The Effect of Fuel Volatility on Sprays from High-Pressure Swirl Injectors

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ABSTRACT

The effect of fuel volatility on the spray distribution of a pressure-swirl atomizer of the type used in direct injection gasoline engines was investigated in a firing optical engine. Planar laser-induced fluorescence (PLIF) and planar Mie scattering were used to visualize the fuel spray. Fuel mixtures consisted of doped and undoped iso-octane and indolene. Dopants were ketones of varied volatility. At high temperature and low pressure with volatile fuel species, the spray changed from the hollow cone structure observed under cold conditions to a solid cone distribution. Observed trends agree well with bubble point calculations and published results. Images of spray development show improved atomization for the initial non-rotating jet as well as the fully-developed spray. Experiments with indolene showed similar results. At atmospheric pressure, indolene sprays showed a transition to flash boiling between 90 and 100 °C Injector temperatures.

INTRODUCTION

The potential benefits associated with gasoline direct injection (GDI) engines in both fuel economy and transient fuel management have been highlighted in several recent publications, and reinforced by the introduction of several engine models into the international market (1-3). While direct-injection spark-ignition engine designs have existed for some time (4), the renewed interest in the technology has been made possible by advances in high-pressure fuel injection technology as well as powerful electronic control techniques. Higher fuel economy is possible through a combination of lower throttling and heat losses during stratified operation, as well as higher maximum compression ratio, higher volumetric efficiency, and more precise fuel delivery. Potential emissions benefits are also possible through better cold start fuel delivery and transient response. However, achieving all of the fuel economy benefits while managing hydrocarbon and nitric oxide emissions, especially under stratified operation, requires a thorough understanding of the processes involved in the vaporization and distribution of the injected fuel.

The successful operation of modern GDI engines depends on matching a combustion chamber shape and intake cylinder flow field which will enable complete air utilization during full load homogeneous operation and provide a well-contained pocket of combustible mixture during part-load, stratified charge operation. Pressure-swirl injectors are often considered the best design for providing appropriate spray characteristics for both of these operating regimes (5). In this study we focus on the fuel distribution during the injection period, which is not strongly influenced by the specific design of a particular combustion chamber shape or flow field. In particular, the role of volatility of light-end components in the fuel on the spray from a pressure-swirl injector is investigated.

EXPERIMENTAL SETUP

The visualization of the spray was performed in a firing square-piston engine using both planar laser-induced fluorescence (PLIF) as well as planar Mie scattering from the spray droplets. Mie scattering has been used widely to observe the external structure of sprays but is not applicable to vapor measurements, and quantitative measurements are difficult. In PLIF, the emitted visible light signal intensity is proportional to the concentration of the fluorescing compound present in the mixture in liquid or vapor form. However, the observed intensity is affected by collision quenching with other molecules, temperature, pressure and laser intensity, rendering quantitative interpretation of results difficult. The use of PLIF in combustion systems and the fluorescent properties of many substances are well described in the literature (6-9). No attempt has been made to develop an absolute calibration for these measurements. Since the measurements were made using the same mixture at similar oxygen concentrations and temperatures, however, quantitative interpretations are possible based on the relative signal distribution of the images.

Imaging system

A Princeton Instruments intensified-CCD camera (576SE ICCD detector and ST138 controller) capable of extremely short exposure times (50 nanoseconds to several seconds) was used to capture images of the fluorescence or Mie scattering signals. The CCD array has 384 rows and 576 columns of pixels, yielding a spatial resolution of approximately 80 μm in the current setup, although this is
further limited by the intensifier. The 60 mm Nikkor camera lens contains glass optics which prevent detection of UV radiation.

Timing of the system is controlled by a pulse generator (Princeton Instruments PG200), which was triggered by the rising edge of the fuel injection signal from the motor controller. After prescribed delays, the pulse generator triggered the camera controller, excimer laser (in the case of PLIF), and the intensifier. The approximately two seconds required to transfer the image data from the camera to the memory of the computer prevents more than one image from being taken in an engine cycle.

Dopant selection

For fuel tracing, a number of aldehydes and ketones have been investigated (6, 7, 10). For these tests, ketones were chosen due to their low oxygen quenching and range of available volatilities. Acetone (boiling point, T\textsubscript{b} = 56 °C) was used to represent the more volatile components in gasoline, while 2-butane (T\textsubscript{b} = 80 °C) and 3-pentanone (T\textsubscript{b} = 102 °C) were used to represent mid- and low-volatility components, respectively. A 10:1 mixture of iso-octane to dopant by volume was used. Variations in the fluorescence intensity due to changes in ambient pressure, temperature, and laser intensity are not large over the conditions encountered. Absorption and emission spectra can be found in the literature for several ketones (9). The absorption spectrum for acetone ranges from 240 nm to 320 nm. The peak absorption band occurs near 280 nm, but the absorption is still significant at 308 nm. The peak emission band is near 420 nm for all of the ketones studied (9).

Laser system

An excimer laser (Lambda Physik Compex 102) operating at 308 nm (XeCl), was used to excite the mixture. The beam exits the laser in a rectangular shape having dimensions of 23 mm tall by 7 mm wide. For the close-up images presented below, the beam is shaped by a pair of cylindrical lenses (focal length 157 mm and 52 mm) and a slit, changing the beam dimensions to 23 mm by 0.5 mm. Approximately 20% of the 70 mJ pulse energy emitted by the laser is actually transmitted to the test volume, limited mainly by attenuation by the slit.

For the wide-field-of-view indoline images, to avoid the loss at the slit, the beam was focussed horizontally with a single lens to a 0.5 mm sheet. A long focal-length lens (1047 mm) was used to minimize thickness variation across the combustion chamber. The beam was also expanded vertically with a cylindrical lens (157 mm) to extend over the entire stroke. A 100 mJ pulse energy was used for these tests.

Planar scattering

Planar scattering experiments were performed using a 1.5 W argon-ion laser (514 nm, Coherent Innova-90). The laser beam was expanded using a cylindrical lens and passed through the same optics and slit used for the PLIF measurements. Some blurring occurred in the scattering images due to the relatively long intensifier gate width (15 μs) required for adequate intensity.

Fig. 1 Schematic of optical engine; horizontal cross section.

Optical engine

The spray visualization experiments were conducted inside of a running engine that has been extensively modified for optical access (Fig. 1). The engine has a square cross section, which allows complete optical access through two of the side walls and a 75.6 mm x 72.6 mm viewing area through a third window. The third window was added to allow the fluorescence to be viewed at 90 degrees from the path of the laser light. Dimensions and specifications for the engine are given in Table 1. The compression ratio for the engine (8:1) is significantly lower than that of several of the prototype DI engines (11 to 12:1), since sealing the optical engine becomes progressively more difficult as the peak pressures increase.

The modifications required for operating the optical engine with direct injection included constructing a new high pressure fuel system and providing a mounting location for the injector within the cylinder head. No effort was made to shape the charge motion for stratified-charge operation so all testing was conducted with a homogenous charge strategy. The head temperatures quoted in the present experiments were taken by a thermocouple imbedded in the cylinder head about 2 mm from the injector tip. To make the measured temperature more representative of the average injector temperature, the engine was preheated.

Table 1. Optical engine parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Cross section</td>
<td>82.5 mm x 82.5 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>114.3 mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>0.77 liter</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>8:1</td>
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<tr>
<td>Number of valves</td>
<td>2</td>
</tr>
<tr>
<td>Head geometry</td>
<td>Flat</td>
</tr>
<tr>
<td>Piston geometry</td>
<td>Flat</td>
</tr>
<tr>
<td>Engine speed</td>
<td>1000 rpm</td>
</tr>
<tr>
<td>Spark timing</td>
<td>25 °bTC</td>
</tr>
<tr>
<td>Injection timing</td>
<td>90 °aTC</td>
</tr>
</tbody>
</table>
High-pressure fuel system

The high fuel pressure required for direct fuel injection (here 5 MPa, compared to 0.1-0.3 MPa for port-fuel injected engines) was generated using a hydraulic accumulator and a compressed nitrogen cylinder. The nitrogen and fuel are separated by a piston-type hydraulic accumulator (Tobul 3AT30-2-S), which prevents the nitrogen from being absorbed by the fuel while it is under pressure. This accumulator is equipped with specially ordered teflon-encapsulated Viton seals to prevent attack by the ketone-doped fuel mixture.

Doped fuel mixtures consisted of a 10:1 ratio of iso-octane (J.T. Baker, 95%) to acetone (9.1 vol.% acetone; Mallinckrodt, 99.5%), 2-butane (Mallinckrodt, 99.5%), or 3-pentanone (Aldrich, 98%). Additional experiments were performed with indolene (Amoco, brand code 15211), 2-methylbutane (E.M. Science, 95%), and undoped iso-octane.

The two fuel injectors used in this study are manufactured by Zexel, Inc. (HFI-2.1: 960040-2330) and Chrysler. These injectors are pressure-swirl atomizers, which impart significant rotational momentum to the fuel to produce a hollow cone spray with a characteristic cone angle. The nominal cone angles for these injectors are 60° for the Zexel and 50° for the Chrysler. The injectors are supplied with fuel at 5 MPa, and are driven by hardware provided with each unit.

RESULTS

Figures 2-6 show inverted, single-shot PLIF and Mie scattering images of fuel sprays. In Figs. 2, 3, and 5, the height of the image represents 25 mm. Laser sheet propagation is from right to left. The two horizontal lines on the left of some of the PLIF images appear as a result of fluorescence of the intake valve surface from laser light scattered from the spray. Shot-to-shot variations were not significant.

Flash Boiling Observations

We have shown elsewhere (11) that a significant change in spray structure can be observed for fuel sprays from pressure-swirl injectors at high head temperature and low intake pressure with volatile fuel species. This transition from a hollow-cone structure to a solid-cone structure has been attributed to flash boiling of the volatile fuel components.

Varied Volatility Tests. In order to compare flash boiling trends with experiments, tests were performed with fuel mixtures with dopants at a range of boiling points at a range of intake pressures. PLIF images of fuel sprays from the Zexel injector using the three ketone dopants at three intake pressures. At low head temperature (30 °C) the variations were not significant. At high 90 °C head temperature, Fig. 2 (from ref. 11) shows significant flash boiling for both the acetone and 2-butane at 0.3 bar, with transition cases observed with acetone at 0.6 bar and 3-pentanone at 0.3 bar.

The analog to the boiling point temperature for multi-component liquids, the bubble point temperature, was calculated for each case in Fig. 2 (11). This value is shown below each image as $T_{BP}$. Assuming that the fuel leaves the

injector at the head temperature (11), the resulting superheat was used as a measure of the tendency for flash boiling. The superheat is shown below each image in Fig. 2 as $\Delta T$. The trends agree well with significant flash boiling observed with a superheat above 30 K, and transition between 20 and 30 K, and no flash boiling effects observed with a superheat below 20 K.

Mie Scattering. Since PLIF cannot distinguish between liquid and vapor, Mie scattering was used to determine if the droplet distribution is disturbed by the flash boiling. Figure 3 (from ref. 11) shows Mie scattering images of iso-octane/acetone sprays at cold and hot head temperatures. In both cases, the distribution observed with Mie scattering is very similar to that observed with PLIF, which indicates that the droplets as well as the dopant are being redistributed by the flash boiling.

Comparison of the integrated image intensity with PLIF and Mie scattering suggests a roughly 43% reduction in droplet diameter by increasing the fuel temperature from 30 °C to the 90 °C flash-boiling case. Over this temperature range, only a 20% reduction in droplet diameter can be attributed to the increase in temperature alone (without the volatility effects) (11).
Spray Development

Since the engine fuel injection process is necessarily a transient one, the development of the spray under flash boiling conditions is of great interest. To visualize spray development, images were taken with progressively longer delays from the start of injection. Figure 4 shows two series of development images from iso-octane/acetone sprays from the Zexel injector. The height of the images represents 32 mm. The upper series shows the development at low temperature, which is similar to images seen in the literature (12, 13). This series demonstrates the formation and breakup of the initial non-rotating jet and the transition to the fully-developed spray. The lower series shows the development of the flash-boiling spray. This spray also exhibits an initial non-rotating jet and the timing of the transition to the rotating spray is similar to the cold spray. The hot spray appears to experience flash boiling from the initial release of fuel, since at all times the image is much more diffuse. Also, the rate of penetration of the initial jet, calculated from the images, is significantly slower for the flash-boiling spray: 66 m/s hot versus 101 m/s cold. These observations suggest that flash boiling improves atomization of not only the fully-developed spray, but also of the initial non-rotating jet. Images of the spray breakup after injector closing suggest similar improvements in atomization.

Single Component Fuel

In order to better determine the superheat required for flash boiling to occur, tests were performed at controlled temperature with a single-component fuel of known boiling point. Specifically, Mie scattering images were taken of 2-methylbutane (T_{gb} = 30 °C) sprays from the Chrysler injector at atmospheric pressure. The injector was heated externally and given at least ten minutes to equilibrate before a series of ten images were taken. These tests show the first significant effects of flash boiling at a superheat of 23 K. This agrees well with the results from the iso-octane/ketone mixtures presented above.

Indolene Results

The applicability of these findings to real-world fuels was investigated by performing PLIF and Mie scattering experiments using indolene. Figure 5 (from ref. 11) shows PLIF and scattering images of fuel sprays with both cold and hot head temperatures. Since the fluorescence intensity of the high-boiling-point aromatic compounds present in indolene is higher than that of the iso-octane/ketone mixtures, the aperture was set to a value three f-stops higher than in the previous experiments to avoid excessive saturation. The structure of these images, however, is very similar to those of the doped iso-octane in Figs. 2 and 3. At low intake pressures. The images indicate a similar degree of flash boiling for indolene as for the iso-octane/acetone mixture.

Vapor. A comparison of volatilities suggests that indolene is more susceptible to flash boiling than the iso-octane/acetone mixture. The temperature at which 10% of the indolene evaporates, the T_{10} point, is in the range of 49-57 °C. A T_{10} point of 87 °C was calculated for the iso-octane/acetone mixture by an isothermal flash calculation and the correlations used for the bubble point calculation (11, 14, 15).

Fixed Temperature. Two sets of experiments were performed to determine the limiting conditions for observing flash boiling in an indolene spray. First, a series of images were taken in the engine at a fixed temperature while varying
the intake pressure (Fig. 6). These tests used the Chrysler injector at 80 °C. The height of the image portion of the figure represents 78 mm. The dashed line, which is 1 cm below the injector tip, shows the position at which the intensity plot below was taken. The light area one-third of the way down the image and the jagged light area two-thirds down, are due to opaque residue left from the graphite piston sealing bars at their TC position. The plateau intensity profile indicates that flash boiling is prominent up to 0.7 bar. The hollow-cone structure becomes apparent in the double-peaked intensity profile at 0.9 bar.

Fixed Pressure. The second set of tests were performed at atmospheric pressure with the injector heated, similar to the single components tests described above. These tests show transition to the flash-boiling structure in the range of 90 to 100 °C. This is well within the range of temperatures an injector would experience in an engine. In agreement with the present results, Oza and Sinnammon (16) show images of pronounced flash boiling in indolene sprays by 100 °C at atmospheric pressure.

DISCUSSION

Flash Boiling

Flash boiling of this nature is typically described as being governed by the bubble nucleation process (16-18). Since the temperatures used here are well below the limits of superheat for these liquids at atmospheric pressure (typically about 90% of the critical temperature) (19), the nucleation rate is strongly influenced by dissolved gasses and low pressure regions in the liquid due to the bulk flow or turbulence. Therefore different injector types may require different amounts of superheat to exhibit flash boiling.

Flash boiling of fuel sprays has been described in the literature for pintle-type injectors (17), as well as plain orifice injectors and poppet injectors (16). Oza and Sinnamon (16) show changes in a methanol spray with a superheat on the order of 10 K, while Senda, et al. (17) describe changes in spray structure with small negative superheats. Brown and York (18) showed a 75% reduction in Sauter mean diameter of a water jet with a superheat of 24 K. Considering the differences in injector types, the transition superheat value of 23 K found in this study seems reasonable.

Spray Structure

The fuel in the flash-boiling spray appears to be gradually redistributed from the cone sheet to the core as the temperature increases. Two mechanisms may explain this behavior. First, due to the centripetal acceleration of the fuel in the swirl chamber of the injector, the pressure in the fuel will be higher at the walls. Boiling is more likely, therefore, near the center of the chamber, along the air core. The boiling would then have little effect on the fuel at the periphery, which would be ejected at the characteristic cone angle. The core of the cone would then be filled with the droplets produced by the flash boiling.

Second, the mechanism by which the fuel is transported to the center of the cone may be the same...
mechanism which causes the cone angle to decrease at increased ambient pressure (3, 20). This well-known phenomenon of hollow-cone spray collapse results from a low-pressure region in the interior of the hollow cone produced by entrainment of air by the fuel spray. Since the smaller droplets produced by the flash-boiling spray produce stronger entrainment and follow the airflow more easily, the droplets and dopant vapor are drawn to the interior of the cone. Evidence to support this theory comes from the fact that while the initial cone angle does not change significantly with intermediate amounts of superheat, the width of the spray downstream is reduced.

While both of these mechanisms may act to some extent, the second is almost certainly involved.

CONCLUSIONS

The structure of the spray from a pressure-swirl injector is strongly affected by the fuel component volatility and the local temperatures and pressures. The following conclusions were drawn from this study:

1. PLIF and Mie scattering images show that at high head temperatures and/or at low loads, flash boiling of volatile components changes the hollow cone structure observed under cold conditions to a solid cone distribution.

2. Bubble-point calculations and single-component-fuel tests suggest that a superheat of about 20 K is required for flash boiling to be vigorous enough to noticeably change the spray characteristics.

3. Flash boiling appears to improve atomization throughout the injection process.

4. A similar flash boiling transition is observed for indolene. At atmospheric pressure this transition occurs between 90 and 100 °C.

5. The observed spray structure can be explained by entrainment of the smaller fuel droplets into the center of the jet by the induced air flow and/or flash boiling of only the interior portion of the injected fuel.

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REFERENCES


