

Spray Characteristics Study of DMF Using Phase Doppler Particle Analyzer

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ABSTRACT

2,5-dimethylfuran (DMF) is currently regarded as a potential alternative fuel to gasoline due to the development of new production technology. In this paper, the spray characteristics of DMF and its blends with gasoline were studied from a high pressure direct injection gasoline injector using the shadowgraph and Phase Doppler Particle Analyzer (PDPA) techniques. This includes the spray penetration, droplet velocity and size distribution of the various mixtures. In parallel commercial gasoline and ethanol were measured in order to compare the characteristics of DMF. A total of 52 points were measured along the spray so that the experimental results could be used for subsequent numerical modeling. In summary, the experimental results showed that DMF and its blends have similar spray properties to gasoline, compared to ethanol. The droplet size of DMF is generally smaller than ethanol and decreases faster with the increase of injection pressure. The mean velocity of DMF spray droplets is similar to gasoline and higher than ethanol. Ultimately, the spray characteristics of DMF are better suited to the gasoline engine technology than its counterpart, ethanol.

INTRODUCTION

Recently, because of the new developments in its production method, 2,5-dimethylfuran (DMF) is regarded by some researchers as a promising alternative fuel [1]. This originates from the claim that DMF can now be produced from glucose with greater efficiency than ethanol. Furthermore, researchers from the same group used a chemical N,N-dimethylacetamide (DMA) to extend the scale of resource into cellulose and lignocellulosic biomass and simplify the chemical transformation. This provides a new paradigm for the use of biomass as a raw material for renewable energy and chemical industries [2]. Since cellulose and lignocellulose are widely used chemicals, which can be produced by most organic

sources, such as untreated corn stover, this development could lead DMF for use as a new renewable bio-fuel.

Compared with ethanol, which is widely regarded as a promising candidate to partially replace gasoline, DMF has several critical advantages. For instance, it has a 40% higher energy density than ethanol (close to that of gasoline), which would prevent the limited cruise mileage incurred by using ethanol. DMF has a higher octane number which bestows a higher compression ratio and results in improved fuel economy and engine performance. In addition, DMF has a very low water insolubility rate which eliminates the problem of water absorption seen with ethanol and thus reduces the difficulty of storage.

However, if DMF is to be used as a fuel in commercial automobile engines, it needs to have specific physical properties. For one, the spray and combustion characteristics play a critical role in characterizing the engine performance and emissions, especially for direct injection (DI) engines. Generally, spray penetration and cone angle indicate the spray shape and are more dependent on the injector design. However, spray droplet size and velocity distribution indicate the liquid fuel breakup, atomization and mixture generation and directly impact combustion performance.

Optical techniques were developed to study the spray characteristics. The shadowgraph technique is a simple and economic way to visual the spray pattern. Shadowgraph images contain important macroscopic spray shape information such as the spray penetration, cone angle and their development process over time. However, since the fuel sprays are composed by very high-speed and densely formed droplets, it is difficult to use the shadowgraph technique to measure more detailed information.

The Phase Doppler Particle Analyzer (PDPA), also called the Phase Doppler Anemometer (PDA) is a sophisticated laser based non-contacting technique used to measure detailed droplet information [3,4,5]. By optimizing the optical components, the PDPA system has the capacity of measuring highly dense droplets with the velocities over 100m/s. This makes it one of the best methods to measure the spray characteristics of the internal combustion engine.

A typical PDPA system, as shown in [Figure 1](#) [6], contains the following components:

- i. High power CW laser (light source)
- ii. Wavelength drifter and beam separator (generate 2 groups of laser beams with different wavelengths; 1 group of green and 1 of blue)
- iii. Transmitter connected to the beam separator by optical fibers (focuses each of the laser beam groups across the same point, called the measuring volume)
- iv. Receiver with photomultiplier (detects the reflecting or refracting light signal)
- v. Computer to control the whole system

Normally the angle between the transmitter and receiver for the optimized scattering light intensity is 70° because the first order refraction of light is dominated at this angle.

The PDPA system works by generating a bright-dark alternating fringe using a group of laser beams at the cross section. When the droplets pass through the fringe, the reflecting or refracting light will be detected and generate a sine-wave signal which is called the Doppler burst. The frequency of the Doppler burst indicates the droplet velocity. Using two groups of laser beams can deliver 2-D information including both the vertical and horizontal movements. Normally 3 photomultipliers are built into the receiver; the phase difference between these signals gives the information of droplet size.

(See [Figure 1](#) after last section of paper.)

Benefitting from several years of development and optimization, the PDPA system is becoming a mature technique for the measurement of automotive engine spray characteristics. It was applied on both gasoline [4] and diesel [3,5] engines and showed good results in order to describe the spray characteristics. The nozzle vicinity measurement is the main challenge of the PDPA system due to the extremely high droplet density, or as is always debated, there are no droplets but only filaments in that area.

Since the spray characteristics and mixture generation play very important roles in the combustion process and thus affect engine performance, it is essential to study the spray behavior. For instance, when ethanol became a promising

candidate for replacing mineral gasoline, extensive work was carried out on different blends with both gasoline and diesel using different optical methods and numerical simulations. On the whole, these studies revealed that ethanol has a rapid evaporation rate and better mixture generation than gasoline when the ambient temperature is relatively high [7]. However, at colder temperatures ethanol (directly injected) suffers from poor evaporation rates, which is one of the reasons for its difficulty during cold starts [8]. Another study, which investigates ethanol and gasoline blends using high-speed imaging and PDPA for the cold start process, reveals that ethanol performs poorly. For instance, it had a shorter penetration, weaker vortices, larger droplet sizes and slower evaporation rates compared with gasoline [9]. Some other comparisons between the spray characteristics of ethanol and gasoline at different temperatures show how the differences increase with temperature [10, 11].

Despite the attention on ethanol research, little has been done on the quantitative analysis. Most of the conclusions were drawn from the spray pattern shapes, which can only give limited support for a subsequent numerical model setup [7, 8, 12]. In this paper, quantitative results were delivered through the PDPA technique for the selected fuel candidates, and will be applied to the computational simulation model setup in the following work. Following the spray characteristics investigation, more work is being carried out in the University of Birmingham to investigate the adaptability of DMF as an automotive alternative fuel, including laminar flame propagation, engine performance and emissions, in-cylinder combustion visualization, etc.

EXPERIMENTAL APPARATUS

The experiment was carried out on commercial gasoline, DMF, their blends (50-50% volume ratio, D50 in the following), and ethanol (for comparison). The main properties of the three fuels are listed in the [appendix](#).

Experimental Setup

The experimental spray system schematic is shown in [Figure 2](#).

The injector used was a 6-hole gasoline direct injection injector. The positions of the holes are optimized for the combustion chamber so that they are not symmetric. Any of the 6 holes were chosen for the experimental setup but an arbitrary one was used for all the tests. The fuel is delivered from a fuel accumulator which is pressurized by a compressed nitrogen bottle. Injection pressure can be varied by adjusting the regulator of the nitrogen bottle. The injection duration is controlled by a computer with a National Instruments timer and counter card (PCI-6602).

Spray pattern images were taken by a high resolution, low speed CCD camera from LaVision. Each image was captured from the injection with a specific time delay. The spray was illuminated by a Xenon stroboscope flash light from Polytech with an intensity of 2.16 J/flash and frequency of 100Hz (highest possible settings).

The TSI 2-D PDPA system uses a 4W Ar⁺ laser to generate two different groups of laser beams with wavelengths of 514.5 and 488nm. The laser beams are transferred to the transmitter by optical fibers. The focal lengths of the optical transmitter and receiver are 250 and 500mm respectively. A 150 μ m slit was used before the photo detector in the receiver to limit the scattering light. A 3-D traverse was used so that the measurement position was precisely controlled (resolution of 60 steps per mm).

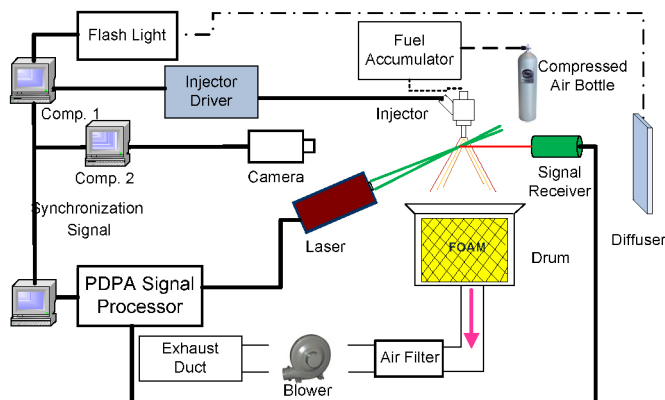


Fig.2. PDPA Experimental Schematic

The three computers which control the fuel injection, flash light, camera and PDPA were finely synchronized between each other so that all the results were on the same time base.

To eliminate the fire risk hazard and environmental pollution, injected fuel was collected and filtered. A piece of foam, normally used in the racing car tanks, was inserted into a drum. This drum was connected with an activated carbon filter and eventually to the exhaust duct through a centrifugal blower. The sponge-like foam stopped the flame propagation and collected liquid fuel. The activated carbon filter from Camfil allows a 0.15s contact time with a flow rate of 300m³/hr; suitable for removing fumes associated with gasoline or diesel droplets. The blower is able to deliver a flow rate up to 300l/m, which gives an air/fuel ratio over 300:1, under the maximum fuel injection ratio. This ratio is far beyond the spark ignition boundary, which eliminates any risk of explosion.

Testing Points and Environment

One spray from the asymmetric 6 sprays was randomly taken for measurement, which can be seen in Figure 3. The sketch

in the bottom right hand corner indicates the view of the measured spray from the right. The axis of the spray was in the vertical plane and perpendicular to the PDPA receiver. The angle between the spray axis and the vertical axis is 50°. Two sets of points on the two perpendicular planes, which intersect at the spray axis, were measured (see Figure 3). Each set contains 52 points with the axial distances in the range of 5-81mm from the nozzle exit, as shown in Figure 3. For PDPA tests, each droplet which flies through the laser pattern and is recorded is taken as one sample. An enormous number of samples are required for statistic analysis. In this test, at each measurement points, 20,000 validated samples were attempted. Since the data rate strongly depends on the local conditions, a 30s timeout period (300 injections) was set for the points with a very low data rate and the 20k sample requirement could not be fulfilled.

All the tests were carried out under ambient conditions (atmospheric pressure and room temperature). The injection duration was fixed to 2ms, since this injection mass will approximately give a 3bar IMEP for the engine when fuelled with gasoline.

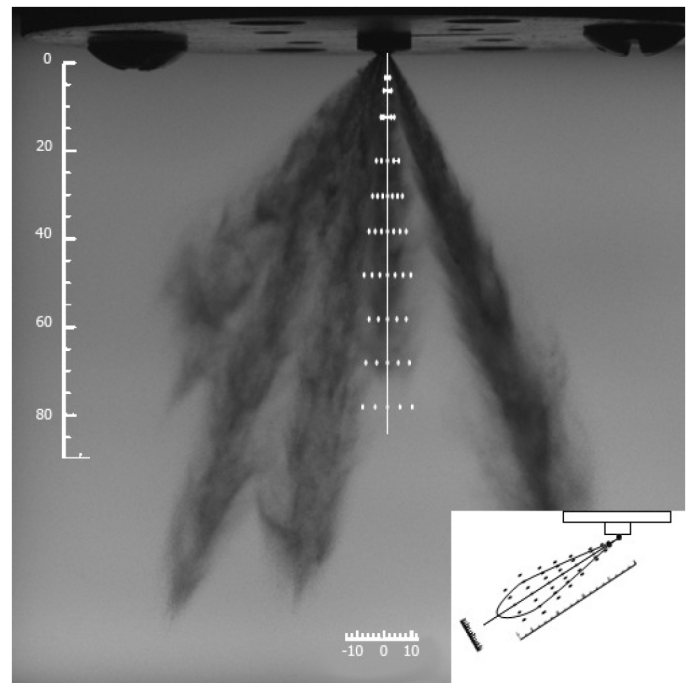


Fig.3. Measuring points on the spray (unit: mm)

RESULTS AND DISCUSSION

Spray Patterns

Such basic information as the fuel penetration and cone angle can be obtained from the spray images. As an example, the spray images of DMF are shown in Figure 4. Although the spray was not parallel to the lens surface, the penetration

length marked beside the photo is the real length after some calculation, as shown in the top right hand of [figure 4](#).

The first spray image was captured 0.8ms after the injection trigger, slightly longer than the 0.7ms solenoid response time. From the pictures, the development of the spray can be clearly seen, but almost no more details about the spray can be obtained.

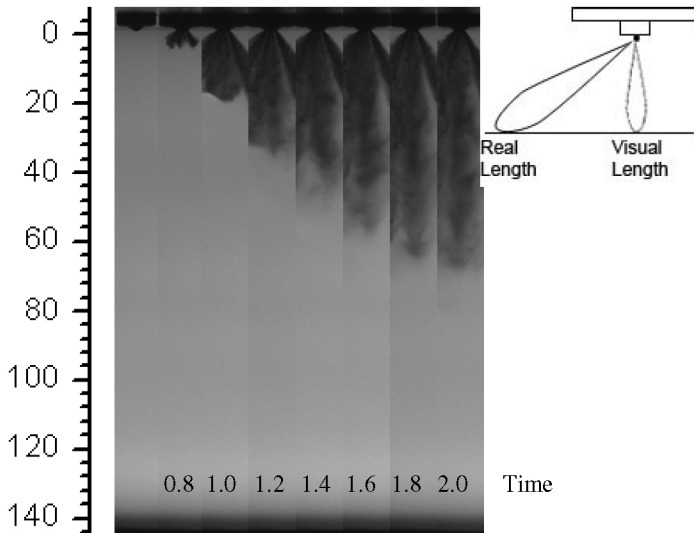


Fig. 4. DMF spray images (injection pressure: 100bar, length unit: mm, time unit: ms)

The spray penetrations of the different fuels are shown in [Figure 5](#). Gasoline has a shorter penetration compared to ethanol, DMF and D50, by approximately 10%. This result conflicts with other publications that stipulate that ethanol had a shorter penetration than gasoline (although in a high temperature environment and maybe more realistic for GDI engine) [9]. The reason for this could be due to the low ambient and fuel temperatures (less than the boiling point, 77.3°C @ 1 atm).

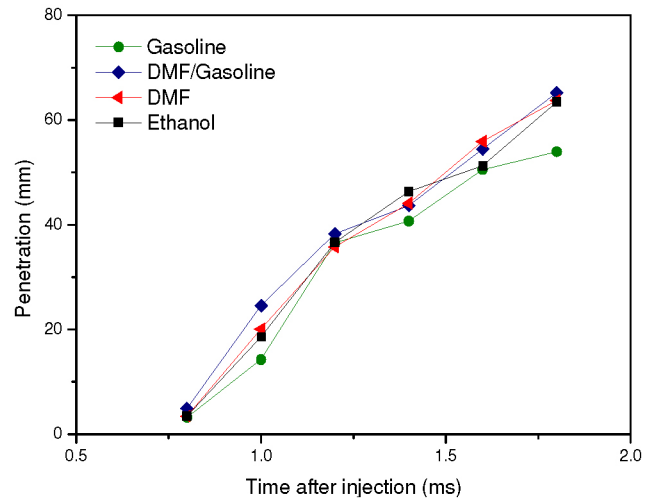


Fig. 5. Penetration of different fuels

The cone angle, another important parameter, has not been measured due to the overlap of the sprays. However, no significant difference can be found from the images as well.

Spray Structure

The description of a spray is shown in [Figure 6](#) by measuring pure gasoline droplet velocities with time, 32mm from the nozzle, under an injection pressure of 100bar.

The spray structure can be artificially divided into two parts: “spray head” and “spray tail” [5], which were marked in the figure. In the spray head, the droplets have a relatively high velocity whose mean is relatively steady. However, in the spray tail, the mean velocity drops quickly until it reaches a low level.

In [Figure 6](#), 1.1ms after the start of injection, the spray head reached the measuring point and the droplets were captured. The delay consists of two parts: the solenoid response time, which is approximately 0.7ms (for this injector), and the spray travelling time. The highest velocity of the droplets was 80m/s and the lowest was 20m/s (approximately), which gives a wide velocity distribution range. The droplet generation process can explain this phenomenon. The first stage of this process includes the liquid filament breakup (after injection) due to the shearing force between the air and the spray envelope. Resultantly, these droplets slow down and are hit by the ensuing droplets, causing their trajectories to rapidly change. As a result, the real velocity of the ensuing droplets with unchanged trajectories is higher than those with changed trajectories.