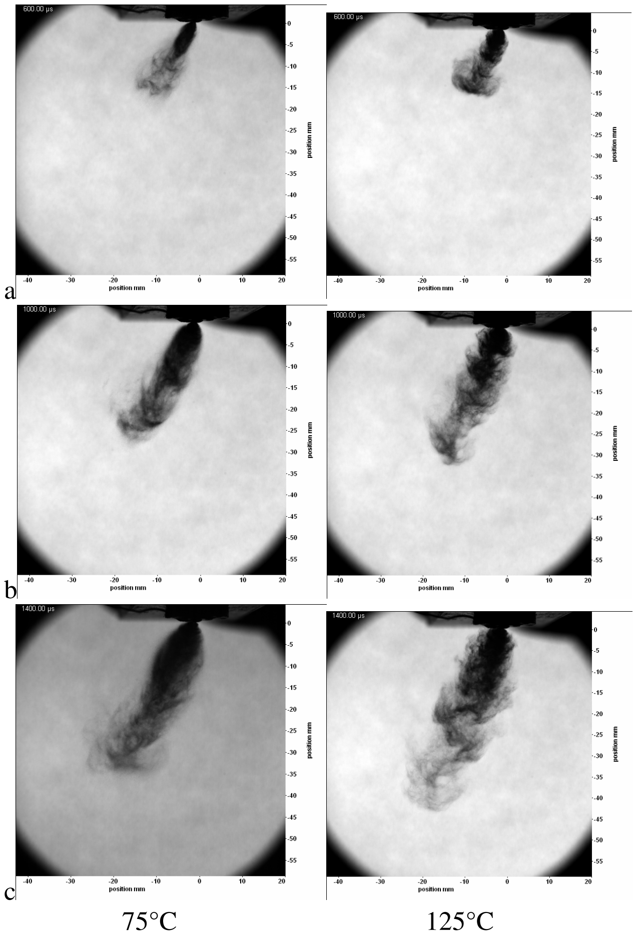


Figure 13: Shadowgraph images of swirl injector n-hexane spray propagation (t_{ASOI} = 600µs(a), 800µs(b), 1000µs(c))

At a higher degree of superheating, the atomization of n-hexane gets a disruptive character without defined spray structure (see Figure 13 for temperature of 125°C)

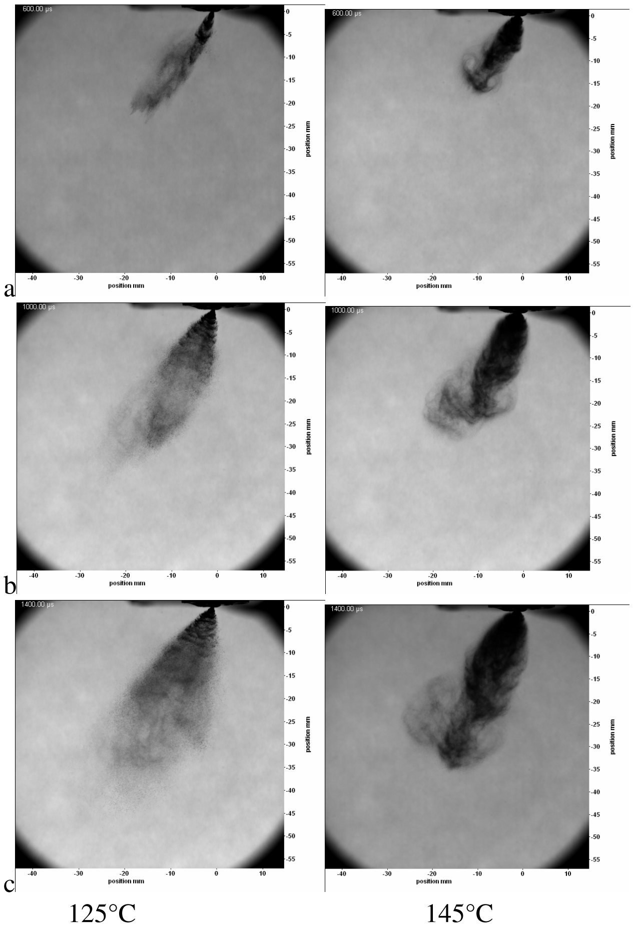


Figure 14: Shadowgraph images of swirl injector n-octane spray propagation (t_{ASOI} = 600µs(a), 800µs(b), 1000µs(c))

PDA-results

In Figures 15 and 16 mean diameters D10 and Sauter mean diameter D32 in dependence of time are shown for gasoline spray of swirl injector at various fuel temperatures. The results are calculated as average values over all measurement positions for every time intervals of Δt=0.2ms.

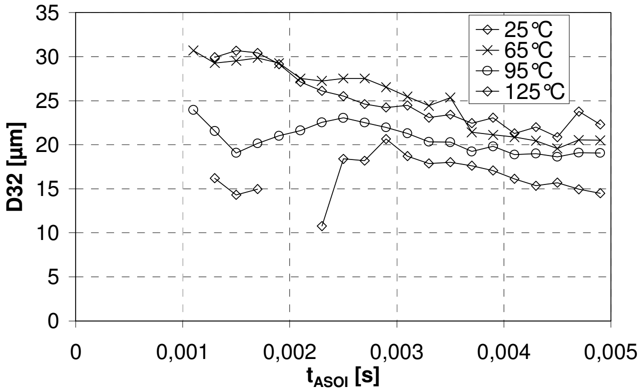


Figure 15: Time resolved Sauter mean diameter D32 for swirl injector spray at various gasoline temperature, z=40mm, p_{inj}=9MPa

With increasing fuel temperatures, a reduction in droplet size is observable. After appearance of flash boiling, there is a pronounced decrease of diameter, that is continued with further temperature increase. This reduction of diameters is also being found for droplets of pre-spray.

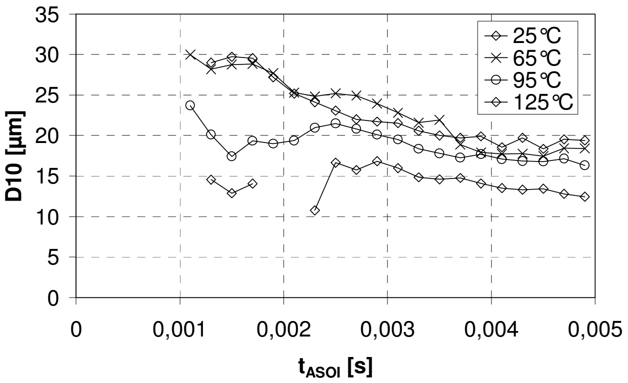


Figure 16: Time resolved mean diameter D10 for swirl injector spray at various gasoline temperature, z=40mm, p_{inj}=9MPa

Figures 17 and 18 show the diameter reduction for n-hexane. Here, a remarkable reduction of diameter is observable not until higher degrees of superheating.

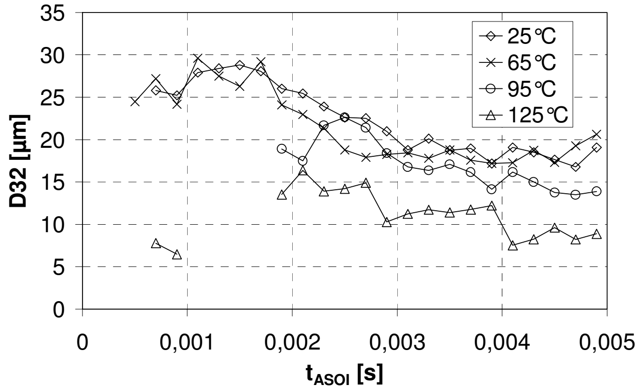


Figure 17: Time resolved Sauter mean diameter D32 for swirl injector spray at various n-hexane temperature, z=20mm, p_{inj}=9MPa

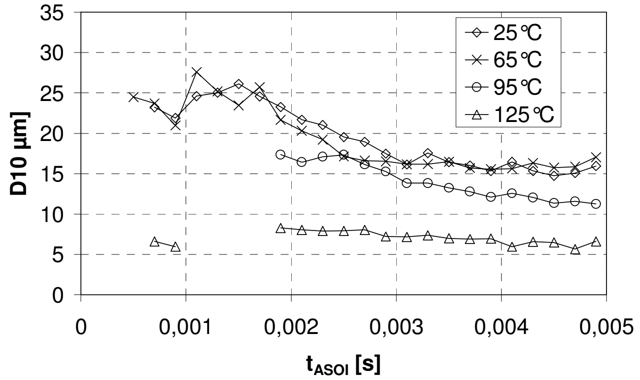


Figure 18: Time resolved mean diameter D10 for swirl injector spray at various n-hexane temperature, z=20mm, p_{inj}=9MPa

At Figure 19 D10 and D32 for the multiple orifice injector spray in dependence of the fluid temperature are being seen. These results are average values over hole measurement time of 5ms at a single measurement position in one of the spray jets of the multiple orifice injector. Considerable decrease of

D32 is followed from increasing fuel temperatures contrary to decrease of D10. Higher temperatures seem result in a more homogeneous spray of smaller droplets at this measurement point. Contrariwise, because of the temperature induced change of spray structure, the examined measurement point is moved into the border area of the spray. Spray at position of spark plug is influenced in the same way, so ignition behaviour might be changed. For assured conclusions, further measurements are necessary.

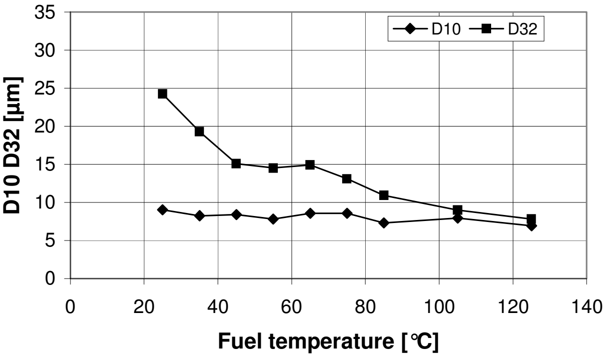


Figure 19: Mean diameter D10 and D32 for multiple orifice injector spray at various gasoline temperatures in a measurement position, z=21mm, p_{inj}=9MPa

CONCLUSIONS

Fuel atomization and spray propagation is strongly dependent on fuel temperature. This dependency is experimentally investigated with high speed visualisation and PDA measurements.

For swirl injector the increase of fuel temperature leads to decreasing droplet diameters and changing spray structure. Changes in spray form are observable by increasing spray cone angles at injector tip and radial penetration of droplets into the initial hollow cone spray. Further increase of fuel temperature above boiling temperature of fuel respectively fuel components leads to collapse of spray structure because of flash boiling.

Spray characteristics of a multiple orifice injector are also influenced by fuel temperature. Increasing fluid temperatures lead to radial expansion of jets and increased cone angles near injector orifices. The initial multiple jet spray structure is totally lost at higher fuel temperatures. Especially overall radial penetration is reduced.

Time between start of injection and start of fluid outflow out of injector orifice is dependent on temperature. Increasing temperatures lead to smaller time difference between triggering injection and outflow.

NOMENCLATURE

D10	Mean diameter	m
D32	Sauter mean diameter	m
p_{inj}	fuel pressure	Pa
t_{ASOI}	Time after start of injection	s

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