Comparison of Models and Experiments for Diesel Fuel Sprays

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ABSTRACT

A comparison between numerical and experimental investigation of spray/wall interaction is presented.

Images of a high injection pressure spray impinging orthogonally on a flat plate at ambient temperature and pressure were taken by stroboflash- CCD camera. Using simultaneously the flow visualization and the light extinction techniques, the Sauter Mean Diameter (SMD) was measured and used as initial conditions in the numerical Kiva code.

A new spray/wall submodel is proposed taking into account the rebound of the droplets on the wall.

INTRODUCTION

The development of new generation of d.i. diesel engines has shown the importance of the design of the combustion system for good performance and low emission levels. However the combination of individual design parameters on the engine have to be carefully selected to ensure the most cost-effective method of meeting the relevant legislated limit. In fact, if the increase of injection rate reduces the exhaust smoke and the fuel consumption, at the same time the amount of fuel injected during the delay period increases with the result that the rate of cylinder pressure rise also increases, raising the peak cycle temperature and hence NOx emissions.

So a high injection rate is only required at high load, where a large quantity of fuel is to be injected and the fuel atomization is directly related to the kinetic energy of the fuel which is determined by the injection rate[1,2,3].

Under light load and idle conditions a high injection rate can result in the injection duration being smaller than the ignition period, with the result that the rate of pressure rise is high, increasing both the noise and NOx emissions. Under these conditions the spray penetration can be excessive resulting in spray impingement on the bowl wall, poor combustion and high emission levels[4]. On the other hand several authors [5,6] affirm that in the modern high speed diesel engines with multihole, swirl assisted combustion system, an impingement of 10-15% of the injected total fuel mass can improve the air-fuel mixing that togheter a more retarded injection timing can give a very good compromise between the engine performance and emission levels.

Starting from the above considerations many efforts are being made on the analysis of the interaction between the spray and combustion wall in order to clarify the role played by this interaction on the air-fuel mixing process. Naber and Reitz [7], and Naber, Enright and Farrel [8] have examined the problem of a diesel spray impinging on the wall comparing numerical and experimental results that we are taking as reference in this paper.

The aim of this work is to present the application of Kiva code [9] to the simulation of a real diesel spray impinging on a wall. A set of experiments has been performed using a high pressure diesel fuel injector operating at ambient temperature and pressure.

A fast stroboflash and CCD camera allowed to take spray images impinging on the wall at different times. A digital images processing (DIP) package provided informations on the spread and locations of the spray operating under different conditions. The SMD of spray droplets, measured by a light extinction technique, has been used as initial conditions in the Kiva code. The results from CCD-DIP are compared to the results of the computed model in its original state, and in a modified state taking into account the rebound of the droplets on the wall.

EXPERIMENTAL SET-UP AND PROCEDURES

The flow visualization and light extinction techniques were used simultaneously.

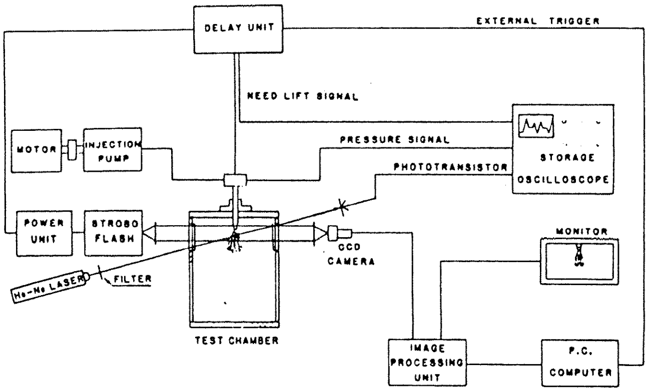

Fig.1 Experimental apparatus.

Fig. 1 shows the experimental apparatus that consists of a stroboflash for lightning the spray (10 Joule energy in a pulse of 10 µs duration); a CCD camera (512 x 512 pixels, 256 gray levels); an injection pump Bosch PE type with plunger of 9 mm, a short pipe line (20 mm lenght, 1.5 mm diameter) and an injector normally used for d.i. diesel engine as shown in fig. 2; a He-Ne Laser (35 mW); a FPT 100 Fairchild phototransistor (0.057 µW/mm^2 to 0.1 mW/mm^2 sensitivity).

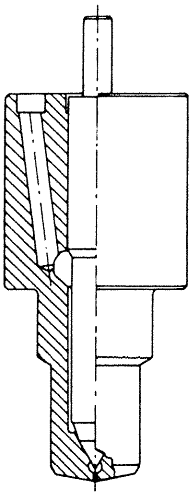

Fig.2 Single-hole fuel injector (0.20mm diameter).

The ISO 4113 oil was sprayed in air at ambient temperature and pressure.
The characteristics of the oil are reported in table 1.

	ISOMethod	Typical value
Density at 15 °C [Kg/l]	3675	0.825
Cin. viscosity at 40 °C [cst]	3104	2.5
Surface tension at 80 °C [N/m]	-	0.0284

Tab.1 Fuel characteristics.

An unit delay based on the needle lift signal triggered the stroboflash, the CCD camera and the transient recorder for the simultaneous acquisition of injection pressure, needle lift, light extinction and spray images. A PC computer was used for the digital image processing and the computation of Sauter Mean Diameter.
Images of the spray impinging on flat plate, disposed orthogonally to the nozzle, were taken at different time from the start of injection.

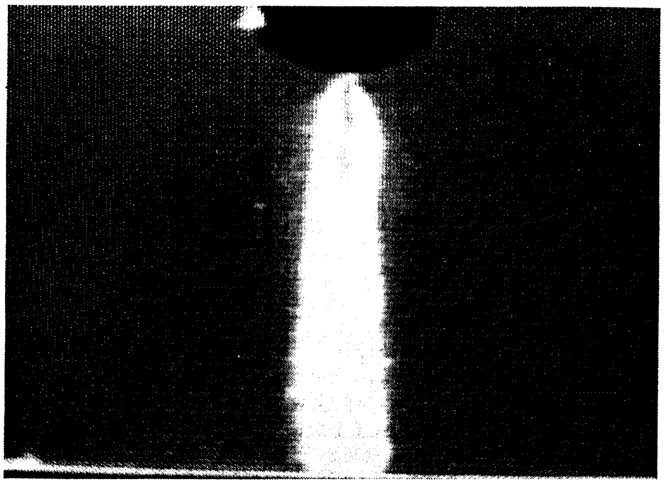

Fig.3 First impact of the spray on the plate located at 20 mm from the nozzle at 160 µs after the start of injection.

Fig. 3 shows the first impact of the spray on the plate located at 20 mm from the nozzle. An injector with a hole diametr of 0,20 mm sprayed 9,5 mm^3/Stroke in a chamber at ambient temperature and pressure.

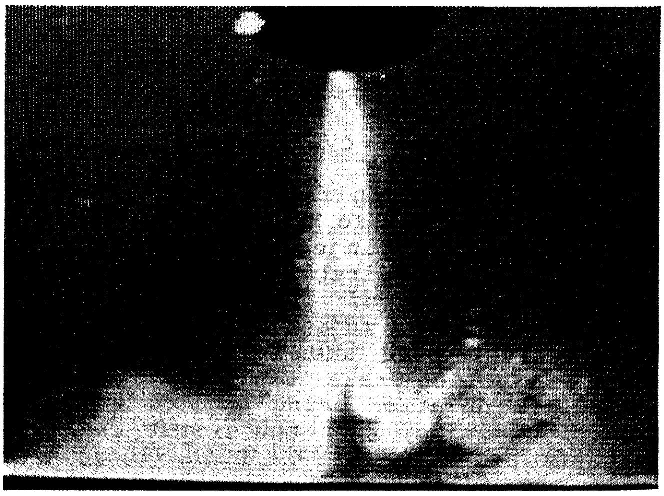

Fig.4 Spray impact on the plate at 280 µs after the start of injection.

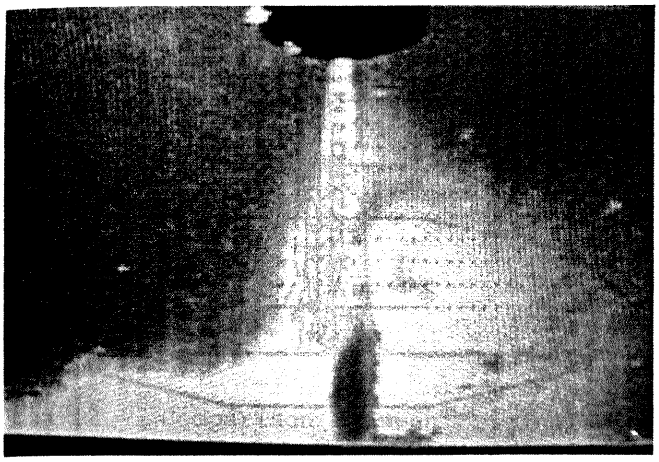

Fig.5 Spray impact on the plate at 340 μs after the start of injection.

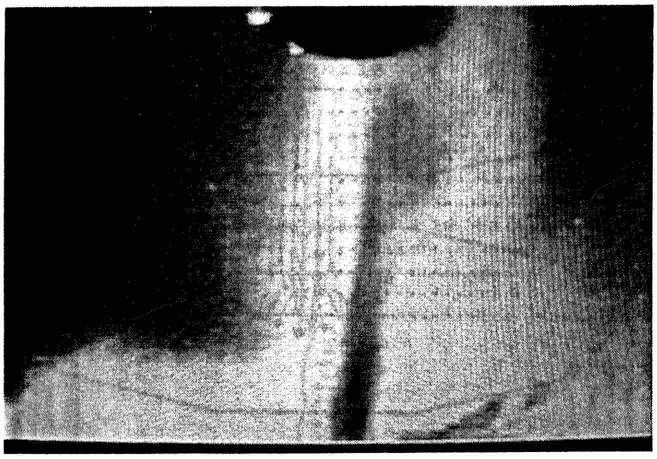

Fig.6 Spray impact on the plate at 460 μs after the start of injection.

Figs. 4,5 and 6 report the impact of the spray at 280 μs, 340 μs and 460 μs after the start of injection. The outline of the spray was used both as initial conditions of the numerical code that for comparison with the output of the Kiva code implemented by our spray submodel.

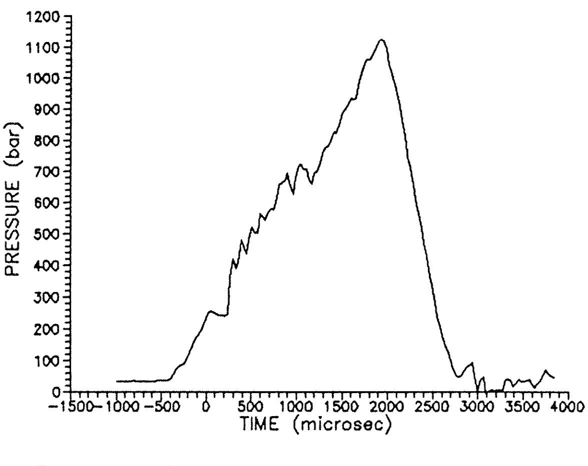

Fig.7 Injection pressure values used in our calculations.

As initial value of the SMD was used that measured by light extinction technique described in more detail in a previous paper [1]. Fig. 7 shows the injection pressure and the SMD values used in our calculation.

NUMERICAL MODEL

The Kiva code was used to model the spray development in the constant closed volume. A stochastic particle technique taking into account the effects of droplet collisions and coalescences was given by O'Rourke [9,10]. The model computes the complete coupling between liquid and gas due to mass, momentum and energy exchanges. The velocity of droplets is evaluated from both normal and tangential component with respect to the wall. In particular the normal component q'_N was assumed as:

$$q'_N = \alpha q_{tot} \qquad (1)$$

and tangential one as:

$$q'_{tg} = (q^2_{tot} + q'^2_N)^{1/2} \qquad (2)$$

where q_{tot} being the total velocity before the impingement and q'_N being the new normal velocity after the impingement.

The α factor is a random number from an uniform distribution from 0 to 0.34.
The equation (2) states that the total velocity is maintained unchanged before and after impingement. Moreover the angle between the new tangential component and the old one is given by:

$$\Psi = \pm \pi/\beta \; \ln(1-\chi \; (1-e^{\beta})) \qquad (3)$$

with χ being an uniform random number varying between 0 to 1. β parameter derives from the solution of implicit equation:

$$\sin \alpha = (e^{\beta+1}/e^{\beta-1}) * (1/1+(\pi/\beta)^2) \qquad (4)$$

where α being the impingement angle from the normal to the plate with respect to the normal. If the radius of the particle is reduced by factor 5 the total mass of droplets is constant before and after the impingement.
From a computational point of view, the problem is quite troublesome, because the rebound of a particle impinging from any direction on the wall to any other direction must be evaluated.
Firstly, this requires the mathematic calculations of the parameters of the equation:

$$ax+by+cz+d=0 \qquad (5)$$

that defines the plane of the wall.
Then the time t_1 needed to reach the wall is calculated.

The new components of normal and tangential velocities are evaluated at the time:

$$t_2=\Delta t-t_1 \quad (6)$$

where Δt is the time step of numerical solution. The new radius r^{new} and particle number N are defined according to:

$$r^{new}=r^{old}/R \quad (7)$$

$$N^{new}=R^3 \ N^{old} \quad (8)$$

where R is the reducing factor of the radius.

Recent developments have focused and improved model of drop breakup [11,12], drop coalescence [12] and improved descriptions of the initial conditions and boundary conditions [13].

This work enphasizes the only spray impingement on the wall proposing a new submodel taking into account the rebound of the droplets on the wall and the initial conditions according to the experiments. However our submodel is very similar to that proposed by Naber and Reitz [7]. The original spray/wall interaction model was modified assuming that, when a fuel droplet hits the wall, it rebounds rather than remaining on the wall as in the original Kiva code.

COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS

The numerical runs were performed starting from initial conditions based on the experiments previously described.

Firstly we run the code without any modifications for the droplet submodel, but we used the real injection pressure values measured on the injector operating on the pump test bench.

Figs. 8,9,10 and 11 report the output of the modified Kiva code relatively to spray velocitiy at different time after the start of injection.

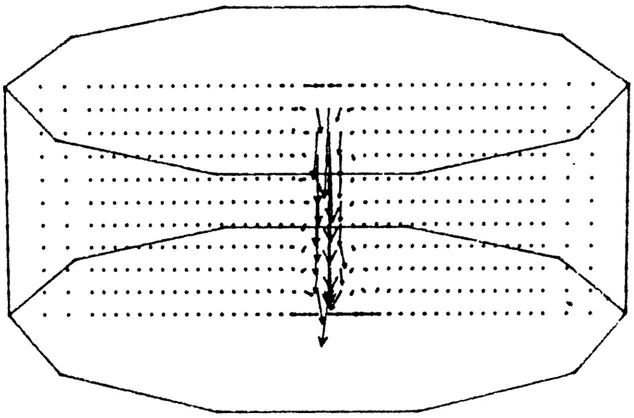

Fig.8 Modified Kiva code output at 160 µs after the start of injection.

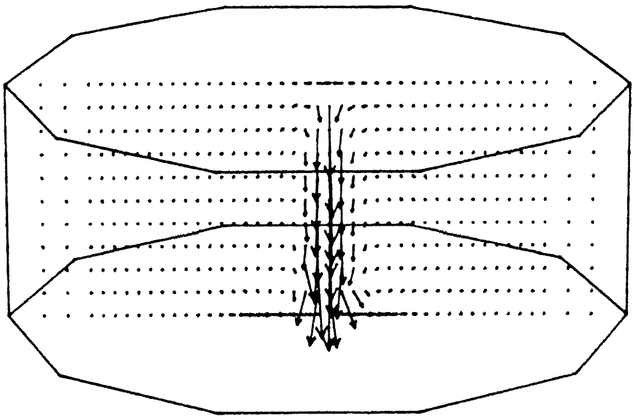

Fig.9 Modified Kiva code output at 260 µs after the start of injection.

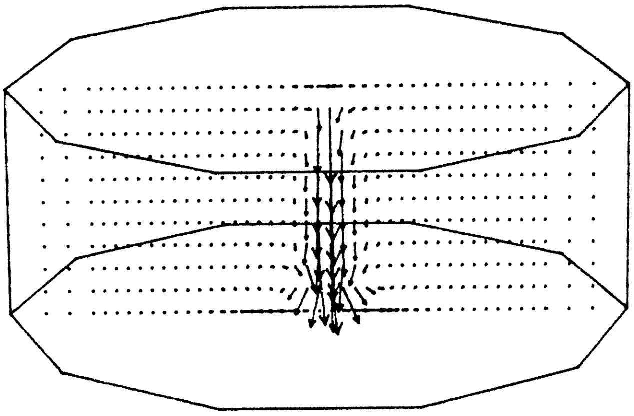

Fig.10 Modified Kiva code output at 340 µs after the start of injection.

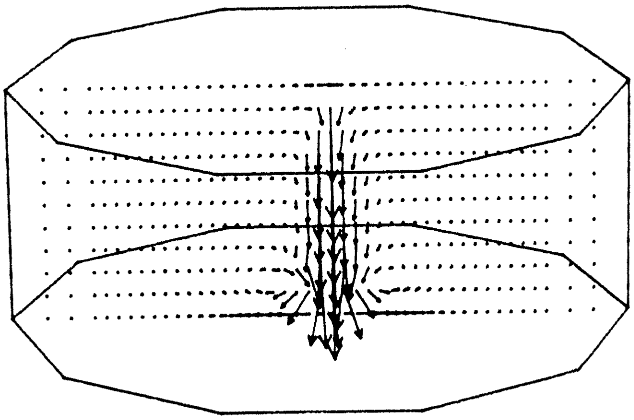

Fig.11 Modified Kiva code output at 480 µs after the start of injection.

The fig. 12 shows the comparison between the predicted spray penetration as computed by the original Kiva code and that measured.

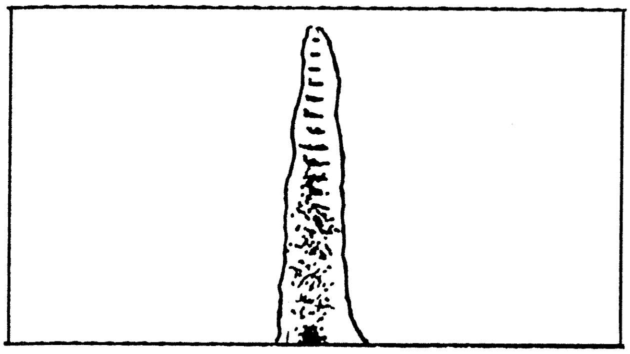

Fig.12 Comparison between original Kiva code and measured spray penetration at 160 μs after the start of injection.

At the first impingement on the flat plate, a very good agreement is noted. Looking the comparisons after the impingement we note a complete disagreement with the experiments as reported in figs. 13,14 and 15. This happens because the original droplet submodel does not take into account the rebound of the droplets on the wall.

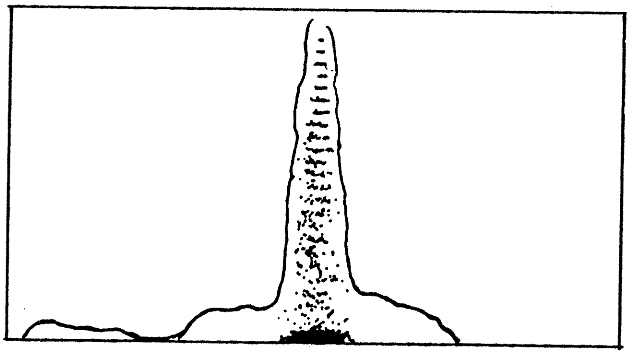

Fig.13 Comparison between original Kiva code and measured spray impingement at 260 μs after the start of injection.

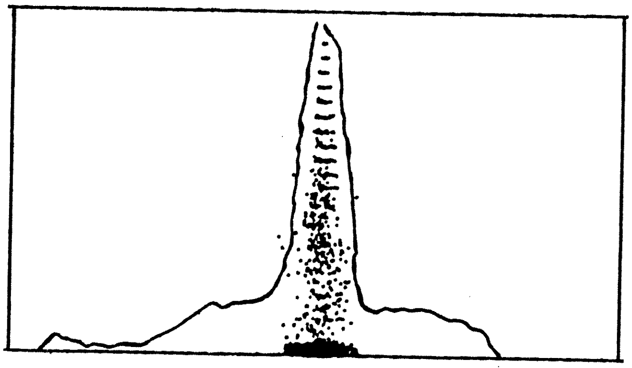

Fig.14 Comparison between original Kiva code and measured spray impingement at 340 μs after the start of injection.

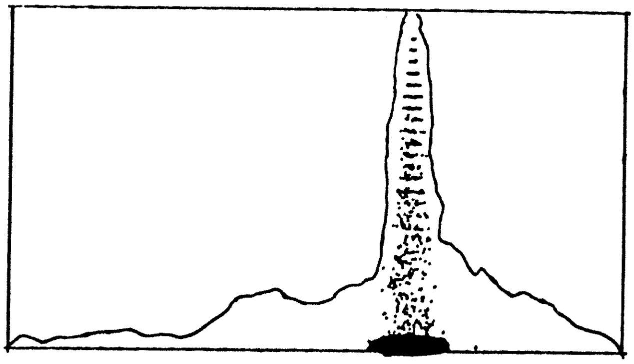

Fig.15 Comparison between original Kiva code and measured spray impingement at 480 μs after the start of injection.

Using the modifications here proposed we can see in the figs. 16,17,18 and 19 a very good agreement with the experiments.

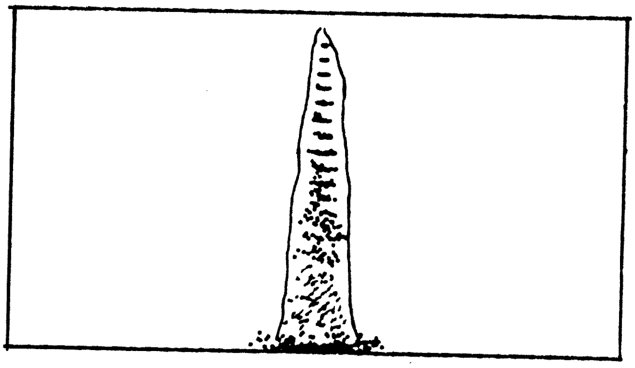

Fig.16 Comparison between modified Kiva code prediction and measured spray penetration at 160 μs after the start of injection.

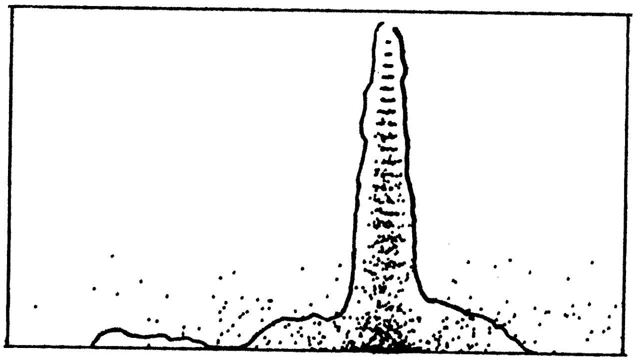

Fig.17 Comparison between modified Kiva code prediction and measured spray impingement at 260 μs after the start of injection.

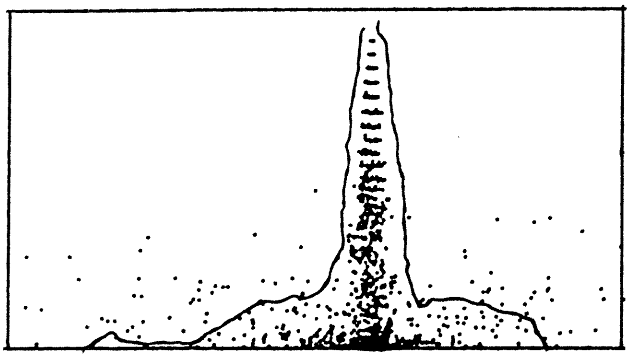

Fig.18 Comparison between modified Kiva code prediction and measured spray impingement at 340 µs after the start of injection.

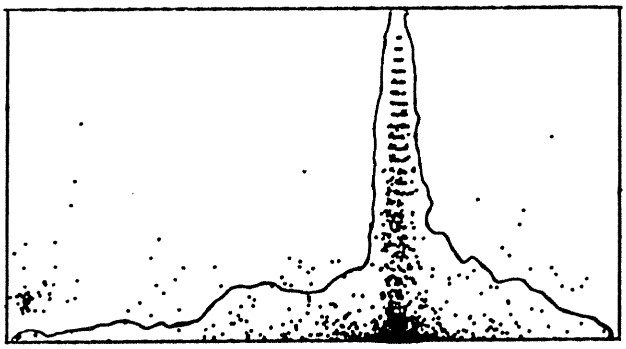

Fig.19 Comparison between modified Kiva code prediction and measured spray impingement at 480 µs after the start of injection.

The above figs also reveal that in the quantitative comparisons the extent of spread of the computed spray generally underestimates the measured spray outlines. This may be because images of sprays are most sensitive to the smallest drops (which scatter light efficiently) and the present computation consider only a limited range of drop size. This result confirms very well that reported by Naber and Reitz in paper [7].

Finally it is interesting to note the evolution of air flow-field in the chamber during the injection process. After the impingement secondary vortexes are present on the boundary of jet implying an improving of the air entrainment in the jet itself.

Figs. 9,10 and 11 report moreover the code outputs at 260, 340 and 480 µs after the start of injection respectively. Here we note that the air motion structure is quite modified by the incoming spray. This effect partly confirms the experimental results that a properly tuned degree of impingement can improve the performances of swirl assisted direct injection combustion systems.

FINAL REMARKS

A comparison between numerical and experimental investigation of spray/wall interaction is presented. A new submodel of spray/wall interaction taking into account the rebound of spray droplets on the wall is proposed in the Kiva code.
The results have shown the following:

- The outputs of the original Kiva code predict very well the spray penetration only until the spray impinges on the wall.
- The outputs of the Kiva code, implemented with the new submodel, are in good agreement with the experiments.
- The spray impingement produces modifications of the structure of the air motion and give a contribution to the air entrainment in the jet.

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