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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.

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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).

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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 150µm 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).

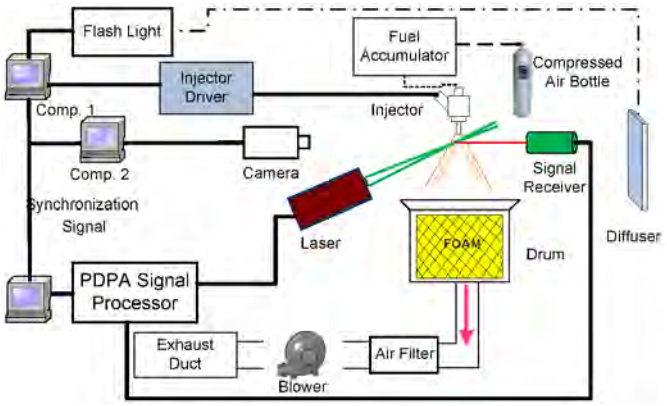


Fig.2. PDPA Experimental Schematic

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 300m^3/ hr; suitable for removing fumes associated with gasoline or diesel droplets. The blower is able to deliver a flow rate up to 3001/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.

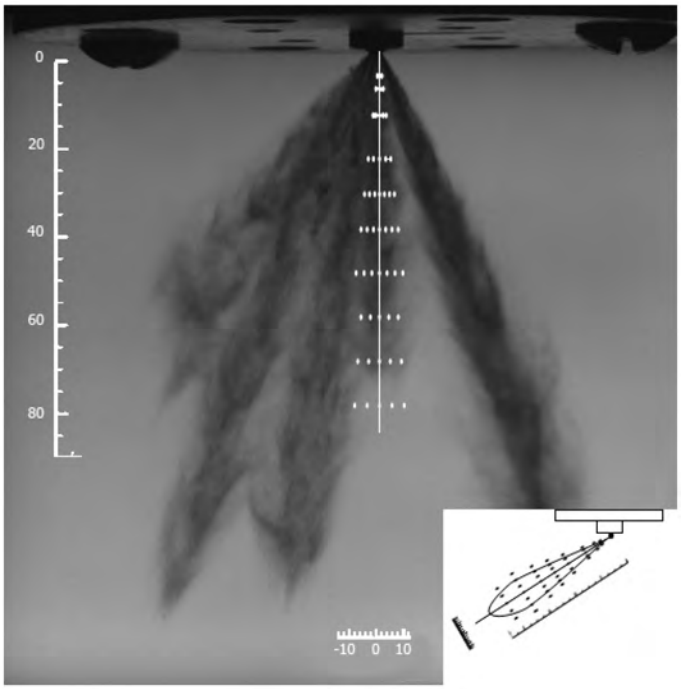


Fig.3. Measuring points on the spray (unit: mm)

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

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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.

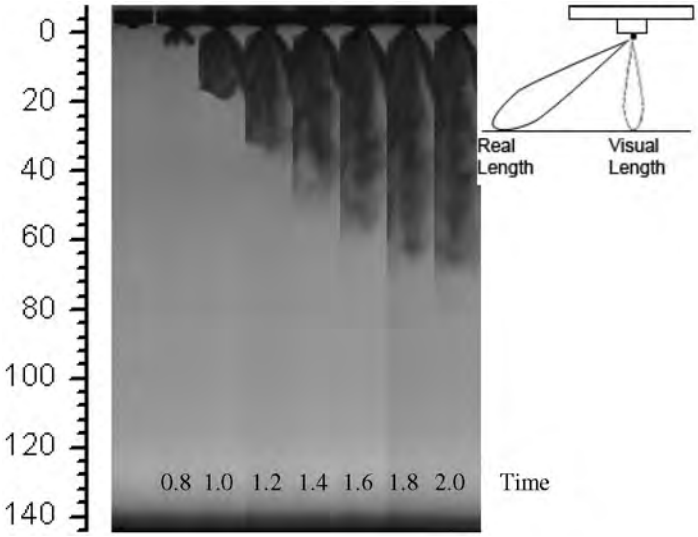


Fig. 4. DMF spray images (injection pressure: 100bar, length unit: mm, time unit: ms)

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).

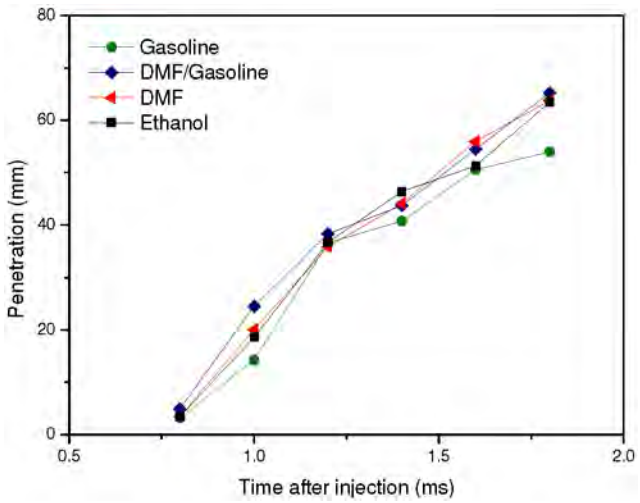


Fig. 5. Penetration of different fuels

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.

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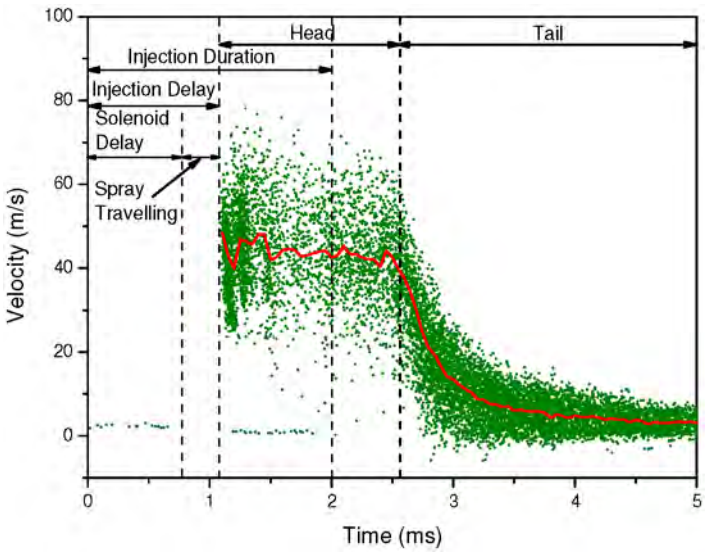


Fig. 6. Gasoline injection vertical velocity and smoothed data (100bar injection pressure)

After the spray head has passed, several droplets with much lower velocity reach the measuring volume, (recognized as the "tail" of the spray). This results in the negative velocity of some droplets which could induce vortices caused by the pressure gradient of the surrounding gas.

Several low velocity droplets were captured before and during the spray head. These droplets are believed to be the residual droplets from the previous injection and were ignored due to the negligible quantity.

For a better comparison between the different fuels, a smooth profile was averaged over 0.05ms time bins. The curve can clearly indicate the spray structure and therefore the trend of velocity development.

Droplet Velocity

The smoothed velocity profiles of gasoline, DMF, D50 and ethanol are plotted in Figure 7 and Figure 8, with the distance to the nozzle in the range 8 to 70mm. The sampling positions were on the axis of the spray and at the edge of the spray.

At an 8mm distance, it took 0.9ms for the spray envelope to reach the measuring volume. The data rates on the axis at this distance were significantly lower than those at further positions due to the high density of droplets; therefore the profiles have heavy fluctuation. Droplets on the axis have significantly higher velocities than at the edge due to the lower energy loss caused by the friction with air, but the structures on both axis and edge at the same distance are similar. For both these cases, gasoline had the highest mean velocity during the spray head, followed by the D50 with slightly lower velocity. For both of the two positions, ethanol had the lowest mean velocities, which were almost 20m/s less than gasoline.

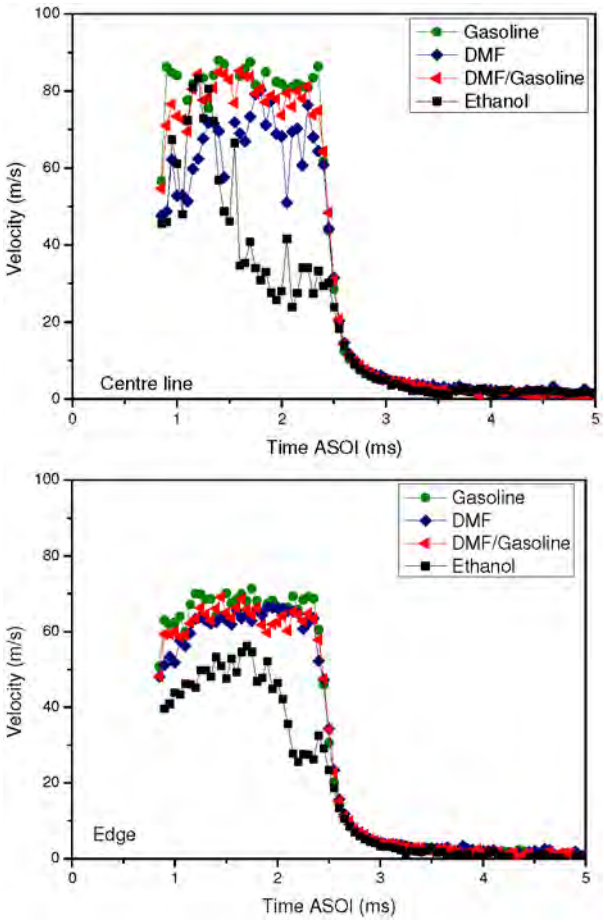


Fig. 7. Droplet velocities at 8mm from the nozzle

Further from the nozzle, as shown in Figure 8, it took as long as 2.15ms for the spray to reach the measuring volume. The mean velocity at these positions was much lower than those closer. Further away from the nozzle the droplets similar velocities on both the centre line and the edge. Gasoline still has the highest mean velocity, but DMF behaved very closely to gasoline and the D50. Again, ethanol had the lowest velocity for the spray head, but in the tail part, the velocity of ethanol was even higher than those of the other three candidates.

For both of the distances from the nozzle (8 and 70mm), ethanol behaved different from the other three fuels. It appears that there was a velocity reduction within the spray head. The reason may be that a great amount of energy was consumed within the break-up process for ethanol due to the high viscosity and the spray momentum decreased quickly. However, this conclusion can't be drawn until more research has been carried out.

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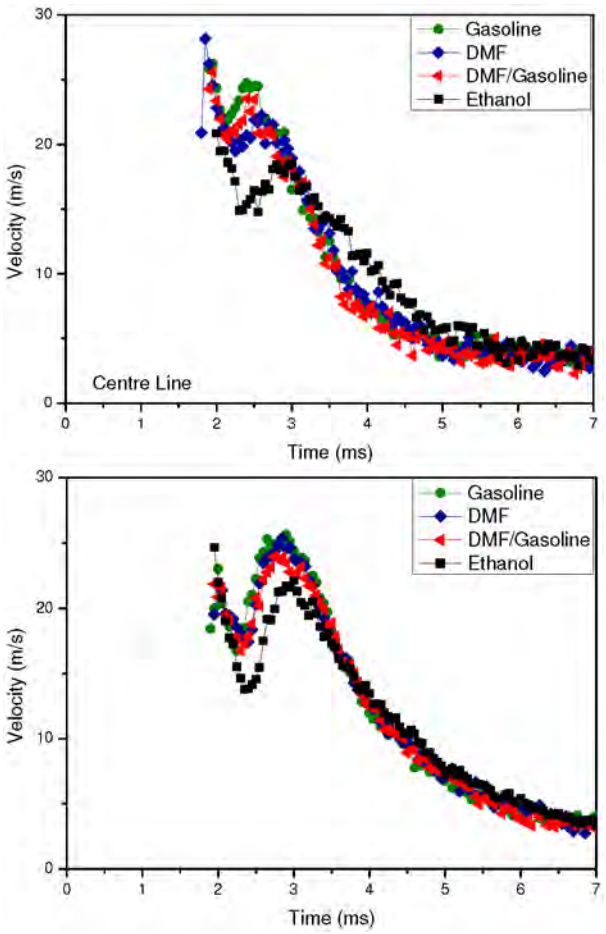


Fig. 8. Droplet velocities at 70mm from the nozzle

When comparing the different distance profiles, it is clear that for 8mm from the nozzle the velocity is quite steady during the spray head, but for long distance, despite the lower mean velocity, there are clear gaps between two peaks for all the tested fuels at both of the axis and edge positions (see Figure 8). This gives the impression that after the first punch of the spray envelope, the momentum of the following droplets decreases due to the collision with the downstream droplets. Subsequent droplets, however, were able to accumulate more energy and generated a second burst, represented by the peak in Figure 8. The spray tails at 70mm are obviously longer than those at 8mm. This is simply because there is more chance for the droplets to hit each other and transfer energy, which makes the velocity distribution more even.

DMF and D50 behave more similarly to gasoline than to ethanol. However, no significant difference can be seen in terms of the mean velocity. From the appendix table, apart from vapor pressure, DMF and gasoline have very close physical properties, which play the most important role on the spray behavior.

Droplet Size Distribution

The Sauter Mean Diameter (SMD, also known as D32) is widely used to describe the size distribution of fuel sprays. It is calculated according to the following formula:

$$D_{32}=\frac{\sum N_i d_i^{\,3}}{\sum N_i d_i^{\,2}} \qquad (1)$$

The SMD maps of all the tested fuels and blends across the spray are shown in Figure 9. This generally agrees with previous research [13,14,15,16], whereby the droplets are smaller on the edge than along the axis and larger near the nozzle than far from the nozzle due to the break-up and evaporation process.

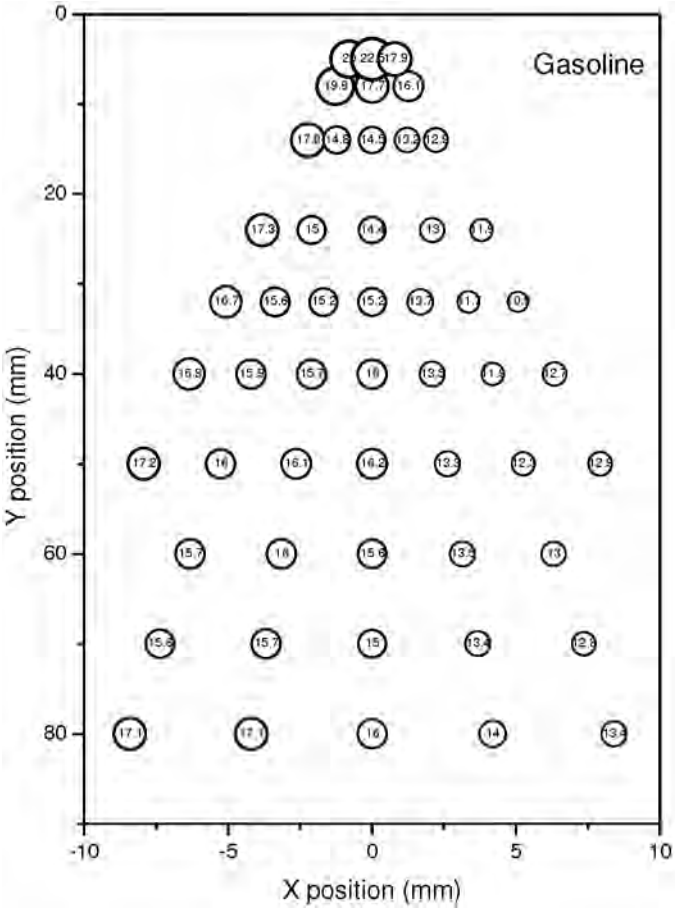
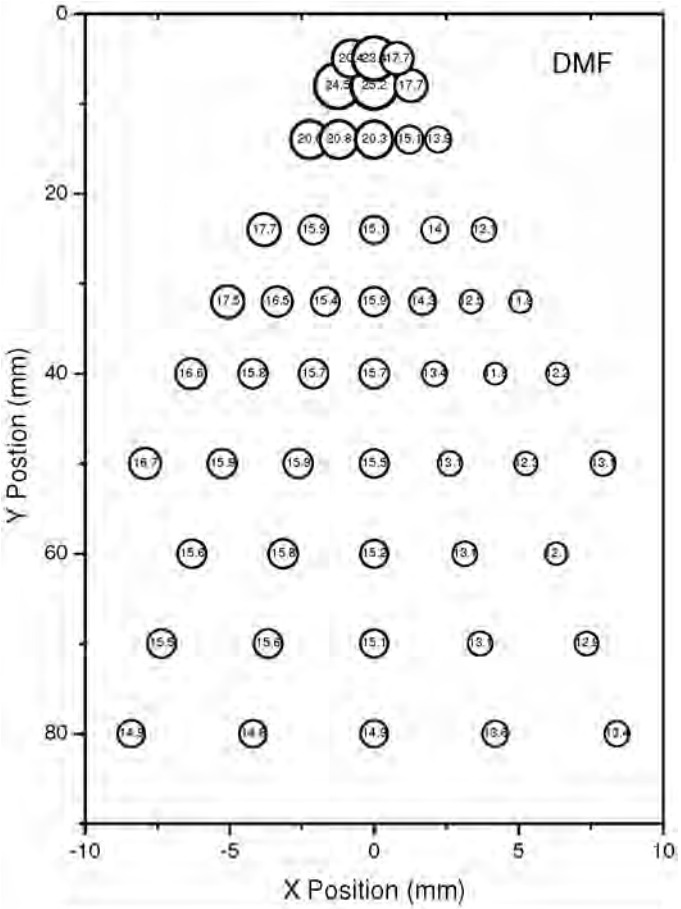


Fig. 9. SMD distribution for different fuels

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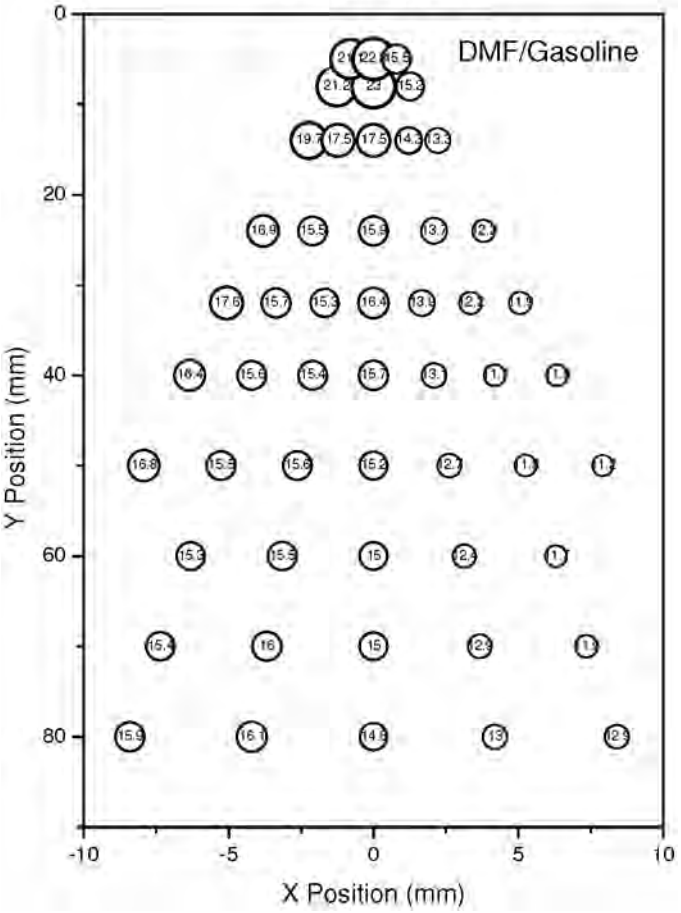


Fig. 9. SMD distribution for different fuels (cont.)

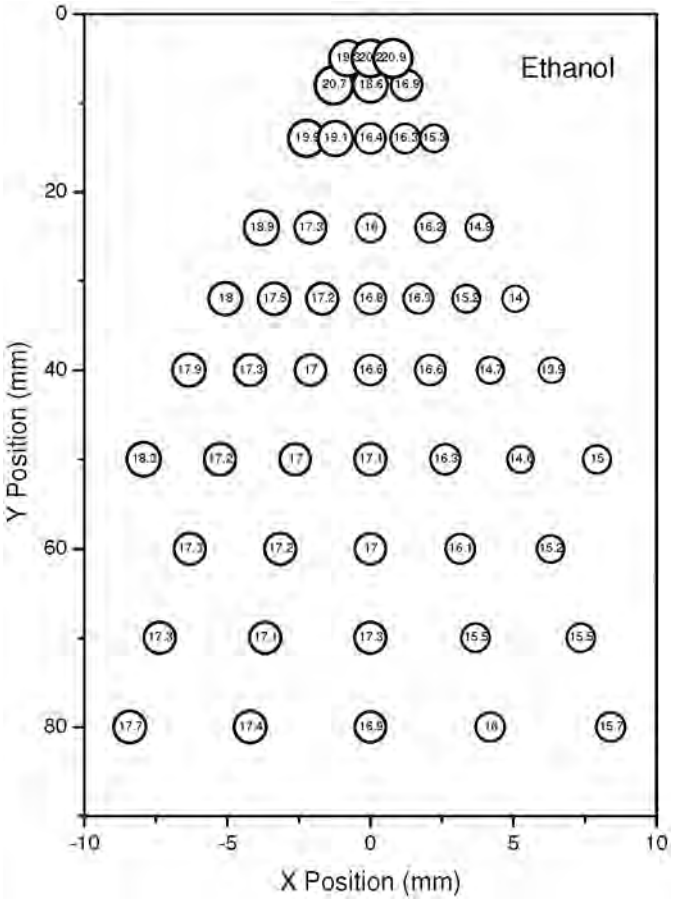


Fig. 9. SMD distribution for different fuels (cont.)

The SMDs of all the fuels along the axis are plotted in the same figure to allow for better comparison, see figure 10. For all of them, the droplet size decreases rapidly soon after the fuel was injected out. After 24mm downstream of the spray, droplet sizes become stable for all the tested fuels, which can be regarded as the accomplishment of the secondary breakup process. The break-up lengths of the four fuels are similar. Primary break-up cannot be detected by this method due to the high density of droplets which can be considered not necessarily droplets but filaments.

For gasoline, the slight increase in droplet size along the axis can be observed, but not for the other three fuels. The D50 behaves more closely to gasoline than neat DMF near the nozzle, but both of them have a greater SMD than gasoline. Further than 40mm away from the nozzle, no significant difference was observed in terms of droplets size between those three fuels.

Ethanol is totally different compared to the other 3 fuels. Near the nozzle, it has the smallest SMD and eventually the highest around 40mm from the nozzle. The SMD variation of ethanol along the axis (from 20.2 to 16.9μm) is lower than

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the other 3 fuels (22.5 to 16µm, 23.4 to 14.9µm, 22.3 to 14.8µm for gasoline, DMF and D50, respectively).

The stable droplet size is mainly affected by three physical properties; vapor density, surface tension and relative velocity. According to Chu's theory [17], the stable droplet size is proportional to the surface tension, inversely proportional to the vapor density and the square of the relative velocity. DMF, ethanol and gasoline have similar surface tensions (25.9, 22.3 and 20dyne cm^{-1}, respectively). However, ethanol has the lowest vapor density at 1.59 (relative to air, see Appendix), which, according to Equation 2 [17], is why ethanol has the largest stable droplet size.

$$r_{stable} = \frac{2 \cdot We_{crit} \sigma}{\rho_g v_{rel}^2} \quad (2)$$

Nevertheless, this theory cannot explain why ethanol has the smallest droplet size near the nozzle. It can be assumed that ethanol has the shortest primary break-up length, which means at the same position near the nozzle, more break-ups have occurred in the ethanol spray than the other two. This assumption can also be supported by the results in Figure 7, where the droplet velocity of ethanol decreases within the spray head.

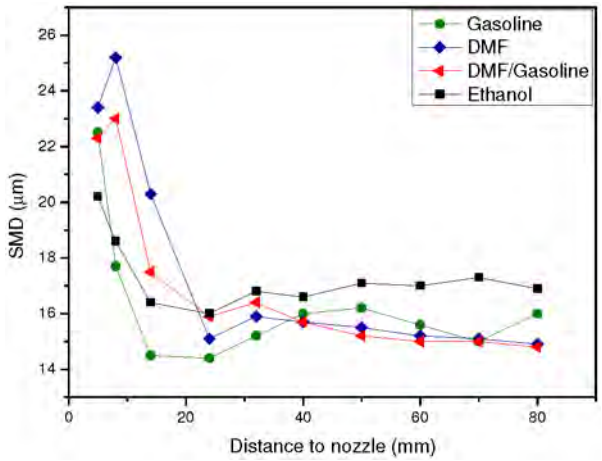


Fig. 10. SMD distribution along the spray axis

The influence of injection pressure was also tested at the same position with all the four fuel compositions, as shown in figure 11. The testing position was chosen on the axis, 32mm from the nozzle. Generally, the higher the injection pressure is, the smaller the SMD becomes. Within the tested pressure region, the profile shows good linearity.

Gasoline, DMF and their subsequent blending mixture behaves similarly. The SMD drops from more than 20µm at an injection pressure of 50bar to approximately 13µm at 150bar. Ethanol, again, performed differently to the others. With increasing injection pressure, the SMD reduction slows down. At 150bar, Ethanol has an SMD more than 15µm, which is 2µm higher than gasoline.

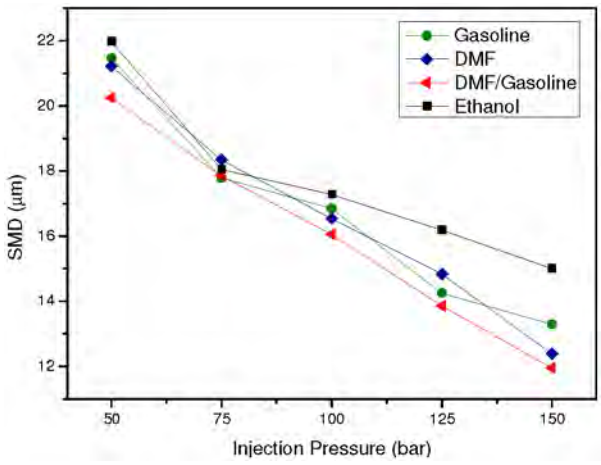


Fig. 11. Influence of injection pressure on SMD

CONCLUSIONS

The spray characteristics of pure DMF, gasoline, ethanol and DMF-gasoline blends are studied by the shadowgraph and PDPA techniques in terms of spray penetration, droplet velocities and size distributions in order to investigate the spray behavior of the new potential fuel, DMF. The following conclusions can be drawn from the experimental results:

1. For all these fuels, the spray structures are similar. The structure changes with the distance away from the nozzle. Downstream of the spray, the boundary of the spray head and the tail becomes unclear because the velocities of droplets become even through the impacts between the droplets.

2. 100% DMF and its blend with gasoline have a slightly lower mean velocity than gasoline. For most of the cases, the difference is less than 10m/s. Ethanol has a significantly lower velocity in the spray head and a faster reduction compared to the others.

3. 100% DMF and its blend with gasoline have significantly higher droplet sizes near the nozzle than gasoline, but the difference becomes negligible downstream. Ethanol has the lowest droplet size near the nozzle, but is only 2µm higher than the ones downstream.

4. The Injection pressure plays an important role in the droplet size. For DMF, gasoline and ethanol, the SMDs decrease to 8.8, 8.3 and 7µm respectively when the injection pressure increases from 50 to 150bar. Increasing the injection pressure benefits the DMF spray more so than ethanol's.

In conclusion, 100% DMF and its blend with gasoline have shown great potential to be adapted in a gasoline engine in terms of the spray characteristics. The combustion

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investigation, engine performance and emissions will be presented in our following papers to describe the adaptability of DMF as an alternative fuel of gasoline.

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REFERENCES

1. Roman-Leshkov Yuriy, Barrett Christopher J., Liu Zhen Y., Dumesic James A., Production of dimethylfuran for liquid fuels from biomass-derived carbohydrates. Nature 447, 2007(7147): p. 982.

2. Binder Joseph B., Raines Ronald T., Simple Chemical Transformation of Lignocellulosic Biomass into Furans for Fuels and Chemicals. J. AM. CHEM. SOC. 9 2009. **131**(No. 5).

3. Pitcher G., Wigley G. (1994). Simultaneous Two-Component Velocity and Dropsize Measurements in a Combusting Diesel Fuel Spray. Seventh International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal.

4. Wigley G., Hargrave G.K., HeathJ. (1998). A High Power, High Resolution LDA/PDA System Applied to Dense Gasoline Direct Injection Sprays. 9th International Symposium on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal.

5. Julien, LACOSTE (2006), Characteristics of Diesel Sprays at High Temperatures and Pressures. PhD Thesis, School of Engineering, University of Brighton.

6. (2005). LDV/PDPA System: Instruction Manual, P/N 1990013, Revision D, TSI.

7. Saitoh, H. and Uchida, K., "Difference of Spray Mixture Formation between Gas-Oil and Ethanol in the Constant Volume Electrical Heating Chamber," SAE Technical Paper 2007-01-3617, 2007.

8. Kapus, P.E., Fuerhapter, A., Fuchs, H., Fraidl, G.K., "Ethanol Direct Injection on Turbocharged SI Engines - Potential and Challenges," SAE Technical Paper 2007-01-1408, 2007.

9. Hemdal, S., Denbratt, I., Dahlander, P., and Wärnberg, J., "Stratified Cold Start Sprays of Gasoline-Ethanol Blends," *SAE Int. J. Fuels Lubr*. **2**(1):683-696, 2009.

10. Aleiferis, P.G., Malcolm, J.S., Todd, A.R., Cairns, A. et al., "An Optical Study of Spray Development and Combustion of Ethanol, Iso-Octane and Gasoline Blends in a DISI Engine," SAE Technical Paper 2008-01-0073, 2008.

11. Serras-Pereira, J., Aleiferis, P.G., Richardson, D., and Wallace, S., "Characteristics of Ethanol, Butanol, Iso-Octane and Gasoline Sprays and Combustion from a Multi-Hole Injector in a DISI Engine," *SAE Int. J. Fuels Lubr*. **1**(1): 893-909, 2008.

12. Hu, C., Jian-Xin, W., Shi-Jin, S., Xin-Liang, A. et al., "Effects of Ethanol in Ester-Ethanol-Diesel Blended Fuels on Spray Behavior and PM Emission," SAE Technical Paper 2006-01-0236, 2006.

13. Hiroyasu, H. and Kadota, T., "Fuel Droplet Size Distribution in Diesel Combustion Chamber," SAE Technical Paper 740715, 1974.

14. Shimizu, M., Arai, M., Hiroyasu, H., Measurements of Breakup Length in High Speed Jet. Bulletin of JSME, 1984. **27**(230).

15. Tabata, M., Fujii, H., Arai, M., Hiroyasu, H., Mean Drop Diameter of a Diesel Spray in a Vaporizing process. JSME International Journal, Series II, 1991. **34**(3).

16. Mitroglou N., Nouri J. M., Gavaises M., Arcoumanis C., Spray Characteristics of a Multi-hole Injector for Direct-Injection Gasoline Engines, Int. J. Engine Res., 2006. **7**(3): p. 255-270.

17. Chu, Cho-Chone C. (1986). One-Dimensional Transient Fluid Model for Fuel-Coolant Interaction Analysis, PhD Thesis, University of Wisconsin-Madison.

ABBREVIATIONS

ASOI
after start of injection

CW
continuous wave

IMEP
indicated mean effective pressure

DMA
N,N-dimethylacetamide

DMF
2,5-dimethylfuren

PDPA
phase Doppler particle analyzer

PDA
phase Doppler anemometer

SMD
Sauter mean diameter (D32)

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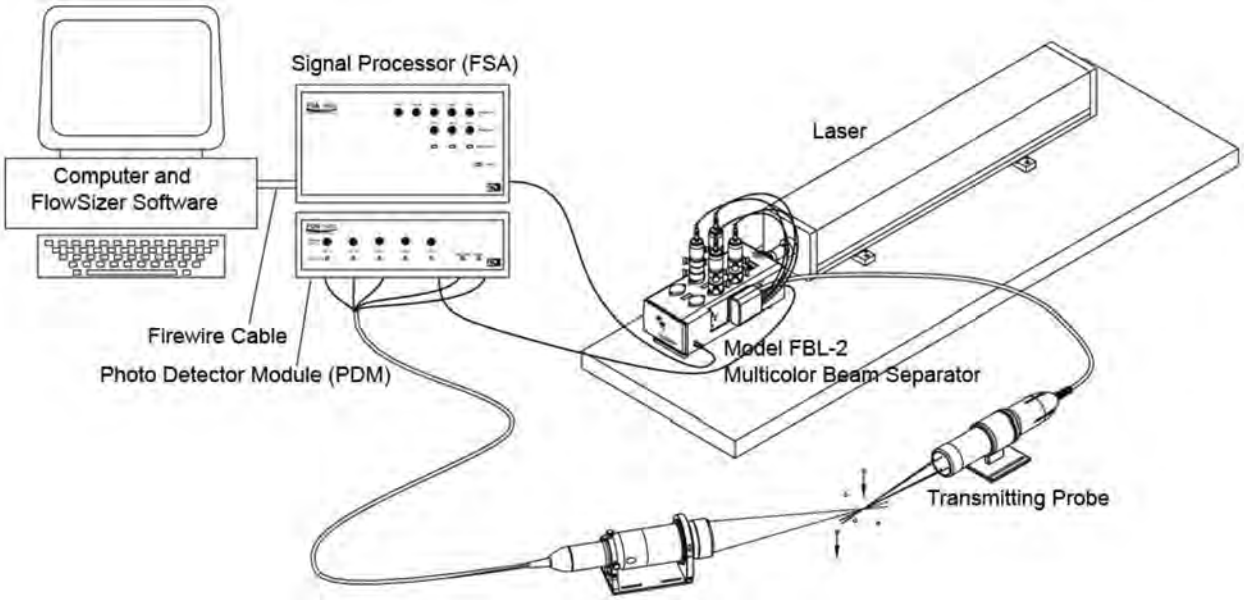
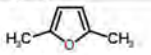


Fig. 1. Components of PDPA system [6]

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APPENDIX

Main properties of DMF, Ethanol and gasoline.

Name(s)	2,5 Dimethylfuran 2,5 Dimethyl-furan 2,5 Dimethylfurane 2,5 Dimethyloxole	Ethanol Ethyl Alcohol Ethyl Hydroxide EtOH	Gasoline Petrol
CAS Registry Number	625-86-5	64-17-5	8006-61-9 86290-81-5
Linear Structure Formula	$(CH_3)_2C_4H_2O$	CH_3OCH_3	Variable
Molecular Formula	C_6H_8O	C_2H_6O	C_2 to C_{14}
Molecule Schematic			Variable
M, Molecular Mass	$96.1289gmol^{-1}$[1]	$46.069gmol^{-1}$[1]	$100-105gmol^{-1}$ [2]
Type of Substance	Heterocyclic	Acyclic	Aliphatic Hydrocarbon Mixture
Appearance	Colourless Liquid	Colourless Liquid	Colourless to amber coulured liquid
Aroma	Spicy, Smokey	Vinous	Petroelem odor
Safety	Flamable, Irritant	Flamable, Irritant, CNS effects	Highly Flamble, Irritant
Water Solubility[3]	Insoluble <1mg/ml @73°F	Highly soluble >=100mg/ml @73°F	Insoluble
MP, Boiling Point (1atm)	−62.8°C[3]	−130°C[4]	-
BP, Boiling Point (1atm)[1]	93.0°C	77.3°C	96.3°C(FBP)
Enthalpy of Vaporization (20°C)[4]	31.91kJmol^{-1}	43.2496kJmol^{-1}	-
Enthalpy of Formation[5]	−97.9kJmol^{-1} @298.15K	−234.963kJmol^{-1}	-
Vapor Pressure	7.2 kPa (22°C)[6]	7.869 kPa[7](25°C)	72.007 kPa[4](25°C)
ρ, Density of Liquid[1]	$895.4kgm^{-3}$ @20°C	$793.63kgm^{-3}$@15°C	-
Vapor Density (air=1)	3.31[7]	1.59[8]	3-4[9]
Refraction Index (20°C)[4]	1.443	1.361	-
Specific Gravity (4°C, 1atm)[4]	0.892-0.898	0.910	-
Molar Volume (4°C, 1atm)[4]	$104.7cm^3$	$59cm^3$	-
Surface Tension[4]	25.9dyne cm^{-1}	22.3dyne cm^{-1}	20dyne cm^{-1}
Polar Surface Area[4]	13.14Å^2	9.23Å^2	-
Viscosity(1atm, 20°C)	0.65cP[10]	1.2cP[11]	0.4-0.5cP[12]
Research Octane Number (RON)	119[3]	110[2]	95[13]
Heating Value[1]	32.88MJkg^{-1}	26.9MJkg^{-1}	43.4MJkg^{-1}

[1] *Beilstein Database April 2008*

[2] *US Department of Energy. Alternative Fuels and Advanced Vehicles Data Centre. October 2008*

[3] *Cameo Chemicals, US Gov. Chemical Data Sheet, 2, 5 Dimethylfuran. October 2008*

[4] Chemspider.com *January 2009 (NB: Prediction Software is utilised by this source when experimental values are unavailable)*

[5] *F M WELLE & Others. Thermochemical Studies for Determination of the Standard Molar Enthalpies of Formation of Alkyl-Substituted Furans and Some Ethers. Structural Chemistry June 1998*

[6] *NTP, 1992*

[7] http://www.iterasi.net/openviewer.aspx?sqrlitid=qpgkevc0qugba9dhaqnsyw

[8] *Material Safety Data Sheet, Ethanol, Absolute.* https://fscimage.fishersci.com/msds/89308.htm

[9] *GASOLINE SAFETY.* http://www.burnsurgery.org/Documents/gasoline_safety.doc

[10] *knovel database*

[11] http://en.wikipedia.org/wiki/Ethanol

[12] http://chemed.chem.purdue.edu/genchem/topicreview/bp/ch14/property.php

[13] *Delphi. Worldwide Emissions Standards, Passenger Cars & Light Duty Trucks. 2008*