Characterisation of a Bio-Ethanol Direct Injection Spray Under Sub-Zero Conditions

I. Evans*[1], P. J. Bowen[1], P. J. Kay[1], J. King[2], G. Knight[2], L. Schmidt[2]
[1] Cardiff School of Engineering, Cardiff University, The Parade, Cardiff CF24 3AA, UK
[2] Ricardo UK, Shoreham Technical Centre, Shoreham-by-Sea, West Sussex BN43 5FG, UK

Abstract

Due to current dependence on depleting fossil fuel reserves, alternative fuels are being considered particularly for the transport sector. Suitable replacement fuels for gasoline are bio-fuels such as bio-ethanol. One of the obstacles preventing the wider use of pure bio-ethanol is its volatility which causes problems at low temperatures. To over come this, blends of bio-ethanol and gasoline - such as E85 (85 % ethanol and 15 % gasoline), are used which have increased volatility thereby increasing reliability during cold starts and running [1]. The addition of gasoline reduces the corrosive nature of ethanol by decreasing the amount of water absorbed by the resulting fuel. A lower air-to-fuel ratio is also required during cold start, thus increasing Unburnt Hydrocarbons (UBHC) and Carbon Monoxide (CO). This can be mitigated by exhaust after treatment systems; however the low system temperatures occurring during cold start and warm up cycles severely limits the effectiveness of these systems. This leads to an increase in UBHC and CO emissions of up to 15 times at -20 ^{o}C compared to that at 23 ^{o}C for gasoline G-DI engines [2].

The objective of this study is to assess the influence of sub-zero fuel temperatures on spray characteristics such as droplet size, velocity and spray pattern of E85 compared to gasoline sprays. Fuel temperatures as low as 243 K (-30 ^{o}C) were achieved, the design and development of the test facility is also discussed. The data presented and analysed in this paper were obtained using a temporally and spatially resolved Phase Doppler Anemometry (PDA) system from fuel injections by a piezo controlled G-DI injector mounted in a constant volume, optical experimental facility.

The results are presented in terms of the spray kinematics and spray quality and are discussed and analysed through comparison with the benchmark spray at atmospheric conditions.

Introduction

Whilst the world's crude oil resources are diminishing and global climate change continues, the use of all liquid fuels (including those for road transport) are set to increase globally by 25 % by 2030 [3] emphasising the need to find an alternative to fossil derived fuels. Bio-fuels such as ethanol are considered as possible alternatives to fossil-derived automotive fuel. However in 2009 both the UK and the European governments decreased their targets for bio-fuel integration into road transport fuel. In the UK, the timescales for penetration were delayed after the release of the UK government's Gallagher Review [4] from 5 % (by volume) by 2010/11 to 5 % by 2013/14. The report highlighted concerns over the net carbon emissions of first generation fuels such as soya and corn derived bio-fuels. These are potentially greater than fossil fuels due to harvesting methods and land clearing, as well as the possible conflict between food and fuel production. However with the potential of second generation bio-fuels such as ethanol from waste plant stalks, household waste and prairie grass, as well as bio-butanol from algae, some of the concerns raised by the first generation fuels are potentially mitigated.

The use of gasoline–ethanol mixtures in spark ignition (SI) engines give rise to several problems related to the differing thermo-fluid properties of gasoline and ethanol. One of the key factors affecting the implementation of ethanol and ethanol blends as substitutes for gasoline is their increased latent heat of evaporation and flash point. These effects are exacerbated at sub-zero temperatures, and can lead to poor atomisation and thus ignition difficulties during cold starting of an SI engine [1]. Although the effects are reduced by the addition of 15 % gasoline to create E85, the effects are still significant enough to cause operational problems. Whilst the fuel rich mixture during the warm up period of an SI engine can increase unburnt hydrocarbon and carbon monoxide emissions, it has been shown that these emissions decrease with the use of high concentration blends of ethanol and gasoline [1]. The same study showed the potential for Nitrogen Oxides (NO_x) emissions to increase at higher concentrations of ethanol due to its higher oxygen content.

No published data has been found concerning the influence of sub-zero temperatures on either gasoline or E85 sprays. This paper aims to study the influence of sub-zero temperatures on both gasoline and E85 sprays, initially within ambient pressure and temperature environments. The results reported include time resolved, two dimensional distribution plots of both droplet diameter and velocity with corresponding high speed Mie-

*Corresponding authors email: EvansIW@cardiff.ac.uk

scattering images from a thin laser sheet. The results obtained by both PDA and high speed imaging can be used to validate new and existing Computational Fluid Dynamics (CFD) codes at these temperatures and thus improve future engine design and development.

Experimental Technique and Facility Development

In order that the effect of each fuel parameter could be understood fully, experiments were carried out in a constant volume High Temperature – High Pressure (HT – HP) test chamber with four windows, three perpendicular to each other and one offset at 70 ^{o}, as shown in Figure 1 An annular curtain of dry air flowing at 130 l/min was used to keep the windows free of droplets and has been proven to have minimal effect on the spray formation; the rig is discussed in more detail elsewhere [5]. The rig was kept at constant atmospheric ambient conditions for the duration of each experiment. A test matrix of 6 experiments was constructed comprising tests with ambient (293 K), 258 K and 243 K fuel temperatures for both gasoline and E85.

The fuel was cooled by the expansion of liquid nitrogen in a 500 mm x 25 mm diameter heat exchanger which was controlled by a mechanically operated valve. The distance between the fuel outlet of the heat exchanger and the injector was minimised and thermal insulation was utilised to reduce any atmospheric heating effects (Figure 1). The temperature of the fuel was monitored at the inlet to the injector with a K–type thermocouple, reading variations of $\pm$ 0.75 K, which is within the error of the thermocouple of $\pm$ 1.5 K, were observed. The fuels used were both commercial blends of E85 and gasoline and is therefore representative of the end use fuels currently available.

The injector was a Bosch piezo driven, symmetrical hollow cone G-DI injector with a nominal cone angle of 90 ^{o} and was used throughout the entire experimental programme. Fuel was supplied at 20 MPa and an injection duration of 0.3 ms was chosen due to the high static flow rate of this injector.

First, a mass rate tube was utilised to measure the instantaneous mass rate trace, providing valuable information about the operation of the injector. This apparatus works by injecting into a rate tube which is filled with the same fluid, this induces a the shock wave that is transmitted along its length. A strain gauge measures the shock wave in the rate tube and the strain induced is proportional to the mass injected. This data is then re-scaled with an average static flow measurement to produce the mass rate trace shown in Figure 2.

The high speed images were taken using a 1 mega pixel Photron APX RS camera capable of filming at 250, 000 frames per second, a filming rate of 4000 fps was used as a compromise between resolution and speed. The spray was illuminated using a laser sheet from a Nd:YAG laser operating in the 2nd harmonic (532 nm) introduced from the left hand side and on the centre plane of the injector, images were recorded perpendicular to the laser sheet. A narrow band pass filter (532 nm ± 2 nm) was used to minimise noise and only record light scattered form the spray. The data presented were averaged from 30 consecutive injections using a post-processing script, at this stage a false colour scheme and grid (10 x 10 mm) were added.

The PDA system utilised comprises of a Coherent Innova 70 multi-line Argon Ion laser, Dantec Fibre Flow transmitter (60x40), and probe (57x50m) with a beam expander (55x12) and Dantec PDA BSA processing unit (9062N0521). Light with wavelengths of 514.5 nm and 488.0 nm and a frequency shift of 40 MHz were used to generate data for the axial and radial velocities respectively. The transmitting optics, along with receiving optics, are mounted on a traverse that allows 3 axes of motion. The traverse is controlled remotely via the PC used to record the data. The PDA system was optimised for the fuel sprays with validation levels in excess of 90 % and data rates around 50 Hz observed. The PDA grid specified was carefully selected to offer the best representation of the whole spray. The grid was finer closer to the injector orifice and coarser further down stream, the same grid was used for each test case.

The data collected by the PDA system is post-processed so that the transient nature of the spray can be analysed in a 'phase-resolved' manner. The data are processed using a mature FORTRAN 90 script [6] that performs a number of functions. First the information is split into 'time-bins', due to the short injection duration the time bin durations increased with time ASOI. Ten 0.1 ms time bins followed by a further eight 0.25 ms time-bins were found to be a good compromise between the number of time-bins and the drops per time-bin. The script then calculates the average properties, such as mean velocity components and SMD, for each location and for each time-bin.

To ensure that the PDA data collected is representative of the spray, the PDA system was programmed to record 15,000 samples at each point, or to timeout after 75 seconds, whichever occurs first (75 seconds corresponds to 300 injections with the injector running at 4 Hz).

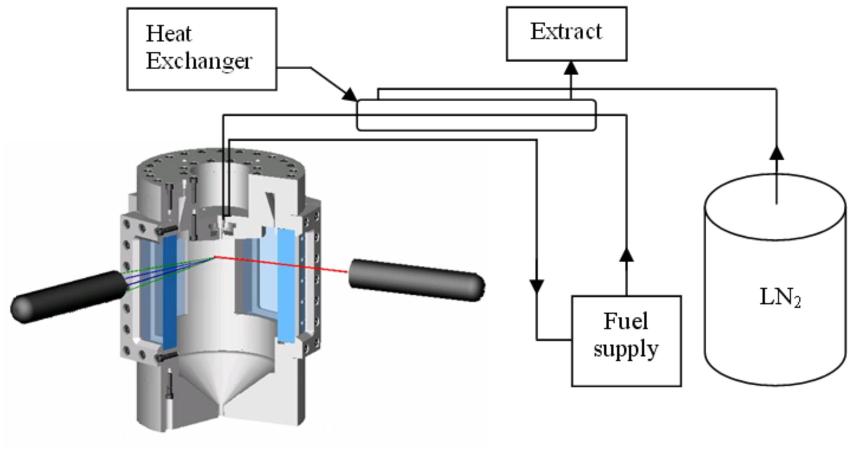

Figure 1. Schematic of the experimental setup showing the fuel cooling circuit

Results and Discussion

Figure 2 shows the instantaneous mass injection rate trace for E85 at atmospheric conditions. The figure shows an electro-mechanical delay of 0.17 ms, followed by an instantaneous mass flow rate increase as the injector opens (early spray development) until the injector stabilises for a fraction of a millisecond (mid spray development) before the injector starts to close (late spray development). The closing delay of 0.09 ms is shorter than the opening delay.

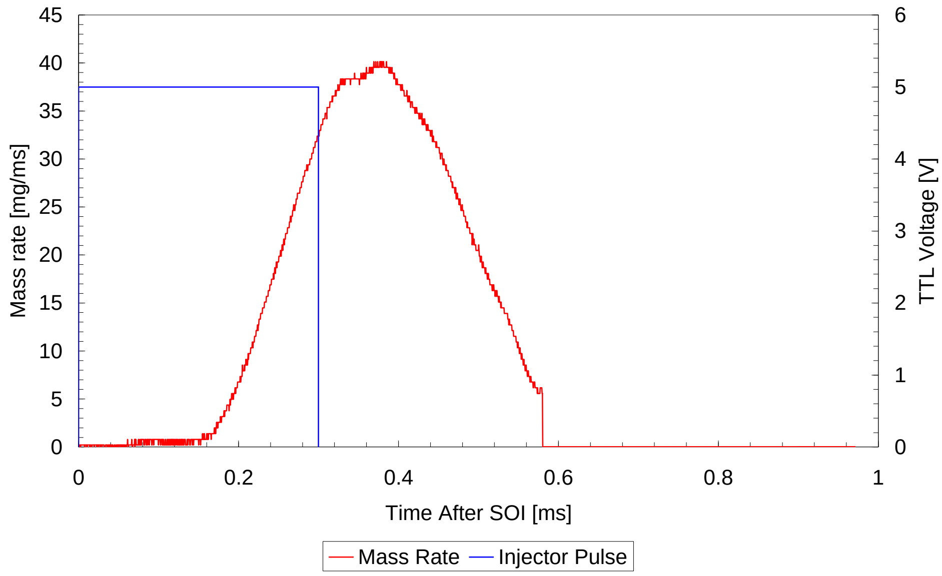

Figure 2. Instantaneous mass injection rate for E85 with a requested injection pulse of 0.3 ms

The transient DI spray from a Bosch hollow cone type injector was investigated using both two dimensional PDA and high speed imaging. The average images for E85 and gasoline data are presented in Figure 3 and Figure 5 respectively. The temporally-resolved data is presented for 0.2 ms (early phase development), 0.4 ms (mid spray development), 0.6 ms (late spray development) and 1.0 ms after start of injection (ASOI), and three-fuel temperatures of 293 K (atmospheric), 258 K (-15 ºC) and 243 K (-30 ºC). The ambient air temperature was maintained at atmospheric temperature, and the injector line pressure and injection duration were 20 MPa and 0.3 ms respectively.

The image results for E85 at ambient (293 K), 258 K and 243 K are shown in Figure 3. The first image where fuel is observed is at 0.2 ms ASOI, which is consistent with the mass rate injection trace shown in Figure 3. At 0.4 ms ASOI, the images show that fuel is still being injected, whereas at 0.6 ms ASOI the fuel spray has detached from the injector – both observations are again consistent with the mass rate injection trace presented. In taking a ‘cut’ though the centre plane of the spray, the spray structure has apparent asymmetrical structure due to the direction of the laser sheet (entering from the left hand side).

It can be seen that the spray penetration decreases in line with the decrease in temperature of the fuel, and that this effect is more noticeable during the later stages of injection. It is likely that this is due largely to the increase in viscosity and surface tension caused by the decrease in fuel temperature. This results in a decrease in jet Weber and Reynolds numbers, with corresponding suppression of primary atomisation. Similar effects can be observed in the gasoline high speed images shown in Figure 5. The changes in spray penetration are comparable between each fuel type for a given temperature range. Neither the E85 nor the gasoline sprays show much change in cone angle with either temperature or fuel variation.

PDA data for both E85 and gasoline are shown in Figure 4 and Figure 6 respectively; data are presented for the conditions and time ASOI corresponding to Figure 3 and Figure 5. The left hand side of the PDA plots are ‘cherry plots’ representing Sauter Mean Diameter (SMD), the size of the cherry and its colour are representative of the SMD. The right hand side of the plot shows the average axial and radial velocity components represented as a single velocity vector. The PDA cherry plots for each condition show the following spray development. The early spray development phase (0.2 ms ASOI) shows relatively large droplets at the tip. The mid spray development (0.4 ms ASOI) shows that generally there are relatively smaller droplets at the injector orifice with the larger droplets at the spray tip. Although the images for the late spray phase show that the injection event has ended, the cherry plots still show data within the region of the injector orifice. These droplets characteristically have low mean velocity magnitude, due to the injector closing. At 1.0 ms ASOI a spray vortex is observed in the velocity vector plot approximately 20 mm down stream. The size of the droplets contained with in the vortex are typically less than 5 microns and therefore able to follow the bulk gas velocity field. Typically the mean droplet diameter for gasoline sprays is lower than that of E85 sprays, due to the fluid properties affecting primary atomisation.

Both the velocity and the penetration of the gasoline sprays decrease as temperature decreases, which can also be seen in the E85 sprays. This reduction is a result of comparatively higher drag forces acting on the droplets, due to the larger mean diameters at lower temperatures, as well as lower initial exit velocities. However, the decrease in mean velocity with temperature appears to be more prominent in the gasoline sprays and requires further investigation. It can bee seen that a reduction in axial velocities of the E85 spray compared to the equivalent temperature gasoline spray has led to a decrease in shear gradient and reduction in entrainment , as reported by Wigley et al. [7].

Conclusions

This paper analysed the effects of sub-zero temperatures on gasoline and E85 sprays from a hollow cone, piezo injector suitable for automotive GDI applications. The following main conclusions can be drawn:

- A self consistent biofuel spray data-set is presented utilising three independent techniques.
- Sufficiently refined temporal and spatial resolution allow the dynamic spray characteristics to be identified
- The typical mean droplet size for gasoline is lower than that of E85 due to fluid properties affecting primary atomisation.
- As fuel temperature decreases, so too does droplet penetration and velocity and this effect is more prominent in the E85 sprays.

References

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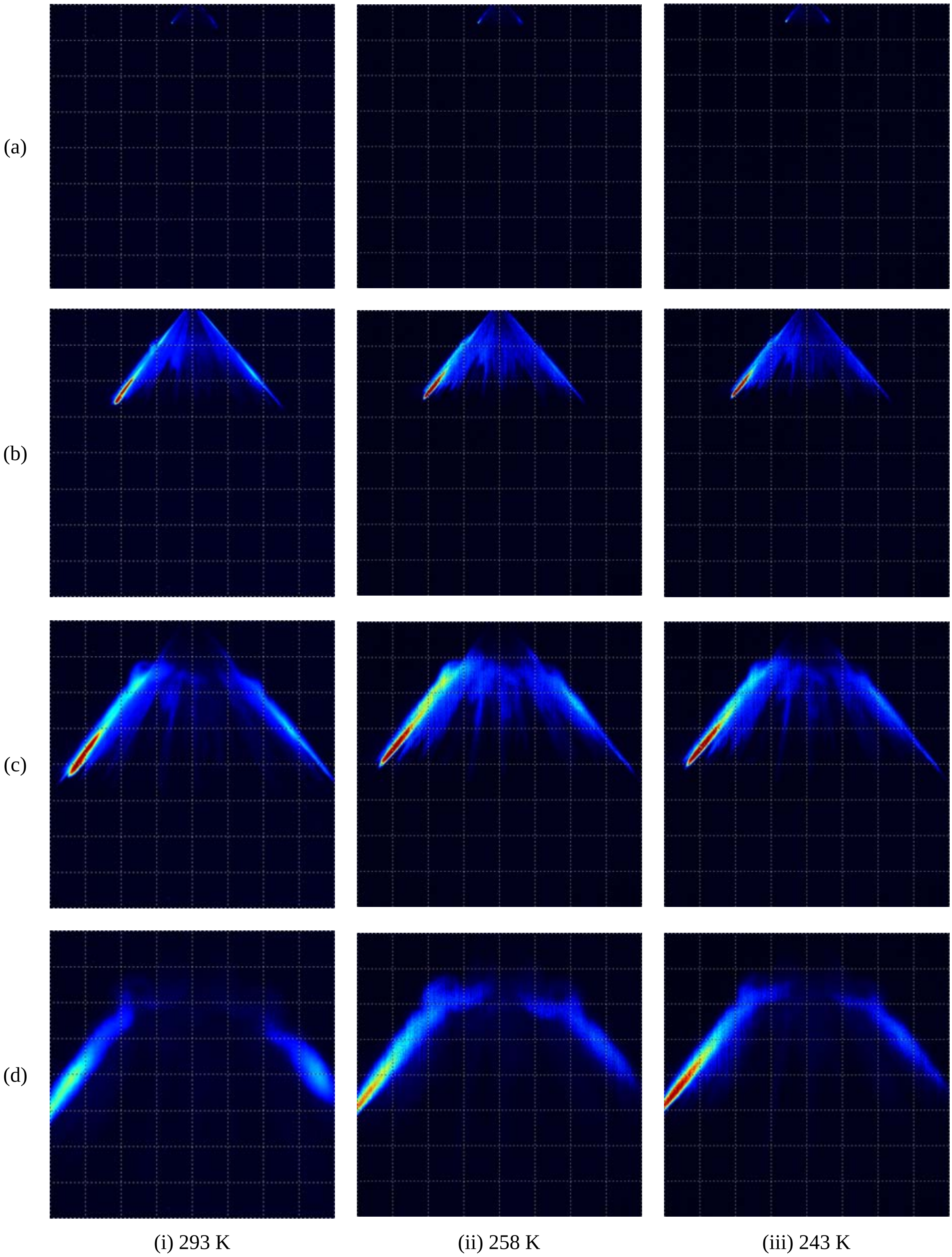
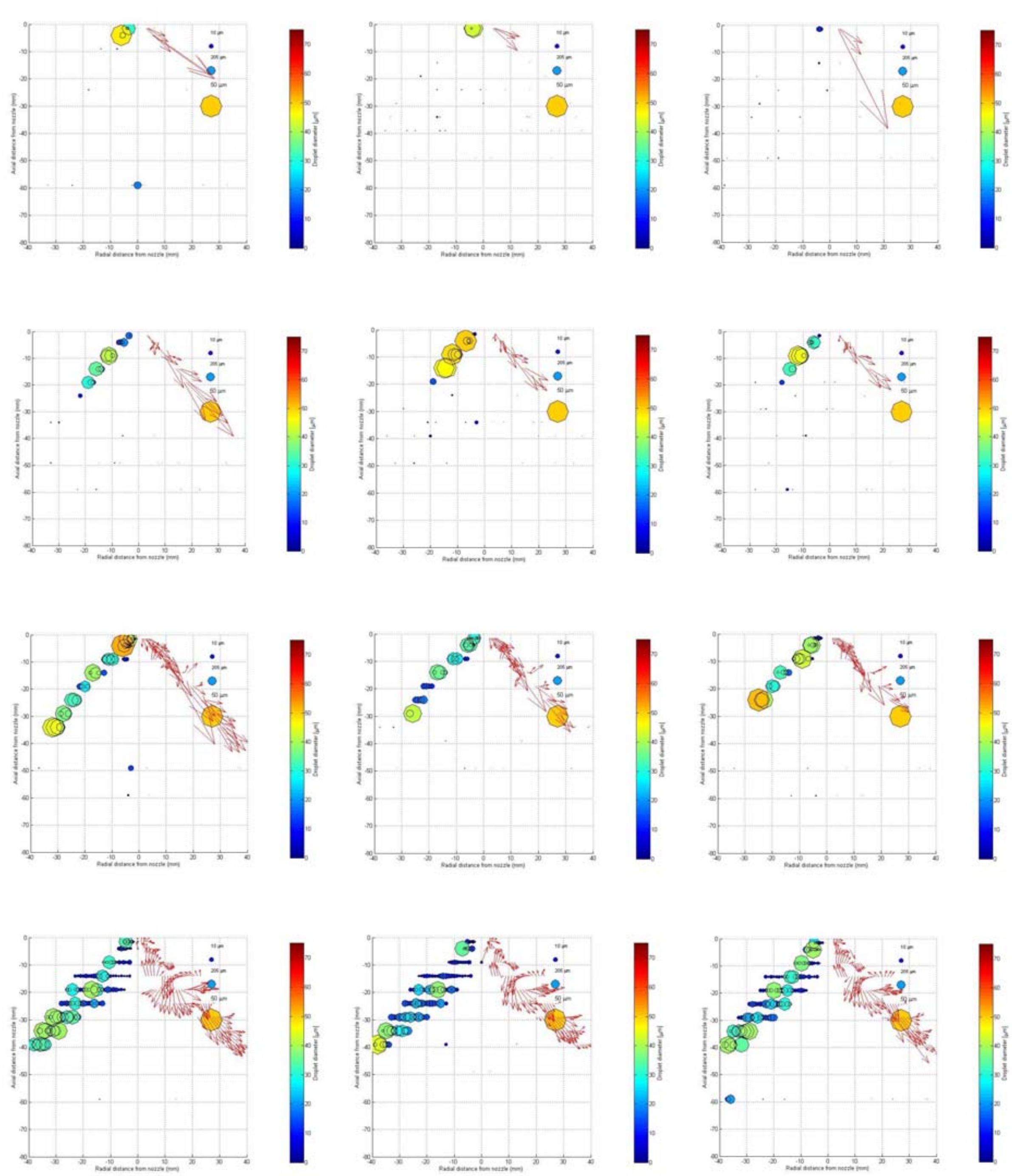


Figure 3. Comparison of an E85 spray images under different fuel temperatures for selected times ASOI: (a) 0.2 ms, (b) 0.4 ms, (c) 0.6 ms, (d) 1.0



(a) (b) (c) (d)

(i) 293 K (ii) 258 K (iii) 243 K

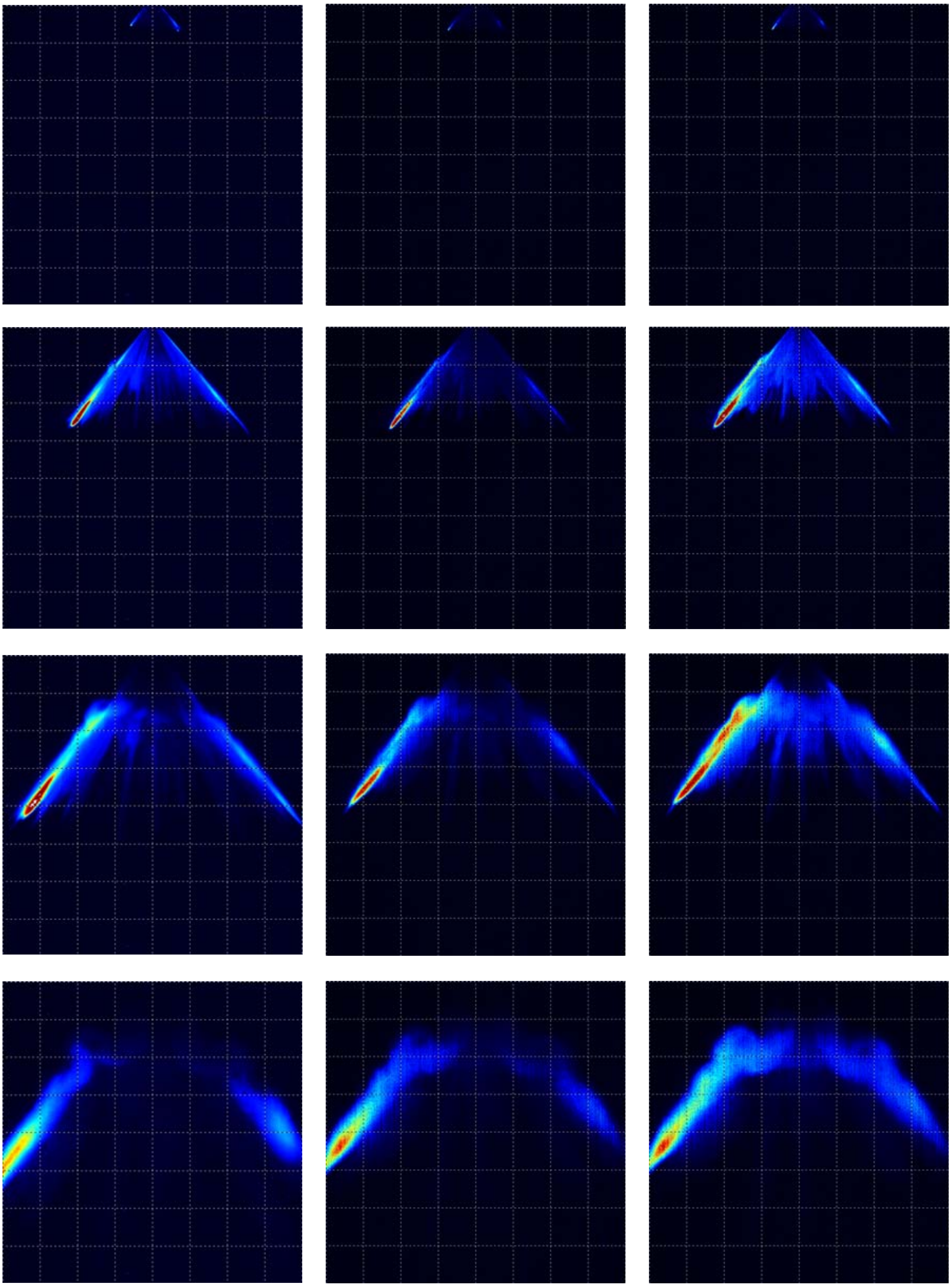
Figure 4. Comparison of an E85 spray PDA data under different fuel temperatures for selected times ASOI: (a) 0.2 ms, (b) 0.4 ms, (c) 0.6 ms, (d) 1.0 ms

(a)

(b)

(c)

(d)



(i) 293 K (ii) 258 K (iii) 243 K

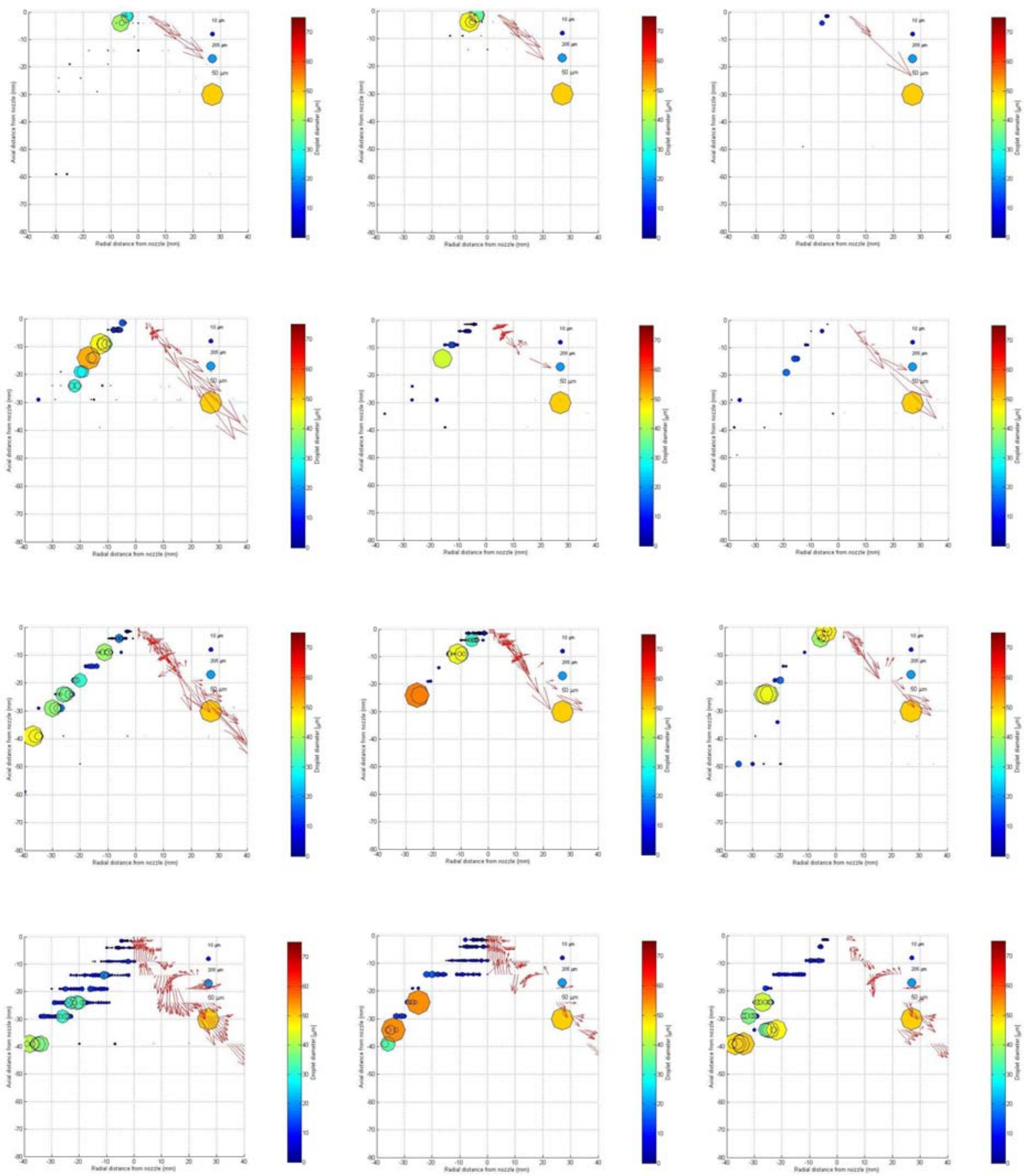
Figure 5. Comparison of a Gasoline spray images under different fuel temperatures for selected times ASOI: (a) 0.2 ms, (b) 0.4 ms, (c) 0.6 ms, (d) 1.0 ms

(a)

(b)

(c)

(d)



(i) 293 K (ii) 258 K (iii) 243 K

Figure 6. Comparison of a Gasoline spray PDA data under different fuel temperatures for selected times ASOI: (a) 0.2 ms, (b) 0.4 ms, (c) 0.6 ms, (d) 1.0 ms