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Simulation of Oblique Evaporating Diesel Sprays, and Comparison with Empirical Correlations and Simulated Straight Sprays

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Abstract

The innovation in software analysis and various available programming facilities have urged the designers at various levels to do indispensable calculations for engine flows. Presently, the 3-D analysis approach is under practice to do simulations for various parameters involving engine operations using various softwares, "Fluent" being the trendiest at the moment for CFD modeling. The present work involves CFD modeling of diesel fuel sprays at a specified angle with cylinder axis. Fuel spray modeling includes sub-models for aerodynamic drag, droplet oscillation and distortion, turbulence effects, droplet breakup, evaporation, and droplet collision and coalescence. The data available from existing published work is used to model the fuel spray and the subsequent simulation results are compared to experimental results to test validity of the proposed models.

Key Words: evaporating diesel sprays, penetration rates, oblique sprays, jet breakup time, over prediction

Nomenclature

P_{inj} fuel Injection Pressure

P_{ch} Chamber Pressure

X_p spray Penetration Distance

Δp difference between injection pressure and chamber pressure

d nozzle diameter

ρ_a chamber air density at any given pressure but maintaining the atmospheric temperature

ρ_g gas density in the chamber at said pressure and temperature

t time span measured from the onset of fuel injection

1. Introduction

Extensive experimental work and a rigorous analytical modeling of C.I. (compression ignition) Engines have suggested a serious need of revising design calculations because of the global energy crisis and internationally imposed emission legislations. With the passage of time different emission control legislations have urged more emphasis towards engine emissions rather than the total power output. This obviously necessitates detailed studies of different engine performance parameters and incorporation of design modifications. Fuel injection system, combustion chamber geometry and air motion in the combustion chamber are the essentials believed to have effect on compression ignition engine performance. Inherently, the intrinsic performance of a C.I. engine of fixed combustion chamber geometry is spray characteristics related.

2. Empirical Correlations

Dent [5] performed far-reaching experimental work on fuel sprays using both cold bomb and hot bomb conditions and made use of the theory of gas jets to derive the following semi-empirical correlation for penetration rates of fuel sprays, measured from the onset of fuel injection. He has defined cold bomb condition as the one that maintains the chamber temperature as atmospheric under any elevated chamber gas pressure.

$$X_{po} = 3.01 \left(\frac{\Delta p}{\rho_g} \right)^{0.25} d_o^{0.5}\ t^{0.5} \tag{1}$$

Where Δp, ρ_g, d_o, t is the pressure differential across the injector, chamber gas density, injector nozzle diameter and time from the start of fuel injection respectively. The correlation equation (1) is dimensionally consistent and amongst the most popular ones but suffers from the disadvantage of over prediction of the initial liquid phase of the spray.

Dent [5] modified his basic correlation for the cold bomb condition to accommodate the effect of hot bomb conditions where hot bomb condition means the one using elevated chamber gas temperature at elevated pressure. He reported the following joint correlation equation for both hot and cold bomb conditions.

$$X_{po} = 3.01 \left(\frac{\Delta p}{\rho_g} \right)^{0.25} d_o^{0.5}\ t^{0.5} \left(\frac{295}{T_g} \right)^{0.25} \tag{2}$$

Here Tg is elevated chamber gas temperature. It is necessary to mention that substitution of the value of Tg equal to that of cold bomb condition i.e. 295 K under-predicts the spray penetration rates for cold bomb condition as observed by Mirza [1].

Realizing the disadvantage of over prediction by Dent's correlation of the initial nozzle tip zone, Hiroyasu and Arai [7] proposed a 2-line fit to their experimental data on fuel sprays. Hiroyasu and Arai [7] used constant pressure injection that formed the basis of formulation of their empirical correlations on jet break up time, jet break up length, liquid phase penetration rates and vapor zone penetration rates of fuel sprays. According to Hiroyasu and Arai [7], injection velocity of the fuel is given by:

$$U_{inj} = C_1 \left(\frac{2\,\Delta p}{\rho_f} \right)^{0.5} \tag{3}$$

Where ρ_f is the fuel density and C_1 is related to coefficient of discharge of the nozzle. For injection times equal or shorter than the jet breakup time, t_b, the jet penetration is

$$X_{po} = C_1 \left(\frac{2\,\Delta p}{\rho_f} \right)^{0.5} t \tag{4}$$

and for injection times equal or larger than the jet breakup time, t_b, the spray jet penetration rate is given by:

$$X_{po} = 2.95 \left(\frac{2\,\Delta p}{\rho_g} \right)^{0.25} d_o^{\,0.5}\ t^{0.5} \tag{5}$$

The 2-line fit of Hiroyasu and Arai [7] requires determination of the jet break up time and jet breakup length for each set of variable pressure differential, fuel density, injector nozzle diameter and the chamber gas density; hence not as attractive as the t½ type single-line fit described above. It is right place to mention that replacing the value of ρ_g by ρ_a which corresponds the cold bomb condition, also under predicts the penetration rates of the fuel spray jet even in the vapor zone, like correlation of Dent [5] as described above. It is further pointed out that Hiroyasu and Arai [7] by themselves state that the penetration rates of vaporizing sprays are about 20% shorter that those of the non-evaporating sprays. Mirza [1] observed this shortcoming too.

Mirza [1] proposed the following dimensionally consistent empirical correlation equation for isothermal non-evaporating fuel sprays under quiescent chamber conditions:

$$Xp = 3.8 \left(\frac{\Delta p}{\rho_a} \right)^{0.25} d_o^{\,0.5}\ t^{0.5} \tag{6}$$

Where ρa is the chamber air density at any elevated pressure but maintained at laboratory room temperature. The proposed correlation equation (6) has the similar disadvantage of over prediction of the initial liquid phase of the spray jet. To eliminate this disadvantage, Mirza [1] proposed its modification using algebraic as well as hyperbolic functions as given below:

$$Xp = 3.8\ t^{F(t)} \left(\frac{\Delta p}{\rho_a} \right)^{0.25} d_o^{\,0.5}\ t^{0.5} \tag{7}$$

Where F (t) is the following algebraic function that smoothly blends the near nozzle zone and spray tip zone.

$$F \quad t \quad = \; {}^{1}\!\big/_{a\,t\,+\,b} \tag{8}$$

having a and b are experimentally determined constants, 1.25 x10-5 and 5.94, respectively. The alternative hyperbolic function, proposed by Mirza [1] equally modifies equation (6), is as under:

$$Xp = 3.8\ \tanh(4.1 \times 10^3 t)^{0.6} \left(\frac{\Delta p}{\rho_a} \right)^{0.25} d_o^{\,0.5}\ t^{0.5} \tag{9}$$

The hyperbolic and algebraic functions smoothly blend the initial nozzle tip and the end spray tip zones of the spray, unlike the 2-line fit of Hiroyasu and Arai [7]. Mirza and Baluch [2, 3] has proposed the following empirical correlation equation for evaporating fuel sprays:

$$Xp = 3.8 \left(\frac{\rho_g}{\rho_a} \right)^{0.25} \left(\frac{\Delta p}{\rho_a} \right)^{0.25} d^{0.5}\ t^{0.5} \tag{10}$$

It must be noticed that ρ_a is calculated at any elevated chamber pressure but at atmospheric temperature, whereas, ρ_g is calculated at elevated pressure and elevated temperature.

3. Simulation and Presentation of Results

Cylinder geometry can be calculated from the number of cylinders and swept volume of each engine cylinder. In the present work, a 1600 cc, 4-cylinder, 4-stroke compression ignition (C.I.) engine is taken as the reference. The bore length (*L*) to cylinder diameter (D) ratio is assumed as 1.1. In other words, each engine cylinder has a swept volume (V) of 400 cc, with *L /D* ratio of 1.1. For the reference case, engine cylinder dimensions are calculated by using the following simple relations

$$\text{Cylinder, } V = \pi D^2 L \tag{11}$$

$$\text{Cylinder, } V = a\pi D^3 \tag{12}$$

Where ‘a’ is the *L /D* ratio of the cylinder, which is 1.1 in all simulated cases presented in the present work.

A 1600 4-cylider, 4-stroke compression engine will hence have 77 mm diameter and 85 mm stroke length, respectively and these dimensions will remain same for CFD simulations throughout this work.

For simulation data, the experimental test case of Mirza [1] is taken as reference which uses mean injection pressure of 22 MPa to produce Diesel spray jet through single hole 0.25 mm diameter orifice nozzle in the quiescent chamber maintained at 2.25 MPa and 800 K. Using a 3D co-ordinate system, Injection and cylinder axis are taken along y-axis. The 3D geometry of the chamber is defined such that the y-x plane at z=0 will pass through the injection axis when the injection angle is taken as zero that is $\alpha = 0°$ but for oblique injection this injection angle is kept 30° from the x-y plane. Fuel and air properties are tabulated in Table 1 and in Table 2 different selected Fluent options are shown. Optimization of fuel injection velocity and particle diameter distribution is carried out, with upper limit using the relationship reported by Mirza [1] and Hiroyasu, Arai [7].

The lower limit of injection velocity is obtained by optimization through simulation of the spray jet taking the experimental data reported by Mirza [1]. Rosin-Rammlar distribution is used for particle size distribution with initial and final particle size of 1×10^{-6}m and 5×10^{-5}m respectively with mean diameter 26.8×10^{-6}m and a spread parameter of 2. Spread parameter defines the shape of size distribution curve, which is assumed exponential in the present case [Fluent].

Unsteady formulation of simulation is carried out using segregated solver of Fluent and validation of the model is made by cross checking the values of density, temperature and absolute pressure obtained by results with given operating environment. Figure 1 shows the simulated results of the spray shape formation. The simulation results include the full range of particle comprising the spray jet, the range being calculated by the software itself. The software, on the basis of distance from nozzle tip, automatically chooses the color of spray body.

4. Discussion and Conclusion

Figure 2 shows the spray shape (simulated) for the evaporating spray and narrate an increase in spray penetration with an increase in the magnitude of fuel injection pressure. For all such cases the over prediction trend by the correlation predictions is because of its natural tendency being of t½ type. The simulated results on spray penetration history are more realistic than the standard t½ type correlation equation predictions which are always larger than the experimental results. The Simulation results of the initial liquid phase gathered by using Reitz’ model, are hence closest to correlation predictions of Hiroyasu and Arai [7] straight line; and that of Mirza and Baluch [2, 3].

Figures 1 shows the comparison of spray shapes for evaporating spray simulations at the conditions stated. Simulated spray images (A) are measured from the commencement of fuel injection, time step has been kept as 0.15 ms while (B) shows the plot for spray simulation shapes using a less refined time-step of 0.30 ms between the two consecutive spray images. Reduction in the time step increases the number of particles as the number of simulations increased and certainly this makes the spray shape relatively better defined. The color bar demonstrates the penetration at time 1.2ms after injection (image at extreme left, part A). So far the interest is only in the spray penetration rate along the axial direction of the cylinder while the radial spread of this particular spray is far less given a thought primarily and so is the case with the provided correlation data. Furthermore as far as figures 1 and 2 (color bar for ‘A’ part) are concerned only the axial trend is of primary interest and the vital parameters along with the penetration rate are discussed in detail later.

Correlation, straight and oblique injection ($\alpha = 30°$, the injection angle has been taken as 30° with –ve y axis in case of oblique injection through out this work) penetrations are compared at the specified conditions as stated (fig.3) to have a close look at their mutual digressions. Figure 4 shows the variation in Xp, plotted against time for variable injection pressure. Three different pressures of 25, 30 and 40 MPa are chosen to investigate on the effect of injection pressure on spray tip penetration, for the evaporating case. Figure 5 shows the comparison of the correlation predictions and simulations. Line through the origin is drawn at an angle of 45 degrees to deeply examine the difference between the two results. Close examination reveals that the most of the data points lye on the 45º line through the origin; showing an excellent match between the published correlation of Mirza and Baluch [3] and the current results.

Figure 6 and 7 show the spray penetration rate and the comparison with variable injector nozzle diameter. Figure 6 shows an increase in spray penetration rates with an increase in nozzle hole diameter. The reason to this effect is also the increase in the mass flow rate of the fuel through the nozzle, which increases the initial spray jet momentum. The match between the two results is again excellent, with a reason to slight disagreement in the initial liquid phase.

Figure 8 demonstrates histories of the spray penetration and comparison of empirical correlation and simulation results, respectively and describes a reduction in spray tip penetration with an increase in chamber pressure i.e. an increase in chamber air density. Reasons to this effect are explained by the increased resistance offered by the elevated pressure air. Again match between the two results is excellent and the maximum digression is not more than 5%. Figure 9 compares the simulations with the correlation predictions and reveals that the most of the data points lye on the 45º line through the origin; showing an excellent match between the published correlation of Mirza and Baluch [2] and the simulation results.

Tables and Figures

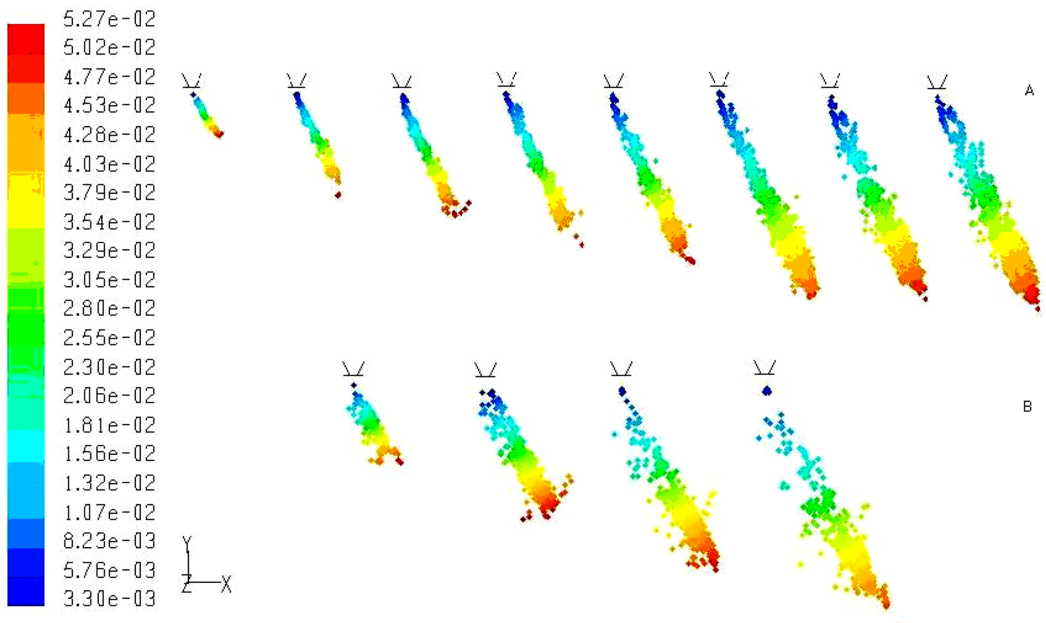
Table 1: Fuel and Air properties

Fuel		Air	
Fuel density	850 kg/m^3	Air density	27.03 kg/m^3
Fuel viscosity	0.00332 kg/ms	Air viscosity	1.789 x10^{-05} kg/ms
Fuel surface tension	0.0190355 N/m		

Table 2 Simulation options of Fluent

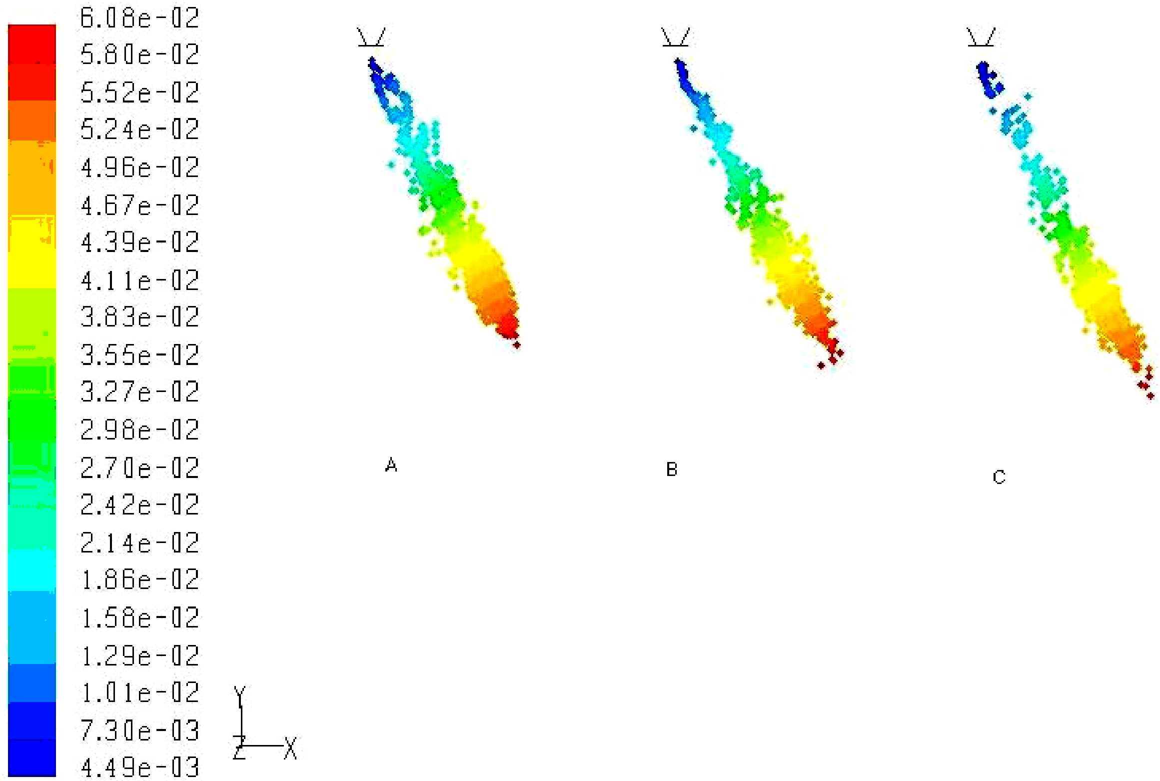
Software	Option
Injection type	Group
No. of particle streams	250 – Chosen
Particle type	Droplet * Inert Combusting Custom
Diameter distribution	Rosin-Rammler * Linear Rosin-Rammler logarithmic
Material	Fuel-oil-liquid
Evaporating species	$C_{19}H_{30}$
Position of injection	0,0.085,0 – Chosen
Temperature	800K
Start time	0.000 ms – Chosen
Stop time	0.0012 ms – Chosen
Velocity magnitude x-component y-component For α = 30°	105 m/s (variable) 90.93 m/s 52.5 m/s
Flow rate	0.0141 kg/s
Min droplet diameter	1.0e-06 m
Max droplet diameter	50.0e-06 m
Mean droplet diameter	26.8e-06 m
Spread parameter	2

*Values taken from the available options



Pch 2.25 MPa, Pinj 22MPa, Nozzle diameter 0.25 mm
Spray injection angle α = 30°, Temperature 800k

Fig. 1: Spray shape (A at 0.15ms interval, B at 0.30ms interval), starting from fuel injection till end of injection, colored by penetration



A=20, B= 40 and C=80 MPa Injection Pressure
PCh 2.25MPa, Nozzle diameter 0.25 mm, Temperature 800k
All at time t = 1.2 ms from start of injection
Spray injection angle α = 30°

Fig. 2: Spray shape starting from fuel injection till end of injection, colored by penetration

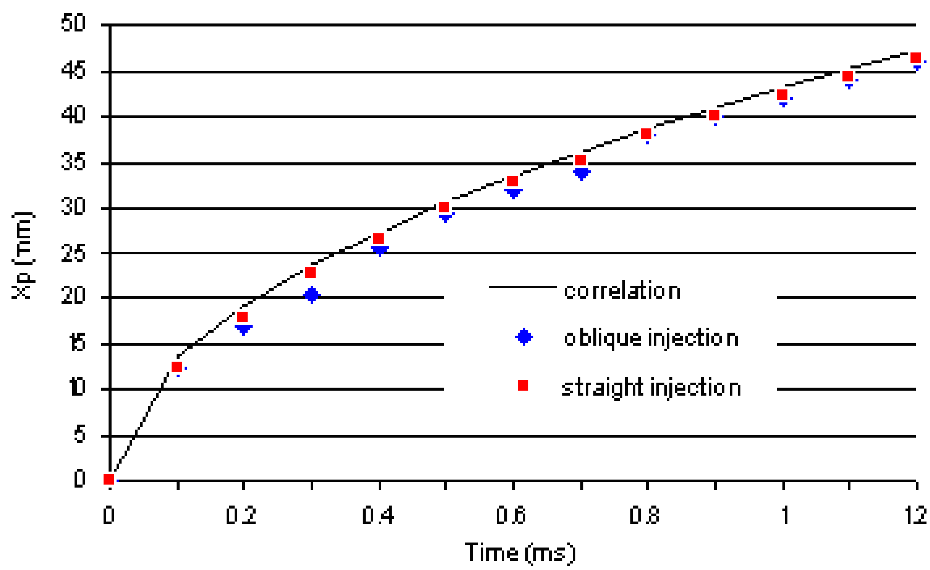
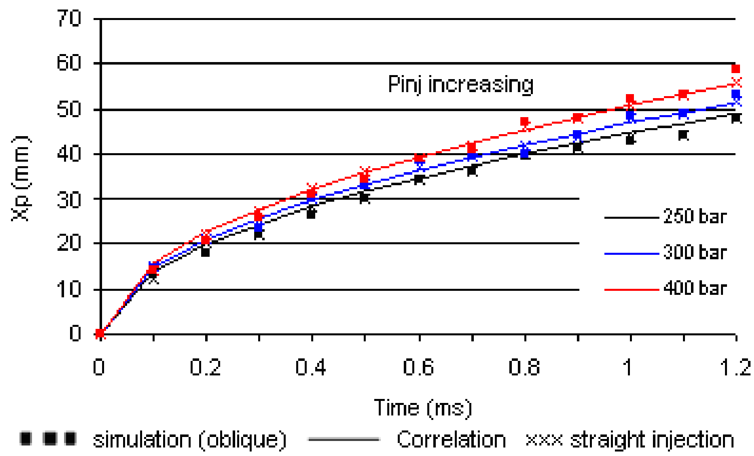


Fig. 3: Spray Tip Penetration vs Time, P_{ch} 2.25MPa, P_{inj} 22MPa, Nozzle dia 0.25mm, Temp 800k



Spray injection angle α = 30°
Pinj varied, Pch 2.25MPa, Nozzle dia 0.25mm, Temp 800k

Fig. 4: Spray Tip Penetration vs Time

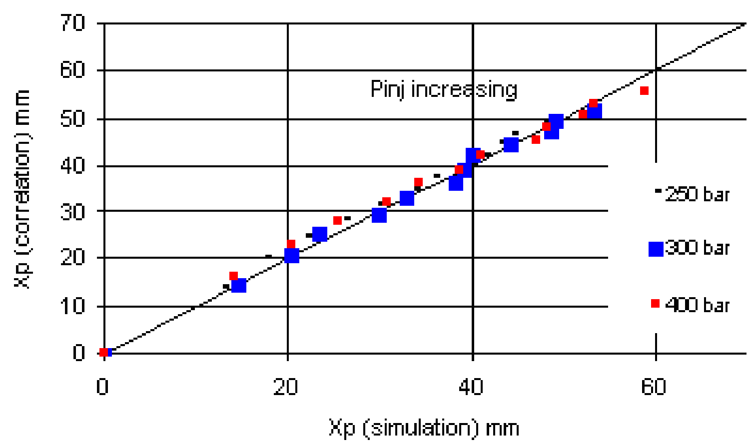
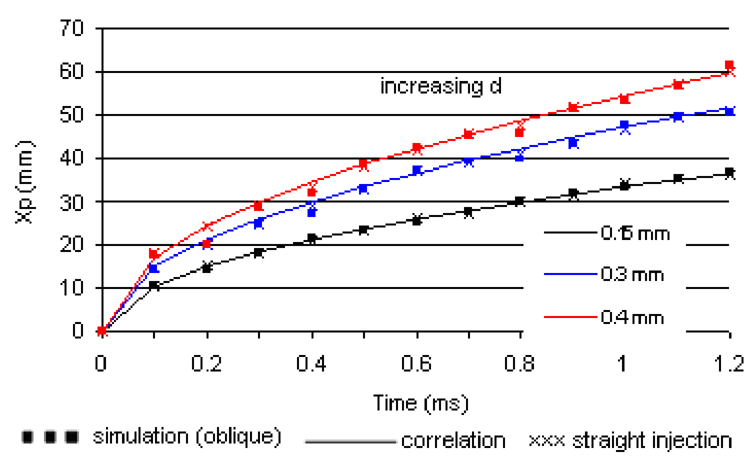


Fig. 5: Penetration (correlation) vs Penetration (simulation)



Spray injection angle α = 30°
Pinj 22MPa, Pch 2.25MPa, Nozzle dia varied, Temp 800k

Fig. 6: Spray Tip Penetration vs Time

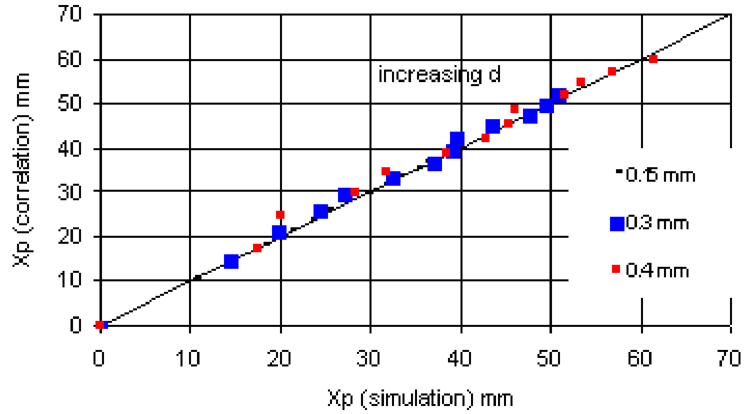
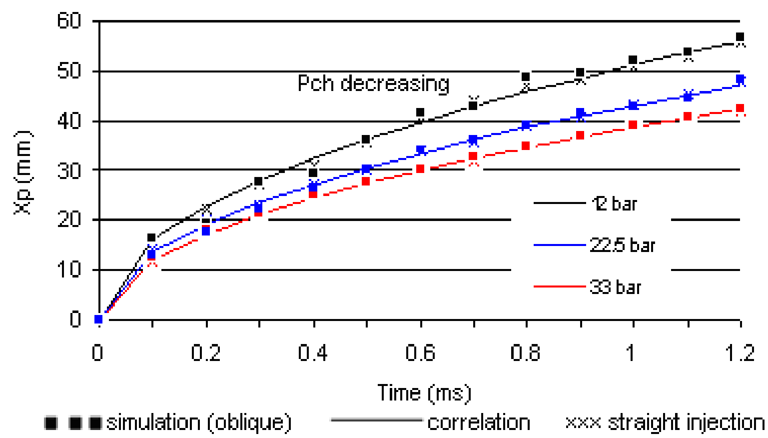


Fig. 7: Penetration (correlation) vs Penetration (simulation)



Spray injection angle $\alpha = 30°$

P_{ch} varied, P_{inj} 22MPa, Nozzle dia 0.25mm, Temp 800k

Fig. 8: Spray Tip Penetration vs Time

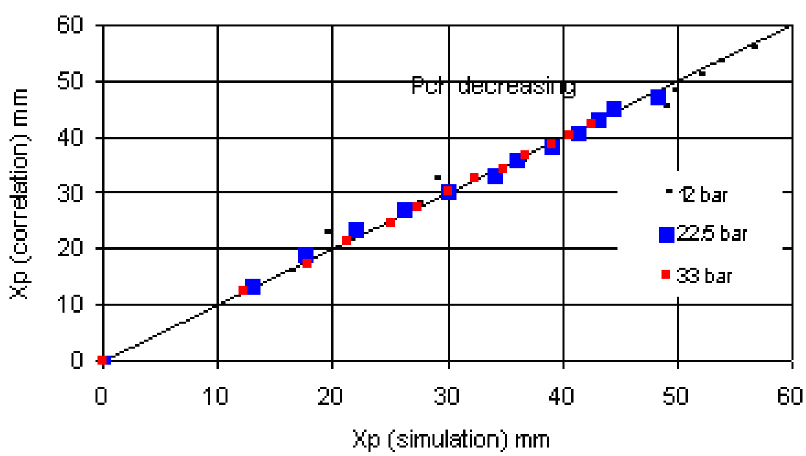


Fig. 9: Penetration (correlation) vs Penetration (simulation)

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