15th Australasian Fluid Mechanics Conference
The University of Sydney, Sydney, Australia
13-17 December 2004

Effect of pulsation rate on spray-spreading rate in an isothermal environment

L. Stamatova, D. Honnery, V.Stamatov, J. Ghojel, J. Soria

Laboratory for Turbulence Research Aerospace & Combustion (LTRAC)
Department of Mechanical Engineering
Monash University, VIC 3800, AUSTRALIA

Abstract

Preliminary results from Planar Laser Induced Fluorescence (PLIF) measurements of pulsed and continuous sprays at isothermal conditions indicate that, at otherwise identical conditions (constant Reynolds number and constant ratio between the injection duration and cycle period), pulsation leads to an increase of the spray-spreading rate of up to four times. Furthermore, the increased pulsation frequency leads to an increase of the spray-spreading rate. PIV measurements are required to provide quantitative data about in-plane velocity and out-of-plane vorticity flow fields.

Introduction

The diesel engine is well known to offer superior fuel consumption compared to the gasoline engine. It is also less complicated, has better torque performance (i.e. over it engine speed range) and is able to run on a wider range of fuels. It is therefore the dominating power plant for heavy-duty transportation needs. However, compared to the conventional, catalyst equipped, gasoline engines, diesel engines emit higher level of oxides of nitrogen (NO_x) and particulate matter. Particulate matter can accumulate in the respiratory system and is associated with numerous adverse health effects, possibly including cancer. Carbon monoxide enters the bloodstream through the lungs and forms carboxyhemoglobin, a compound that inhibits the blood's capacity to carry oxygen to organs and tissues. Infants, elderly persons, and individuals with heart and/or respiratory diseases are particularly sensitive to carbon monoxide poisoning. Hydrocarbons together with nitrogen oxides react in sunlight to form ground-level ozone, a major component of smog. A number of exhaust hydrocarbons are also toxic, with the potential to cause cancer [1, 2, 3, 4].

Overall performance of diesel engines is influenced by various flow mechanical factors, such as in-cylinder gas flows, fuel spray characteristics, mixing between fuel and gas, combustion characteristics and so on. Among them, the fuel spray characteristics often impose a commanding influence on the combustion phenomena, which in turn control the emission rate of nitrogen oxide and diesel particulate. The fundamental background for the high emissions of NO_x and soot from the diesel engine, despite an overall lean operation, is the fuel heterogeneity in the combustion chamber [5], [6]. This fuel heterogeneity stems from the procedure to introduce the fuel into a high temperature atmosphere when the piston is near dead centre. Diesel fuel autoignites readily when heated and the mixing between fuel and air is very limited before combustion commences. This creates a mixing controlled combustion situation with very hot combustion zones were the fuel and oxygen meet. The production of NO_x is favoured here. Fuel rich regions are encountered in the central parts of the reacting fuel spray and these promote the formation of soot. A schematic illustration of a spay flame structure is shown in Figure 1.

Greater mixing is required to reduce pollutants emission, but in diesel engines the degree of mixing is fixed by the geometry of the combustion chamber (which may provide swirl and tumble of the two streams) and spray nozzle (cone angle and droplet size). One way of overcoming this limitation may be to pulse the spray during combustion. In pulsing sprays the supply of external fluid is not steady. These sprays consist of periodic pockets of fluids injected into the surrounding air.

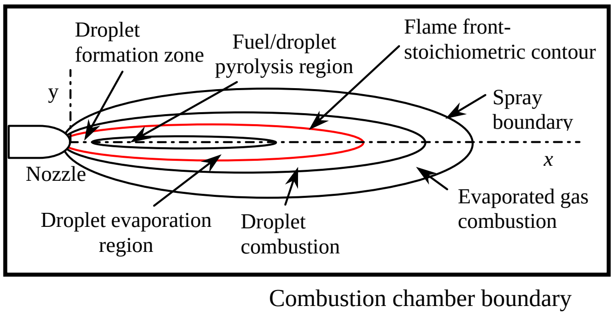


Fig. 1. A schematic illustration of a spay flame structure.

The structures at the boundary of the spray are responsible for the mixing of droplets with the surroundings. The radial spread is sensitive to the initial conditions including the supply of liquid, which in pulsing sprays is not constant and periodically oscillates. Mixing rate can be quantified using the spray-spreading rate and the decay of droplets number and velocity along the spray trajectory [7].

Important non-dimensional groups characterising pulsing sprays are Reynolds ($Re_d = \rho Ud/\mu$) and Strouhal ($St_d = fd/U$) numbers. Here ρ, and μ are the density and viscosity of the liquid, U is the relative velocity between gas- and liquid-phases, d - diameter of the orifice and f is the frequency of pulsation. The jet exit velocity, U, is determined on the basis of mass conservation over the one pulse cycle.

A comparison of round fully pulsed jets has been performed in the laser Doppler anemometry measurements of Bremhorst [8]. The experiments have shown, that like a continuous round jet, a fully pulsed jet has a centreline velocity that decays inversely with stream-wise distance. However, the rate of decay is much slower than comparable “steady jets”. This decrease in stream-wise velocity is balanced by an increase in the volume flow-rate. Bremhorst [8] measured significantly higher Reynolds stresses for the pulsed turbulent jets and an increased entrainment, up to twice the value for a continuous stream.

The primary aim is to determine via measurement the degree to which mixing is enhanced in a spray by pulsation. Questions to be examined are: (i) What rates of pulsation increase spray and surrounding gas mixing and by what degree;

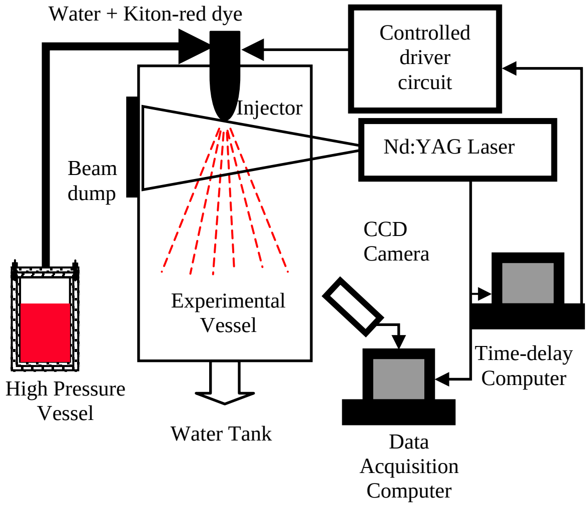


Fig. 2. A schematic diagram of the experimental setup.

(ii) What is the influence of the pulsation time ratio (fluid pulse to total pulse cycle time ratio) on mixing.

To overcome the difficulties of the high pressure, intermittent combustion environment found in engines, current investigation considers a non-reactive, single, round sprays in an isothermal environment. The PLIF technique was used to provide qualitative data about the spray evolution, decay and mixing with the surrounding air. The Reynolds number based on the orifice diameter was kept constant. The frequency of pulsation and the injection duration, *S*, were varied. Here the injection duration is defined as that fraction of the cycle period for which the spray was turned on. Note that the ratio *S*/*T*, where *T* is the cycle period, was kept constant at 0.7 to ensure a constant flow rate during time-averaging experiments.

Experimental approach

The LTRAC's isothermal spray system was used for the current experiments. A schematic diagram of the experimental setup is given in Figure 2.

The spray was produced by sending a high-pressure stream of liquid (water) to a pintle type, fuel injector. The operating pressure of the injector can vary from 500 to 1500 kPa, the maximal frequency of pulsation is 230 Hz, and the minimal injection duration is 2 ms. A current controlled driver circuit (CCDC) controlled the motion of the liquid (water) trough the injector, ensuring very short (<1 ms) response time. Due to the inertia effect of the mass of the fluid being pumped, there is a delay, leading to a ramp up of the nozzle exit velocity from zero to the constant velocity, even when CCDC has a response time of <1ms. In order to take into account the inertia effect of the mass of the fluid, the fluid velocity was determined from the accumulated mass injected during multiple (>1000 times) pulsation of the jet.

A single cavity, Q-switched, pulsed Nd:YAG laser model "Brilliant B" was used to irradiate the spray. The fundamental wavelength of the laser, 1064 nm, was frequency doubled to 532 nm. Kiton Red, which emits at 584 nm for a 532 nm incident wavelength was used as the fluorescent dye. Suitable optics was used to create a laser sheet about 1 mm thick. The light sheet was aligned to pass along the central axis, *x*, of the spray.

A 12-bit, 1280 x 1024 pixels Pixel-Fly CCD camera coupled with a Pentium based PC with data processing software was used for image acquisition. Illumination of the spray results in the spray droplets scattering both incident and fluorescent wavelengths. The camera was fitted with a suitable filter to separate scattered 532 nm and fluorescent 584 nm signals. Only the fluorescent signal was collected.

In order to obtain phase-matched data, the performance of the injector, lasers and cameras need to be precisely synchronised. The Nd:YAG laser sent triggering impulses to the data acquisition equipment and time-delay computer. The time-delay computer used Real-time Linux software to send TTL signals to CCDC that turns the injector on.

Experimental results

Four different cases were studied. In all of the cases, the line pressure was kept constant at 1000 kPa, which corresponds to Re_d = 3567 (based on the diameter of the orifice of 1 mm). The experimental conditions are summarised in Table 1.

	Case 1	Case 2	Case 3	Case 4
f (1/s)	167	83	42	21
T (ms)	6	12	24	48
Re_d	3567	3567	3567	3567
St_d	0.0468	0.0233	0.0118	0.0059
S (ms)	4	8	17	34
S/*T*	0.7	0.7	0.7	0.7

Table 1. Summary of the experimental conditions.

A typical spray evolution is shown in Figure 3. Case 1 (Table 1) was considered. Instantaneous images were taken every 1 ms. The multistage interaction between the liquid-phase and the surrounding gas-phase includes the following steps: (a) the emerging jet becomes partly mixed with the surrounding gas-phase due to jet turbulence; (b) shortly after the start of injection, the jet spreads out in the *y*-direction, this leads to velocity decrease in the *x*-direction; (c) the degree of atomisation increases due to the break-up of large droplets as the jet moves further along the x axis; (d) an outer vortex deflects the droplets outwards and opens the spray cone.

Time-averaged contour plots were used to calculate the spray-spreading rate. 256 instantaneous images were taken per plot. Here the spray-spreading rate is defined as L_y/L_x where L_y and L_x are the limits of the spray in the radial, *y*, and central, *x*, directions. For the purposes of the current work, the limits are defined as the length and width of a contour for which the intensity of the fluorescence signal from the spray decays to 27% ($2/e^2$) from the maximum intensity of the signal from the same spray. These contours are plotted in Figure 4 for the four cases of interest for the current work. The contour of a continuous spray taken at the same Re_d number is shown for comparison. The spray-spreading rate, L_y/L_x of the continuous spray was 0.04. The spray-spreading rates of the pulsed sprays, cases 1-4 were found to be much higher (~0.16), being independent of the frequency of pulsation. The shape of the spray changes as the frequency of pulsation decreases, showing gradually more of the features of the continuous spray.

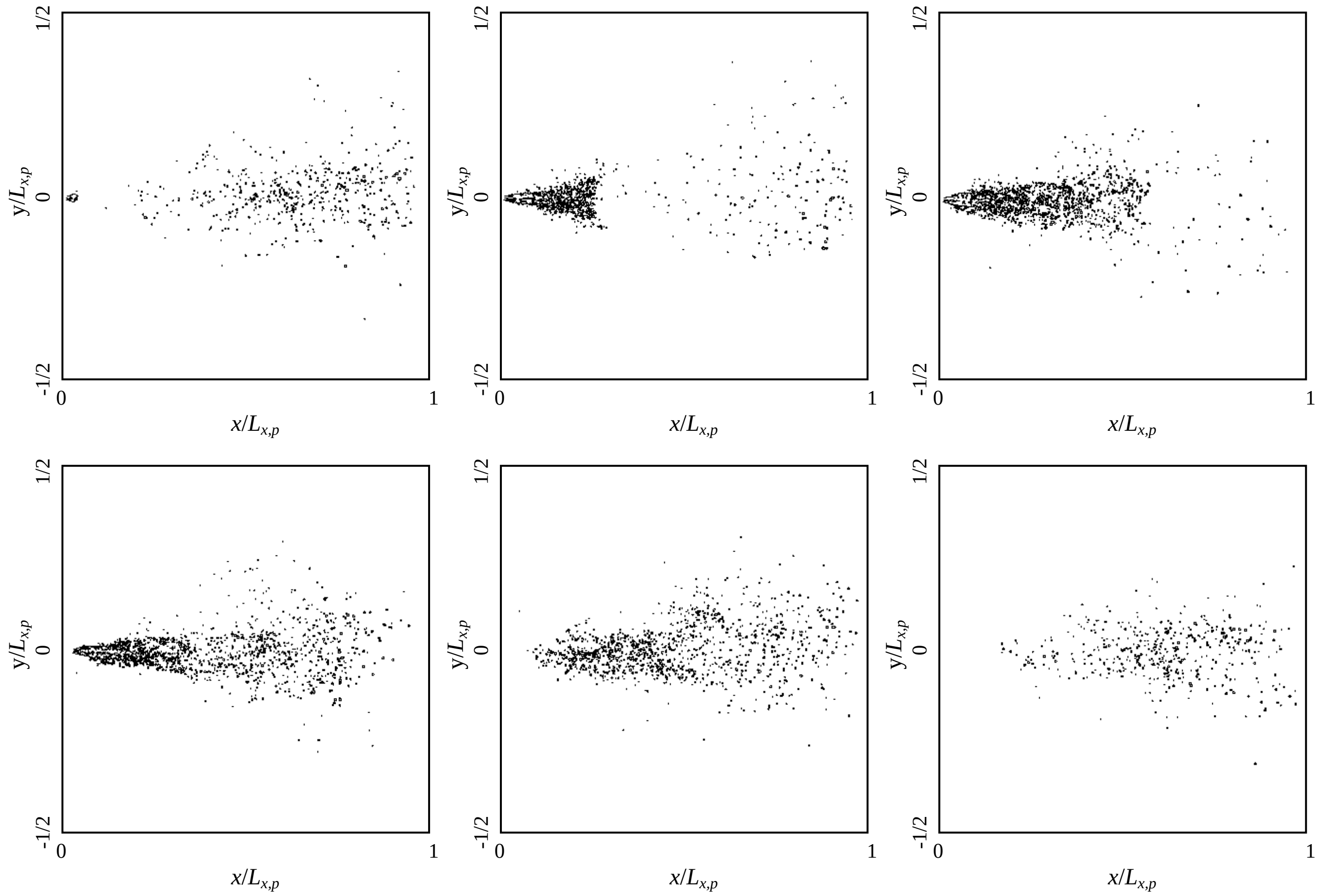
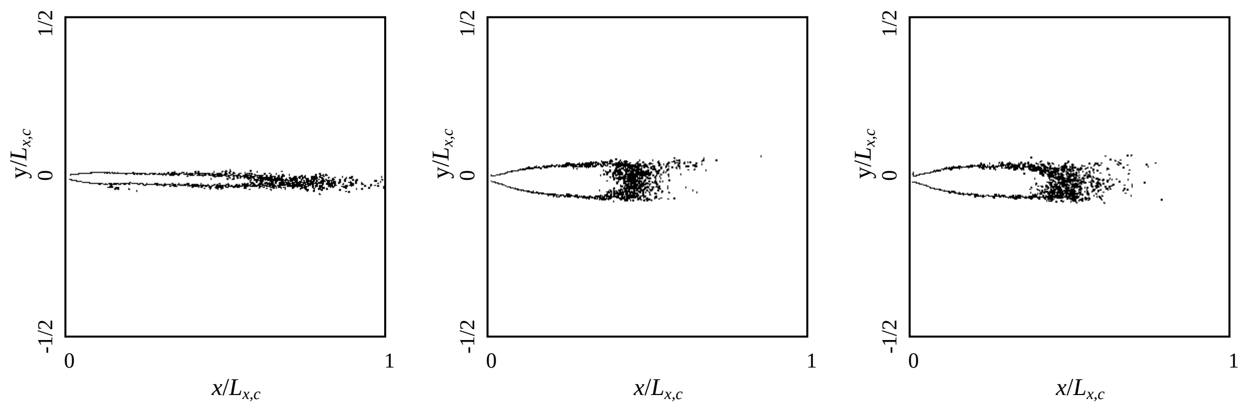


Fig. 3. A typical pulsed spray evolution, Re_d = 3567, St_d = 0.0468, S = 4 ms. $L_{x,p}$ is the maximal length of the spray.



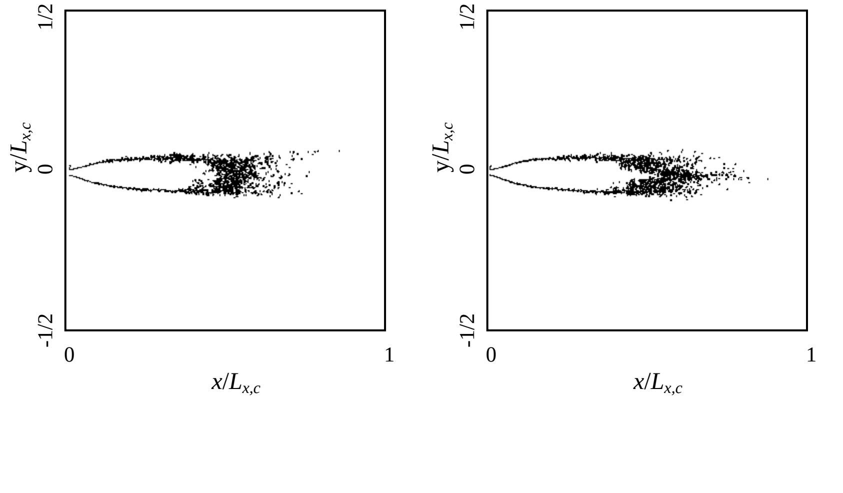


Fig. 4. Time-averaged contour plots of continuous and pulsed sprays at Re_d of 3567. $L_{x,c}$ is the length of the continuous spray.

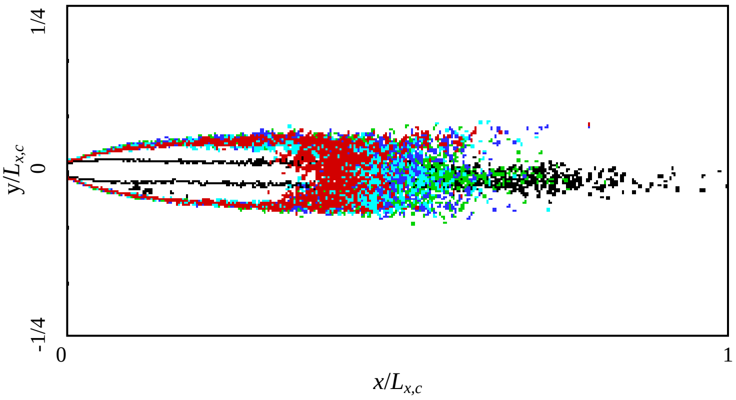


Fig. 5. Limits of pulsed sprays 1-4 compared with this of the continuous spray (marked in black) at Re_d of 3567. Spray 1 is marked in red, spray 2 – in cyan, spray 3 – in blue, and spray 4 – in green. $L_{x,c}$ is the length of the continuous spray.

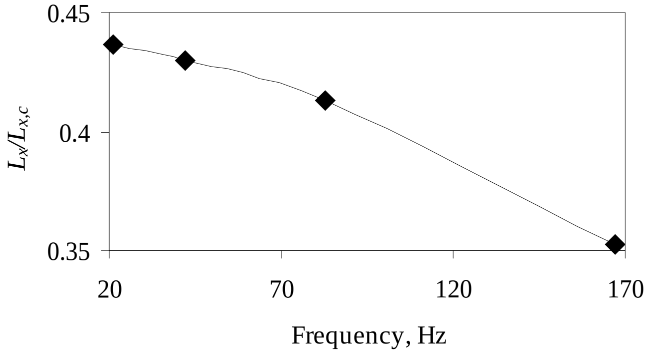


Fig. 6. Normalised length of pulsed sprays 1-4, $L_x/L_{x,c}$, versus frequency of pulsation. $L_{x,c}$ is the length of the continuous spray.

The size of sprays 1-4 is compared with that of the continuous spray in Figures 5 and 6. The sprays limits were calculated on the base of the 27% decay from the maximal signal intensity of the continuous spray. It can be seen that the pulsed sprays are shorter and wider compared with the continuous spray (Figure 5), which in turn should ensure better mixing between the spray and the surrounding air. Furthermore, while the width of the pulsed sprays remains approximately constant, the length of the sprays is inversely proportional to the pulsation frequency, Figure 6. At otherwise identical conditions (constant Reynolds number and constant ratio between the injection duration and cycle period), the increased pulsation frequency leads to an increase of the spray-spreading rate.

Conclusions

Preliminary results from PLIF measurements of pulsed and continuous sprays at isothermal conditions indicate that, at otherwise identical conditions (constant Reynolds number and constant ratio between the injection duration and cycle period), pulsation leads to an increase of the spray-spreading rate of up to four times. Furthermore, the increased pulsation frequency leads to an increase of the spray-spreading rate. PIV measurements are required to provide quantitative data about in-plane velocity and out-of-plane vorticity flow fields.

References

1 US Environmental Protection Agency, *Study of Exhaust Emissions from Diesel Trucks and Commercially Available Idle-Reducing Devices*, Certification and Compliance Division, Office of Transportation and Air Quality, EPA420-R-02-025, October, 2002.

2 Mage, D.T. & Zali, O., *Motor vehicle air pollution*, World Health Organisation, Geneva, 1992.

3 World Health Organisation: *Diesel Fuel and Exhaust Emissions*, Stuttgart, Environmental health criteria, 171, 1996.

4 Sher, F. (Editor) *Handbook of Air Pollution from Internal Combustion Engines*, Academic Press, London, 1998.

5 Turns, S.R., *An Introduction to Combustion: Concepts and Applications*, 2nd Ed., McGraw-Hill, Singapore, 2000.

6 Glassman, I., *Combustion*, Academic Press Inc. Ltd., London, 1987.

7 Cater, J., *An experimental investigation of viscous vortex rings and zero-net-mass flux jets*, PhD thesis, Monash University, 2002.

8 Bremhorst, K. & Hollis, P., Velocity field of an axisymmetric pulsed, subsonic air jet, *AIAA Journal*, **28** (12), 1990, 2043-2049.