AN ANALYSIS OF THE FUEL-AIR MIXTURE DISTRIBUTION WITHIN A CYLINDER OF A DIRECT INJECTION DIESEL ENGINE

by

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ABSTRACT

The validity of simple equations for the penetration of diesel fuel sprays in engine cylinders was investigated. Several forms of these simple equations obtained from the Literature were compared to engine data, both with and without the effects of air swirl. From this comparison, a particular equation was selected as the best representative, and was then used to illustrate the prediction of penetration for an actual engine.

Results of the study show that the simple models based on the gas jet theory are particularly suitable for large bore, quiescent engines and give penetration data to within 15% accuracy.

NOMENCLATURE

α	half cone angle of jet
A	cross-sectional area
d_o	diameter of nozzle
D	density
K	constant
L	length of nozzle
n	engine speed
P	pressure
ΔP	pressure drop across nozzle
r_S	swirl ratio
S	penetration distance
t	time after injection
T	temperature of cylinder gas
V	velocity

Subscripts

amb	based on cylinder gas properties
o	at nozzle exit
s	at tip of jet
SWIRL	including effects of swirl

INTRODUCTION

Intense efforts are being made today in every field to reduce the consumption of petroleum, while still increasing the output of the machines that use it. At present a major portion of petroleum distillates is used in internal combustion reciprocating engines, of which there exist two major categories: The Spark Ignition (SI) engine, which is more commonly associated with low-power applications such as the automobile, and the Compression Ignition (CI) or Diesel engine, which is commonly associated with high-power applications such as trucks, locomotives and stationary equipment. The diesel engine is generally the more efficient of the two. Furthermore, within the category of diesel engines, the direct-injection (DI) engine is more efficient than the indirect injection (IDI) or prechamber, engine. This report is limited to the DI diesel engine.

The major disadvantages of DI diesel engines are noise and emissions. The engine process which dominates these phenomena in a diesel engine, together with efficiency, is the mixing of the liquid fuel spray with the cylinder air. Thus, it is of paramount importance in design that the position of a fuel spray be known at all conditions. The whole process however, is complicated by some effects that are not well understood, namely the effects of the turbulence of the cylinder air and the transient nature of the fuel jet.

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PROBLEM STATEMENT

The design of diesel combustion chambers requires knowledge of numerous factors. Considerations have to be made from strength and metallurigal stand-points, and also, more importantly, with respect to efficient mixing and combustion. For this reason, knowledge of the penetration of fuel spray into the cylinder air, as a function of engine conditions, is important. Fuel impingement on the chamber walls is acceptable only for a class of small high speed diesel engines, in which wall temperatures are very high and cause nearly instantaneous vaporization of impinging fuel. In these engines a good deal of air swirl is present which assists in removing successive layers of vaporized fuel from the walls. In larger bore, quiescent type diesels, impingement on the cylinder walls (with the low swirl rates) would be very undesirable, leading to low economy and increased hydrocarbon emissions. On the other hand, under-penetration is also very undesirable, as inefficient use of the volume of air results. (In a 6 inch bore cylinder, one third of the air is contained in a 1/2" annulus of the walls.)

It is clear that an accurate method for calculating the penetration of fuel in a diesel is a fundamental criteria for design, and this has been the subject of numerous papers in the past. Studies have been made mainly by three methods:

(1) Direct observation of the process in real engines equipped with quartz windows and high-speed photography apparatus. This method is very expensive and time consuming, albeit the most accurate. It also requires the interpretation of data, which is often subjective.

(2) Numerical analysis or simulations. This method is also very tedious and expensive. None-the-less, it is the most flexible, allowing variation of all the controlling parameters.

(3) Simple mathematical models based on various approximations.

This latter method is attractive due to its very low cost and easy application. The equations are usually not tailored to a particular engine, but are generally applicable.

The object of this work was to substantiate the validity of simple models for the quantitative prediction of fuel spray penetration as a function of engine conditions. In addition, this work sought to select, or if necessary formulate, an appropriate simple model. The use of the model was then illustrated by examining penetration in a particular engine. The project was realized by performing a thorough literature review, correlating the results into a concise form and, from this, composing the final model.

LITERATURE REVIEW

To obtain necessary information for this work, an extensive literature survey was completed. The object of this survey was to seek out all the literature relevant to spray penetration, and in particular those papers that presented a simple method for calculating penetration. This project is a continuation of some previous work by Earles [1], who used data from the Southwest Research Institute. SWRI constructed a simple apparatus which was designed to simulate fuel injection in a diesel engine cylinder by using the injection of dyed water into a piston-bowl shaped container filled with swirling clear water. The technique could only be accurate if a homogeneous liquid/liquid injection was an accurate model of high-pressure fuel/high-pressure air injection process.

This assumption would be true only if a real fuel spray behaved like a gas jet. A gas jet is defined as the result of high-pressure injection of a gas into a body of the same gas at a relatively low pressure. Fuel sprays, once the fuel jet breaks up into small droplets, can be thought of as an air-jet bearing a fog of fuel. The region before breakup called the intact length, has been found experimentally by many to be very short, (a few nozzle diameters) and in some cases non-existent.

The mechanism of jet breakup is not thoroughly understood. Reitz and Bracco [2] suggest that breakup occurs in four regimes, with the fourth; the Atomization regime, being the one that diesel sprays operate in. After breakup however, the process of propagation is well understood. Momentum of the fuel droplets is transferred to local air, which gets entrained into the jet, expanding the jet and slowing down the droplets. Figure 1 is a schematic illustration of this process. At the same time, there is a transfer of mass from liquid to vapor phases by evaporation of the fuel. Obviously far enough downstream the density of the plume closely approaches the density of the surrouding air.

The general result of this brief evaluation was that a simple equation based on the gas jet theory and various other assumptions, may quite accurately predict spray penetration. The derivation of one such simple gas jet equation, using the conservation of momentum, is given in Appendix A.

Description of other work

The literature review on penetration distance in DI engines involved nine separate investigations and, in general, most of the equations obtained from these investigations for penetration had the same functional relationships. Table I lists these works, the limitations and the results of each. Table II is a summary of all the correlations obtained from the reviewed papers. In Table II, all the correlations have been converted to the form:

$$S = Kt^a \Delta P^b D_{AMB}{}^c \alpha^d do^e T^f D_L{}^g L^h$$

where S is the penetration distance,

K	proportionality constant
t	time after injection
ΔP	pressure across injector nozzle
D_{AMB}	density of cylinder gas
α	jet half-cone angle
do	nozzle diameter
T	temperature of cylinder gas
D_L	density of liquid injected
L	length of nozzle

Joachim and Beardsley [3] showed in their 1927 work of fuel injection into a pressurized chamber (called a bomb), that increasing chamber pressure or gas density had the effect of reducing penetration. They had no proposed formula for the calculation of penetration however, Öz [4] produced an equation from analytical derivation, using jet theory and frictional losses, which contained a constant to be derived by simple experiment for each injection system. Although it is of a different form than the general consensus, it is important to note that it showed a square-root dependence on time, which is the consensus. Melton [5] and Wood [6], approaching the problem from an analytical point of view, proposed penetration equations based on simple conservation of momentum, as shown in Appendix A. Dent [7] obtained very similar equations by a different method and also improved this theory by indluding a term for dependence on the temperature of the gas. He then substantiated the gas jet equation's validity by correlating data from several previous works for comparison to his equation.

A classical work by Hiroyasu et al [8], using a sophisticated bomb with the provision for air swirl, yielded an equation that closely duplicates the gas jet equation, but was obtained empirically. Hiroyasu et al [8] were able, through their technique of high-speed photography, to improve the gas jet equation further by including a separate correlation for the intact length penetration. Finally, Sinnamon et al [9] produced a mathematical simulation of fuel spray trajectory that consists of integral continuity and momentum equations written for a steady state gas jet. Their work is too complex to present here as it requires iteration by numerical methods. However, they clearly demonstrate the accuracy of the gas jet theory in comparisons with real-engine data from a stratified-charge engine. Sinnamon et al's [9] engine data is used for comparisons to the model results of this paper.

DISCUSSION

Fig. 2 shows a penetration plot of all the simple equations obtained from the literature search. These results are for the engine and injection conditions of Sinnamon et al's experiments. From this graph, the equation presented by Hiroyasu et al [8] most accurately matches the penetration at times below 1.2 ms or 7 deg at 1000 rpm. Beyond this, the empirically obtained equation of Taylor et al* is more accurate. All equations, however, show the correct trend. It is important at this point to note that most of the equations show under-penetration. This common error can be explained by the fact that the real data is taken from a stratified-charge engine. In diesel engines, fuel is injected close to the top of the compression stroke. The air in the cylinder is at very high pressures and, as pointed out by Bracco [2], atomization occurs more readily at high gas pressures. Thus, the fuel spray behaves more as a gas jet. In stratified-charge engines however, fuel is injected early on the compression stroke (as injection does not control ignition timing) when cylinder pressures are lower. Breakup would occur later, leading to higher penetrations than anticipated by equations based on the gas jet theory for diesel engines.

Table 2 shows a close similarity between the equations of Melton [5], Wood [6], Dent [7] and Hiryasu et al [8]. All are of the general form:

$$S = K \left(\frac{2\Delta P}{\rho} \right)^{\frac{1}{4}} (d_o\, t)^{\frac{1}{2}}$$

Where the constant coefficient K varies for each. This would seem to indicate that the gas jet equation can be "forced" to fit engine data by manipulation of this coefficient. However, Fig. 2 shows that

*Obtained from Kuo and Bracco [10].

despite a coefficient specified under different experimental conditions, Hiroyasu et al.'s [8] equation is quite accurate.

Bracco et al. [2] performed exhaustive tests to determine the variation of the spray cone angle, 2α (see Fig. 1), as a function of operating conditions and nozzle length and geometry. They showed quite clearly that, as opposed to gas jet theory, the cone angle was not a constant for a given liquid and gas density, but varied with nozzle geometry. This direct contradiction to the gas jet theory does not apply to penetration except where the cone angle is part of the penetration equation. Reitz and Bracco [2] acknowledge Hiroyasu et al.'s [8] work and found a similar change from linear to square-root dependence on time, for penetration.

Use of Reitz and Bracco's [2] equation for α in conjunction with those penetration equations that include the effect of α leads to predictions of penetration that are almost 2 times too high. This indicates that, for the conditions studied, this equation cannot be accurately applied.

PROPOSED RELATION

On the grounds that they recognize the existence of two propagation modes and because the relations were obtained from realistic bomb studies, the equation selected by the author is that of Hiroyasu et al. [8]. This model is as accurate as the others (and in some cases, more accurate) and consists of two equations, one for each mode:

$$S_{t < t_{BREAK}} = 0.39\left(\frac{2\Delta P}{D_L}\right)^{1/2} t \quad (m)$$

$$S_{t \geq t_{BREAK}} = 2.95\left(\frac{2\Delta P}{D_{AMB}}\right)^{1/4} (dt)^{1/2} \quad (m)$$

where $t_{BREAK} = \dfrac{28.65\, D_L\, do}{D_{AMB}\Delta P}$

Furthermore, Hiroyasu et al. [8] correlated the effect of air swirl on penetration, and this further enhances the applicability of their equations. Their swirl equation,

$$S_{SWIRL} = S.\left(1 + \frac{\pi r_s ns}{30\, V_o}\right)^{-1}$$

is plotted in Fig. 3, together with a similar equation by Wood [6] against engine data. Clearly, the Hiroyasu correlation is the more accurate of the two. This further reinforces the author's choice.

Lastly, the earlier part of injection is of more interest to design engineers because turbulent mixing, that occurs after ignition and is a result of the combustion event, dominates mixing in the later stages of fuel spray propagation. This last argument suggests the use of the Hiroyasu et al. [8] equation, which is very accurate in the early stages of injection.

APPLICATION

To illustrate the use of the model, it has been applied to the Caterpillar 3400 Series 6 Cylinder engine. Dimensions and other engine parameters were obtained from a paper by Kirk and Krull [11], and are listed below:

Direct Injection 6 Cylinder engine, with no induced swirl and central injection,

Bore	5.4 in
Stroke	6.4 in
Compression ratio	15:1
Injector nozzle	0.0105 in dia X 6
Injector opening pressure	2700 psi

A short computer program incorporating the Hiroyasu et al [8] equation was written and is shown in Appendix B. The pressure and density of the cylinder gas were determined by the ratio between the volume at injection and the volume at BDC. The volume at injection is, of course, set by injection timing. For a volume ratio of 0.075, typical of injection at 20 deg BTDC, the resulting penetration plot is shown in Fig. 4.

The Caterpillar engine has a combustion bowl as shown in Fig. 5. From this schematic and Fig. 4, impingement would occur in approximately 0.75 msec or 4.5 deg crank angle @ 1000 rpm. An ignition delay period, calculated using an equation proposed by Shipinski*, is approximately 2.6° crank angle at these conditions. For low swirl engines, combustion should be significantly started before the fuel spray impinges onto the walls. Fig. 4 shows impingement occuring after the estimated ignition delay. This comparison indicates the

*Obtained from Sorenson [12].

correct order-of-magnitude estimate for the penetration rate. Further refined calculations would require more detailed engine specifications. If injection timing was retarded from 20 deg BTDC which was an assumed value, two effects would occur: The ignition delay would be shortened, and the penetration would be slower, both due to higher cylinder gas pressures. This would lead to increased burning time before impingement, which would be desirable. The penetration plot for injection timing of TDC is also shown on Fig. 4, and the predicted trends are readily visible.

CONCLUSION

Simple equations based on the Conservation of Momentum have been examined as an approximation for fuel spray penetration in CI engines. Although greater accuracy is available by using more complicated numerical models or by direct observation in specially designed experimental engines, simple models are valuable for quick engineering design and evaluation. It has been shown that application of the gas jet theory to fuel sprays will yeild realistic penetration data, and facilitate design. The particular correlation recommended is that of Hiroyasu et al [8], and this is well justified by its superior accuracy. It is necessary to repeat once more that this method is particularly suitable to large, low speed diesel engines, where swirl has less effect on penetration and optimizing penetration is important.

WORK BY	OBJECTIVE	METHODS	PROPOSED EQUATION	RESTRICTIONS
Earles, 1980 [1]	Test Liquid Injection technique	Correlation of experimental data from liquid injection apparatus		
Reitz & Bracco 1979, [2]	Investigation of effects of noz-design and cylinder conditions on spray angle	Bomb tests. Injection of various compressed gases. Photographic measurements	$\tan\alpha = \left[\frac{1}{A}4\pi\left(\frac{D_{AMB}}{D_L}\right)^{1/2}\left[f\left(\frac{D_L}{D_{AMB}}\left(\frac{Re_l}{We_l}\right)^2\right)\right]\right]$ A = constant dependent on nozzle geometry.	Effect of swirl or temperature of cylinder gas not considered.
Joachim & Beardsley, 1927 [3]	Study effects of fuel and gas densities on characteristics of fuel sprays.	Bomb tests, as above.		
Oz, 1969 [4]	Eliminate high-pressure experimentation for determining penetration.	Analytical, jet theory & frictional forces. Results supported by data from others.	$S = (t)^{1/2} a e^{-0.04 P_{AMB}}$ a is determined by experiment for each injection system.	Effect of swirl not studied.
Melton, 1979 [5]	Advocate jet theory over ballistic approach to penetration.	Analytical, conservation of momentum.	$S = \left(\frac{V_o d_o}{\alpha}\left(\frac{d_o}{D_{AMB}}\right)^{1/2} t + 1\right)^{1/2} - 1$ $\alpha \simeq 0.085$	Effect of swirl not considered.
Wood, 1980 [6]	Obtain simple penetration equation for general application.	Analytical, conservation of momentum. Effect of swirl included.	$S = \left(\frac{d_o}{\alpha} t\right)^{1/2}\left(\frac{2\Delta P}{D_{AMB}}\right)^{1/4}$ $S_{SWIRL} = S\left(1 + 0.4\left(\frac{n r_s \pi}{30} t\right)^2\right)$	$\alpha = 11^o \pm 2^o$
Dent, 1971 [7]	Correlation of bomb & engine data.	Analytical, co-axial jet mixing theory. Results supported by data from others.	$S = 13.6\,(d_o t)^{1/2}\left(\frac{\Delta P}{D_{AMB}} \cdot \frac{530}{T}\right)^{1/4}$	$2 < L_o/d_o < 4$; $t > 0.5$ (ms)
Hiroyasu, Kadota, & Arai, 1978 [8]	Detailed characterization of fuel spray	Bomb tests. Single injections of fuel into nitrogen at various temperatures & pressures. Photographic measurements. Effects of swirl investigated.	$S_{t<t_{BREAK}} = 0.39\left(\frac{\Delta P}{\Delta L}\right)^{1/2} t$ $S_{t\geq t_{BREAK}} = 2.95(d_o t)^{1/2}\left(\frac{\Delta P}{D_{AMB}}\right)^{1/4}$ $t_{BREAK} = 28.65\,\frac{D_L}{D_{AMB}} \cdot \frac{d_o}{\Delta P}$ $S_{SWIRL} = S\left(1 + \frac{\pi r_s n s}{30 V_o}\right)^{-1}$	none
Sinnamon, Lancaster, & Steiner, 1980 [9]	Derivation of an analytical model for fuel spray trajectory in stratified charge engines.	Experimental. Use of single-cylinder engine with quartz window, & schlieren photography, to study fuel sprays under varied conditions. Analytical, conservation equations in 2 dimensions for steady state gas jet.	complicated set of integral equations.	none for penetration.

TABLE I. Summary of Works Studied with Applicable Results.

AUTHOR	METHOD	POWER OF PARAMETER								
		t a	ΔP b	ΔAMB c	α d	d_o e	T f	D_L g	L L	
Wood (SWRI)	Analytical	0.5	0.25	-0.25	-0.5	0.5	-	-	-	
Dent	Analytical	0.5	0.25	-0.25	-	0.5	-0.25	-	-	
Melton	Analytical	0.5	0.25	-0.25	-0.5	0.5	-	-	-	
Hiroyasu et al.	Analytical/	0.5	0.25	-0.25	-	0.5	-	-	-	$t \geq t_{Break}$
	Empirical	1	0.5	-	-	-	-	-0.5	-	$t < t_{Break}$
Taylor et al.	Empirical	0.64	0.32	-0.32	-	0.18	-	-	0.18	
Lyshevskiy	Analytical	0.5	0.3	-0.5	-	0.4	-	0.4	-	
Wakuri et al.	Analytical/ Experimental	0.5	0.25	-0.25	-0.5	0.5	-	-	-	
Oz	Analytical	0.5	-	used as ex- ponent	-	-	-	-	-	
Williams	Analytical	0.5	0.25	-0.25	-	0.5	-	-	-	
Chiu et al.	Emperical	0.6	0.25	-0.35	-	0.5	-	0.4	-	

General Equation:

$$S \propto t^a \Delta P^b \Delta_{AMB}^c \; \alpha^d do^e T^f \Delta_L^g L^h$$

TABLE II. The Powers of Various Penetration-Determining Parameters for Some Equations.

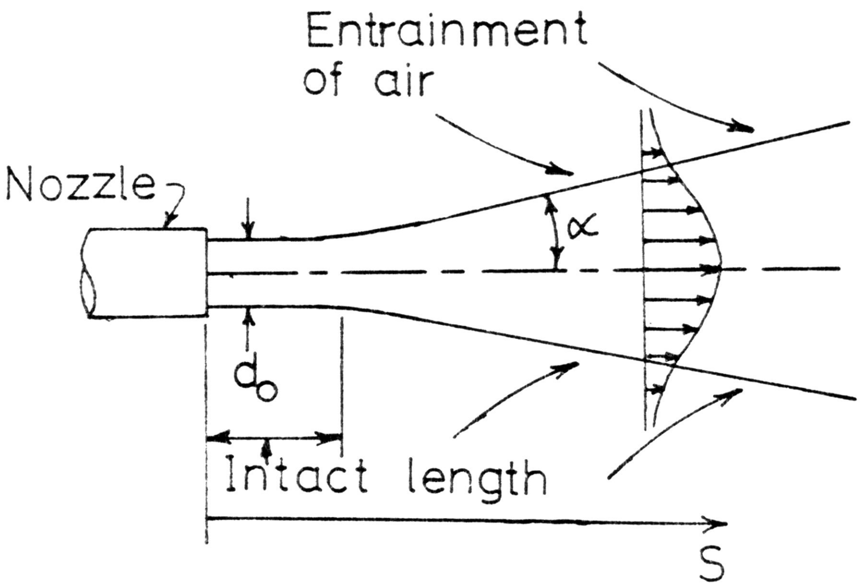

FIGURE 1. Schematic of Fuel Spray.

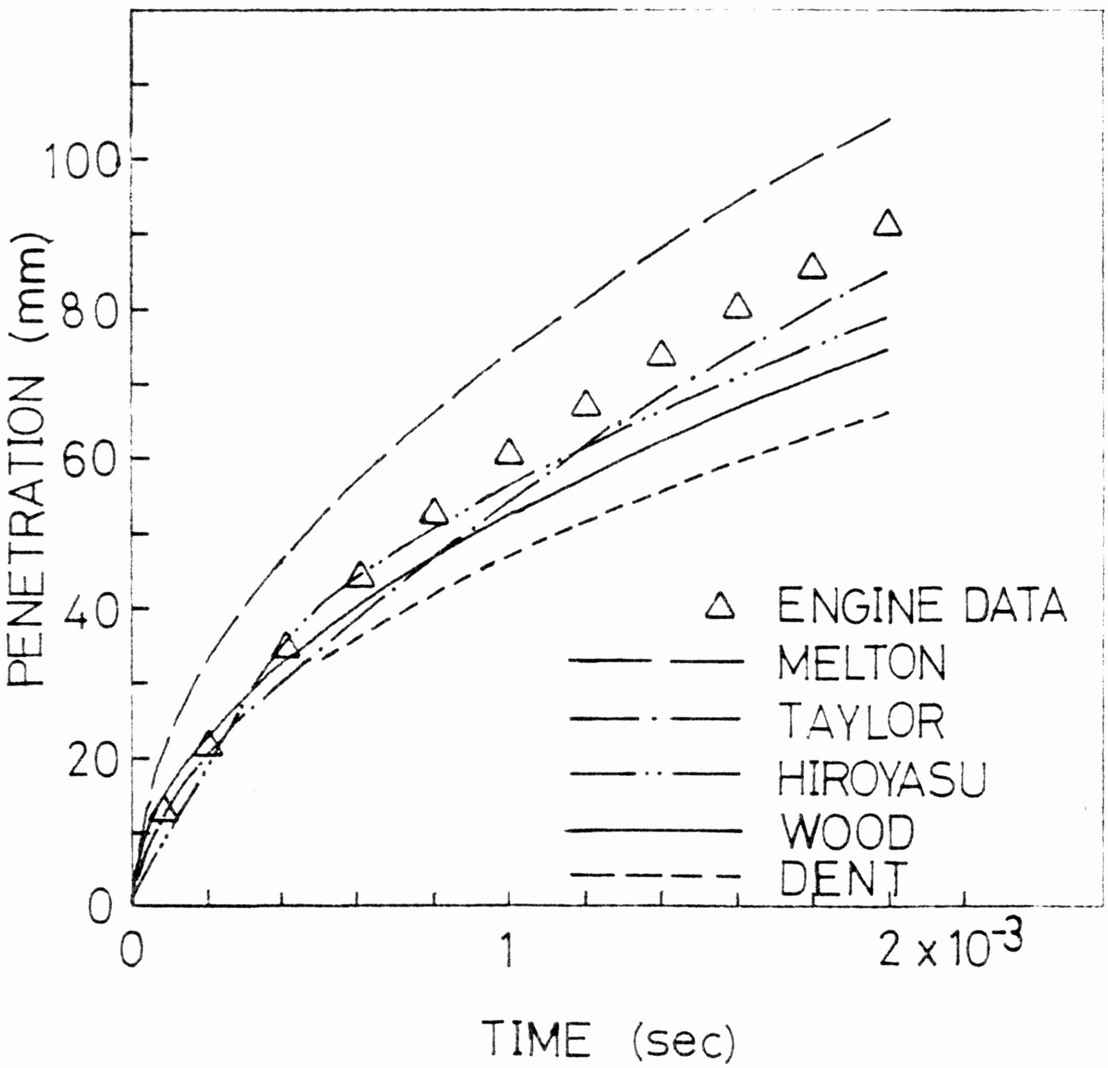

FIGURE 2. Comparison of simple penetration equations to engine data.

Engine Conditions: do = 0.203 mm; ΔP = 17827 kPa; D_{AMB} = 6.25 kg/m^3; α = 10 deg; D_L = 721 kg/m^3; no swirl
Speed = 1000 rpm (1 ms = 6 deg CA)

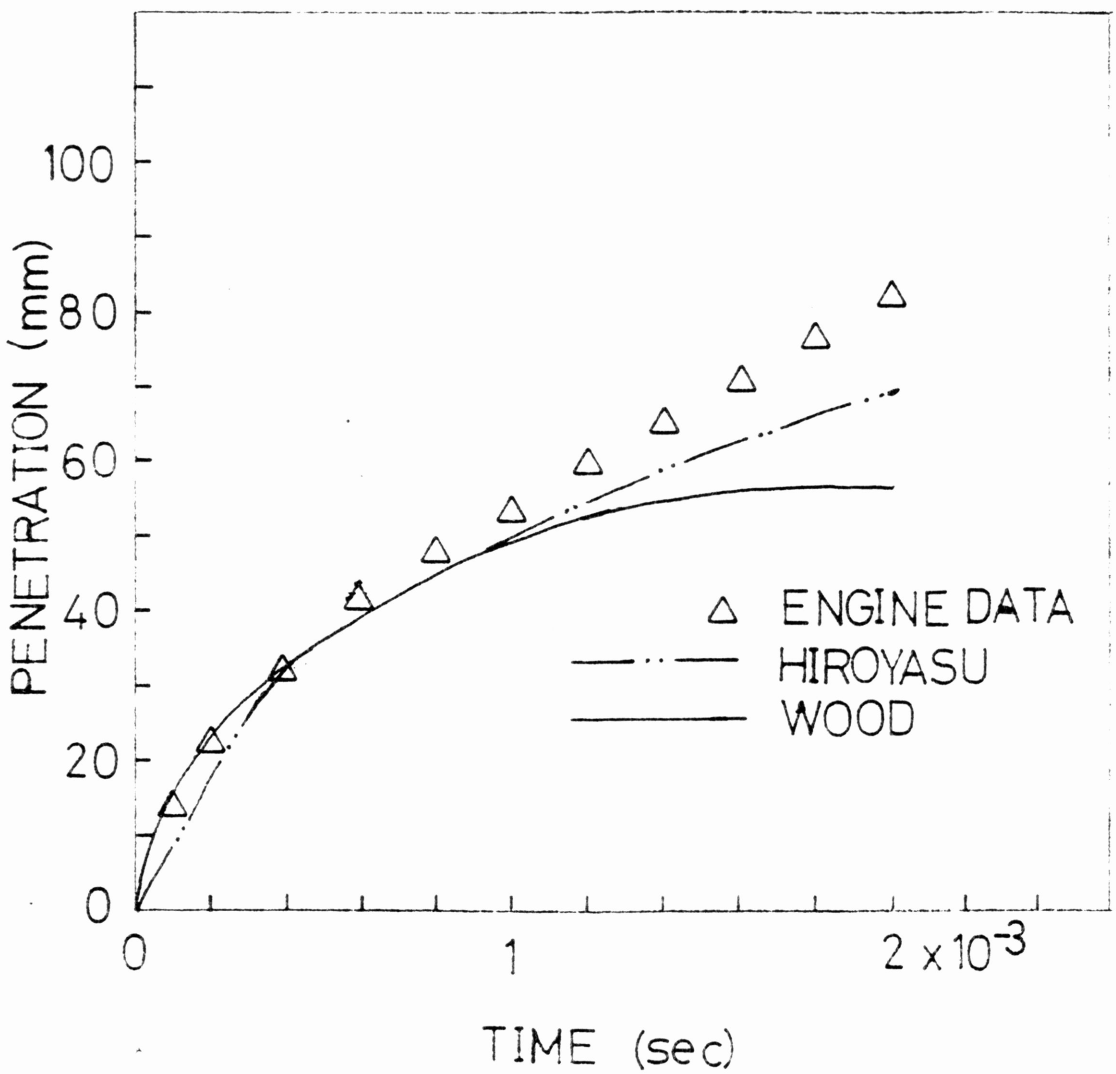

FIGURE 3. Comparison of simple penetration equations to engine data including effects of swirl.

Engine Conditions: do = 0.203 mm; P = 17827 kPa; D_{AMB} = 6.25 kg/m^3; = 10 deg; D_L = 721 kg/m^3; r_s = 6
Speed = 1000 rpm (1 ms = 6 deg CA)

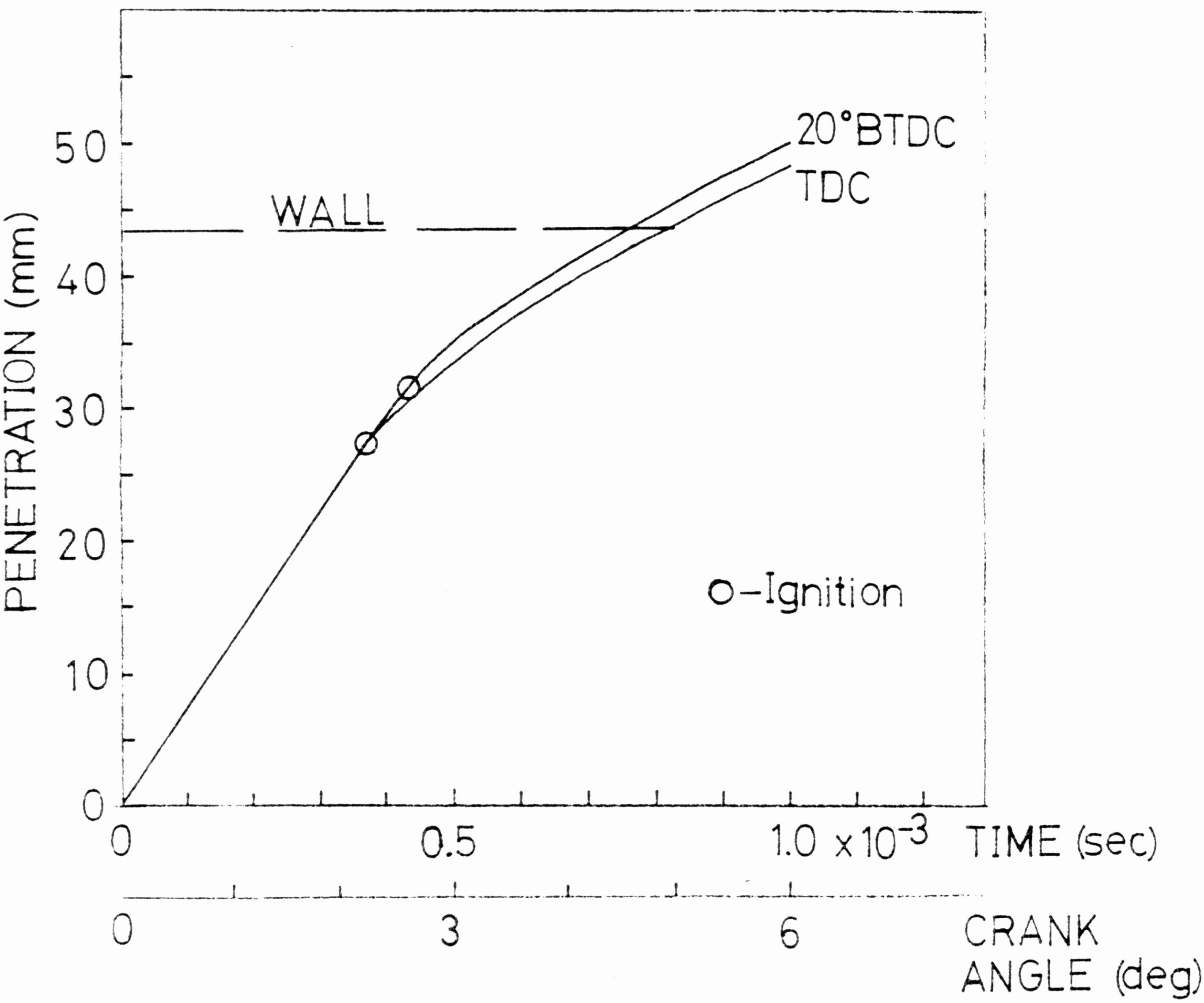

FIGURE 4. Penetration plot for the Caterpillar 3400 Series Engine.

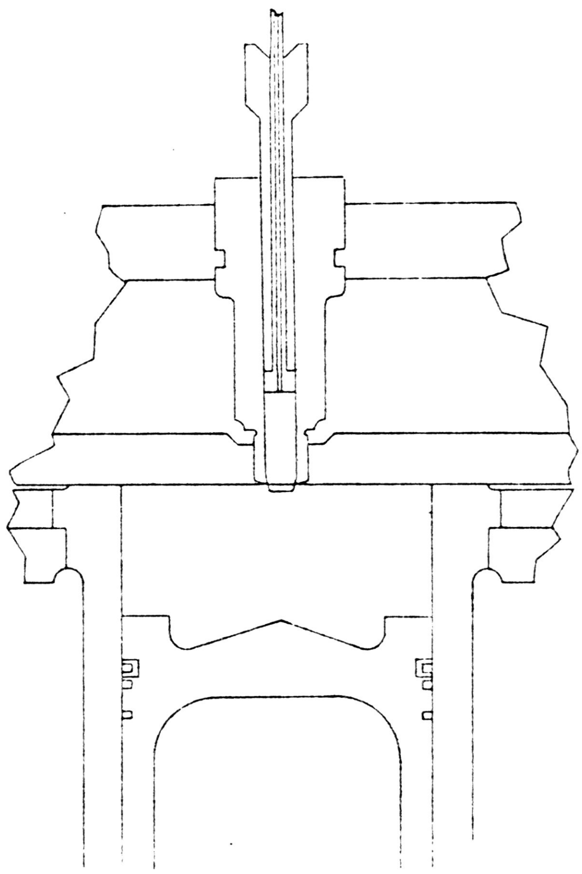

FIGURE 5. Schematic of a cylinder of the Caterpillar 3400 Series Engine.

APPENDIX A

Development of a simple gas jet equation.

By employing the following assumptions:

1. Momentum is conserved normal to the jet axis
2. The jet has straight sides
3. The shape of the velocity profile is preserved
4. Divergence begins at the orifice
5. Steady state flow is achieved
6. The flow across the nozzle is incompressible

the penetration of a jet can be derived by simple integration.

Where subscipts o and s stand for "at nozzle exit" and "at jet tip" respectively, by Conservation of Momentum:

$$D_o A_o V_o^2 = D_s A_s V_s^2$$

For a nozzle discharge coefficient of 1.0,

$$V_o = \left(\frac{2\Delta P}{D_o}\right)^{1/2}$$

For the small angles α, encountered

$$A_s = \pi\left(\frac{do}{2} + \alpha S\right)^2$$

Also

$$V_s = \frac{ds}{dt}$$

Substituting, and solving for S, assuming that $D_s = D_{amb}$,

$$S = \frac{do}{2\alpha}\left[\left(\frac{4\alpha}{do}\left(\frac{2\Delta P}{D_{amb}}\right)^{1/2} t + 1\right)^{1/2} - 1\right]$$

The final assumption, that $D_s = D_{amb}$, is true for a liquid injection, as described in the text.

APPENDIX B

Listing of program to calculate penetration using Hiroyasu et al [8] correlation.

```
      DATA RPM,P1,T1,INJP,DL,DO/1000.,100000.,350.,
     +18616500,850.,.000267/
5     READ (5,300) VRATIO
300   FORMAT (F6.4)
      IF (VRATIO .EQ. 0.0) GO TO 40
      WRITE (6,100) VRATIO
100   FORMAT ('1',T20,'VOLUME RATIO = ',F6.4,/,T20,'TIME',
     +5X,'PENETRATION',5X,'CRANK ANGLE',/,T20,'(MS)',8X,
     +'(MM)',12X,'(DEG)',/)
      PAMB=P1*VRATIO**(-1.35)
      TAMB=T1*(PAMB/P1)**.259259
      DAMB=(PAMB/TAMB)*(28.97/8.315E 3)
      DELP=INJP-PAMB
      TBREAK=28.65*DL*DO/SQRT(DAMB*DELP)
      DO 10 I=1,40
      T=I/10000.
      IF (T.GE.TBREAK) GO TO 20
      S=0.39*SQRT(2*DELP/DL)*T
      GO TO 30
20    S=2.95*SQRT(DO*T*SQRT(DELP/DAMB))
30    CA=T*RPM*6
      T=T*1000
      S=S*1000
      WRITE (6,200) T,S,CA
200   FORMAT (' ',T20,F3.1,8X,F5.1,12X,F5.2)
10    CONTINUE
      GO TO 5
40    STOP
      END

//$DATA
```

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