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EFFECTS OF INJECTOR NOZZLE GEOMETRY ON SPRAY CHARACTERISTICS, AN ANALYSIS

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ABSTRACT

Air and fuel must be mixed correctly such that there is perfect combustion, this calls for fuel atomization by injection. In this study the effects of different parameters such as number of orifices, length and diameter of orifices (or nozzle hole), diameter of nozzle sac and the angle of needle seat, in injectors, were investigated with the use of rate of injection and sac pressure. The unit pump of the OM-457 diesel engine was modeled on Avl-Hydsim. The results illustrate that the sac pressure was decreased 46%, if the number of holes were doubled although the rate of injection had an immense change. Also the sac pressure was increase up to 60%, if the diameter of orifices were decrease 40% in spite of the semi-constant injection rate.

KEYWORDS: Injection, OM-457 Engine, Nozzle Geometry, Atomization, Penetration Depth

The diesel engine is a compression ignition internal combustion engine. Fuel is combusted in these engines by injection at the point of compression where the in-cylinder pressure is highest of the cycle. The diesel cycle differs from spark ignition in that it is more efficient in combustion, due to the differences in the Diesel and Otto cycle respectively. [1] Currently the design of injection systems has beenguided so that there exists a higher efficiency, lower emissions and greater power. This has led to designs withhigher nozzle pressures. As injection pressure increases, the size of fuel droplets is also decreased such that the fuel will begin to atomize. This atomization of fuel particles allows for quicker mixing of fuel and air in the engine cylinder. Quick mixing is vital to attaining enhanced characteristics as the combustion time is very limited.

The effects of injection parameters like nozzle geometry, injection pressure, ambient conditions and fuel properties on droplet size distribution were studied by several researchers (Hiroyasu &Kadota, 1974; [2] Arai et al., 1985 and Tabata et al., 1991, Tabata et al. (1991) examined the effects of ambient temperature on Diesel spray drop size by using the Fraunhofer diffraction technique in a high pressure environment[3]. Farrar-Khan et al. (1992) studied the influence of the nozzle sac volume on spray penetration, atomization and velocity [4]. Four multi - hole nozzles with a sac volume varying from 0 to 1.34 mm3 were investigated at an injection pressure of 21.5 MPa. A reduction in sac volume reduced the SMD by 3 to 4 µm. Minami et al. (1990) attempted to investigate high pressure Diesel spray using holography, high speed and shadow photography[5]. Also, those who have done work on unit injector geometric properties include L.G. Dodge[6], Byong-Seok Kim[7], Chang [8].

Fuel injection systems have been saturated with methods of increasing pressures, now all that remains is to use this complete range of pressures to optimize a solution which will further aid the improvement of injection with relation to spray atomization, fuel penetration depth, minimal delay, and monitored leakage. The problems with different designs of injectors are the limits that restrict the designer from achieving required performances. This study was undertaken to help with finding methods to meet these goals.

The engine that was considered for this analysis was the OM-457 turbo diesel engine. This engine is a relatively heavy duty engine as the weight exceeds 1000 kg. The other specifications are illustrated in **Table 1** [9].

Table 1: OM 457 Properties

MAX Power (KW)	MAX Torque (Nm)	Weight(Kg)	CR	Cylinders No	Bore (mm)	Stroke (mm)	Capacity(cc)
250 @2000rpm	1600 @1100rpm	1045	17:1	6	128	155	12,000

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Unit injectors were used on this engine as it was much bigger than conventional diesels, the reliability would otherwise be affected with more conventional systems such as common rail injector systems. The unit injector as is shown in Figure 1was composed of a unit injector pump which was mechanically worked by a cam mechanism. The unit pump was contained within the crank case with a high pressure line leading up to the cylinder head which contained the injector.

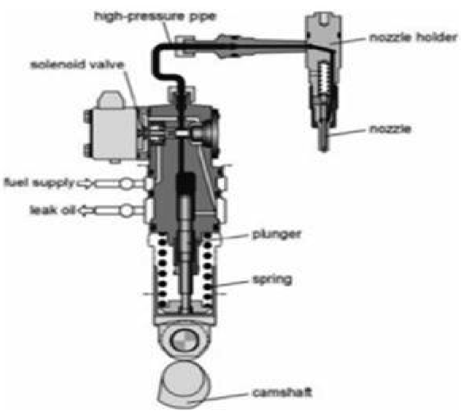
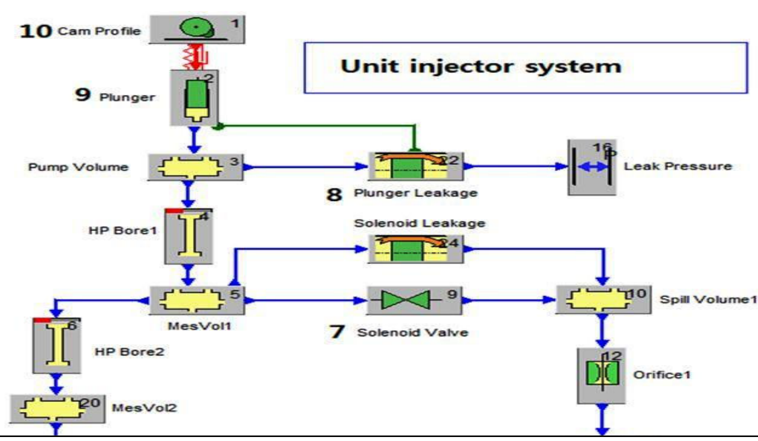


Figure 1: Schematic view of Unit Injector

AVl Hydsim is a zero dimensional CFD analysis of dynamic hydraulic and hydro-mechanical systems. It operates using fluid dynamics and vibrations in multi-body systems. The main application of Hydsim is simulation of fuel injection systems. This program has been mainly developed for diesel engine injectors. As for post-processing the results AVL Impress was used [10].

Simulation process

A base model was created in order to create a reference point for evaluation of the results that were produced with respect to changes in injection geometry. The parameters that were considered included the number of orifices, length and diameter of orifices, diameter of nozzle sac and the angle of the needle seat. In all of the studied cases the main goal was to achieve a single case which would have the required properties in order to increase the likely hood of lower emissions, increased power and lowered fuel consumption.The studied investigation of nozzle geometry took all key factors into consideration and obtained a combined result of all considered parameters, this was the prime difference between this study and previous work done. Also, in the modeling process, fluid properties (constants) were measured as functions of pressure. Furthermore, the leakage rate of the nozzle and needle were considered in the simulation process.The model is shown in Figure 2.



NO.	Element
1	Nozzle SAC
2	The amount of fuel in the nozzle SAC
3	Boundary conditions
4	Needle properties
5	Needle holding springs
6	Leakage from needle to reticulate back into injector
7	Timing solenoid
8	Leakage to fuel tank
9	High Pressure pump

10	Pump Cam

Figure 2: schematic view of Unit Injector

Base model modeling

In this project the whole concern were focused on nozzle geometry that shown in Figure 3.The main parameters of this injector are illustrated in Table 2: Unit Injector Nozzle **main parameters**. The unit injector system was modeled in standard ambient condition by considering the global diesel full at 1500 RPM. [11].

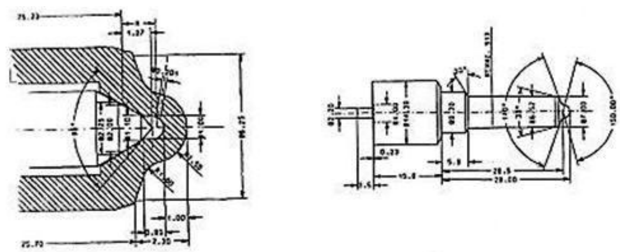


Figure 3: Unit Injector Nozzle Specifications

Table 2: Unit Injector Nozzle main parameters

Number of Holes	SAC Diameter (mm)	Nozzle Angles (deg)	Orifices/Nozzle Diameter (mm)	Needle Seat Angle (rad)	Length of Orifices (mm)	Discharge Coefficient	Spring Stiffness (KN/m)	Needle Mass (gram)
6	2.5	75.0	0.5	1.04	1.5	.7	270	33

Case study parameters

In total four parameters were studied. The affects of these parameters on the spray pressure, penetration depth, injection rate, and total injection volume (per pulse) were taken into consideration. The sought result was to obtain a case for each parameter which represented the highest injection pressure, highest penetration depth, and lowest injection volume per cycle.

The four parameters included;Nozzle numbers, the numbers of spray holes in the injector nozzle were changed while keeping the sizes and all other aspects constant.Diameter of nozzle orifices,Needle seat angles, and the needle seat angle was changed without changing the length or width of the needle. The last parameter is Nozzle SAC diameter.

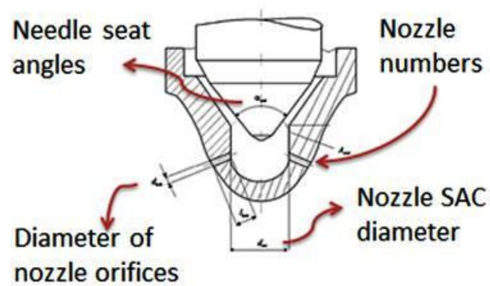


Figure 4: Unit Injector Nozzle Specifications

In order to study the effects of each parameter two or three cases were made that are completely same else that specific parameter. The details of all cases are depicted inTable **3**.

Table 3: Case Study

Cases	Hole Number	Hole Diameter [mm]	Needle Seat Angle[rad]	Diameter of Nozzle SAC [mm]
Basic Model	6	0.5	1.05	2.5

Case#1	**5**	0.5	1.05	2.5
Case#2	**7**	0.5	1.05	2.5
Case#3	**8**	0.5	1.05	2.5
Case#4	6	**0.4**	1.05	2.5
Case#5	6	**0.6**	1.05	2.5
Case#6	6	0.5	**0.5**	2.5
Case#7	6	0.5	**1.5**	2.5
Case#8	6	0.5	1.05	**2**
Case#9	6	0.5	1.05	**3**

RESULTS

After modeling was completed the results were extracted from AVL using AVL Impress. The results included graphs of injection pressure, injection rate, injection volume, and penetration depth. Also, each result are analyzed by embedding the mathematics equation and the experimental results of the other projects.

Nozzle numbers (HN)

The results obtained show that the less the number of holes there were, the injection pressure would increase. The increase in injection pressure due to fewer holes helped to lower soot especially in small engines [1]. As flow rate increased the injection pressure decreased. According to Eq-1 that derived from the bulk modulus equation, which can calculate the pressure rate in a chamber as fluid is transferred from that chamber to another chamber and vice versa [12].

$$\frac{dp}{dt} = -\frac{E}{V - \sum_{i=1}^{n_m} A_i . x_i}\left(\sum_{i=1}^{n_{in}} \dot{Q}_{in} - \sum_{i=1}^{n_{out}} \dot{Q}_{out} + \sum_{i=1}^{n_m} A_i . U_i\right) \quad \text{(Eq-1)}$$

So, when the nozzle hole number increase the $A_i.X_i$increase , therefor the pressure rate decrease. This fact depicted in Figure 5and Figure 6.

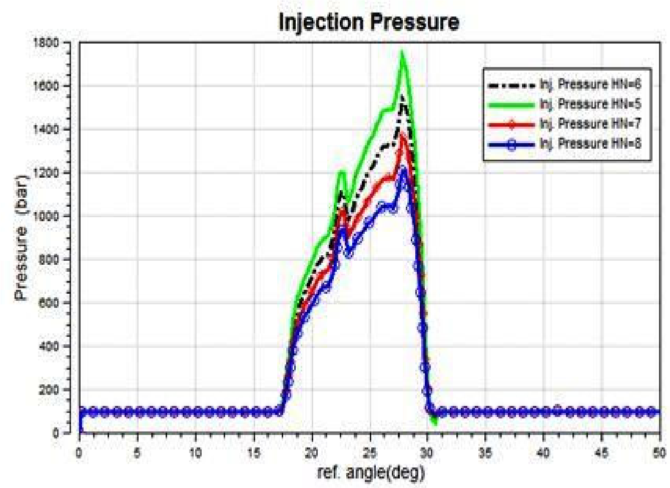


Figure 5: Injection pressure in different nozzle hole number

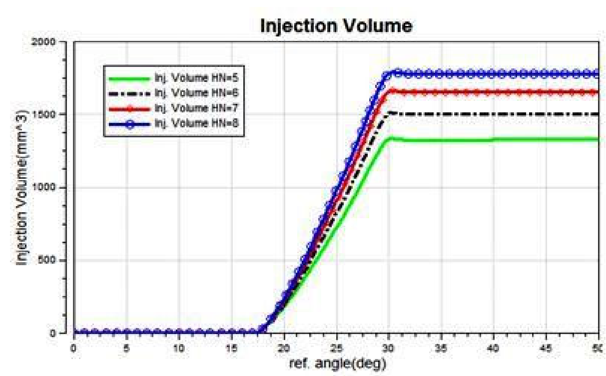


Figure 6: Injection volume in different nozzle hole number

With the increase of nozzle number, from 5 to 8 the injection pressure is also increased by 45 percent.BMEP is lowered as the hole number was increased.The increase of hole number was responsible for an increase of injection volume, SFC would increase by 38 percent. The atomization of fuel was also decreased as the hole number increased.These results are comply with the experimental results in other projects [13,14].

The most desirable design has the least number of injection holes as possible so that there may be a completely homogeneous mixture in the combustion cylinder, as the hole number (HN) increases the atomization decreases, SFC goes up, penetration decreases. But the number of holes is limited by the amount of spray angle that is required to completely fill the cylinder. The spray angle also has an effect of the penetration depth. HN is a very important and sensitive factor for consideration. Fewer holes in the injector would then be useful for small bore engines that are either using high or very low compression ratios because of the high penetration depth and increased atomization respectively.

Diameter of nozzle holes (HD, hole diameter)

The diameter of holes has profound effect on full injection system. Almost all the characteristics of injection changed as the diameter changed.

From continuity equations it is seen that when a volume, that has a flow passing through it, is changed the speed and pressure are also changed. As the cross sectional area of the nozzle diameters was decreased the speed increased and so the dynamic pressure decreased as well. Furthermore as the pressure increased the penetration depth also increased. Penetration depth was be calculated by Eq-2 [15].

$\boldsymbol{S = 2.95(\Delta P/\rho)^{0.25}\sqrt{d.t}}$	Eq-2

From formula 3 (Arai) [6] the hole diameter was determined to be much more important than the difference in injection pressures, in terms of penetration depth. The effects of small holes and high injection pressures were very noticeable [1]. As the hole diameter was decreased and the rate of injection was decreased the atomization was also increased so SFC was lowered due to less volume of fuel used per cycle. If the hole diameter was to increase, the emissions would increase; the type of emissions would then be HC and PM. In terms of atomization, the greater the diameter is then the atomization is decreased, penetration depth is increased and the pressure is also decreased. The results in Figure 7and Figure 8 show that the 50 percent increase in diameter of the nozzle holes was responsible for a 42 percent drop in pressure, and SFC would also increase [6]. Emissions are also increased as the hole diameter was increased as there would be un-penetrated fuel leading to unburned fuel in exhaust.

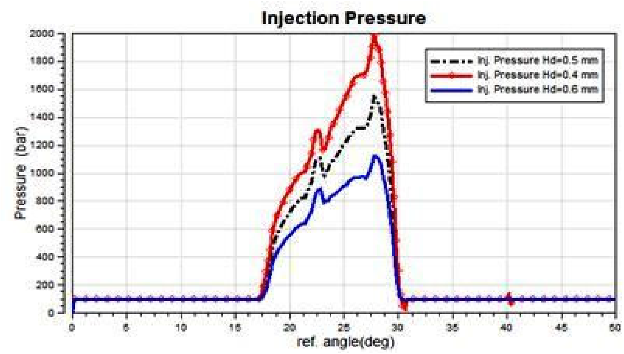


Figure 7: Injection pressure in different nozzle hole diameter

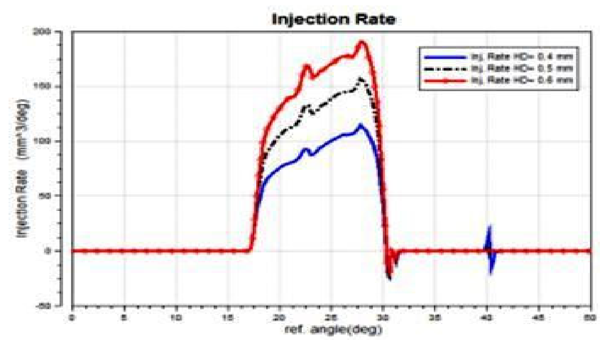


Figure 8: Injection Rate in different nozzle hole diameter

According to Eq-3 as the Injection rate increase the Whole fuel that injected to cylinder increased (refer to Figure 9) [18].

$Q = C_a.(P_1 \_ P_2).\sqrt{\left(\frac{2}{\rho}.\lvert P_1 \_ P_2\rvert\right)}$	Eq-3

This equation was used to give the flow rate between two chambers of pressures P1 and P2 i.e. above and below nozzle seat. The equation was derived from equations of momentum and continuity. The hole diameter has the less effect on penetration that is shown in Figure 10. These result are comply with the experimental test that work out in other projects. [16,17].

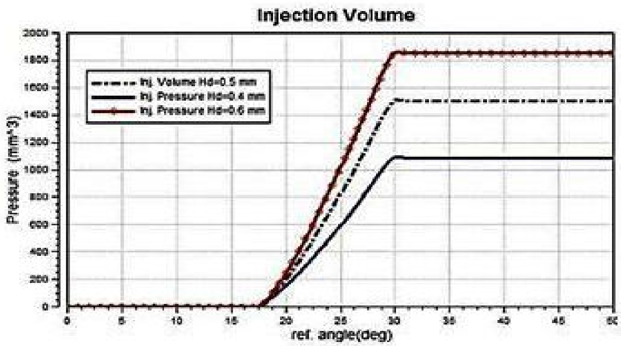


Figure 9: Injection volume in different nozzle hole diameter

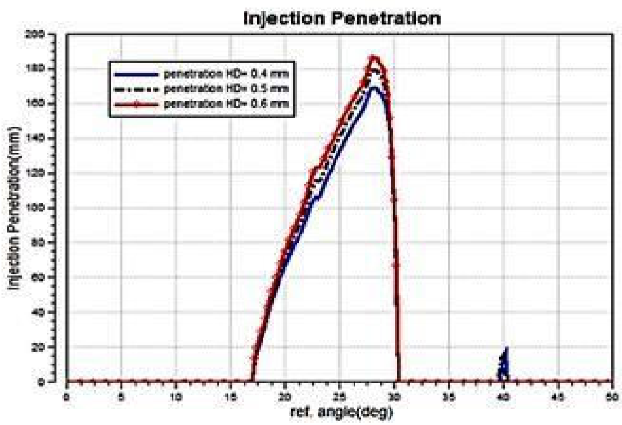


Figure 10: Injection penetration in different nozzle hole diameter

Nozzle SAC diameter (DS)

The needle size was not changed as the nozzle sac diameter was changed. As the nozzle sac diameter was increased or decreased the swept volume within the nozzle seat was also changed (Area of seat). This fact can easily be explain by Eq-4 that is nominated bulk modulus [18].

$dv = -\frac{V}{E}.dp$	Eq-4

When the nozzle sac was increased by 50 percent the pressure rose 17 percent and the flow rate was increased almost 1 percent. One reason for increase in pressure as the nozzle sac was increased although the flow rate not changed dramatically was the decrease in resistance on the side of the needle; the needle seat passageway is shortened in terms of resistance i.e. less bend angle. These results are shown in Figure 11 to Figure 14.

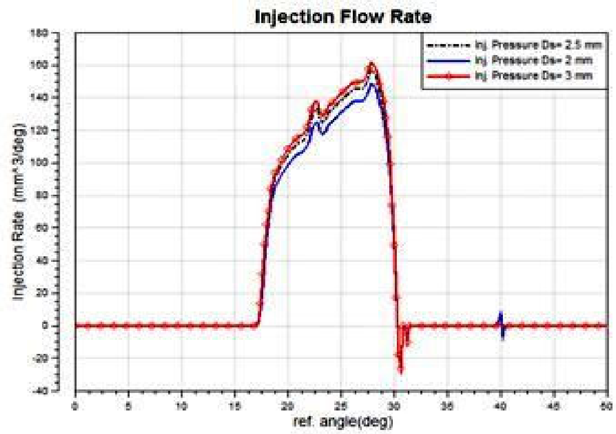


Figure 11: Injection volume in different nozzle SAC diameter

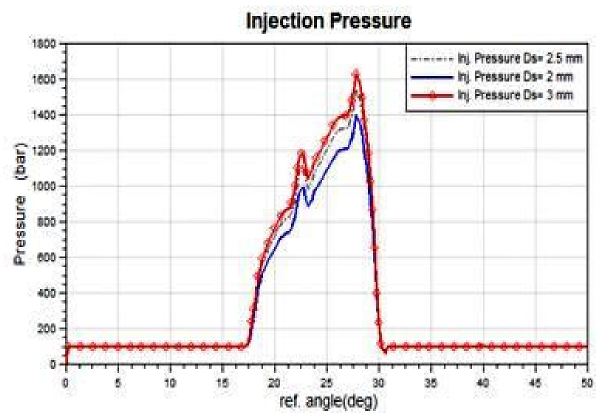


Figure 12: Injection rate in different nozzle SAC diameter

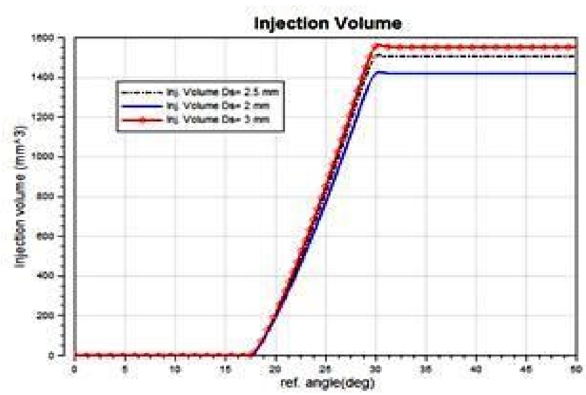


Figure 13: Injection volume in different nozzle SAC diameter

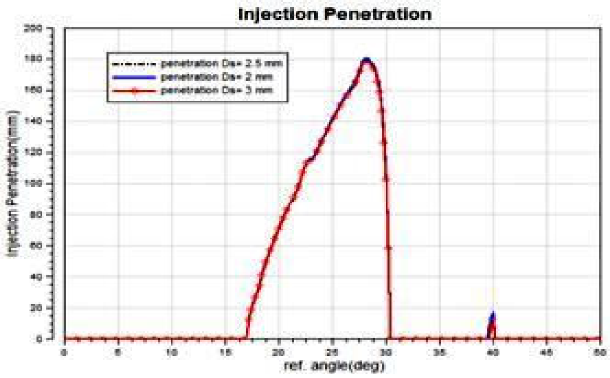


Figure 14: Injection volume in different nozzle SAC diameter

The nozzle sac diameter had a noticeable effect on the injection pressure but not the flow rate of the injector holes. This can be explained by the expansion of fuel in the nozzle tip due to the temperature of the injector tip. A rise of 200 bar was measured, this extra pressure would not escape into the combustion cylinder as the pressure in the cylinder is too great. Although, the increase in pressure does result in a slight increase in leakage of fuel into the cylinder. The hydrostatic force of fuel in the nozzle sac must be considered so that there it does not exceed that of the needle springs, when changing the nozzle sac diameter in previous injector designs. It can be concluded that the nozzle sac diameter contributes mainly to injection pressure and injection volume but not to injection flow and penetration depth.

Needle seat angles (NS)

The fuel injection behavior can prove by embedding the Eq-3 and Eq-4. As the needle seat angle was decrease the pressure was also decreased because of the decrease in resistance on the seat passageway. If the NS was increased then the resistance that was caused created a temporary seal between the nozzle sac and the rest of the injector. This also affected the pressure in the nozzle sac due to the temperature of the injector causing expansion and about 200 bars of pressure. (refer to Figure 15 and Figure 16). The flow rate and flow volume was not considerably affected by the needle seat angle changes. Also, Penetration is not affected by the needle seat angle.

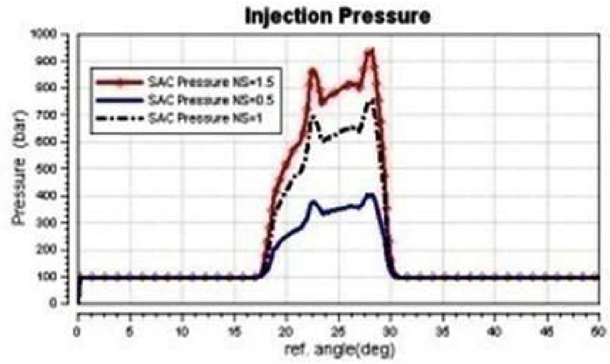


Figure 15: Injection volume in different nozzle SAC diameter

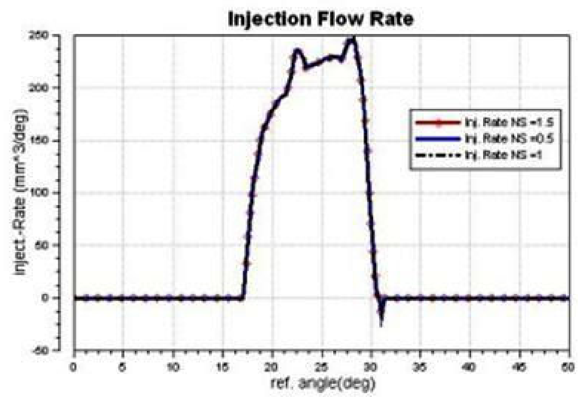


Figure 16: Injection rate in different nozzle SAC diameter

The needle seat angle had a very noticeable effect on the injection pressures; the more the needle seat angle was decreased resulted in small increments of decrease in pressure until the needle seat was opened. When the needle seat had completely opened then injection pressure sharply drops, this is due to the needle seat not sealing the pressurized fuel in the nozzle sac from the fuel in the injector itself causing a great drop in injection pressure. These results prove by the experimental test that work out by the other [4].

In order to study the effect of all these parameters on penetration the Figure 17 depicted this fact. Penetration of all cases was compiled. The needle seat angle was least effective in terms of penetration depth. A decrease in hole number showed an increase in penetration depth. An increase in Nozzle sac diameter showed an exponential decrease of penetration.

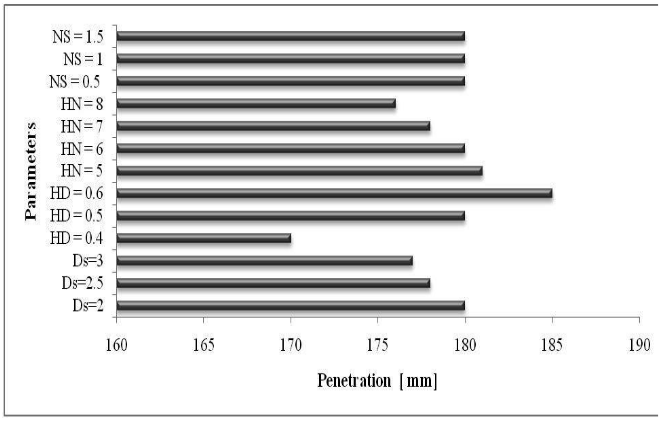


Figure 17: Injection volume in different nozzle SAC diameter

Also, for comparing the effect of Needle seat angle and SAC diameter together an extra case was carried out to help show the decrease in pressure due to low needle seat angles. In this case the Nozzle sac diameter was considered for maximum injection pressure (DS=3) and the needle seat angle was considered as open (NS=0.5). The previous maximum injection pressure for Nozzle sac diameter (DS=3) was about 1600 bars of injection pressure but when the needle seat angle was opened there was a drop of about 1100 bars. This illustrated the importance of correctly choosing a compatible needle seat angle for any design. (refer to

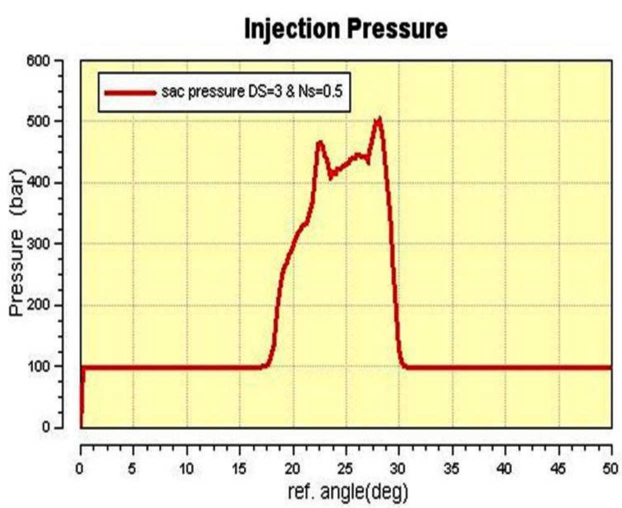


Figure 18)

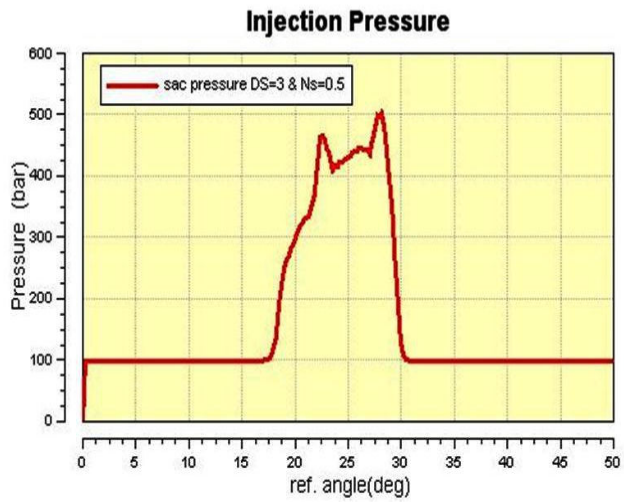


Figure 18: Injection Pressure in extra model

CONCLUSION

For all diesel engines the greatest geometrical factor that affects engine performance would be the hole diameter, it is also the most sensitive and limited factor. For dieselengines the main goal in injector design would be to have to highest injection pressure without having large losses of increased injector hole number. The number of holes needs to remain higher than conventional engines as to have the best in cylinder mixtures, but a need for efficiently creating pressure is also required as the increase in holes will create less pressure. The solution then would be to increase the nozzle sac diameter and needle seat angle greatly. The increase in both these parameters will not only convert the temperature in the injector tip to pressure effectively, but will also help with cooling the injector itself. This method would justify the use of higher holes in the injector design.

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