Experimental observations of fuel sprays in gasoline engines

S. Begg
The Sir Harry Ricardo Laboratories
Centre for Automotive Engineering

13th April – Workshop- New mathematical tools for modelling the processes in IC engines: a dialogue between mathematicians and engineers
Contents of presentation

• Current objectives in gasoline engine research
• Progression in gasoline fuel injection systems
• Key characteristics of fuel sprays
• Optical diagnostics commonly applied to sprays
• The Phase Doppler anemometer
• Conclusions and modelling challenges for fuel sprays
Current objectives in gasoline engine research

- Significant simultaneous reduction in emissions and consumption
  - Direct injection, downsizing, boosting, VVA technologies...
- Fuel injection system optimisation
  - Metering, variable needle lift, phasing, targeting, atomisation, multi-shot, fuel blends...
- Engine management system
  - Crank-angled resolved, poor cycles identified, multi-strike ignition...

Understanding the fuel injection process is key to the mixture preparation... the ‘trial and error’ approach is no longer adequate...
Progression in fuel injection systems

- Single point and multi-point port fuel injection (PFI)
  - 2-12 bar fuel pressure / fixed OVI and CVI injection timing
  - High cyclic variations, poor lean operation, poor tolerance to EGR

- 1st generation direct injection (G-DI)
  - 10-120 bar fuel pressure / range of injection timings
  - Optimised flow structures / stratification of charge
  - Sensitivity to fuel injector location and spray characteristics
  - Relatively high ubHC and NOx emissions
Progression in fuel injection systems

- 1\textsuperscript{st} generation direct injection (G-DI)
  - 10-120 bar fuel pressure / range of injection timings
  - Single and multi-hole solenoid

(Preussner et al., (1998))
Progression in fuel injection systems

- 2nd generation direct injection - high degree of specialism
  - 150 - ?? bar fuel injection pressure / variable needle lift / multi-shot
  - Outward pintle or multi-hole, solenoid and piezo

BMW stratified, 16° Spark plug / Injector

Images courtesy of collaborative project with Uni. Of Cardiff and Ricardo, 0.3 to 0.9 ms ASOI, 200 bar, ambient pressure gas
Progression in fuel injection systems

- 2nd generation direct injection
  - 200 bar fuel injection pressure/outward pintle solenoid injector
  - Laser light-sheet (Mie scattering) highlights head vortex-ring-like structures

Images courtesy of collaborative project with Uni. Of Cardiff and Ricardo, 0.3 to 1.2 ms ASOI, E85 at 200 bar, ambient pressure gas
Key characteristics of the fuel spray

- Spray geometry (cone, separation, deflection angles)
- Length scales (penetration/impingement)
- Droplet atomisation ‘quality’
- Time scales (0.1 to 100 ms range)
- Shot-to-shot repeatability
- Vortex ring-like structures

Images courtesy of collaborative project with Uni. Of Cardiff and Ricardo
Optical diagnostics commonly applied to sprays

- Photographic
- Planar Mie techniques
- Planar inelastic scattering techniques
- Phase Doppler Anemometry

1 Nouri et al., 2007, 2 (Fansler et al., 2006)
Optical diagnostics commonly applied to sprays

- Simple static chamber
Optical diagnostics commonly applied to sprays

- Steady-flow rig
Optical diagnostics commonly applied to sprays

- Fired, optical engine
Spray imaging- chamber

PFI multi-stream

Off-axis pressure-swirl

Flat fan

Fan images courtesy of collaborative project with Uni. Of Cardiff and Ricardo
Combining Spray Imaging with PDA

- axial and radial waves
- droplet stripping
- asymmetry
- ‘hesitation’ due to necking of the liquid stream
Spray imaging- motored engine

Top-entry G-DI – effect of in-cylinder pressure

Early Injection  
60° - 121°

Late Injection  
301°- 318°

Onset

Middle

End
Phase Doppler anemometer (PDA)

- Conventional PDA

\[ I_{(x,y,z)} = I_1 S(\theta, \phi, q, n) \]

\[ q = \frac{\pi d_p}{\lambda} \]
Phase Doppler anemometer (PDA)

- Polar distribution of light intensity

\[ d_p \approx 1.0 \lambda \]

\[ d_p \approx 10 \lambda \]

Brewster’s angle used to collect first order refraction \( p=1 \)

\[
d_p = -\Phi \left( \frac{\lambda}{2\pi} \right) \left( \frac{\sqrt{2(1 + \cos \theta \cos \varphi \cos \phi)(1 + n^2 - n\sqrt{2(1 + \cos \theta \cos \varphi \cos \phi)})}}{n \sin \theta \sin \varphi} \right)
\]
Phase Doppler anemometer (PDA)

- Typical features of time series at two locations in a high-pressure spray

\[ r = 0, \ x = 15 \text{ mm} \quad r = 10, \ x = 15 \text{ mm} \]
PDA– Spray chamber

Initial Phase

Quasi-steady Phase

Trailing Phase
Combining imaging with PDA—Spray chamber

Distance (mm) 0

Injector ‘D’

Injector ‘F’

Injector ‘G’

Fully-developed Spray Region

Droplet Velocity Distribution

Droplet Diameter Distribution
Vortex ring-like structures

- Development of a generalised vortex ring model

Chronological sequence of high-speed photographs, (left to right) recorded using a laser light sheet, in a G-DI spray in an optical engine with full glass cylinder liner.

The distribution of the vorticity magnitude for $t=3.75$ ms
Phase Doppler anemometer (PDA)

- Vortex-ring like features in a high-pressure spray
Phase Doppler anemometer (PDA)

- Reconstruction of the spatial distribution of the droplet velocity and size
- Data ensemble-averaged within arbitrary time bins
- Track features (e.g. translation of region of maximal vorticity)
Vortex ring-like structures

Chronological sequence of high-speed photographs, recorded using a laser light sheet, (left to right) in a static spray chamber, 150 bar fuel pressure, 6 barg gas pressure, 1 to 10 ms ASOI, gasoline fuel.

Images courtesy of collaborative project with Uni. Of Cardiff and Ricardo
Phase Doppler anemometer (PDA) – motored engine
Phase Doppler anemometer (PDA) – motored engine

- Comparison of static chamber results with reciprocating engine

Homogeneous operation

Stratified operation
Phase Doppler anemometer (PDA)

- Comparison of higher order number and moment mean diameters for reciprocating engine (e.g. $d_{30}$)

Homogeneous operation
Phase Doppler anemometer (PDA)

- Comparison of higher order number and moment mean diameters for reciprocating engine (e.g. $d_{30}$)
Conclusions and modelling challenges for fuel sprays

- Future experiments must address a single injection event
  - to capture the characteristics at crank angle resolution
  - within a single cycle and from one consecutive cycle to the next
  - correlation with poor cycles of combustion
- Modelling must incorporate the finer details
  - evolution of vortex ring models
  - fuel injection and gas flow coupling
  - multi-component fuels and fuel blends
  - integration of chemical kinetic models with physical models
Acknowledgements

- EPSRC and equipment loan pool
- University of Cardiff (Prof. P. Bowen, Dr M. Alonso and Dr P. Kay)
- Ricardo UK Ltd
- DTI/TSB 2/4 SIGHT and 2/4 CAR programmes
- Staff and students of the CAE
Experimental observations of fuel sprays in gasoline engines

S. Begg
Centre for Automotive Engineering
www.brighton.ac.uk/cae