Experimental investigation of spray characteristics of fuel blends having low cetane number and high volatility in a diesel fuel injection system

M. J. Cárdenas*, D. Cordes, R. Kneer
Institute of Heat and Mass Transfer, RWTH Aachen University, Germany
cardenas@wsa.rwth-aachen.de and kneer@wsa.rwth-aachen.de

Abstract

High speed images were used to experimentally investigate the spray characteristics of fuel blends having low cetane number and high volatility properties using a common diesel fuel injection system. Low cetane-number fuels have been chosen, as their resistance to autoignition provides a sufficient ignition delay enabling improved mixing of air and fuel. As the mixing rate depends on the local fuel vapor concentration, high volatility, which assures faster vaporization, also tends to improve the mixing. Therefore, an ethanol-diesel blend and a gasoline-diesel blend have been investigated. One fuel blend was composed of 29.4% ethanol and 68.6% diesel fuel and 2% 1-dodecanol to improve miscibility and the other blend consisted of 40% gasoline and 60% diesel fuel. For Both blends a standard diesel fuel was used, which also served as reference for comparison.

Single injections have been visualized using a high speed camera and compared to standard diesel fuel sprays at different ambient conditions and injection pressures. Typically, 50 injections were recorded to extract the penetration length and spray cone angle of the spray liquid phase from the images.

For all ambient conditions and injection pressures diesel presented the highest spray penetration length values for the same injection time. The results showed that at lower ambient pressures the spray penetration length values of both blends were similar. Once either the ambient or the injection pressure was increased, the ethanol-diesel blend showed higher penetration length values than the gasoline-diesel blend.

For the ambient temperature variation the penetration length values for each fuel were almost equal, while the values of the spray cone angle decreased with increasing ambient temperature. In any other cases, the behavior of the spray cone angle values was inverse to the behavior of the penetration length values for all fuels.

Introduction

Different alternative combustion methods for diesel engines, which are intended to reduce emissions and have been known for many years, are now becoming more interesting because more advanced diesel injection systems are available. One of these methods, which has the potential to reduce soot and NOx simultaneously, is the homogeneous charge compression ignition (HCCI) combustion. However, it is challenging to control the ignition timing process for this combustion method. To resolve this issue, there are few common methods to control the mixture auto-ignition phasing: for example the use of variable intake charge temperatures [1], exhaust gas recirculation (EGR) [1, 2] or changing the fuel properties. Finding alternative fuels for combustion engines has been the focus of intensive studies in the last years also because stricter regulations for emissions from vehicles have been established around the world. These regulations introduced stricter limits on pollutant emissions, particularly for emissions of nitrogen particulates and oxides. Regenerative fuels like biodiesel and alcohol fuels like methanol [3, 4], butane [5, 6] and ethanol [7-9] are in the center of the attention due to economic and ecological reasons. The use of pure regenerative fuels in internal combustion engines is only possible if the engine is designed or modified for that purpose. Therefore, mixing these regenerative fuels with already existing fuels like diesel fuel and gasoline presents an interesting solution.

This paper evaluates the potential of fuel blends from regenerative and not regenerative fuels having low cetane numbers and high volatility to reduce engine out emissions especially running on HCCI combustion mode. For this reason low cetane number fuels have been chosen, as their resistance to autoignition provides a sufficient ignition delay enabling improved mixing of air and fuel. As the mixing rate depends on the local fuel vapor concentration, high volatility, which assures faster vaporization, also tends to improve the mixing. Therefore, a gasoline-diesel blend and an ethanol-diesel blend have been investigated. Gasoline, having a high volatility and resistance to autoignition, should enable a more uniform in-cylinder charge. Having the same advantageous properties as gasoline and also being a renewable bio-based resource, ethanol also provides oxygen to the mixture and therefore may lead to reduce particulate emissions in diesel engines. However, the addition of ethanol to diesel fuel affects certain properties with particular reference to viscosity and lubricity [10] or may affect the injector sealing.

* Corresponding author: cardenas@wsa.rwth-aachen.de

Experimental Methods

PRESSURED CHAMBER - The spray characteristics of the fuels considered for these experiments were investigated in a pressurized chamber, which was continually provided with an air flow of about 25 m^3/h. The air flow was delivered by a compressor and heated electrically to the desired temperature before entering the chamber.

As the fluid in the chamber is air, combustion could take place after injection. However, in the scope of this investigation, this phenomenon was not investigated.

The pressured chamber allowed optical access to the spray jet from many directions. In this case the investigated spray jet was injected upward in the chamber, whilst being illuminated and recorded from the front. The arrangement of the camera and the pressured chamber is depicted in Fig. 1.

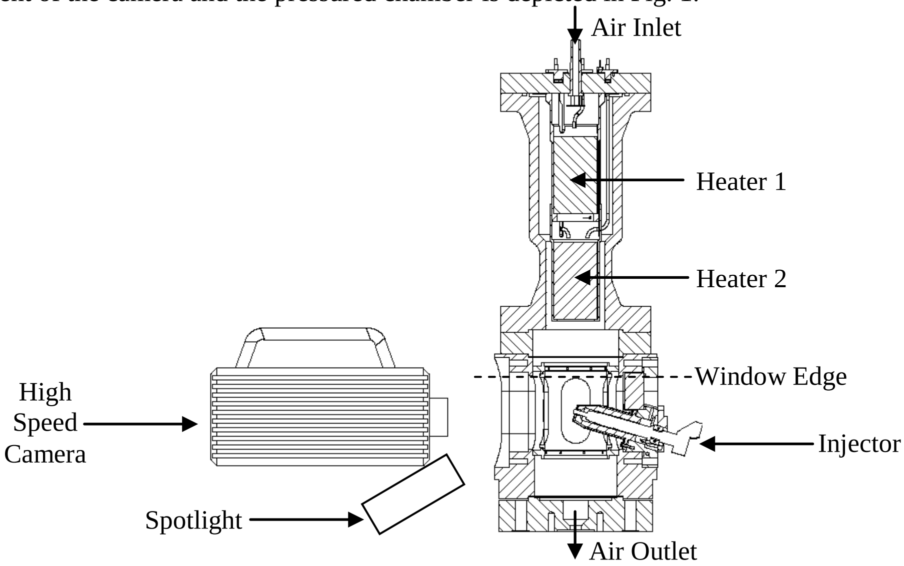

Figure 1 Sketch of the visualization setup in the chamber with four window openings, side view.

For this investigation the ambient conditions in the pressurized chamber have been set according to Table 1.

	P_{amb} [bar]			
T_{amb} [K]	15	24	35	40
510	x			
560	x			
620	x			
680	~~x~~	x	~~x~~	x

Table 1: Experimental conditions in the pressurized chamber

All measurements were conducted at 700 bar injection pressure and in addition, two operation points were also investigated at 1000 and 1250 bar (~~x~~) injection pressure. The energizing time of the injector was 800 µs for all test conditions.

The nozzle investigated is installed on a solenoid valve Bosch injector. It is designed as a sac-hole nozzle with a ks-factor of 1.3 and has 7 orifices, each having a diameter of 0.141mm. Only the spray from one orifice is investigated, with the spray propagating in vertical, upward direction.

FUELS – One of the fuel blends investigated in this paper was composed of 40% gasoline and 60% diesel fuel and the other blend consisted of 29.4% ethanol and 68.6% diesel fuel and 2% 1-dodecanol to improve miscibility. Both blends were prepared with a standard diesel fuel (EN 590), which also served as a reference for comparison. Detailed specifications of the fuels are given in Table 2. The preparation of these mixtures does not present any concerns regarding miscibility for gasoline and diesel fuel blends. On the other hand, ethanol has miscibility problems with diesel fuels. Ethanol solubility in diesel is affected mainly by two factors, temperature and water content of the blend. Prevention of this separation can be accomplished by adding an emulsifier or a co-solvent. Emulsification usually requires heating and blending steps to generate the final blend, whereas co-solvents allow fuels to be ‘‘splash-blended’’, thus simplifying the blending process [7].

Large percentages of ethanol in the blend also influence its miscibility in diesel fuel and will affect the amount of additive required to achieve a stable blend.

To prevent diesel fuel and ethanol from separating 1-dodecanol was employed as co-solvent in this investigation. The advantage of using 1-dodecanol as co-solvent is that this alcohol has similar chemical properties in terms of cetane number like ethanol, also reducing the cetane number of the blend. Other commercial additives like Beraid 3540 [11], Puranol [12], Hexanol [13] or also another fuel like Biodiesel [14], could prevent the separation of the blend, but at the same time the additives would improve the ignition, which would be adverse to the scope of this investigation.

Sayin et al. [4] tested volume percentages of 5% and 10% of ethanol with 95% and 90% of diesel fuel, respectively. 1-dodecanol was added in proportions of 1% by volume to each diesel–ethanol blend to satisfy mixture homogeneity and for prevention of phase-separation. Cheung et al. [15], Di et al. [16] and Wang et al. [17] used four blended fuels containing 6.1%, 12.2%, 18.2% and 24.2% ethanol. The first three blends contain 1% 1-dodecanol while blend-4 requires 1.5% of 1-dodecanol to ensure sufficient mixing. In this paper, 2% of 1-dodecanol was added to the diesel-ethanol blend. This blend was stored and operated at least at 25°C because it was observed, that phase separation occurred as the fuel temperature fell below 17°C.

Properties	Unit	Diesel	Gasoline	Ethanol	1-Dodecanol	Gasoline-diesel blend	Ethanol-diesel blend
Density	kg/m^3	826.4 25.25°C	756.8 25°C	785.2 25.16°C	833 25 °C	800.3 24.85°C	812.3 25.25°C
Surface Tension	mN/m	27.984 25.08°C	21.348 26.09°C	22.073 25.03	n/a	24.345 25.08°C	24.242 25.04°C
Cetane number		52.0-54.0	-	-			
RON		-	95.0 Min	-	-	-	-
MON		-	85.0 Min	-	-	-	-
Water	% wt	0.05 Max	n/a	< 0.34	n/a	n/a	n/a
Diesel	vol.%	-	-	-	-	60	68,6
Gasoline	vol.%	-	-	-	-	40	-
Ethanol	vol.%	-	-	-	-	-	29,4
1-Dodecanol	vol.%	-	-	-	-	-	2

Table 2: General properties of the fuels

VISUALIZATION - a Spotlight of 700 Watt has been employed to detect the envelope of the spray liquid phase. A high speed camera (Photron Fastcam SAx) is used as a detector. Typically, 50 injections were recorded to extract the penetration length and spray cone angle from the images. An automatic image processing tool based on Matlab has been developed for this purpose.

The spray penetration length is defined in this investigation as the furthest spray jet distance from the nozzle that is unbroken, see Fig. 2. The penetration length values could be recorded up to the window edge, see Fig. 1.

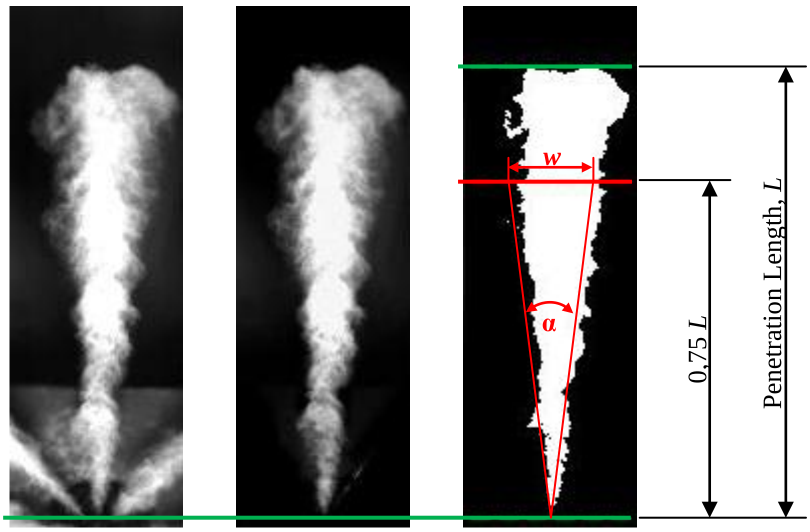

Figure 2 Single original diesel fuel shot (left), Subtraction of background and periphery (center) and selection of the largest spray region (right) and description to determine the spray cone angle

The spray cone angle was determined until few timesteps after injector closing. A a result, the entire cross-section was not always available. Therefore, the spray cone angle is defined as the angle generated from the distances between the nozzle hole to a selected location on the spray axis and the spray jet width (*w*) measured at this position. The chosen location corresponds to 75% of the penetration length (*L*) of the spray jet, see Fig. 2. The spray cone angle (1) is calculated as follows:

$$\propto = 2\arctan\left(\frac{0{,}5\,w}{0{,}75\,L}\right) \quad (1)$$

Results and Discussion

The macroscopic characteristics of the spray, here the penetration length of the liquid phase and the spray cone angle, were evaluated to understand the air-fuel mixing process [18]. The penetration length of the liquid phase and spray cone angle of diesel fuel and fuel blends of gasoline-diesel and ethanol-diesel fuels were studied under different ambient conditions and injection pressures. Three independent parameter variations were conducted. Under constant ambient temperature and injection pressure, the ambient pressure was increased. Then, keeping the ambient conditions constant, the injection pressure was varied. Finally, while keeping ambient and injection pressure constant, the ambient temperature was varied.

AMBIENT PRESSURE VARIATION – Keeping the ambient temperature constant at 680 K, the ambient pressure was increased from 15 bar up to 40 bar. With the increase of the ambient pressure the penetration length values were decreased and the spray cone angle increased for all fuels, as is shown in Fig. 3.

Diesel fuel had slightly higher penetration length values compared to both blends at each of these operation points. The blends presented the same penetration length values at lower ambient pressures. However, at higher ambient pressures there was a slight increase of the penetration length of the spray jet from the ethanol-diesel blend compared to the spray jet from the gasoline-diesel blend. For the spray cone angle, the fuels showed a behavior, that was inverse to the one described above for the penetration length. This means, that diesel fuel presented the narrowest spray jet at each ambient pressure and the blends presented wider spray jets, with the ethanol-diesel blend having a narrower spray as the gasoline-diesel blend at higher values of ambient pressures.

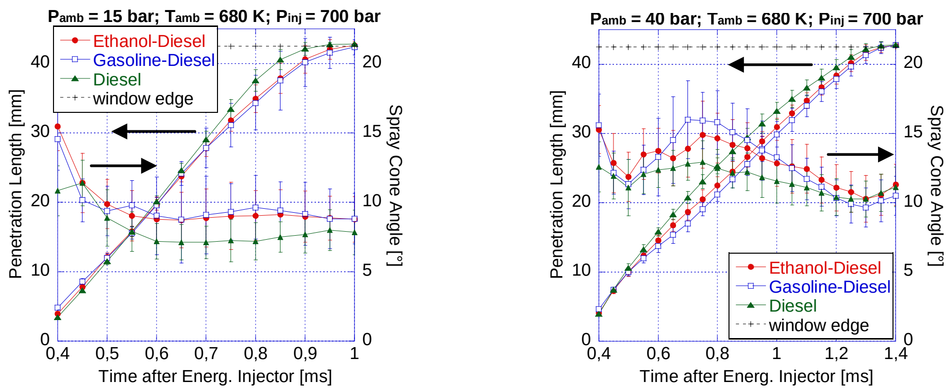

Figure 3 Comparison of the penetration length and spray cone angle of the ethanol-diesel blend, gasoline-diesel blend and diesel fuel at different ambient pressures 15 bar (left) and 40 bar (right)

INJECTION PRESSURE VARIATION – It was already shown that the blended fuels presented similar lower penetration length values compared to diesel fuel for low ambient pressures at 700 bar injection pressure. For increased injection pressures, the gasoline-diesel blend showed smaller penetration length values for every point in time after energizing the injector compared to the ethanol-diesel blend and furthermore, the ethanol-diesel blend had equally high penetration length values as the diesel fuel at the end of the measurement range (window edge), as is shown in Fig. 4, for 1000 and 1250 bar injection pressure.

At higher ambient pressures an even a larger injection pressure was required to produce the same behavior observed at lower ambient pressures.

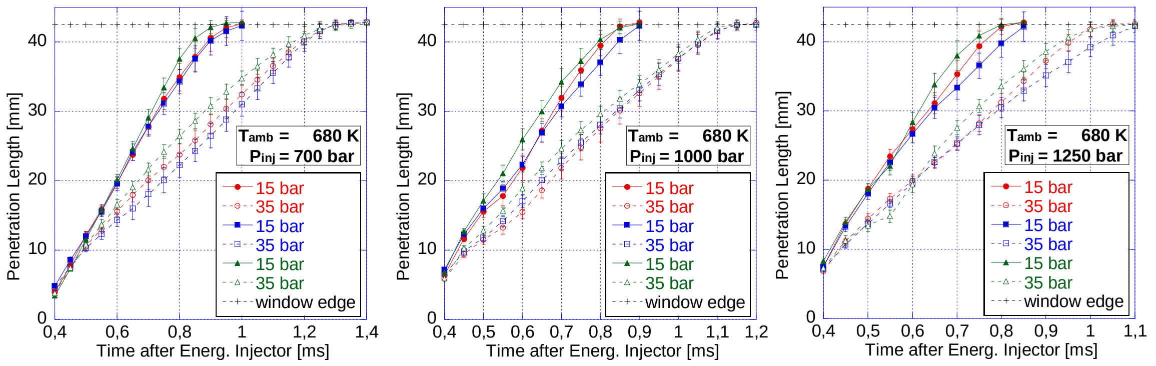

Figure 4 Comparison of the penetration length of the ethanol-diesel blend (red), gasoline-diesel blend (blue) and diesel fuel (green) at different ambient and injection pressures (700 bar – left, 1000 bar – center, 1250 bar – right) at constant ambient temperature

AMBIENT TEMPERATURE VARIATION – With the increase of the ambient temperature no differences in penetration length values were detected for the gasoline-diesel blend or diesel fuel, see Fig. 5 (center and right). The ethanol-diesel blend the penetration length values for 680 K were higher than the values for all other investigated lower temperatures. However the spray cone angle values were decreased with the increase of the ambient temperature, especially for the ethanol-diesel blend at 680 K, see Fig. 6. These results showed that the vaporization of the fuels seems to happen at the border of the spray jet and the spray tip keeps the same momentum remaining the same energy and therefore generating the same penetration length values.

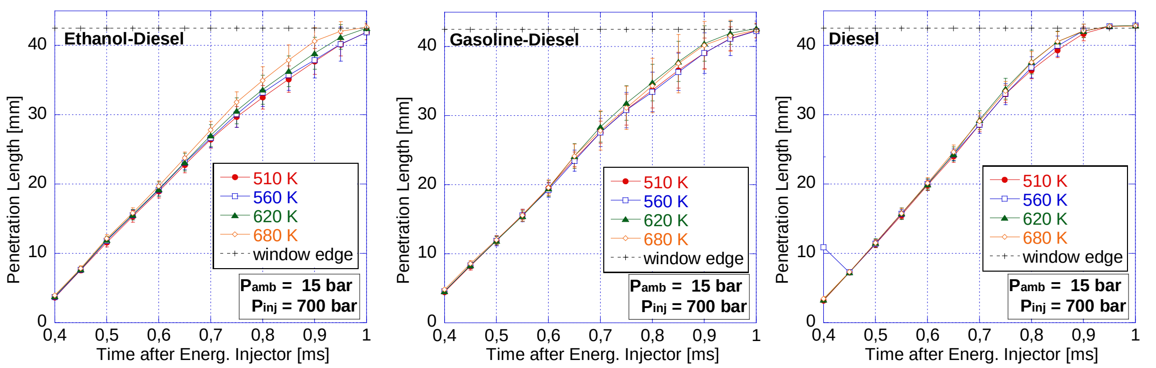

Figure 5 Comparison of the penetration length of the ethanol-diesel blend (left), gasoline-diesel blend (center) and diesel fuel (right) at different ambient temperatures and at a constant ambient pressure

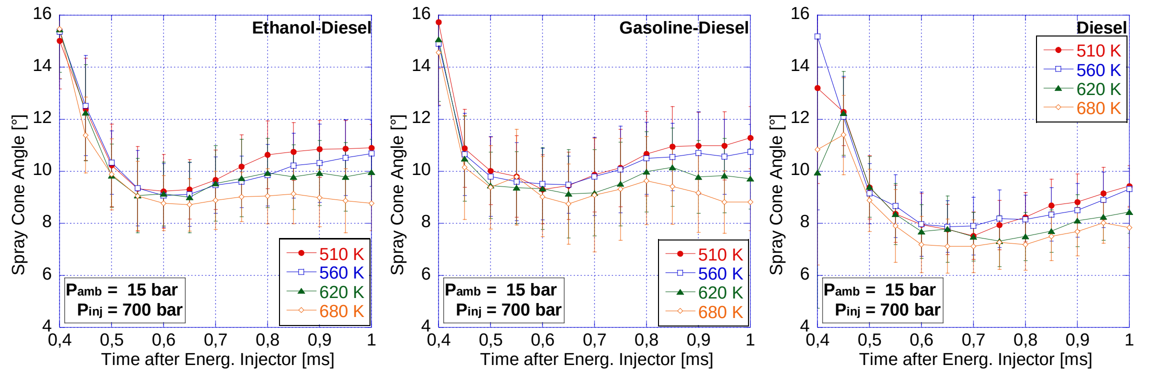

Figure 6 Comparison of the spray cone angle of the ethanol-diesel blend (left), gasoline-diesel blend (center) and diesel fuel (right) at different ambient temperatures and at a constant ambient pressure

Summary and Conclusions

During the development of this investigation several issues had to be faced. Due to the injector leakage caused by using ethanol, the hardware was replaced and the measurements were repeated. During the operation of the injection system, the composition of the ethanol-diesel blend was visually monitored and at temperatures around 17°C it was detected that the mixture separated in two phases. Therefore, the fuel temperature was strictly controlled and kept above 25 °C to avoid the phase separation and consequently no phase separation was detected.

Varying the temperature was expected to influence the all macroscopic characteristics of the spray studied here. However, only the spray cone angle was influenced by the ambient temperature. As expected, the increase of the ambient pressure reduced the penetration length but increased the spray cone angle for all investigated fuels. Some differences were detected in the behavior of the blends, for low ambient pressures and constant ambient temperature, the ethanol-diesel blend presented the same values of penetration length and spray cone angle as the gasoline-diesel blend. However, with the increase of the ambient temperature a slight increase of the penetration length of the ethanol-diesel blend compared to the gasoline-diesel blend was noticed. When the ambient pressure was also increased, the ethanol-diesel blend presented a slightly higher increase of the penetration length and the spray cone angle was also slightly narrower than for the gasoline-diesel blend. The same behavior was observed when the injection pressure was increased.

In conclusions, when the ambient temperature and pressure were increased, the spray behavior of the gasoline-diesel blend and the ethanol-diesel blend changed. The spray penetration length values of the gasoline-diesel blend increased more slowly than the spray penetration length values of the ethanol-diesel blend.

These were the first stages to characterize the sprays from fuel blends having low cetane number and high volatility compared to diesel fuel in a diesel injection system. The next steps are to determine the interaction between partially (pilot or post-injection) and completed injections (main injection) macroscopically and finally a qualitative characterization of the spray will be realized applying Phase Doppler Anemometry.

Acknowledgements

The authors would like to thank the German Research Foundation (DFG) for financial support in the framework of Collaborate Research Project SFB 686.

References

[1] Lü, X.-C., Chen, W., Huang, Z., Fuel 84: 1084–1092 (2005).

[2] Nakano, M., Mandokoro, Y., Kubo, S., Yamazaki, S., International Journal of Engine Research 1: 269-279 (2000).

[3] Bayraktar, H., Fuel 87: 158–164 (2008).

[4] Sayin, C., Fuel 89: 3410–3415 (2010).

[5] Mehta, R. N., Chakraborty, M., Mahanta, P., Parikh, P. A.., Industrial and Engineering Chemistry Research 4:, 7660–7665 (2010)

[6] Valentino, G., Corcione, F. E., Iannuzzi, S. E., Serra, S., Fuel 92: 295–307 (2012).

[7] Hansen, A. C., Zhang, Q., Lyne, P.W.L., Bioresource Technology 96: 277–285 (2005)

[8] Hea, B.-Q., Shuaia, S.-J., Wanga, J.-X., Heb, H., Atmospheric Environment 37: 4965–4971 (2003)

[9] Lapuerta, Lapuerta, Armas, O., García-Contreras, R., Fuel 86: 1351–1357 (2007)

[10] Pidol, L., Lecointe, B., Starck, L., Jeuland, N.,

[11] Kwanchareon, P., Luengnaruemitchai, A., Jai-In, S., Fuel 86: 1053–1061 (2007)

[12] Ahmed, I., SAE technical Paper 2001-01-2475

[13] Sathiyagnanam, A.P., Saravanan, C.G., Gopalakrishnan, M, Proceedings of the World Congress on Engineering II (2010)

[14] Hulwan, D. B., Joshi, S. V., Applied Energy 88: 5042–5055 (2011)

[15] Cheung, C.S., Di, Y., Huang, Z., Atmospheric Environment 42: 8843–8851(2008)

[16] Di, Cheung, C.S., Huang, Z., Aerosol Science and Technology 43:455–465 (2009)

[17] Wang, X., Cheung, C.S., Di, Y., Huang, Z., Fuel 94: 317–323 (2012)

[18] Desantes, J.M., Benajes, J., Arrègle, J., Delage, A., Thermo- and fluid-dynamic processes in diesel engines Springer, Berlin: 81–105 (2002)