Structure of Evaporating Diesel Sprays

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Abstract

Performance of compression ignition engine is known to be spray characteristics related. Precise experimental information on fuel sprays is of utmost importance to model the fuel spray formation and its development in the engine combustion chamber. The previous experimental work of the present author on non-evaporating sprays produced by using a FIAT single-hole orifice type nozzle and a distribution type commercial fuel injection pump forms the basis to derive correlations for penetration rates, break up times and lengths of diesel sprays. The results are compared with the existing published work and the agreement is found ideal. The correlations derived can be useful to do CFD modeling of sprays under variable conditions of injector nozzle hole diameter, fuel injection pressure, combustion chamber pressure and temperature or air density.

Key words: Penetration rates; Non-evaporating diesel sprays; Evaporating diesel sprays; Break up times; Break up lengths

1. Introduction

A number of research workers including Dent [1] and Williams [2] have reported dimensionally consistent semi-empirical $t^{1/2}$ type correlations for spray penetration rates. The exiting literature, however, shows a large disagreement on the value of the constant of such correlation equations. All such correlations have the inability to predict the initial liquid phase or break up zone of the spray. The spray can either be non-evaporating (produced under cold bomb conditions) or evaporating (produced under hot bomb conditions). Hence the ideal correlation equation must be a generalized correlation that could predict effects due to variation in either of chamber air pressure or temperature. Dent [1] has recommended insertion of an additional term, in terms of temperatures ratio for the hot bomb condition into the correlation equation for sprays produced under non-evaporating or cold bomb quiescent condition, to accommodate variation in spray length due to elevated temperature effects. Resultantly, the cold bomb conditions and the hot bomb conditions are intermixed, hence not separable.

Hiroyasu and Arai [3] have given a 2-line fit to model both the liquid as well as the vapor zone of the spray body. Their correlation equations on the spray tip penetration, for liquid and vapor phases also do not differentiate between the non-evaporating sprays and the evaporating sprays. However, their work does mention reduction in spray length of evaporating sprays by about 20% compared to that of non-evaporating sprays.

The previous work of the present author [4] on penetration rates of non-evaporating sprays is used here and formed as a base line to derive correlation equations for break up lengths and times of diesel sprays under evaporating conditions.

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:

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

Being in agreement with the findings of Heywood [5], where ρf is the fuel density, A is the nozzle hole area, Δp is the mean pressure differential across the nozzle and C1 is the constant related to coefficient of discharge of the orifice type injector nozzle. Figure 1 shows the fuel-line pressure diagram of the pump-line-injector combination.

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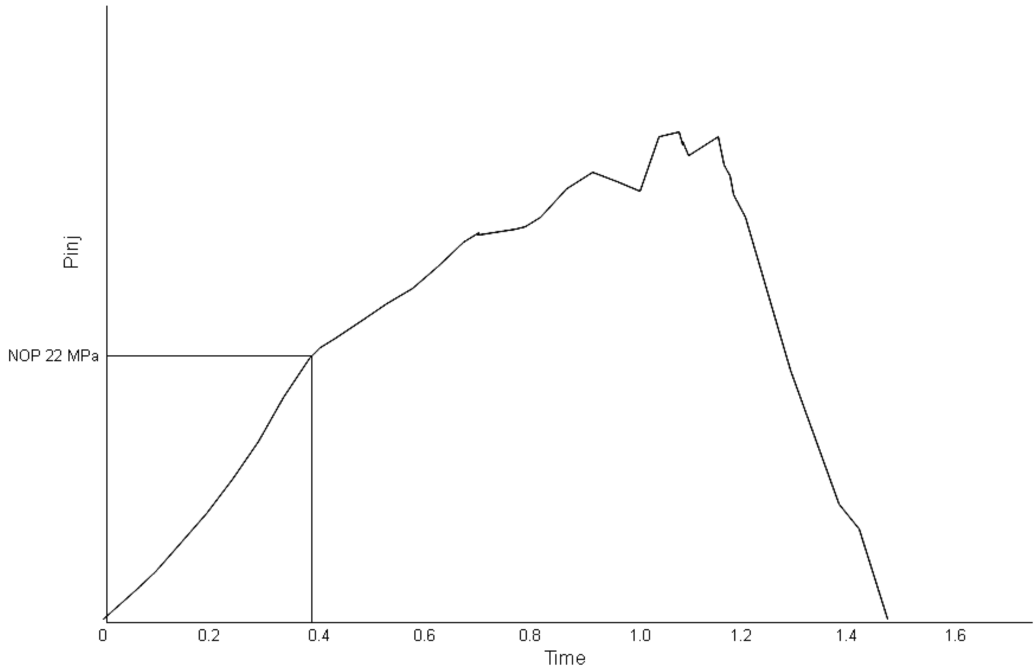

Figure 1: Fuel Line Pressure Diagram

3. Non-evaporating sprays

Figure 2 shows experimental distance-time history of the non-evaporating diesel spray produced under quiescent chamber condition maintained at 2.25 MPa equivalent air pressure and atmospheric temperature of 290 K. Close examination of Figure 2 shows that the initial near nozzle tip zone can be approximated by the following dimensionally consistent linear relationship.

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

where 'Xpo' is the spray tip penetration, and 't' is the time measured from start of fuel injection. Value of the constant C1, C1 = 0.39, with minor variation in the third decimal place gives an ideal fit to the experimental spray length.

The following dimensionally consistent $t^{1/2}$ type correlation equation, previously reported by the present author and similar to that of Dent [1] and Williams [2], gives an excellent fit to the penetration length (Xpo) of non evaporating diesel sprays in the vapor zone, under variable conditions of pressure differential across the nozzle, chamber air density due to variation in chamber pressure only, and nozzle diameter.

$$Xpo = C_2 \left(\frac{\Delta p}{\rho_a}\right)^{0.25} d^{0.5}\, t^{0.5} \qquad (3)$$

where experimentally determined value of the constant C2 is 3.8.

Referring Figure 2 again, the dotted line is prediction of the correlation equation (3) which suffers from the disadvantage of over prediction of the initial/liquid phase of the spray, also reported by other researchers like Dent [1] and Williams [2].

Figure 3 shows the straight line fit to the initial liquid phase of the spray. The straight line follows the correlation Equation (2) given above.

4. Evaporating sprays

Recalling that ρ_a in equation (3) above, is defined as the density of the combustion chamber air at high pressure maintained at atmospheric temperature, 290 K (called as the cold bomb condition). The density of air at the same high pressure but at elevated temperature above atmospheric temperature (called the hot bomb condition) is now denoted by ρ_g. The ratio of ρ_g/ρ_a is then introduced as a new parameter, which is less than unity for evaporating sprays (hot bomb conditions) and equal to unity for the non-evaporating sprays (referenced cold bomb condition).

Following the finding of Hiroyasu and Arai [3] that the spray length of evaporating spray decreases compared to the length of the non-evaporating spray, modification to equation (3) is proposed as under:

$$X_{po} = C_2\left(\frac{\rho_g}{\rho_a}\right)^{0.25}\left(\frac{\Delta P}{\rho_a}\right)^{0.25} d^{0.5}t^{0.5} \qquad (4)$$

The proposed parameter $(\rho_a/\rho_g)^{0.25}$ in Equation (4) is similar to the term $(T_a/T_g)^{0.25}$ as reported by Dent [1]. Equation (4) also suffers from the disadvantage of over prediction of the near nozzle tip liquid phase.

5. Specific cases

For high pressure chamber at ambient temperature of 290 K, and at elevated air temperature of 800 K that will cause evaporation, the bracketed term of density ratio, $(\rho_a/\rho_g)^{0.25}$ of equation (4) becomes replaceable by the constant 0.776 reducing equation (4) as follows:

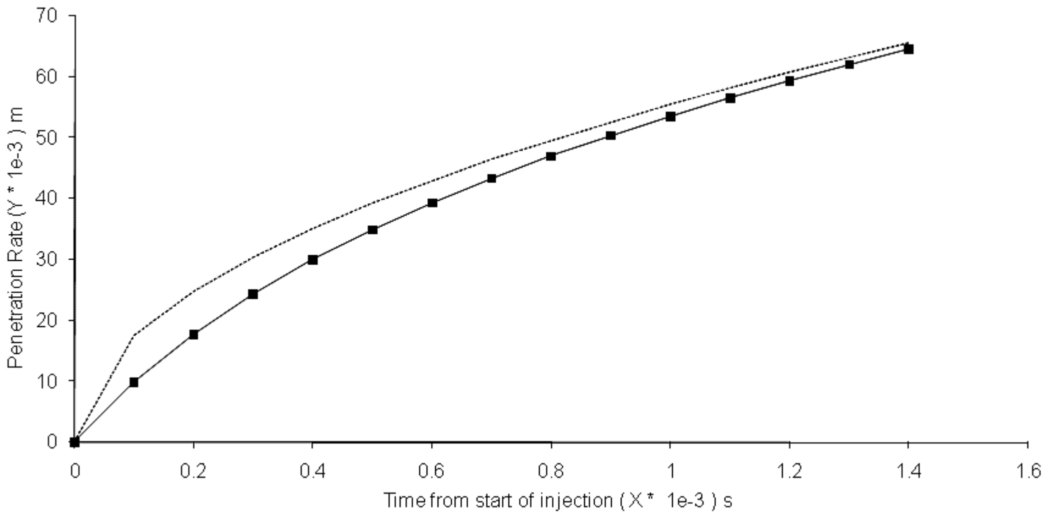

Figure 2: Distance-Time history of Non-Evaporating Spray (Pinj =22MPa, Pair=2.25MPa, Dia=0.25 mm, Air Density =27kg/cub.m, temp=290K, fuel density=850kg/cub.m)

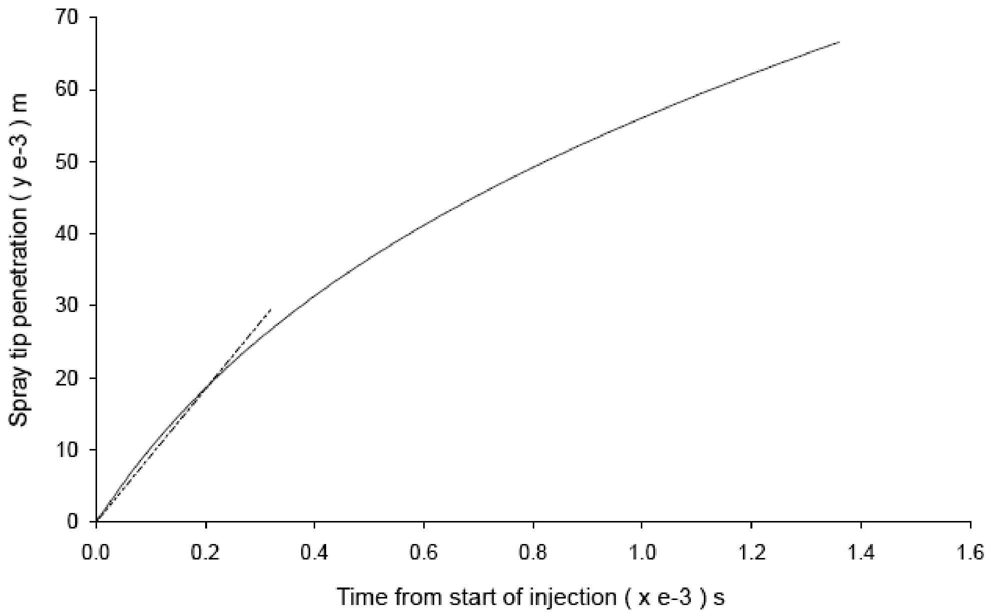

Figure 3: 2-Line fit to Spray Penetration History (Pinj = 22MPa, Dia=0.25mm, Air density =27kg/cub. m, temp=290K, Fuel Density =850Kg/cub. m)

$$X_{po} = 2.95\left(\frac{\Delta P}{\rho_a}\right)^{0.25} d^{0.5} t^{0.5} \quad (5)$$

The constant 2.95 is the same as reported by Hiroyasu and Arai [3]

For the ambient temperature of 295 K as taken by Dent [1], and elevated air temperature of 750 K that causes evaporation of the spray body, the bracketed term of density ratio $(\rho_a/\rho_g)^{0.25}$ can be replaced by the calculated typical value of 0.792, giving the following dimensionally consistent correlation equation for spray penetration rates for hot bomb condition:

$$X_{po} = 3.01\left(\frac{\Delta P}{\rho_a}\right)^{0.25} d^{0.5} t^{0.5} \quad (6)$$

The constant of the equation, 3.01, is the same as reported by Dent [1].

6. Point of intersection

It has been described above that the initial liquid phased spray length is closely modeled by the straight line relationship given by the correlation equation (2); and the vaporous spray length can be modeled by the $t^{1/2}$ equation (4). The point of intersection of these two correlation equations is hence of importance. Hiroyasu and Arai [3] have defined it as jet break up point. For time, t = t_b, length of the spray Xpo = X_b Then equating the two equations gives:

$$t_b = \left(\frac{C_2}{\sqrt{2}C_1}\right)^2 \left(\frac{\rho_g}{\rho_a}\right)^{0.5} \left(\frac{d\rho_f}{(\Delta P\rho_a)^{0.5}}\right) \quad (7)$$

Resultantly, for ambient temperature of 290 K and elevated temperature of 800 K, the following dimensionally consistent correlation equation emerges for the jet break up time of the evaporating spray:

$$t_b = \left(\frac{C_2}{\sqrt{2}C_1}\right)^2 \left(\frac{d\rho_f}{(\Delta P\rho_a)^{0.5}}\right) 0.605 \quad (8)$$

The constants C_1 and C_2 relate to the straight-line fit and the $t^{1/2}$ type fit, respectively.

7. Specific cases

The combination of C_2 = 3.9, and C_1 = 0.40, or the combination of C_2 = 3.8, and C_1 = 0.39, gives the following dimensionally consistent correlations for the spray jet break up time and jet break up length.

$$t_b = 28.7\left(\frac{d\,\rho_f}{(\Delta p\,\rho_a)^{0.5}}\right) \quad (9)$$

$$X_b = 0.39\left(\frac{2\Delta p}{\rho_f}\right)^{0.5} t_b \quad (10)$$

which are the same as reported by Hiroyasu and Arai [3] but derived using different approach.

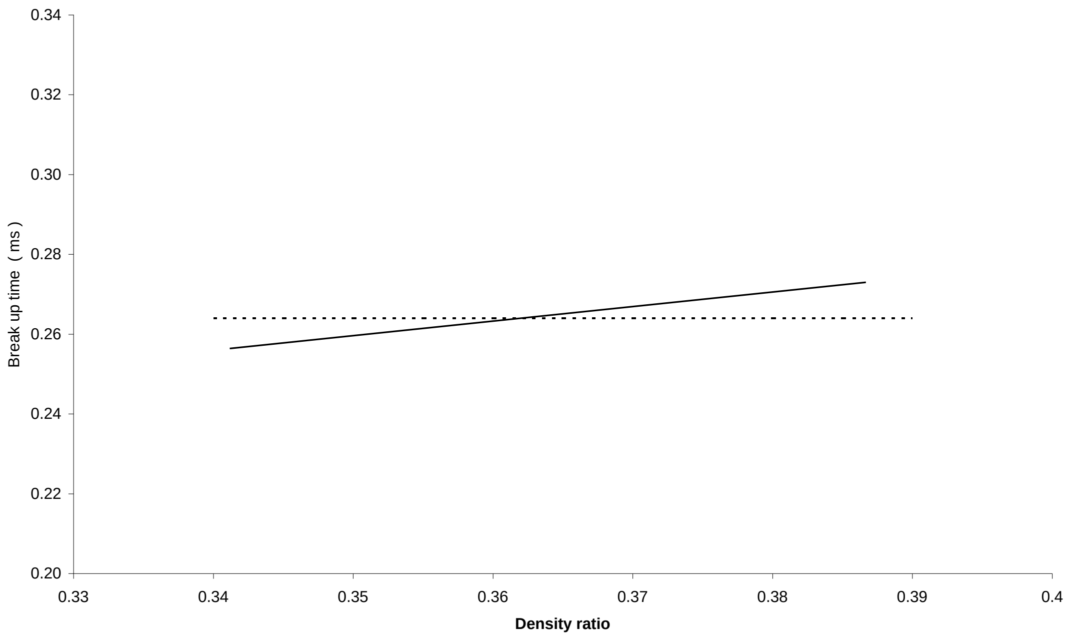

Figure 4: Graph Between Jet breakup time & Density Ratio (Dotted line shows correlation of Hiroyasu. Firm line shows generalized correlation results)

Alternatively, by substituting the value of C_2, $C_2 = 3.8$, and keeping the nozzle coefficient C_1 as variable, equation (9) gives the modified form as follows:

$$t_b = \frac{4.346}{C_1^2}\left(\frac{d\,\rho_f}{(\Delta p\,\rho_a)^{0.5}}\right) \qquad (11)$$

which is the same as proposed by Jung and Assanis [6].

Figure 4 shows the variation of jet break up time against the density ratio (ρ_a/ρ_g). The line parallel to the horizontal axis is the prediction of the correlation of Hiroyasu and Arai, whereas, the slanting dotted line represent the small variation due the variation in the density ratio. Considering the Hiroyasu's result as the reference, a variation of 5% in the density ratio gives a variation of 2.5% in the jet break up time. The correlation equation of Hiroyasu for the jet break time and length relate to the specific chamber conditions of 800 K.

8. Conclusion

The near nozzle tip zone of the spray closely follows a dimensionally consistent linear/ straight-line relationship, whereas, the spray tip zone follows the popular $t^{1/2}$ type relationship. The correlation equations of Hiroyasu and Arai [3], and Dent [1] are the specific cases with an additional term as given in Equation (7) described above. The presented $t^{1/2}$ type correlation equation is reducible to non-evaporating (cold bomb) as well as evaporating (hot bomb) conditions. The break up time of the fuel spray jet is however independent of the chamber air temperature. Taking 800 K as reference condition for evaporating sprays, a 5% variation in the elevated temperature of the high pressure chamber air gives a 2.5% variation in the jet break up time or the intersection point.

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
T_a	cold bomb temperature
T_g	hot bomb temperature
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
ρ_g	Chamber air density under hot bomb condition
X_b	Break up distance
t_b	break up time