Structure of Non-Evaporating Diesel Sprays

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Abstract

Need is always felt of some rational experimental information on fuel spray jet formation, its development and dispersion in the combustion chamber of an internal combustion engine. The latest study uses computational fluid dynamics for the modeling of engine flows. The original experimental work of the present author on non-evaporating sprays produced by a single-hole orifice type nozzle using a distribution type commercial fuel injection pump forms the basis to derive correlations for penetration rates, break up times and lengths of non-evaporating diesel sprays. The correlations derived can be used to do CFD modeling of sprays under variable conditions of injector nozzle hole diameter, fuel injection pressure and combustion chamber pressure.

Keywords: Non-evaporating diesel sprays; Penetration rates; Break up times; Break up lengths

1. Introduction

A non-evaporating fuel spray is defined as the spray produced under variable chamber pressure condition by maintaining the chamber temperature equal to the ambient temperature. Similar study on evaporating sprays is reported by the present authors separately [1] elsewhere. The fuel spray jet is known to have the initial liquid phase zone, and the end vapor zone. The jet break up mechanism is however not correctly understood. An effort is hence made in the present work to investigate on the non-evaporating spray structure to report realistic information on jet break up mechanism.

Semi-empirical "$t^{1/2}$" type correlation equation is the most popular fit to the fuel spray jets produced under quiescent conditions similar to that of prevailing in the combustion chamber of real internal combustion engines. The work of Hiroyasu and Arai [2] has not explicitly reported any correlation equation on non-evaporating sprays, although, they do mention that the length of evaporating spray is reduced by almost 20%, compared to the non-evaporating diesel sprays. Dent [3] has also reported the reduction of spray length with the increase in chamber air temperature, but there is no set of explicit correlation equations on non-evaporating fuel sprays. The explicit information on non-evaporating spray break up is also missing. The present work formulates the spray jet break up time, the spray jet break up length and the velocity of the jet in the break up zone. The derived correlations are compared with those of the evaporating fuel sprays.

2. Fuel injection rate

For the reference condition, with needle opening pressure of 22 MPa and the air equivalent chamber pressure of 2.25 MPa, used in previous work of the present author [4], the data is re-analyzed and the fuel injection flow rate is found computable by the following relationship:

$$m_f = \rho_f A\, C_1 \left(\frac{2\Delta p}{\rho_f}\right)^{0.5} \qquad (1)$$

where ρ_f is the fuel density, A is the nozzle hole area, Δp is the mean pressure differential across the nozzle and C_1 is the constant equal to 0.39 related to coefficient of discharge of the injector nozzle, being in agreement with the findings of Heywood [5].

3. Vaporous zone

The following dimensionally consistent $t^{1/2}$ correlation equation, similar to that of Dent [3] and Williams [6], gives an excellent fit to the penetration length (X_{po}) of non evaporating diesel sprays in the vapor zone, under variable conditions of mean pressure differential across the nozzle, chamber air density and nozzle diameter

$$X_{po} = C_2 \left(\frac{\Delta p}{\rho_a}\right)^{0.25} d^{0.5}\, t^{0.5} \qquad (2)$$

where experimentally determined value of the constant C_2 is 3.8, ρ_a is the chamber air density at a given pressure but at atmospheric temperature.

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Figure 1 shows experimental distance-time history of the non-evaporating diesel spray produced under quiescent chamber condition maintained at 2.25 MPa and atmospheric temperature of 290 K. Figure 2 shows comparison of the predictions of correlation equation (2) and the experimental results of Mirza [3]. Examination of Figure 2 shows large over prediction of the correlation equation (2) in the initial near nozzle tip zone of the spray. The following hyperbolic modification to Equation (2) eliminates the over prediction of the initial nozzle tip zone of the spray.

$$X_{po} = C_2 \left(\frac{\Delta p}{\rho_a}\right)^{0.25} d^{0.5}\, t^{0.5} \tanh\left(4.1\text{x } 10^3\, t\right)^{0.5} \qquad (3)$$

In Figure 2 line through the experimental data points is the prediction of the modified correlation equation (3). The hyperbolic expression of Equation (3) can be made dimensionless using one of the experimental results as the reference condition. Close examination of Figure 2 shows that the initial liquid phase of the spray can also be modeled by a straight-line relationship, which is described in the subsequent text.

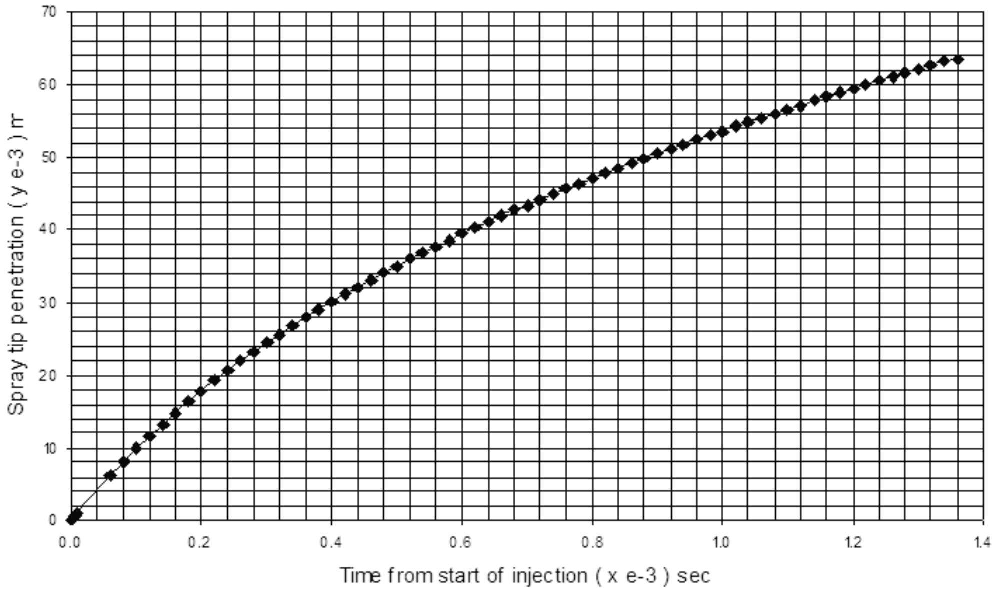

Figure 1: Experimental distance-time history of spray
(Pinj=22 MPa, Pair= 2.25 Mpa, Dia=0.25 mm, air density=27 kg/cub. m,
Chamber air temperature = 290 K, fuel density= 850 kg/cub.m)

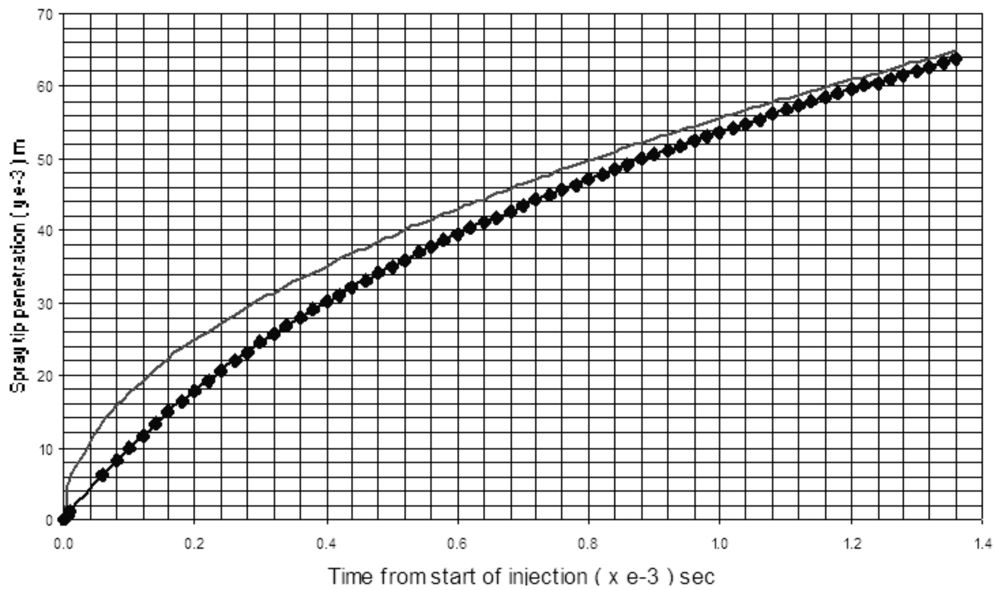

Figure 2: Comparison of prediction and experiment
(Pinj=22 MPa, Pair= 2.25 Mpa, Dia=0.25 mm, air density=27 kg/cub. m,
Chamber air temperature = 290 K, fuel density= 850 kg/cub.m
Upper curve is correlation prediction, lower is experimental data)

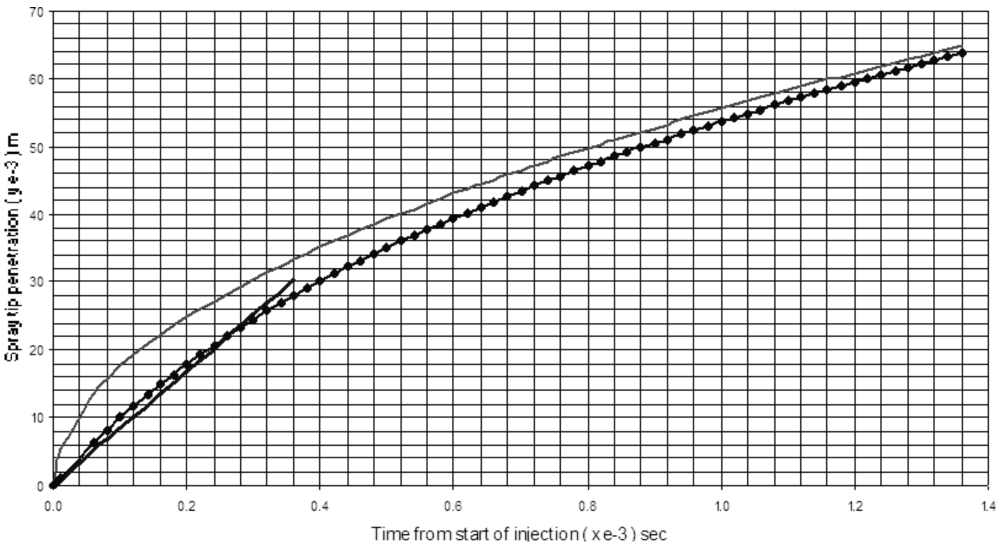

Figure 3: Modeling of near nozzle tip zone of spray
(Upper curve is correlation prediction, Lower curve is experimental data
and straight line represents initial liquid zone modeling)

4. Initial spray zone

Figure 3 shows the experimental data, the predictions of the original $t^{1/2}$ type correlation equation (2) and the modified correlation Equation (3) predictions superimposed by the straight-line fit which is given as under:

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

where 'X_{po}' is the spray tip penetration, and 't' is the time measured from start of fuel injection. Value of the constant $C_{1,}$ $C_1 = 0.39$, with minor variation in the third decimal place gives an ideal fit to the experimental spray length, irrespective of the fuel-line pressure profile variations.

5. Point of intersection

The point of intersection of the above Equations (3) and (4), is defined as "jet break up point" of non evaporating spray, and denoted by (t_b, X_b). Hence following the definition that, for $t = t_{b,}$ $X_{po} = X_{b,}$ equations (3) and (4) give

$$t_b = \left(\frac{C_2}{\sqrt{2}\, C_1}\right)^2 \left(\frac{d\, \rho_f}{(\Delta p\, \rho_a)^{0.5}}\right) \tanh^2 (4.1 \times 10^3\, t_b)^{0.5} \qquad (5)$$

Equation (5) can be re-written in the following form to solve it iteratively.

$$t_b - \left(\frac{C_2}{\sqrt{2}\, C_1}\right)^2 \left(\frac{d\, \rho_f}{(\Delta p\, \rho_a)^{0.5}}\right) \tanh^2 (4.1 \times 10^3\, t_b)^{0.5} = 0 \qquad (6)$$

Equation (6) is of the form f (t_b) = 0, the solution of which is possible by an iterative scheme to give value of t_b.

Use is now made of the experimental data of Mirza [4] on non-evaporating sprays. Figure 4 shows plot of 'f (t_b)' against 't_b'. The curve intersects horizontal 't_b' axis at 0.26 ms.

The hyperbolic expression in equation (5) when simplified gives a value of 0.6, reducing Equation (6) to the following form:

$$t_b = 0.6 \left(\frac{C_2}{\sqrt{2}\, C_1}\right)^2 \left(\frac{d\, \rho_f}{(\Delta p\, \rho_a)^{0.5}}\right) \qquad (7)$$

Further insertion of the value of the constants C_2 and C_1, which are 3.8 and 0.39 respectively, gives the following simplified form of the correlation equation for jet break up time of non-evaporating fuel sprays.

$$t_b = 28.7 \left(\frac{d\, \rho_f}{(\Delta p\, \rho_a)^{0.5}}\right) \qquad (8)$$

where

$$X_b = U_b\, t_b \qquad (9)$$

and

$$U_b = C_1 \left(\frac{2\Delta p}{\rho_f}\right)^{0.5} \qquad (10)$$

Figure (5) shows plot of the straight-line fit (Equation (2)), modified correlation (Equation 3) and the correlation Equation of Mirza [1] for evaporating fuel sprays. All these three curves intersect at the common point, which is defined as the spray jet break up point.

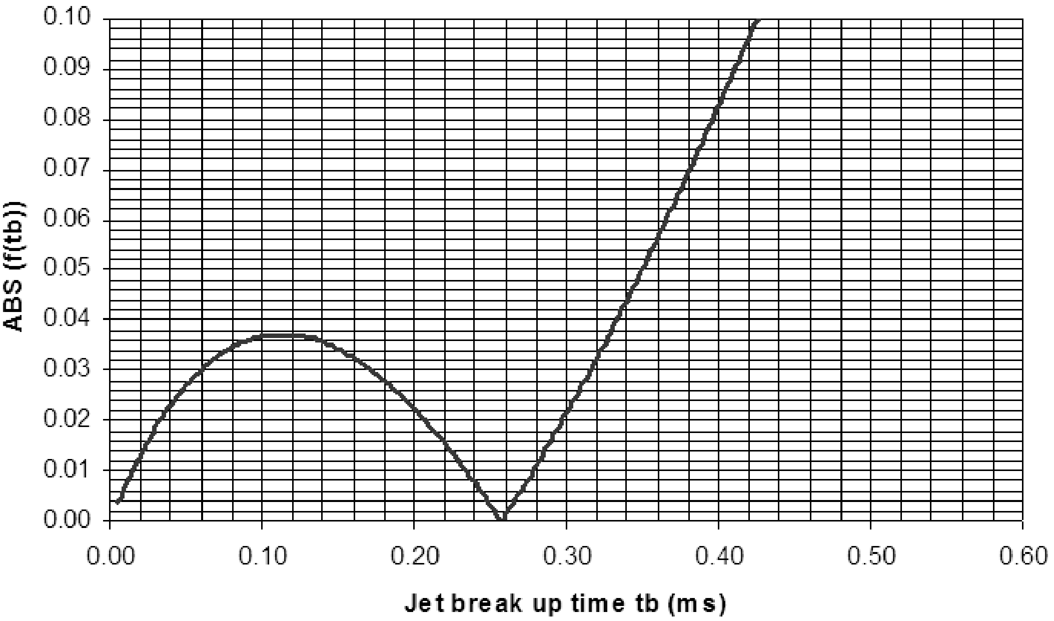

Figure 4: Iterative solution for Jet break up time
(Pinj=22 MPa, Pair= 2.25 Mpa, Dia=0.25 mm, air density=27 kg/cub. m,
Temp= 290 K, fuel density= 850 kg/cub.m)

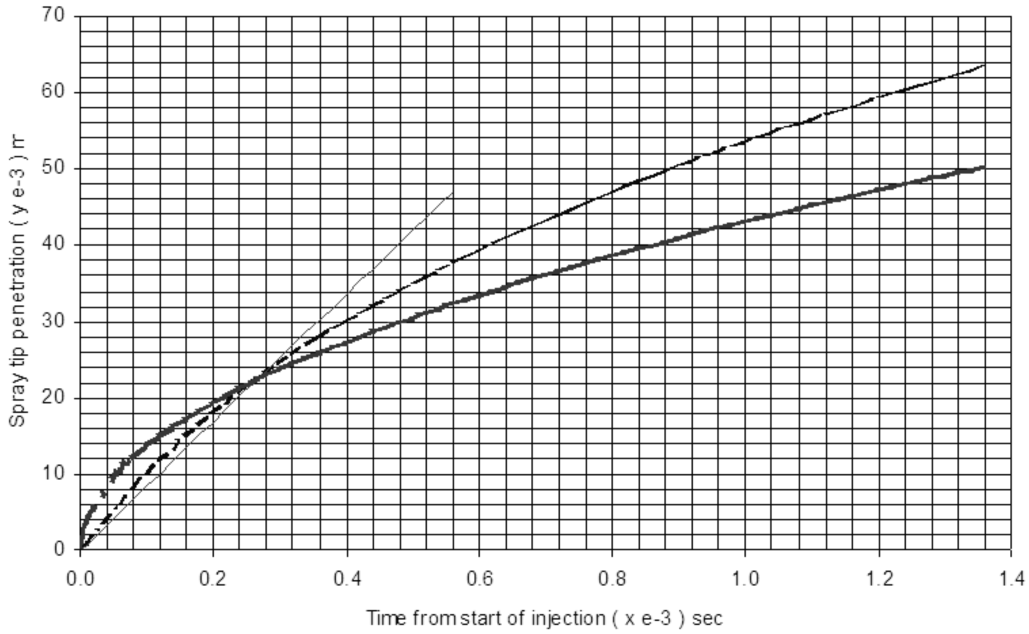

Figure 5: Intersection of straight line,t^(1/2) andhyperbolic equation fits
(Pinj=22 MPa, Pair= 2.25 Mpa, Dia=0.25 mm, air density=27 kg/cub. m,
temp= 290 K, fuel density= 850 kg/cub.m)

6. Results

The near nozzle tip zone of the spray closely follows a dimensionally consistent linear / straight-line relationship, whereas, the spray tip zone follows the modified popular $t^{1/2}$ type relationship using a hyperbolic function. The constant of the correlation equation for the non-evaporating spray jet comes out to be the same which means that the break up time and length of a fuel spray is independent of the chamber air temperature. The correlations presented are useful to check validity of the CFD predictions of in chamber flows of an engine.

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Nomenclature

Xp_o	Penetration length
d	Nozzle diameter
t	time after injection
P_{inj}	injector pressure
Δp	pressure differential
C_1 , C_2	Constants
A	Area of Nozzle
m_f	Mass flow rate fuel
ρ_f	Density of fuel
ρ_a	Chamber air density under cold bomb condition
X_b	Break up distance
t_b	break up time