Flash boiling effect on swirled injector spray angle

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Abstract

A swirled injector for gasoline direct injection was used to investigate the effect of fuel flash boiling on the initial angle of the spray.

The hollow cone spray was injected into a constant pressure bomb filled with quiescent air. The fuel was fed at 7 MPa constant pressure to the injector. Three parameters were changed to study the effect of the injection conditions on the spray angle: fuel composition, fuel temperature and air pressure in the test bomb.

The injector tip was heated up to 150°C to keep the fuel to be injected at the desired temperature.

Different blends of iso-octane and n-pentane were used to obtain fuels with different bubble temperature at the same air pressure.

In a reduced set of experiments, only with pure fuels, the ambient pressure was varied to change the bubble temperature independently from the fuel temperature.

It was observed that, when the fuel conditions exceed the bubble point, the spray angle, measured close to the injector, becomes wider. This angle was chosen as an indicator of the flash boiling intensity.

The experimental results show that the angle value is well fitted by a unique correlation if it is expressed as a function of the ratio $\Pi= P_b/ P_{air}$ between the fuel bubble pressure and the bomb pressure

Introduction

The spray structure in a GDI engine is of primary importance because of its influence on the overall process of mixture preparation and distribution. Injector characterisation procedures had for a long time neglected the effect of fuel heating on the spray structure. However in some running condition the injected fuel temperature and the cylinder pressure conditions during injection can cause the onset of flash vaporisation. This phenomenon causes dramatic changes in spray structure in terms of both spray geometry and droplet diameters. In this paper some experimental result obtained using simple monocomponent and bicomponent fuels are described.

In literature the atomisation of flashing liquid jets had been studied under different aspects. The early works by Brown and York [1] and by Lienhard et al. [2, 3] established the basic principles of the phenomenon. However, the practical utilisation of fuel superheating as a way of enhancing the performances of a diesel engine was already studied by Gerrish and Ayer in the thirties [4]. The first works focussed on the case of a superheated liquid jet and showed that the jet atomisation was greatly enhanced when the fluid was sufficiently superheated. This mechanism, presenting the benefits of increasing atomisation, widening initial spray cone angle and reducing penetration, was then considered very attractive for direct injection engines (either diesel or gasoline) [5]. It was also suggested as mechanism for producing small droplet sizes from simple low-pressure injector systems [6].

Senda and coworkers [7] measured spray angle, break-up length and Sauter mean diameter of a pintle-type injector with decreasing ambient pressure in a closed bomb apparatus using n-pentane and n-hexane. They measured a non-monotonic change in all three properties as flash boiling occurred. In particular they measured a contraction in the spray cone angle and an increase in the Sauter mean diameter as the bomb backpressure approached the vapour pressure. When the backpressure fell below the vapour pressure a rapid expansion of the angle and a decrease of the diameters was noticed for both fuels.

Aquino et al. [8] studied the actual occurrence of flash boiling in a port injection engine. They noticed that there were many engine working conditions in which flash boiling occurred. In this case the unwanted changes in the spray characteristics could be detrimental to the engine transient response, intake valve temperature and hydrocarbon emissions.

Sunwoo et al. [9] suggested to employ flash boiling as a strategy to improve atomisation during engine warm-up.

Van DerWege and Hochgreb [10-11] performed a series of test in an optically accessed direct injection monocylinder engine. They observed that, increasing the injector temperature beyond a certain value, evaporation caused both an increase of the initial cone angle and a reduction in the mean droplet diameter. An identical conclusion, together with the observation of an increase of spray tip penetration, was reached at CNR-IENI from experiments performed in a constant volume bomb [12].

Experimental setup and procedure

The experimental apparatus usually employed at CNR-IENI for unsteady spray optical diagnostics was slightly modified for this study.

The stainless steel injection bomb (sketched in Figure 1) has internal diameter 206 mm and height 300 mm. It has four 100 mm diameter 40 mm thick glass windows positioned at 0°, 110°, 180° and 270° angles. It can be pressurised up to 1 MPa and electrically heated up to 473 K. A swirl injector (Magneti Marelli) was utilised for the tests. 2-2-4 trimethylpentane (iso-octane) and n-pentane, either pure or blended, were used as fuels. The injector injected downward on the bomb axis and was placed in a holder presenting a cavity for the heat exchange fluid circulation. SAE 15W-40 oil, heated in a thermostatic bath, was forced by a circulation pump in the injector holder. A K-type thermocouple, placed in contact with the injector tip wall, was used to control the injector temperature. The thermocouple signal was converted to temperature and displayed by a multimeter. The indicated value was then corrected according to a calibration curve previously obtained. Due to the low injection frequency (<1 Hz) and the low fuel flow rate, the fuel present inside the injector nozzle was in thermal equilibrium with the wall. A 0.5 mm diameter thermocouple was placed inside the injector pipe at the position of the internal filter and was used to control the fuel temperature stability.

A piston accumulator was used to pressurise the fuel at 7 MPa by means of pressurised nitrogen. A membrane-type accumulator was placed near the injector to dampen pressure oscillations during injector opening. Pressure variations of ±150 kPa around a steady value were measured by means of a Kistler 601A transducer placed at the end of the injector hose.

Two different series of tests were performed. The first was done using pure fuels and changing the bomb backpressure, while in the second one the bomb backpressure was kept constant at 101 kPa and different fuel blends were used. Particular attention was paid to the cleaning of the fuel circuit when the fuel was changed. In fact, the presence of even small residuals from the previous charge, causes fuel composition changes to be strong enough to affect the experimental results.

The spray bomb was pressurised by means of compressed air and, for tests below atmospheric pressure, a compressed air vacuum generator was used. The bomb pressure was measured by means of a Kistler 4075A10 transducer.

The injection opening pulse duration was set at 3 ms by the control unit.

After pressurising the fuel circuit and the injection bomb the test series started with a first point at ambient temperature. Then the thermostatic bath temperature was increased by steps allowing the injector temperature to reach its equilibrium value. When the equilibrium was obtained a series of injection were commanded by a function generator that triggered the injection control unit with a frequency of 0.5 Hz

Visualisations were used to measure the spray angle. For the first series of tests a single shot 8-bit black and white TV camera (FlashCam by PCO GmbH) was used for the visualisations. The camera has a CCD of 752 by 572 pixels 11µm by 11µm, but the image is captured on a single field giving a 752 by 286 spatial resolution with 11µm by 22µm effective pixel dimension.

The second series was performed with a Hamamatsu Orca 12 bit camera, which has a resolution of 1280 by 1024 pixels with 6.7 by 6.7 µm pixels.

Both cameras were placed to have theirs maximum resolution in the direction of the spray width. A Nikon 80-200 zoom lens and bellows extension were used. In both cases the width of the field of view was approximately 4 mm.

A back light visualisation was obtained by means of a flash lamp placed on the view axis behind the spray. A diffuser was placed between the lamp and the spray. A delay of 1.5 ms with respect to the injection trigger was applied both to camera and flash triggers. This delay value was chosen to have a fully developed quasi-steady spray in the vicinity of the injector. The exposure time was controlled by the flash duration (~10µs). By setting a long exposure time, a blur image was obtained, with the result of smoothing the spray surface irregularities. For each one of the studied working conditions, many images were captured.

The spray profile was obtained from the binarized image, fixing a threshold of 128 (out of the 256 gray levels of the 8-bit image) for the image background. The initial angle value was calculated from the angular coefficients of the straight lines obtained by the linear fitting of a portion of the spray profile. The fitting was calculated starting at a distance of 0.15 mm from the nozzle for 1 mm of the profile length as shown in Figure 2.

Experimental results

Series of images were collected changing nozzle temperature, bomb pressure and fuel composition. An example of the effect of the nozzle temperature increase is given in Figure 3, were n-pentane spray profiles at 101 kPa bomb pressure are shown. As the nozzle temperature increases, the initial spray angle stays almost unchanged approximately up to 50°C. After this temperature value is reached, the angle starts to increase with temperature until, for very high temperatures, the spray profile is almost attached to the injector nose wall. Obviously a different fuel composition and a different bomb pressure give similar results at different nozzle temperature values.

Figure 4 shows the results obtained in terms of initial spray angle vs. nozzle temperature for different n-pentane/iso-octane mixtures at bomb pressure 101 kPa. As the flash boiling phenomenon is connected to the boiling temperature of the fuel, it is evident that, at constant pressure, increasing the content of the higher boiling component in the mixture, a shift toward higher values of the temperature at which the spray angle starts to increase is obtained. That means also that for any fuel this temperature increases with the bomb pressure.

Normalising the spray angle by dividing it by its cold conditions value and substituting the fuel temperature with the corresponding vapour pressure (bubble pressure for mixtures [13]) divided by the bomb pressure ($\Pi=P_b/P_{air}$), the data plot is transformed as in Figure 5. The figure shows that, in these coordinates, the different fuel composition data merge in a single curve. It is also observed that flash boiling begins to have effect on initial spray angle for a normalised vapour pressure value of the order of two.

With the same procedure, the data obtained for pure n-pentane at 200 and 300 kPa and for pure iso-octane at 20, 40, 50 and 70 kPa bomb pressure are added to the previous data in Figure 6. Also these results are consistent with the observation that all data coalesce in a single curve.

Conclusions

The fuel flash boiling changes dramatically the spray structure of a high pressure swirled injector. In fact it causes an increase of initial spray angle and spray tip penetration and a decrease in droplet diameters. With respect to the initial spray cone angle, a good correlation between the data obtained from tests performed with different fuels and different backpressures was find. In fact, when the data were plotted in terms of the nondimensional pressure Π, equal to the ratio between the fuel vapour (or bubble) pressure and the bomb back pressure ($\Pi=P_b/P_{air}$), the data result well fitted by a single curve. The Π value for which the increase of the spray cone angle begins to be remarkable is approximately two.

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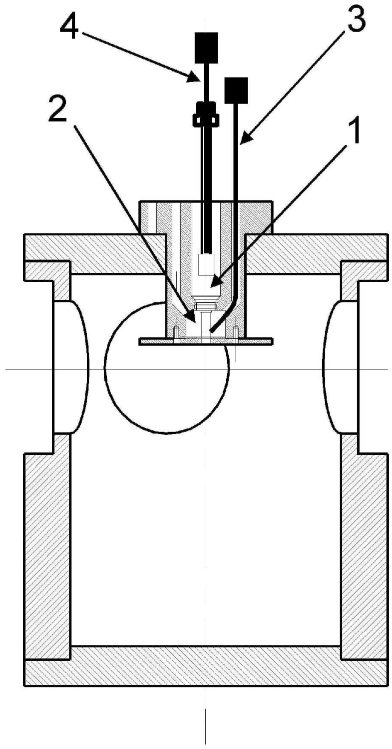

Figure 1. Injection bomb sketch. 1) injector, 2) fluid circulation cavity 3) nozzle thermocouple, 4) fuel filter thermocouple.

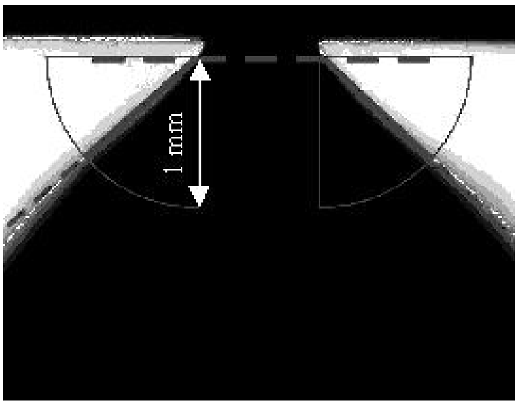

Figure 2. Example of angle determination from spray profile linear fitting.

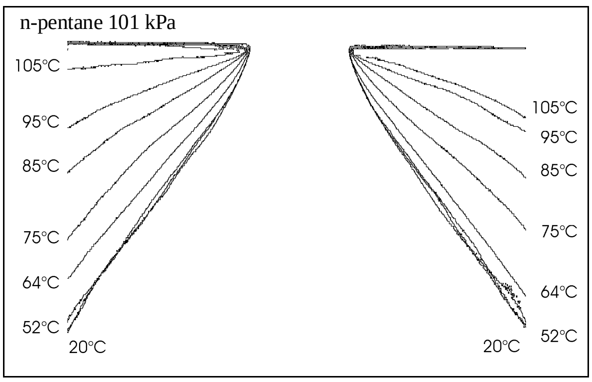

Figure 3. Changes in spray profile in terms of injector nose temperature

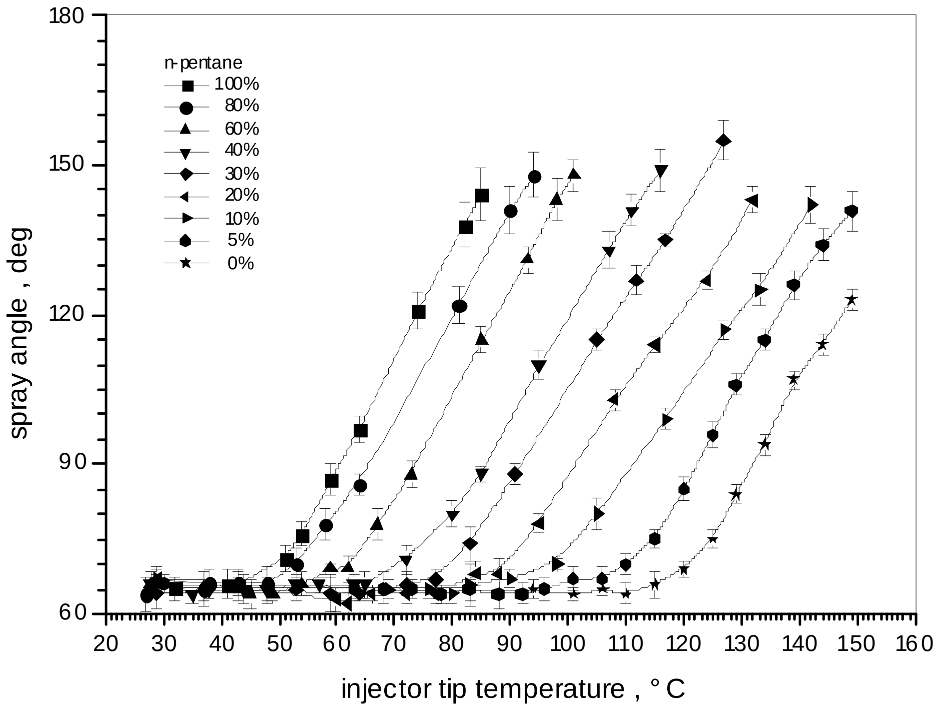

Figure 4. Initial spray angle vs. nozzle temperature for different n-pentane/iso-octane blends at 101 kPa bomb pressure.

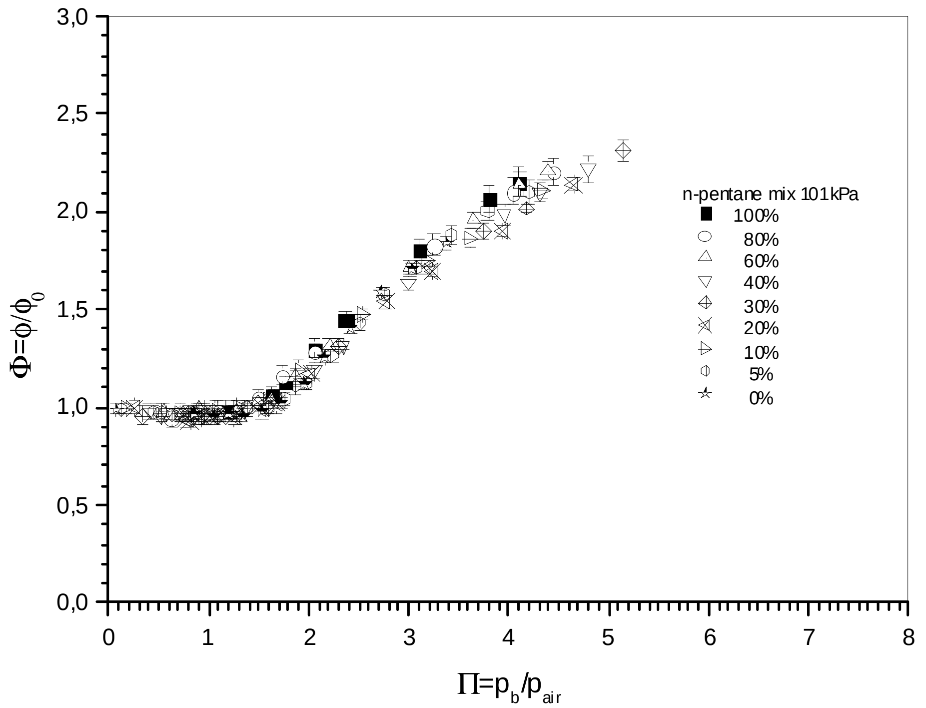

Figure 5. Plot of n-pentane / iso-octane blends data in nondimensional coordinates

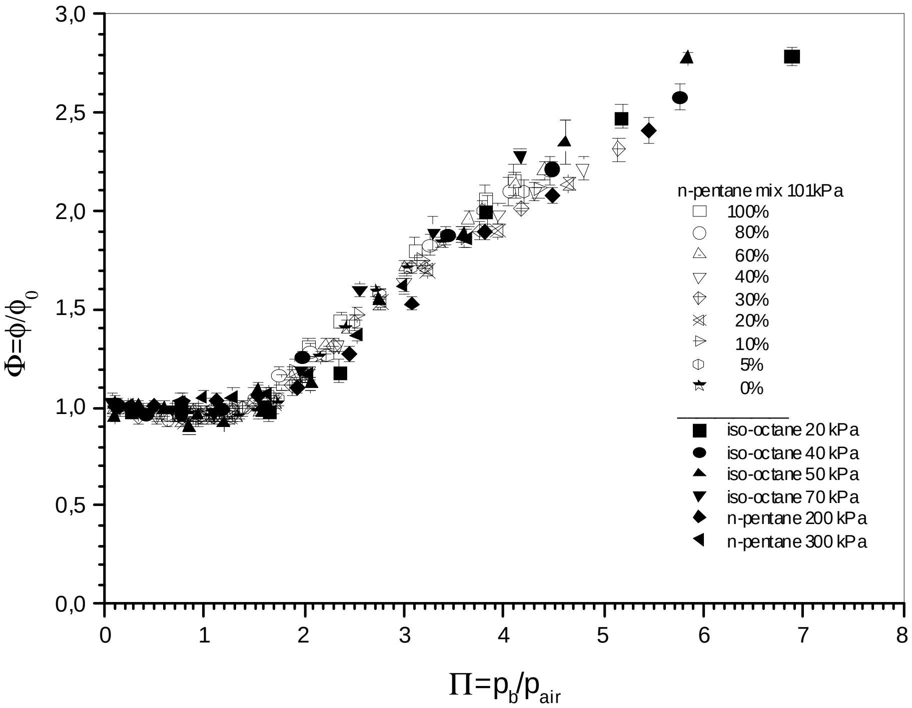

Figure 6. Results of pure n-pentane and iso-octane tests at different pressures superimposed on mixture data at 101 kPa