Spray growth of regular, synthetic, oxygenated and biodiesels in an optical engine

Citation for published version (APA):
Klein-Douwel, R. J. H., Donkerbroek, A. J., Luijten, C. C. M., Boot, M. D., Somers, L. M. T., Dam, N. J., & Meulen, ter, J. J. (2009). Spray growth of regular, synthetic, oxygenated and biodiesels in an optical engine. In *Proceedings of the 7th International Symposium Towards Clean Diesel Engines (TCDE 2009), 4-5 June 2009, Aachen, Germany* (pp. CEUR-).

Document status and date:
Published: 01/01/2009

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 04. Oct. 2023

Spray Growth of Regular, Synthetic, Oxygenated and Biodiesels in an Optical Engine

R.J.H. Klein-Douwel[1]*, A.J. Donkerbroek[1], C.C.M. Luijten[2], M.D. Boot[2], L.M.T. Somers[2],
N.J. Dam[1], J.J. ter Meulen[1]
[1]Applied Molecular Physics, Institute for Molecules and Materials,
Radboud University Nijmegen, The Netherlands
[2]Mechanical Engineering, Eindhoven University of Technology, The Netherlands

Spray formation has been studied in an optically accessible heavy-duty diesel engine for regular diesel, synthetic, oxygenated and biofuels using a high-speed digital camera. Images are analyzed with custom made algorithms to obtain spray penetration length and spray cone angle as function of time. Results from 2 out of the 8 nozzle sprays have been used in the data analysis. Variation in spray equilibrium length and angle is observed between the fuels tested. Modelling of the fuel injection, taking great care to account for individual fuel properties, shows good correspondence with experimental results.

Introduction

Pollutant emissions from diesel engines are subject to ever more stringent regulations and several ways are open to achieve emission reductions. One of them is the use of fuels other than regular diesel, either from biological origin or containing oxygen or a lower fraction of (large) polycyclic aromatic hydrocarbons, in order to reduce soot and/or NO_x emissions (see for instance Refs. [1,2]). While exhaust measurements [2] already reveal important data, additional valuable insight is given by studies in an optically accessible engine. The latter is described in for instance Ref. [1], in which the internal combustion process is studied for the same fuels as used here. A very important aspect, however, taking place before combustion starts, is fuel injection and mixing with the cylinder gas content. This is the subject of the current study.

Fuels

Spray formation has been studied in an optically accessible heavy-duty diesel engine for a range of fuels: regular diesel, a Fischer-Tropsch synthetic fuel, pure Jatropha oil, Jatropha methyl ester (JME), rapeseed methyl ester (RME), tripropyleneglycolmonomethylether (TPGME, $C_{10}H_{22}O_4$), model fuel Idea (70% n-decane and 30% α-methylnaphthalene) and Fischer-Tropsch fuel blended with either cyclohexanone or cyclohexane (the latter two 50/50 blends). Full details of the fuels used are given in Ref. [1].

Experimental setup

The experimental setup is shown in Fig. 1. Sprays emanating from the injector nozzle are illuminated with an Ar^+ laser and light scattering from the fuel spray is recorded through the piston window with a digital high-speed camera ($>3 \cdot 10^4$ frames per second, >200 images per cycle), which is synchronized to the engine's crank shaft (rotating at 1430 rpm). The interval between two successive images is 0.3º ca. Sample digital movies recorded in the engine using various fuels are given as supplementary material in Ref. [1].

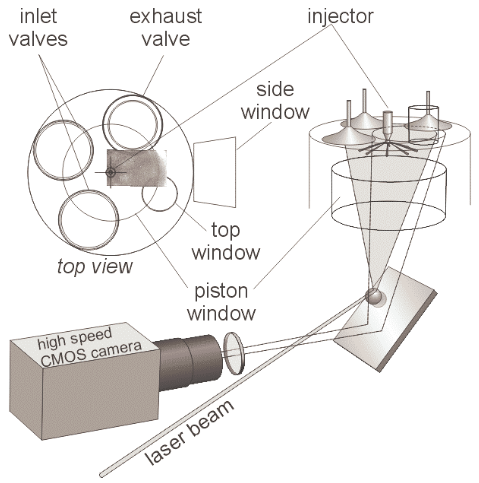


Fig. 1: Experimental setup

Image analysis

Laser light scatters off the liquid fuel spray and the images are inverted ("negative") in order to allow processing by custom made algorithms. Full details are given in Refs. [3,4]. An example of a spray contour thus obtained is shown in Fig. 2. The angle ϑ_Δ is the spray angle as defined in Ref. [4,5], which irons out spray shape irregularities, whereas the angle ϑ_{cone} is defined in Ref. [3].

Spray growth analysis - diesel

Results from two out of the eight nozzle sprays have been used in the data analysis in order to check reproducibility between nozzle holes. Typical spray growth analysis results are presented in Fig. 3. Penetration of the liquid is found to stabilize around an equilibrium value, the so-called liquid length L, for

---

[*] Corresponding author: R.Klein-Douwel@science.ru.nl

Towards Clean Diesel Engines, TCDE2009

all fuels. However, at the time ignition takes place, the equilibrium length significantly decreases due to heating by the flame. Simultaneously the spray angle decreases towards an equilibrium value $\vartheta_{\Delta,eq}$.

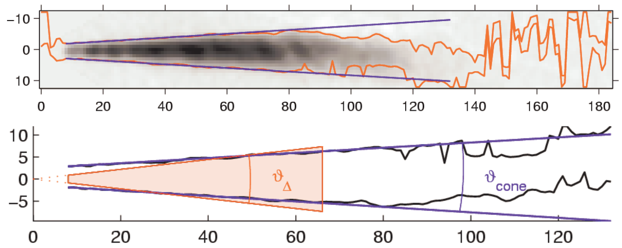
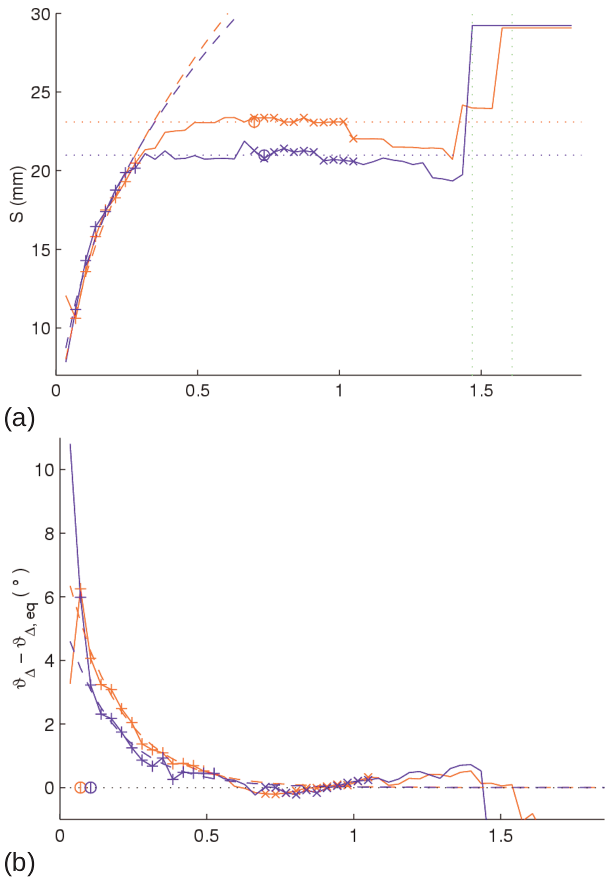
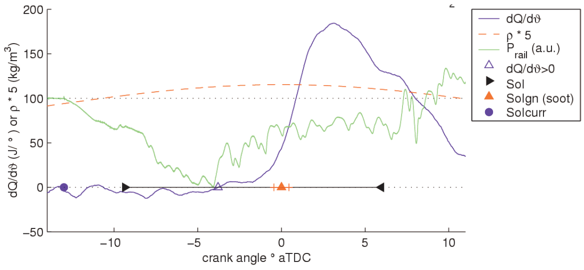


Fig. 2: Spray contour and cone angles as obtained from a typical single high-speed image.

Measurements have been done both with air and with simulated EGR, i.e. a gas mixture with an artificially lowered oxygen concentration of 15%. Since EGR increases the ignition delay, the period in which the steady liquid length is observed is longer, enabling a more accurate evaluation of the steady liquid length.





(c)

Fig. 3: Spray length (a) and and spray angle (b) versus time of a diesel injection at EGR conditions. (c) corresponding heat release rate, common rail pressure, gas density and indication of injection duration ("SoI").

Spray growth - all fuels

A comparison of the steady liquid lengths of the various fuels investigated is given in Fig. 4. It appears that differences between fuels are of the same order as the differences between two individual sprays (typically a few mm's on an average liquid length of 20 mm). Most notably, the steady liquid length of pure Jatropha, which has a very high viscosity, is not significantly larger than that of other fuels.

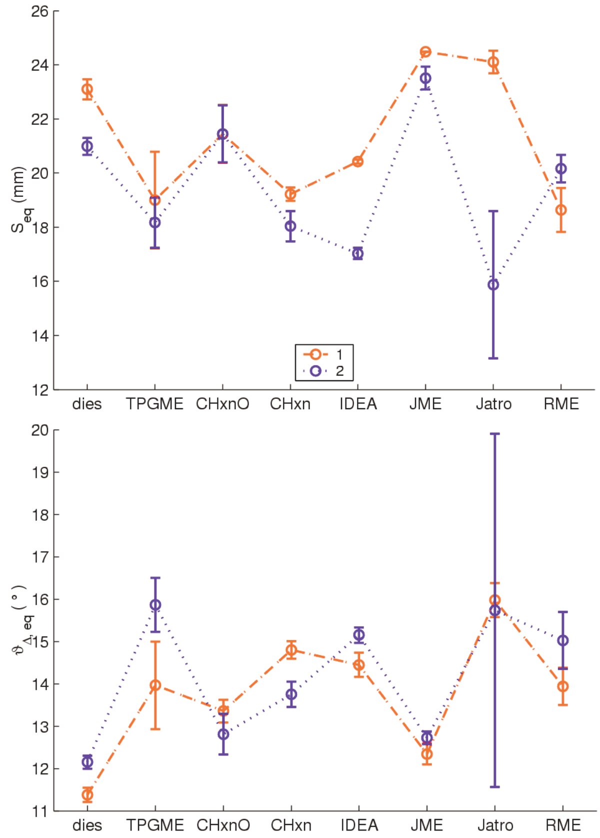


Fig. 4: Spray equilibrium length (top) and angle (bottom) for the various fuels investigated for the case of EGR and start of fuel delivery at -4.5º aTDC.

Modelling spray growth

Modelling results for the spray equilibrium length are shown in Fig. 5. The initial spray penetration speed is found to be well described by the model of Naber and Siebers [5]. Model values for the steady liquid length are obtained using the model by Siebers based on the assumption of mixing-limited evaporation. Considerable effort was spent on collecting reliable physico-chemical properties for the fuels of interest. Both diesel and Fischer-Tropsch fuel are modelled as n-heptadecane, which has been proven to be the n-alkane resembling the evaporation behaviour of diesel best. Jatropha oil is modelled as triolein, which is one of its main constituents. Consistent with this, JME is modelled as methyloleate, properties of which are readily available. RME was modelled by the same substance, which is justified by the small variance in relevant fluid properties of methylesters, alkanes and organic acids having approximately the same carbon chain length.

Using fluid properties as above, considerable differences in steady liquid lengths were found from the liquid length model. For pure Jatropha, the (very small) model values are unreliable, since the mixing-limited assumption can no longer be expected to hold. For the other fuels, model values are in the same range as experimental values, provided that an empirical constant in the Siebers model is replaced by its theoretical value. Moreover, the spray cone angle in the model had to be taken from literature correlations, since the liquid cone angle measured in this work does not cover the vapour phase and therefore gives too small values, leading to a severe overprediction of liquid lengths.

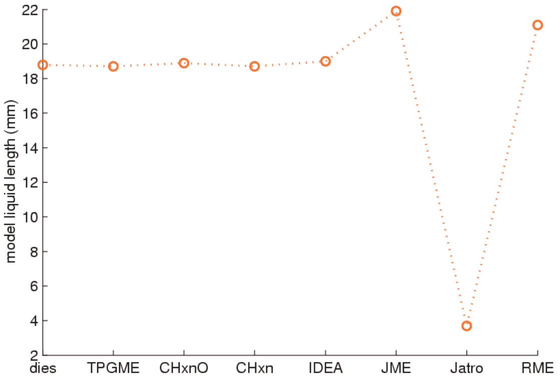


Fig. 5: modelled equilibrium spray lengths for various fuels.

Conclusions

High speed digital imaging of the liquid fuel sprays in an optically accessible heavy-duty diesel engine, operating on a range of relevant fuels, has been used to determine the equilibrium lengths and cone angles of the fuel sprays. Variation in these two parameters is observed between fuels and as function of injection timing, but also between two neighbouring sprays during a single injection, typically a few mm on an average length of about 20 mm. Since the laser light scattering originates from the liquid phase of the fuel only, the obtained spray angle does not include the vapour phase and is therefore somewhat smaller than may be expected. In the model the spray cone angle is therefore taken from literature correlations. Modelling of the fuel injection, taking great care of individual fuel properties, yields liquid lengths rather close to the experimental values (only a few mm lower), except for pure Jatropha oil, where a modelling assumption is expected to break down. The model is therefore able to make useful predictions for the various fuels tested.

Acknowledgments

The help of E.L.M. Rabé in esterifying the Jatropha oil is gratefully acknowledged, as are useful discussions with X.L.J. Seykens (Eindhoven University of Technology) and financial support from Technology Foundation STW.

References

[1] R.J.H. Klein-Douwel, A.J. Donkerbroek, A.P. van Vliet, M.D. Boot, L.M.T. Somers, R.S.G. Baert, N.J. Dam, J.J. ter Meulen, *Soot and chemiluminescence in diesel combustion of bio-derived, oxygenated and reference fuels,* Proc. Combust. Inst. **32**, 2817-2825 (2009).

[2] M.D. Boot, P.J.M. Frijters, R.J.H. Klein-Douwel, R.S.G. Baert, *Oxygenated fuel composition impact on Heavy-Duty diesel engine emissions,* SAE Technical Paper 2007-01-2018 (2007).

[3] R.J.H. Klein-Douwel, P.J.M. Frijters, L.M.T. Somers, W.A. de Boer, R.S.G. Baert, *Macroscopic diesel fuel spray shadowgraphy using high speed digital imaging in a high pressure cell,* Fuel, **86**, 1994 - 2007 (2007)

[4] R.J.H. Klein-Douwel, P.J.M. Frijters, X.L.J. Seykens, L.M.T. Somers, R.S.G. Baert, *Gas density and rail pressure effects on diesel spray growth from a heavy-duty common rail injector,* Energy & Fuels (2008) (doi: 10.1021/ef8003569)

[5] J.D. Naber, D.L. Siebers, *Effects of Gas Density and Vaporization on Penetration and Dispersion of Diesel Sprays,* SAE Technical Paper 960034 (1996)