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Measurement of a Direct Gasoline-Water-Emulsion-Injection

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Abstract
The investigation focus for combustion engines is on reduction of emissions as well as fuel consumption. By introducing the gasoline direct injection combined with downsizing the efficiency and the fuel consumption of gasoline engines has been optimized. An additional potential to the previous solutions provides the water injection. The article include the results of the fundamental research of water injection for combustion engines, it shows the influence of the amount of water in a water-gasoline-emulsion on the spray in a high pressure injection chamber. Therefor the spray of a gasoline direct injection injector is visualized by a high speed camera using the shadowgraph technique.

Keywords
Direct Injection System, Gasoline-Water-Emulsion, Spray Measurement, Spray angle and Penetration

Introduction - The water injection
Water injection was introduced very early in the development of combustion engines, especially for aircrafts and race cars. However it could not make its way to large-scale serial applications. In the first place the water-injection benefits from its high evaporation enthalpy. It can be used for the reduction of the intake air temperature to increase the engine power, to increase the efficiency and reduce the emissions.

Mode of action and influence on combustion

Water has a six times higher evaporation enthalpy and a doubled higher heat capacity as gasoline. Both leads to a temperature reduction. On the one hand, based on the evaporation, the temperature level before the actual combustion is lower and on the other hand, the evaporated water acts like an inert gas to lower the combustion temperature by increasing the global heat capacity. Therefore full load enrichment is no longer needed. The effects of water injection on the combustion are shown in Figure [1].

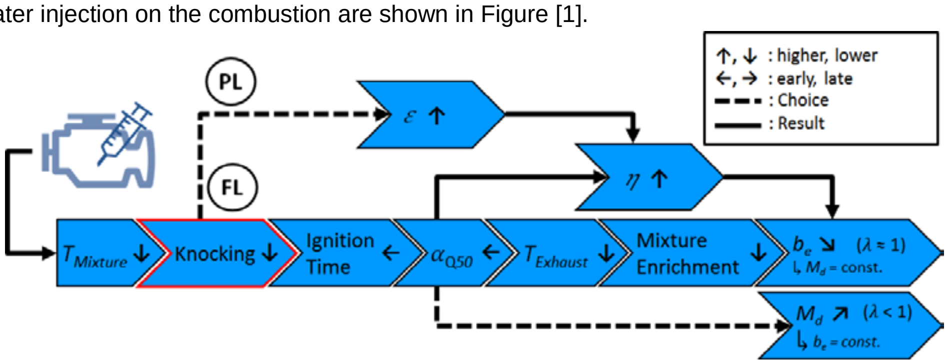

Figure 1. Influence of water injection on combustion

Durst [1] compared the various systems in his publication. He investigated in an intake water injection system, a mixture injection system and a water direct injection system. Each system was able to increase the proportion of water up to 50 % without any kind of spark failure or cycle fluctuations [1]. Additional, all investigated methods reduce fuel consumption, emissions (particle, HC, CO) and lead to an optimized mass fraction burned 50 %. At full load with 40 % of water it was possible to reduce the gas mixture temperature by 40 K. Also the point of mass fraction burned 50 % was relocated around 6 ° crank angle towards the ignition TDC (top dead center). The biggest advantage of water injection for efficiency and emissions (particle, HC, CO) could be seen in high RPM and high load. Except the NO_X emissions, which increase in conditions of high RPM and high load. At their maximum they reach a 4 times higher level with water injection [1]. The reason is the higher level of oxygen compared to full load operation point with fuel enrichment. The higher level of oxygen is promoting NO_X formation reactions. However the 3-Way-Catalytic converter works best with lambda = 1, so the NO_X emissions can be converted.

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Methods of water injection

There are different ways to add water to the combustion process. Figure 2 shows four different methods. The systems differ in costs, in the application effort and in the influence on the combustion.

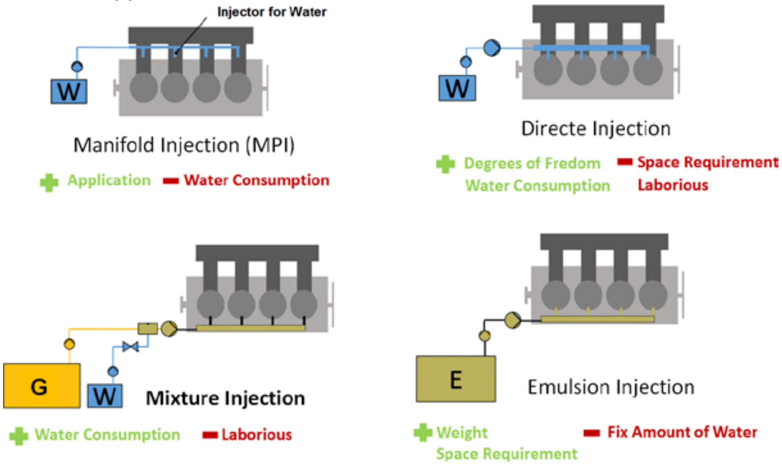

Figure 2. Methods of water injection

Airbox Injection

The manifold injection is characterized by the injection of water with one main injector or cylinder selective injectors in the intake system after the intercooler. The main advantage is the easy continuous injection of water, without synchronization to the crank angle [1].

Manifold Injection

The water injection takes place near to the intake valve. It is individual for every cylinder and needs to be synchronized to the crank angle. The advantage is a higher amount of water which enters the cylinder liquidly. But it is still more water necessary to have the same effects as the direct injection

Mixture and Emulsion Injection

The fuel need to be mixed before injected into the cylinder. Gasoline and water can be mixed by three different systems. First is a mixture injection, without producing a real emulsion. This could be done by using the high pressure pump (HDP5) [3] [4]. Therefor it is mandatory to bring both fluids together in front of the pump. Second way is the creation of a macro emulsion with an onboard system with/without using surfactant. The emulsion is created shortly before injection and isn't stored. Disadvantages of the system are the delay on the water injection, because of the production and flow time and the high amount of energy to create the emulsion [5]. Third option to add water to the combustion is to fuel the car with a micro emulsion. The micro water gasoline emulsion is thermodynamic stable, nano-disperse, temperature invariant, non-corrosive and can be store unlimited [2]. Two disadvantages are the fix amount of water in the emulsion and the complex micro emulsion production [6].

Separate Water injection

The water is injected by a separate independent high pressure injector. This system offers most flexibility for the injection timing and for the amount of water, but the system is very complex [1].

On Injector Mixture Injection

For this kind of water injection a special injector is necessary where water and gasoline are mixed direct in the injector and injected together through one nozzle. Some research was done for stationary Diesel engines [7] [8]. A disadvantage is the need for a separate high pressure water system.

Scientific Basis

An emulsion is a drop shaped distribution of at least two not mixable fluids [9] [10]. To generate an emulsion you need an inner phase (disperse phase) from fine particles and a liquid outer phase which enclose the fine particles of the first liquid [10] [11]. The average droplet diameter is from 100 nanometers to one millimeter. The larger the average droplet diameter the more intensive is the white color of the emulsion. With help of the droplet diameter emulsions are divided in macro- and micro emulsions. Micro emulsions have a smaller droplet diameter, are optical clear and are formed spontaneous. Macro emulsions are always thermodynamic unstable, which leads in a segregation process [11]. It's possible to stabilize the macro emulsion, but it is only possible to extend the time of segregate. Emulsions tend to minimize their surface free energy ΔG, which is the product of interfacial tension γ and the change in size of the interfaces ΔA.

$$\Delta G = \gamma \cdot \Delta A \quad (1)$$

The balance of a stable condition is reached, when the surface free energy equals $\Delta G = 0$ [9]. This can be reached by reducing the interfacial tension γ (adding a surfactant) or by reducing the interfaces ΔA (segregation of the fluids). But due to the fact, the interfacial tension γ couldn't be zero, a macro emulsion can never be stable. Consequently, the smaller the droplets the more unstable the emulsion [9] is without protection.

Instability Phenomena

The stability of an emulsion is defined by the time in which it is useable without the phenomena of segregation [12]. Typical phenomena of segregation are sedimentation, flocculation, Ostwald-Maturation, coalescence and phase inversion. Sedimentation and flocculation are reversible by simply mix the emulsion by shaking or stirring to undo both stability phenomena. Ostwald-Maturation and coalescence are irreversible phenomena which end in the segregation of the emulsion.

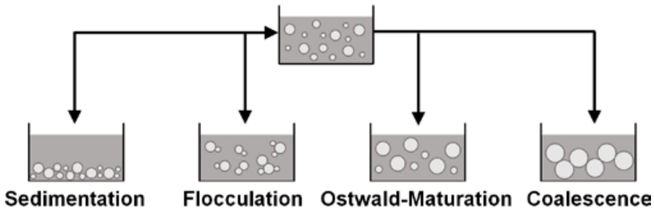

Figure 3. Instability Phenomena

Sedimentation is the subsidence of water caused by the density difference [13]. The kinetic stability of the emulsion can be raised by a smaller droplet diameter. Flocculation is the loose accumulation of droplets, without losing its phase boundary. These process can be reduced by steric, electrostatic or electro steric mechanisms [12]. Ostwald-Maturation describes the irreversible growing of big droplets at the expense of small droplets [13]. Coalescence is the irreversible merge of small droplets to big droplets by reducing the interface and surface energy. The reason for coalescence is the strive for an energy minimum and for a minimal surface volume ratio [10]. Another instability phenomenon is phase inversion, which leads in an inversion from W/O-emulsion to O/W-emulsion or reversed. It can be caused by energy input, temperature changes or changes in the composition of the components [14].

Stabilization of an emulsion

Steric stabilization of an emulsion is meant to add a surfactant with a large space extension. The surfactant gets absorbed on the boundaries of the water drops and prevents the accumulation of further water drops [12]. Stabilization is also termed as kinetic stabilization and is different from thermodynamic stabilization. Macro emulsions are not stable due to the fact of minimization of boundary surfaces and free energy. With a surfactant this process can be slowed down to a level where the emulsion is stable for weeks or even years. This condition is termed as metastable, inert or kinetic stable [16]. All influences that reduce the movement of the droplets increase the stability of the emulsion [15].

Water-Gasoline-Emulsion as passenger car fuel

The fluids water and gasoline are not mixable because of their chemical molecular structure. But it is possible to create a metastable macro emulsion with surfactant and emulsifying apparatus. The product is a water-oil-emulsion. The use of a surfactant causes the investigation of emissions produced by the combustion of the surfactant. Experiments with a test engine using water proportions from 0 to 50 % show that most benefits are reached with a water proportion of 40 – 50 %. Even with 50% proportion of water the cycle variations are very low [1]. It is not known if a homogenous emulsion is necessary for a good combustion. Experiments by Durst [1] and Böhm [3] show that it is sufficient to mix water and gasoline in front of the high pressure pump [3]. But it is not known what kind of mixture is produced by this system of Durst [1] and Böhm [3]. Literature research indicates that the use of emulsified fuel with surfactant cause additional emissions after the combustion. Faced with a large number of different surfactants it is difficult to conclude a general statement, but it could be assumed that it is appropriate to use surfactants with elements which are already part of the fuel mixture like carbon, hydrogen, oxygen and nitrogen. All surfactant containing phosphorus and sulphur should not been used. Most of the surfactants are long chain molecules with a slow and incomplete combustion which results in particle emissions. This fact was proven in studies on a diesel-water-emulsion [4].

Measuring System and Optical Evaluation

Test Bench and Parameter

The performed studies are aimed to homogenous turbo charged gasoline engines with direct injection often used in small and mid-range cars. The injection well as the chamber pressure, the chamber temperature and the injection time are based on that conditions.

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State of the art for injection pressure of modern passenger gasoline direct injection engines is 200 bar. Next generations aim is 350 bar. In low load operation points the injection pressure drops to 80 bar. For measurement 50, 125 and 200 bar was defined. These measurement points should give a general statement for the influence of the injection pressure.

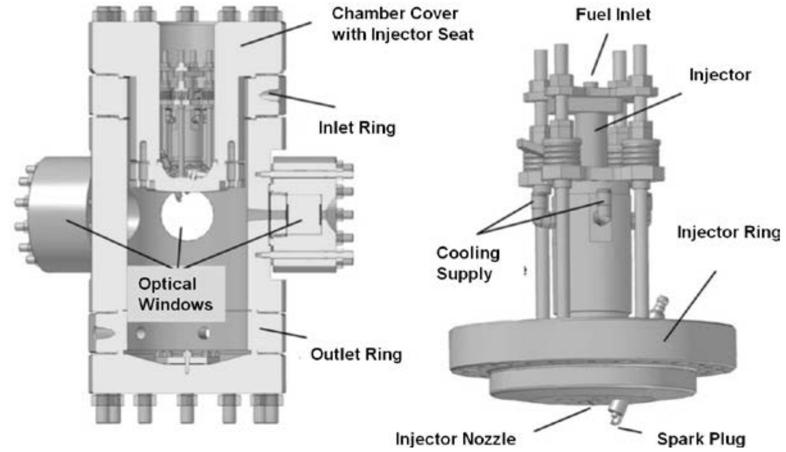

Figure 4. The Pressure Chamber for Injection Tests [17]

The injection time for homogeneous direct injection gasoline engines is during the induction stroke. For turbo charged SI-engines the cylinder pressure during the induction stroke is nearly the boost pressure. The chamber pressure is defined to 1 and 2 bar, for two engine load scenarios.

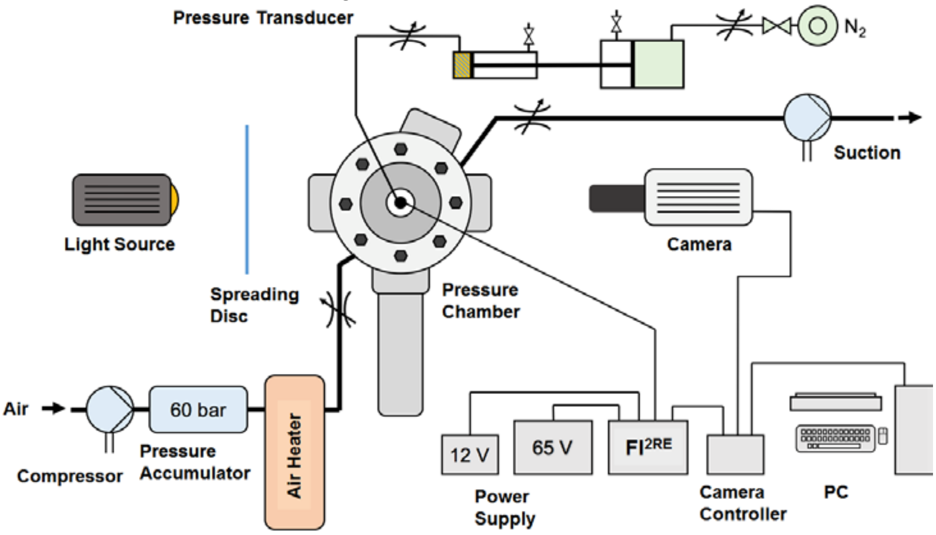

Figure 5. Schematic Test Bench Structure

The pressure chamber is for the optical measurements and investigation of the injector spray. The pressure of the chamber can be set from p_{dk} = 1 to 60 bar and the temperature can be adjusted from 20 °C up to 200 °C. The volume of the chamber is 13 liters and the shape is cylindrical with four 80 mm windows.

The temperature of the fresh air in the cylinder depends on the boost air temperature and the amount of thermal energy transferred from the cylinder head, cylinder wall, residual gas and piston surface. Following the temperatures of a modern turbo charged engine with 65 kW per liter as an example the boost air temperature at 21 °C atmosphere temperature rises from 18 to 52 °C. The engine temperature in running condition is between 83 °C and 93 °C. The surface temperature of the piston is around 300 °C, depending on the engine load [26]. Based on this the temperature for the pressure chamber was set to t_{dk} = 100 °C.

The used injector [HDEV 5) is a six-hole solenoid direct injection injector with central installation position and a maximal injection pressure of 200 bar. For the control of the injector a FI^{2ER} control unit of IAV Ltd. was used.

The used measurement is shadowgraph techniques. The injected spray is illuminated with an intense light source and recorded with a high speed camera. The data from the measurements were analysed by the software DaVis 7.2 from LaVision. The algorithm is automatically detecting the spray boundaries, the penetration and the spray angle [15].For every injection 100 pictures (Frames) with a frequency of 10 kHz was taken.

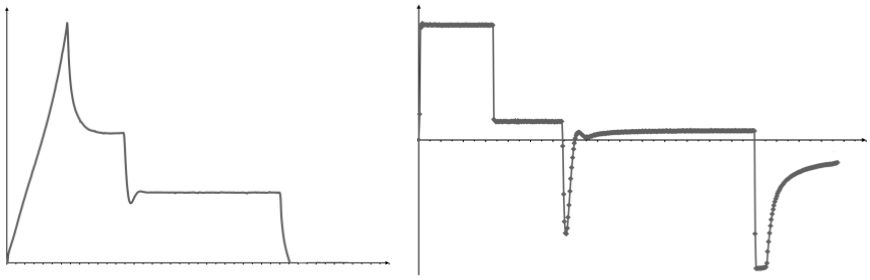

Figure 6. Control Parameters for the Injector (left power, right voltage) [18]

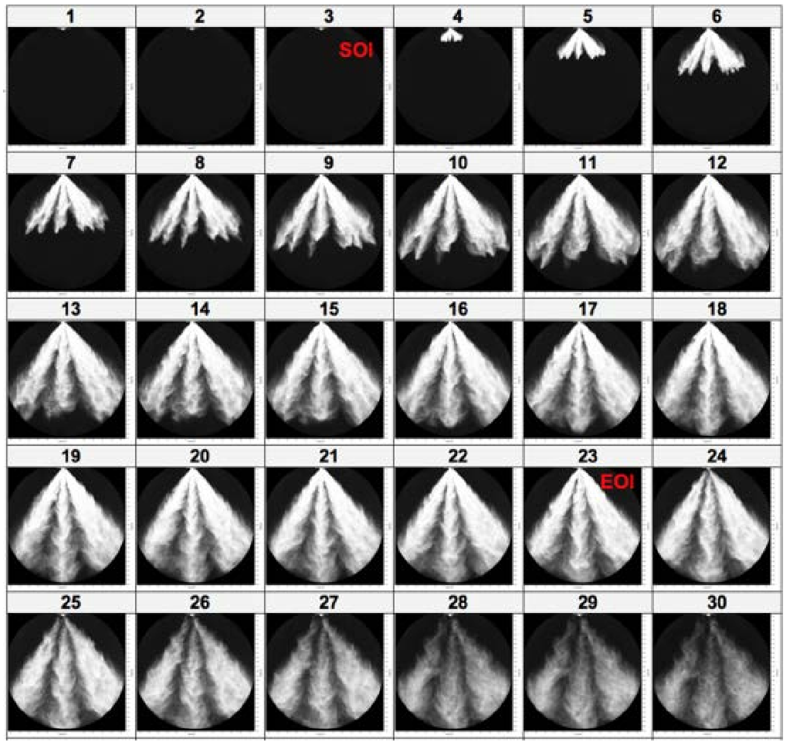

Figure 7. Spray evolution over injection time (water proportion Δw = 0%, p_{dk} = 2 bar, p_{inj} = 200 bar)

The measurements were taken as shown in table 1. The injection duration is 2 ms. Both, the activation of the injection and of the camera are trigger by the controller for an accurate timing. Every measurement was repeated twenty times.

Table 1. Measurement Plan

Chamber Temperature	Chamber Pressure	Injection Pressure	Amount of Water				
			0 %	25 %	50 %	75 %	100 %
100°C	2 bar	50 bar	20 x	20 x	20 x	20 x	20 x
		125 bar	20 x	20 x	20 x	20 x	20 x
		200 bar	20 x	20 x	20 x	20 x	20 x
	1 bar	50 bar	20 x	20 x	20 x	20 x	20 x
		125 bar	20 x	20 x	20 x	20 x	20 x
		200 bar	20 x	20 x	20 x	20 x	20 x

The Spray Records

Figure 7 shows the chronology of an injection with pure gasoline fuel at 2 bar chamber and 200 bar injection pressure. It is obvious that the start of injection (SOI) is in frame 3 and ends (EOI) is in frame 23 due to 2 ms injection time. The penetration length of the spray exceeds the windows of the chamber at frame 12, which means it only can be analyzed up to 0.9 ms after SOI. The control power for the injector indicates that it is opening up to frame 10. Consequently most of the analyzed measurements are during the opening phase of the nozzle, which has to be considered because of cavitation effects in the needle seat.

Influence of the Proportion of Water

Penetration

The spray measurements in Figure 8 show that with an increasing amount of water the penetration is decreasing, this becomes obvious especially for p_{inj} = 125 bar and p_{inj} = 200 bar. With p_{inj} = 50 bar the penetration remains nearly constant, but nevertheless the peripheral spray cones have a slightly lower penetration.

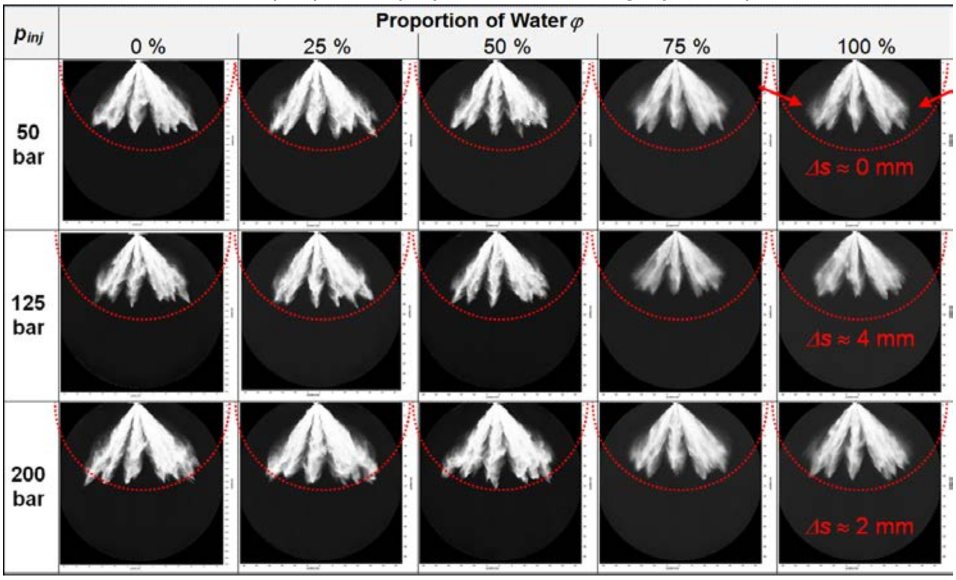

Figure 8. Spray images at 2 bar Chamber Pressure from 0 to 100 % water

The properties of water and gasoline are shown in table 2. The values show that water has a 30 % higher density and a magnificent higher viscosity. The consequence of equation 2 is that the outlet velocity v_{out} and subsequently the penetration length (s) are smaller with a higher density, subsequently with a higher amount of water.

$$s(t) \sim \sqrt[2]{v_{out}} \sim \frac{1}{\sqrt[2]{\rho_f}} \qquad (2)$$

Quality of atomization

Figure 8 shows that the spray cones gets wider with less proportion of water. This is an indication for a better atomization. The quality of atomization is higher with an increased Reynolds- and Ohnesorge-umber. Both parameters are influenced by the fluid density ρ_f, the outlet velocity v_{out}, droplet size d_{Tr}, the dynamic fluid viscosity η_f and the surface tension σ_f. As you can see in Table 2 water have a 33 % higher density, a 67 % higher dynamic viscosity and a 222 % higher surface tension than gasoline. Also the outlet velocity is decreasing with higher amount of water. The equation for the Re- and Oh- number shows clearly that the influence parameters on the quality of atomization are opposed. In conclusion from the equations and spray measurements it can be said that the quality of atomization is higher with a lower proportion of water in the emulsion. Furthermore in table 2 the Re-, the We- and the Oh – number are calculated assuming that the outlet velocity and the droplet size are equal. Both assumptions don't fit the reality so the effects would be higher because of lower Re-, We- and Oh- numbers. Another influence on the quality of atomization is the boiling temperature of water (100 °C) and the boiling range of gasoline 95 E5(25 – 215 °C) [18].

Table 2. Comparison of Properties of Gasoline 95 Octane and Water [18]

	ρ_f (at 15 °C)	η_f (at 20 °C)	σ_f (at 20 °C)	*Re**	*We**	*Oh**
Gasoline 95 Octane E5	100 % (750 kg/m³)	100 % (0,6 × 10⁻³ Pa s)	100 % (22,6 × 10⁻³ N/m)	100 %	100 %	100 %
Water	133 % (1000 kg/m³)	167 % (1 × 10⁻³ Pa s)	322 % (72,75 × 10⁻³ N/m)	80 %	41%	80 %

Volume of Injection

The spray picture of Figure 8 shows that a spray of pure gasoline has a higher grey level dynamic as a spray of pure water. This indicates that the gasoline spray has a higher density. In conclusion the volume of injection is higher with less amount of water in the emulsion. This fact can be confirmed with the equation of outflow volume.

$$\dot{V}_K = \mu \cdot A_{noz} \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho_K}} = \mu \cdot A_{noz} \cdot v_{out} \tag{3}$$

A higher proportion of water within the emulsion leads to a higher density of the fluid injected. This results in a lower flow speed inside the nozzle and therefore to a reduced penetration.

Spray Angle

The pictures of the injection in Figure 8 also show that the spray angle is increased with higher amount of water. The spray gets wider and the tip of the spray is thinning out.

Influence of the Injection Pressure

In Figure 9 the chronological sequences of injection with Δw = 50% proportion of water, a chamber pressure of p_{dk} = 2 bar and injection pressures from p_{inj} = 50 to 200 bar are shown.

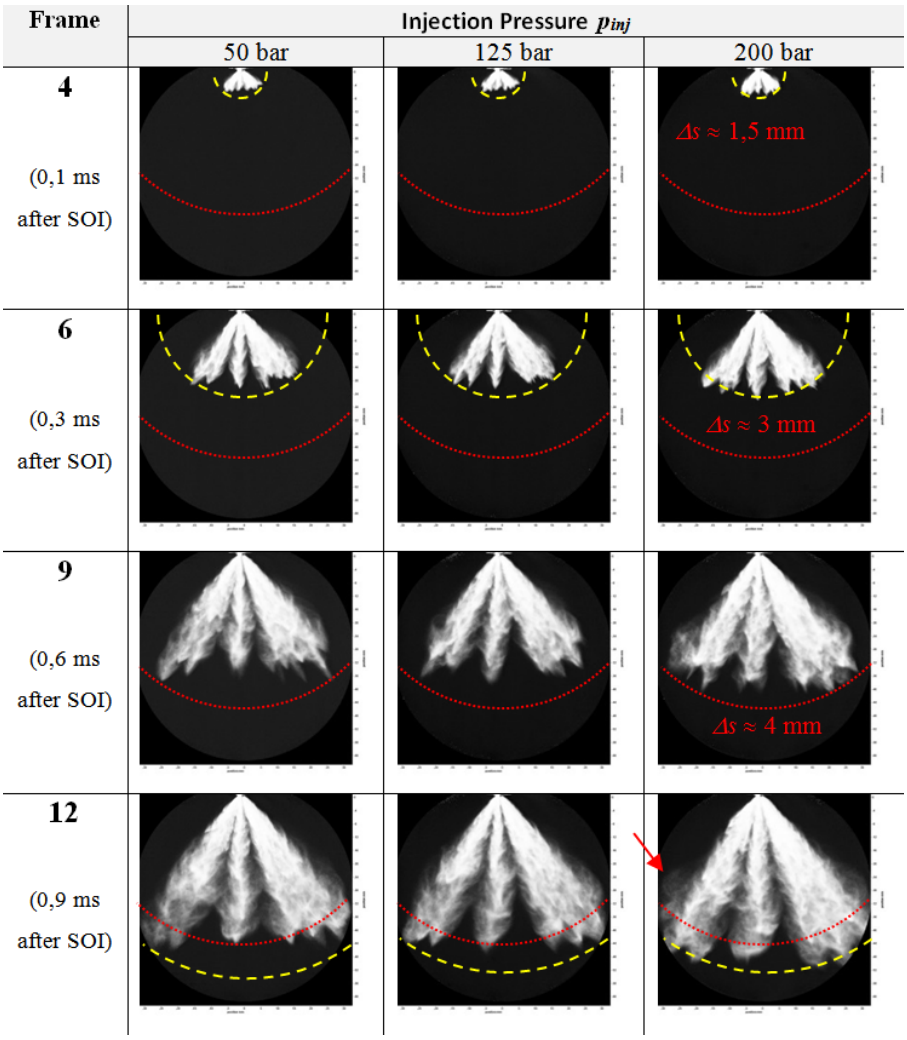

Figure 9. Chronological sequences of injection (proportion of water Δw = 50%, p_{dk} = 2 bar)

Penetration

The measurements show that the spray penetration is higher with rising injection pressure. That is the result of a higher nozzle velocity caused by the higher injection pressure. It is valid that the injection outlet speed and the spray penetration length are proportional to the square root of the injection pressure which theory is consistent with all empiric models in the literature [18][19][20].

Quality of atomization

It is striking that the sides of the spray are wider with higher injection pressure. That is an indication for a better quality of atomization. It is valid, that the atomization gets better with increased Reynolds- and Ohnesorge-number. The Reynolds-number becomes higher if the outlet velocity is rising and the outlet velocity is higher with a high injection pressure. In conclusion the quality of atomization gets better if the injection pressure-level is higher.

Spray Angle

As you can see in Figure 9 the injection pressure has no significant influence on the spray angle near the nozzle. But in a higher distance to the nozzle the spray interacts with the gas in the chamber and gets thinner/lighter. The result of the rising evaporation with higher injection pressure is a smaller spray angle in distance to the nozzle.

Influence of the chamber pressure

Penetration

The comparison between 1 and 2 bar chamber pressure in Figure 10 shows the influence on the length of penetration. The higher the chamber pressure the less the penetration length. It takes 0.4 ms after SOI before the effect is visible.

Quality of Atomization

The boundary areas of the spray are wider with 1 bar chamber pressure compared to 2 bar. The logical conclusion is that the quality of atomization is higher with higher pressure, because of the higher gas density in the chamber. It is also visible that the spray is less dense with higher chamber pressure which is an indication for a better evaporation.

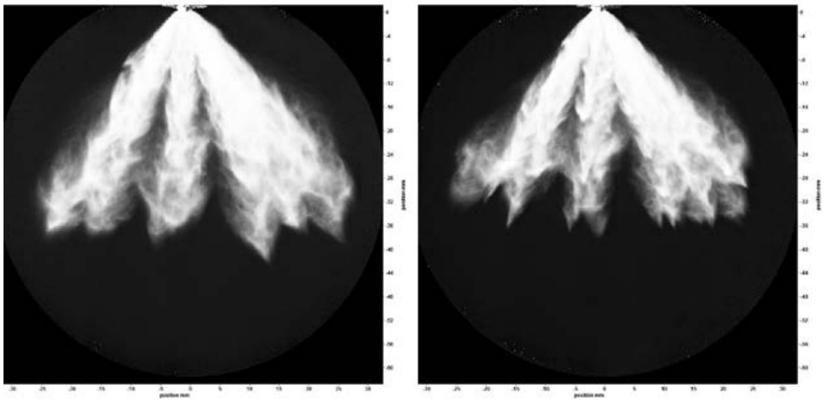

Figure 10. Picture of the Spray at 1 (left) and 2 bar (right) chamber pressure (proportion of water Δw = 50%, Injection Pressure p_{inj}= 200 bar)

Spray Angle

The influence of the chamber pressure on the spray angle is insignificant small which is visible in Figure 10. With 1 bar chamber pressure the spray angle is slightly wider then with 2 bar chamber pressure.

Conclusions

It is not possible to create a kinetic stable water-gasoline-emulsion without using a surfactant. With the use of the two surfactants it was possible to create a kinetic stable macro emulsion with various proportions of water. Studies have shown that the current penetration length is less with rising proportion of water. The reason is the lower outlet velocity of the spray with higher proportion of water, because of the higher density. As a reaction the spray evade to the sides, which makes the spray angle bigger and the spray looks wider. It was shown with fluid mechanical equations that the high surface tension and the high viscosity of water reduce the quality of atomization for water-gasoline-emulsions with rising proportion of water.

Acknowledgements

It has to be clarified if a real emulsion is necessary for a combustion with low cyclic variations, with low emissions and a good efficiency. It must be investigated how the injection volume behave with rising proportion of water to ensure a constant engine power. From the authors point of view it will make sense to do more optical investigations with different measuring methods to validate the result of this study. Furthermore the injector has to be observed and analyzed for damages caused by the -emulsion injected.

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