

Stratified Cold Start Sprays of Gasoline-Ethanol Blends

Stina Hemdal, Ingemar Denbratt and Petter Dahlander

Chalmers University of Technology, Sweden

Jonas Wärnberg

General Motors Powertrain, Sweden

Copyright © 2009 SAE International

ABSTRACT

Gasoline and gasoline-ethanol sprays from an outward-opening piezo-injector were studied in a constant volume/pressure chamber using high-speed imaging and phase doppler anemometry (PDA) under stratified cold start conditions corresponding to a vehicle ambient temperature of 243 K (-30°C/-22°F); in-cylinder air pressure of 5 bar, air temperature of 350 K (-30°C/-22°F) and fuel temperature of 243 K. The effects of varying in-cylinder pressure and temperature, fuel injection pressure and fuel temperature on the formation of gasoline, E75 and pure ethanol sprays were investigated. The results indicate that fuel composition affects spray behaviour, but less than expected. Furthermore, varying the temperature of the fuel or the air surrounding the spray also had minor effects. As expected, the fuel injection pressure was found to have the strongest influence on spray formation under stratified conditions.

INTRODUCTION

Strategies for reducing our reliance on crude oil for vehicle propulsion include improving efficiency using charge stratification in conjunction with direct injection by outward-opening piezo-injectors and substitution of gasoline with ethanol. However, various technical issues have to be addressed before these strategies can be optimally applied in practice, one of which is to improve their performance in cold starts. The study presented here examines the effects of injection pressure, fuel

temperature and fuel composition on characteristics of sprays of various gasoline/ethanol blends during cold starts, with temperatures down to 243 K (-30°C/-22°F), mimicked in a constant volume, constant pressure spray chamber with good optical access for phase doppler anemometry and high speed video camera measurements. As well as assessing the effects of these parameters on spray variables, their effects on unburned hydrocarbons and combustion stability are also considered

The direct injection of fuel in spark-ignited, four stroke engines was first employed in passenger vehicles with the introduction of the Mercedes 300 SL in 1954 [1], when the focus was purely on power output. With the exception of the Ford PROCO [2], which never went into series production, there was little subsequent interest in this strategy until the mid-1990s, when the objectives had switched to reducing fuel consumption and harmful exhaust gas emissions, while maintaining or slightly increasing power output [3, 4, 5, 6]. Direct injection technology has also shifted, from wall-guided stratified charge systems (Mitsubishi GDI, [7]), through homogenous charge systems (Opel DiG, [8]) to stratified air/spray-guided combustion systems with piezo-actuated, outward-opening injectors (Mercedes, BMW, Siemens [3, 4, 9]). Stratifying the charge reduces the need for throttling, and hence can reduce pumping losses [10, 11]. Further, piezo-actuated injectors are very fast, which helps to increase injection precision. The precise timing and high spray atomization rates they deliver [12, 13, 10] also enable further advances in

converter heating strategies, reducing the time from start before full converter efficiency is reached [3, 5]. Furthermore, the direct injection of fuel decreases combustion temperatures, thus reducing the susceptibility to knock [1, 7] and improving volumetric efficiency [14] courtesy of the in-cylinder fuel evaporation. However stratification of the combustion tends to increase tail-pipe NO_x emissions because the NO_x conversion efficiency of three-way catalysts is very low under conditions with excess oxygen, and thus the application of so-called NO_x traps [3, 4] is needed to decrease these emissions.

Another notable trend is that flex-fuel vehicles, running on blends of gasoline with up to 85% ethanol (E85) are rapidly gaining popularity in some markets, especially northern Europe and USA, and even neat ethanol (E100) is used in Brazil. This provides one of many possible ways to help reduce our reliance on crude oil and decrease fossil CO₂ emissions [15, 16]. It should be noted that production of ethanol (especially from sugarcane) may have complex socio-economic effects [17, 18], but such considerations are beyond the scope of this paper, which focuses on the tank-to-crank application of ethanol.

Ethanol and gasoline blends with high ethanol contents have many advantageous attributes as vehicle fuels, relative to pure gasoline, notably allowing absolute energy efficiency to be improved by 3-6% [19, 20], or even up to 24% [21], and reducing the need for enrichment during high load operation to protect components. This is because ethanol has a high research octane number, ca. 110 [23], and high specific heat of evaporation [24], which helps to decrease combustion temperatures [19]. The potential scope to increase power in boosted (turbo or supercharged) applications by using blends is especially great [20, 21, 22]. On the other hand, ethanol has a lower heating value than gasoline, so the range of vehicles running on blends will be reduced, unless the volume of their fuel tanks is increased [22].

A further problem associated with current, port-injected vehicles tuned to use blends with high ethanol contents, such as E85, is that either a separate gasoline supply [25] or a block heater [26] is needed to ensure successful cold starts at temperatures lower than 258 K (-15°C/5°F), and even at considerably higher temperatures extreme enrichment [19, 26] is generally needed. This is because only the lighter compounds in the gasoline will evaporate and ignite at low temperatures since ethanol has a higher heat of evaporation and higher boiling temperature than the lightest gasoline fractions. However, a well-designed stratified direct injection system could enable reliable starts even at lower temperatures [21, 27]. Injecting the fuel late during the compression stroke into a high-

temperature, high-pressure environment with a finely dispersed spray, greatly improves atomization [27, 28, 13, 29] and should even allow the vaporization of neat ethanol. This approach places very high demands on charge formation, and thus the choice of injector type, injection strategy and positioning of the injector relative to the spark plug, but fortunately ethanol has a wider ignitability window than gasoline [23]. To assure stratification very high fuel injection pressures are needed. Hence, since the high pressure fuel pump is usually driven by the camshaft, a slightly longer cranking period before starting is required to reach sufficient pressure [30, 28].

In this study spray behaviour is investigated at conditions simulating a start at 243 K ambient temperature, which relates to a start in arctic conditions, the lowest temperature at which a vehicle is expected to start without outside assistance. At cold start the fuel, as well as the walls of the cylinder and the piston, are cold. At stratified conditions the fuel is injected during the compression stroke leading to a high in-cylinder pressure. At an assumed in-cylinder pressure around 5 bar gives an air temperature slightly below 370 K (7°C/-207°F) [27]. As mentioned above, the injection pressure may not yet have reached the design pressure. These conditions are mimicked in a spray chamber and the spray formation is visualized in order to map the influence of pressure, temperature, injection strategies and composition of the fuel.

EXPERIMENTAL

Spray formation was investigated in a constant volume/constant pressure spray chamber that provides a constant air flow of 4000 litres/hour at 5 bars absolute pressure, which helps to ventilate the spray droplets. The air velocity (~0.06 m/s) is significantly lower than the spray velocity (>35 m/s) and thus does not interfere with the spray formation. The chamber has good optical access through two pairs of large, circular windows located on opposite sides to each other (Figure 2). The atmosphere inside the chamber can be pressurized up to 6 bars and heated up to around 350 K (77°C/171°F), but not cooled to below room temperature. A piezo-actuated outward-opening injector with a design pressure of 200 bars was mounted at the top of the chamber in a custom-designed cooling device based on the same principles as an expansion refrigerator (using a cooling medium to draw heat from the injector near the nozzle). The cooling device is capable of lowering the temperature of the injector down to 243 K [12]. The fuel temperature was verified by spraying it, at the injection frequency used in the experiments, onto a fast thermocouple. Both the in-cylinder air temperature and the fuel temperature were constantly monitored by thermocouples during all measurements.

Two types of engine conditions were simulated in the spray chamber: Homogenous Cold Start Conditions, HCSC, (in-cylinder air at atmospheric pressure and room temperature, with the fuel cooled to 243 K) and Stratified Cold Start Conditions, SCSC, (atmosphere in the chamber pressurized to 5 bars and heated to 350 K, with fuel cooled to 243 K). In addition, sprays were examined in two other stratified conditions; one in which both the air and fuel were at room temperature (295 K (22°C/72°F)) and one in which the chamber air was heated (350 K) and the fuel was not cooled (320 K (-47°C/117°F)). All the permutations of test conditions are presented in Table 1. None of the conditions applied in the investigation may be relevant to the operation of real engines, except the SCSC conditions, but they were used to quantify the influence of the altered parameters.

Sprays from both single injections and triple injection sequences, with a total ideal opening duration of 0.4 ms in both cases, were investigated for all cases. For the triple pulses the injections were split into a 0.2 ms main injection, 0.3 ms dwell, 0.15 ms second injection, further 0.2 ms dwell and a post-injection of 0.05 ms, as illustrated in Figure 1. A 200 bar single pulse injection of gasoline at room temperature was experimentally shown to deliver 13 mg of fuel. However, less mass may be delivered by a triple injection with the same total needle opening time as a single injection since the needle does not lift (or close) instantaneously. Further, differences in the densities, viscosities and temperatures of the fuels used in the tests will also affect the delivered mass. To elucidate the effects of varying the fuel pressure on spray parameters experiments were also performed with several fuel injection pressures (FIP).

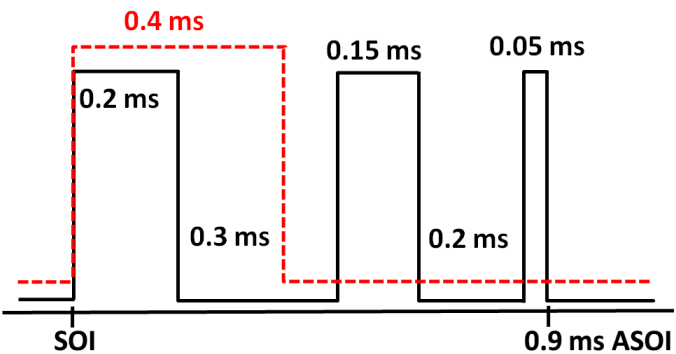


Figure 1. Schematic diagram of the triple and single injection strategies used in the experiments, indicated by the solid and dashed lines, respectively.

Table 1. Summary of experimental matrix

Case:	Chamber air pressure [bar]	Chamber air temperature [K]	Fuel temperature [K]
SCSC	5	350	243
Room temp stratified charge	5	295	295
Heated air stratified charge	5	350	320
HCSC	1.3	295	243
Fuels:	Fuel injection pressure [bar]		
Gasoline	50	125	200
E75	50	125	200
E100	50	125	200

The experimental matrix is summarized in Table 1, and the gasoline and ethanol blends used in the tests, together with selected physical properties, are shown in Table 2. Properties of gasoline and ethanol have been interpolated to estimate values for blends in some studies, but here only empirically determined values are presented.

Table 2. Fuel properties

	Gasoline	E75	E100
Standard (if not indicated otherwise)	CEC legislative fuel /RF-02- 03		Fischer Scientific product-id: E/0650DF/08
Density @ 293 K/1 bar [kg/m ³]	740-755		790
Surface tension @ 293 K/1 bar [N/m ²] [32]	0.0216		0.0228
Viscosity @ 293 K/1 bar [kg/(m*s)] [32]	0.000292		0.00120
Lower heating value [MJ/kg] ref[31]	44		26,9
Heat of evaporization [kJ/kg] ref[31]	350		840
Vapour pressure [kPa] (acc EN 13016-1)	56-60	50.6 [GMPT]	
Ethanol content [vol%]	0	74 [GMPT]	>99.8
Water content [vol%]	0	0.04 [GMPT]	<0.2
Boiling point [K] [@ 1 bar]	24-40% @ 343 K 83-90% @ 423 K		351.5
Refractive index (own research data) [@ 293 K]	1.43	1.37	1.365
Research Octane Number	95		107 [31]

([GMPT] = Results from the GMPT fuel lab at the Trollhättan Technical Development Centre)

The sprays formed under each set of test conditions were visualized using a 12 bit monochrome Vision Research Phantom V 7.1 high speed camera with an AI Nikkor 50 mm f/2.0 lens. The exposure times in each case were 5 μ s. The sprays were illuminated through the side windows of the chamber using two 250 W Dedocool floodlights, providing images of white sprays against a black background. A plate with a square grid was used to set the focus and calibrate the length scale in the images. The acquisition rate was 11000 images per

second, resulting in a time-step of 0.09 ms between frames. For each examined spray sequences of 10 images were captured and for each time step after the start of injection (ASOI) the 10 images were individually processed in MATLAB to acquire data on the sprays' vertical penetration and velocity in the corresponding conditions. In the liquid penetration curves (presented below), in addition to mean values minimum and maximum values are indicated by error-bars.

The sizes and velocities of drops in the sprays were also measured, using a two-dimensional TSI phase doppler anemometry (PDA) system with the 488 and 514 nm light from an argon-ion laser. The off-set angle was set to 65 degrees in order to minimize effects of variations in the refractive index due to temperature gradients in the sprays. The mean diameter (D10) and Sauter mean diameter (SMD or D32) of droplets in the sprays were acquired at selected measuring points using Flowsizer software. Since the PDA measurements were performed on multi-component fuels the refractive indices of the fuels were measured using a small refractometer cell. A schematic image of the experimental set-up for both the spray visualization and PDA measurements is shown in Figure 2 and the PDA coordinate system and measurement positions are shown in Figure 3.

Figure 4 shows the mean particle measurement frequency and time delay until the first particle was observed, as a function of the radial distance from the symmetry axis for single injections of gasoline at 50 bar FIP under SCSC.

The data show that the average particle frequency has a global maximum 16 mm from the axis, and the time until the first particle was detected was minimal at this distance. Thus, measurements acquired for this distance were deemed most appropriate for the presentation and analyses of particle sizes. Similar graphs were produced for each of the measurement cases in order to identify the most appropriate radial positions to present particle size measurements. The particle sizes presented below are calculated from measurements sampled from 0 to 4 ms after the electrical pulse (AEP) that initiated the injections, which started 0.1 ms AEP with an injection frequency of 0.5 Hz.

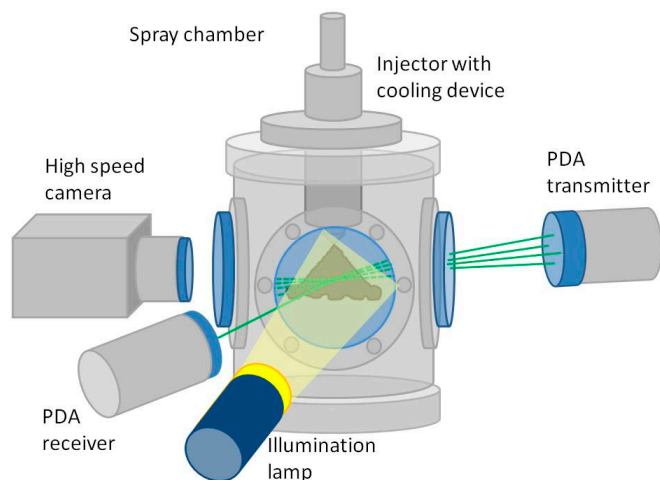


Figure 2. Schematic diagram of the experimental set-up

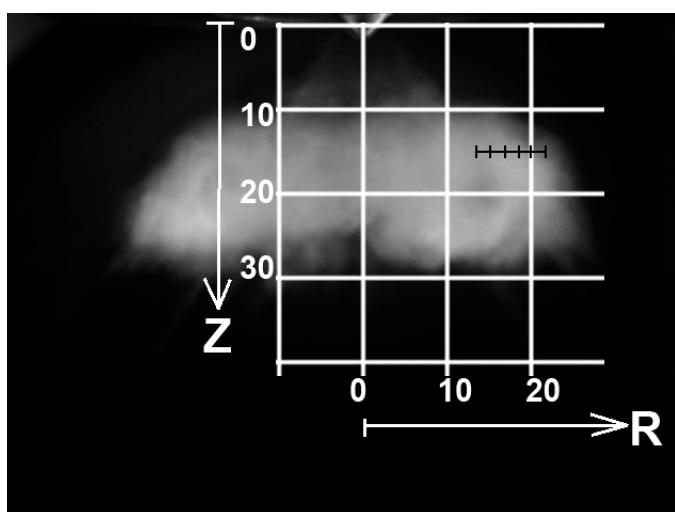


Figure 3. Coordinate system and measurement points used for the PDA measurements (black crosses). Gradations along the scale bar indicate mm.

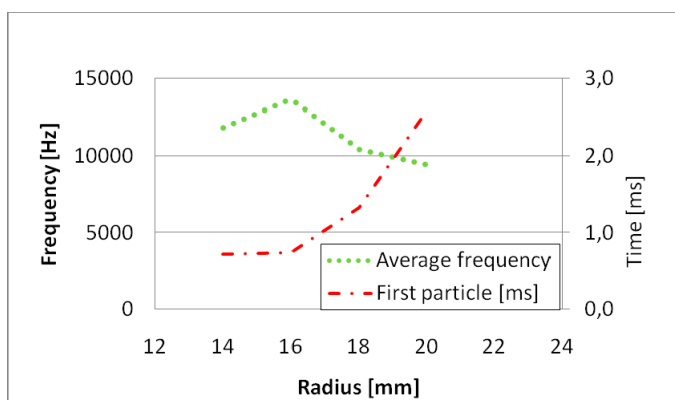


Figure 4. Particle measurement frequency and time until first particle was observed as a function of radial distance from the symmetry axis.

RESULTS AND DISCUSSION

Sprays from the outward opening piezo-actuated injector used in this study form hollow cones, with slight variations in wall thickness, indicated by the streaks in the pictures. At the front of the cone the sprays break up because friction with the surrounding air creates an upward vortex motion and a counter-rotating vortex close to the symmetry axis. These vortices help entrain air from beneath and the sides of the sprays, as illustrated in Figure 5.

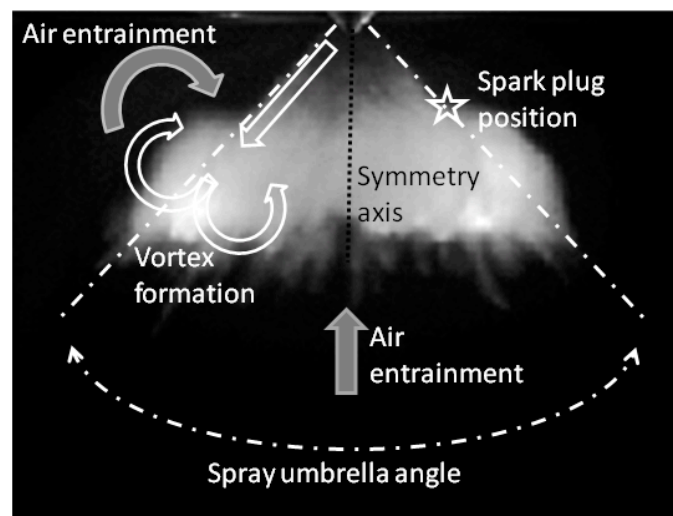


Figure 5. Schematic diagram of vortex formation and air entrainment in a spray, and the approximate spark plug position, superimposed on an image of a spray.

The figure also indicates a common position for the spark plug, approximately 10 mm beneath and to the side of the symmetry axis of the injector. One of the greatest advantages of good vortex formation is that it helps to transport fuel vapour towards the spark plug. The spray behaviour will be affected by in-cylinder pressure, fuel injection pressure, chamber ambient temperature, fuel temperature, injection strategies and composition of the fuels. In order to characterize the influence of these parameters on the formation of sprays of E75, E100 and gasoline the variables quantified and analyzed in this study were;

- Liquid penetration
- Spray front velocity
- Droplet sizes

Data on the two first variables were extracted from high speed images and the droplet sizes were obtained from PDA measurements 15 mm downstream from the nozzle and 14-22 mm radially from the symmetry axis, as shown in Figure 3. The spray penetration indicates the probability of piston wetting (the longer the penetration the greater the risk of wetting the piston) while the spray