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Key Words

Cavitation; Erosion; Fuel Injection; Fuel Atomization; Vena Contracta

Research Article

Direct Visualization of Cavitation Erosion Near the Needle Seat Area on Real-Size Diesel Fuel Injectors

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Abstract

Fuel injection nozzles play a crucial role when it comes to operation, efficiency, and emissions from diesel engines. In a nozzle, at sharp edges due to the abrupt change in flow direction, the fluid flow streamlines are being contracted. The fluid is accelerated in this section thus reducing the pressure creating ideal conditions for cavitation. Cavitation number can characterize the conditions required to satisfy cavitation. Even though a considerable number of researchers have observed cavitation in injectors, a strong emphasis has not been given to the material degradation taking place within the injector sac volume and the needle seating. The current investigation is based on observations of a real-size injector, which was subjected to cavitation and comparison of its topology features with that of a new one. Material composition and material parameters were analysed. Cavitation erosion resistance of the material was also determined. Experiments were carried out to determine the mass flow rate of four injector nozzles that have done 40,000 km, 81,000 km, 120,000 km with a new one. Observation of cavitation erosion in the needle seat area on a real-size diesel fuel injector was compared with that of a new one. Comparing the experimental observations with evidence from literature it was revealed that a severe cavitation erosion is occurring in the needle seat area within the sac volume of injectors. Further literature supports this observation as there were cases where injectors have failed due to cavitation.

Introduction

Fuel injection nozzles play a crucial role when it comes to operation, efficiency, and emissions from diesel engines. Injectors are expected to operate at high pressure conditions in order to atomize the diesel fuel during injection. Many researchers have studied the atomization process by means of near-nozzle field visualization techniques [1-4]. In a nozzle, at sharp edges due to the abrupt change in flow direction the streamlines are being contracted. The boundary layer separates from the wall thus giving rise to a recirculation phenomenon [5]. The contraction due to recirculation effect reduces the effective cross sectional area of the fluid flow [6]. The fluid is accelerated in this section thus reducing the pressure creating ideal conditions for cavitation [6]. Under certain fluid flow conditions, a liquid may be subject to lower pressure. When the pressure drops, the liquid may start to boil at a lower temperature than it used to boil under atmospheric conditions. Boiling creates vapor bubbles. Due to flow dynamics, the liquid may be subject to a higher pressure a moment later. The vapor bubbles collapse when they enter the high pressure region. When the vapor bubble collapses on the surface of a metal, it gives rise to a microscopic bombardment. Cavitation and its occurrence is a phenomena that has a high relevance to materials science. Nozzles of diesel engines typically operate with a pressure of 250 MPa or higher [7].

Hydrodynamic cavitation can occur in liquids that flow, when flowing through Venturi nozzles, in narrow passages. Cavitation in static liquids known as acoustic cavitation, may occur when they are subjected to an oscillating pressure field or sudden and rapid acceleration of a solid body with sharp edges in static liquid [8]. Macêdo et al. have reported a failure of a diesel fuel injector predominantly due to cavitation erosion [9]. Even though cavitation physically deteriorates the injector internal geometry, fuel passage and the needle, the formation of vapor bubbles due to cavitation enhances fuel atomization thus improving the air fuel mixture formation.

Cavitation Inside an Injector

The sharp edges present in the inlet of the injector nozzle hole change the internal flow. The flow inside the injector is at extreme high pressure. During the flow, the effective cross section gets reduced due to contractions (vena contracta) of the streamlines. This results in formation of a recirculation zone between the restricted section (vena contracta) and the orifice wall. In this zone, there is a pressure depression due to the acceleration of the fluid. The restricted cross section demands high velocity of flow. According to the Bernoulli equation, the kinetic energy increase will result in a loss of pressure head. Due to this phenomena, the local pressure reduces to a value which is lower than the vapor pressure at certain locations. The drop of pressure which is less than the saturation pressure at a given temperature, air bubbles are produced creating a favorable condition for cavitation [10,11]. The collapse of cavitation bubbles will promote the jet break-up [10]. The phenomena explained is sketched in Figure 1.

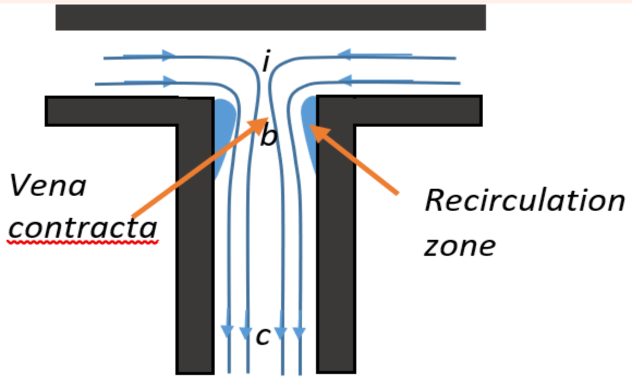

Figure 1: Fuel separation inside a diesel fuel injector.

Theoretical Background

Referring to the schematic diagram depicted in Figure 1, the following derivations are being made.

Mass flow for the condition shown in Figure 1 is given by [11];

$$\dot{m} = \int_{A_0} u\rho dA \text{ --- (1)}$$

Momentum flow for this condition is given by [11];

$$\dot{M} = \int_{A_0} u^2 \rho dA \text{ --- (2)}$$

From (1) and (2), the effective velocity can be derived as:

$$u_{eff} = \frac{\dot{M}}{\dot{m}} \text{ --- (3)}$$

From (2) and (3), the effective area is given by

$$A_{eff} = \frac{\dot{m}^2}{\rho \dot{M}} \text{ --- (4)}$$

The effective area is smaller than the geometrical area due to vena contracta. Using Bernoulli's equation, between the inlet (P_i) and the outlet (P_b) of the nozzle hole the theoretical exit velocity (u_{th})can be obtained.

$$P_i = P_b + \frac{1}{2}\rho u_{th}^2 \text{ --- (5)}$$

Reformulating,

$$\frac{2}{\rho}(P_i - P_b) = u_{th}^2 \text{ or } u_{th}^2 = \frac{2}{\rho}(\Delta P) \text{--- (6)}$$

The actual mass flow can be related to theoretical mass flow through a non-dimensional discharge coefficient Cd,

$$C_d = \frac{\dot{m}}{\dot{m}_{th}} \text{--- (7)}$$

Expressing $\dot{m}_{th}\dot{m}_{th}$using eq (1),

$$C_d = \frac{\dot{m}}{A_b \rho u_{th}} \text{ --- (8)}$$

Substitute $u_{th}u_{th}$ from eq (6),

$$C_d = \frac{\dot{m}}{A_B\sqrt{(2\rho\Delta P)}} \text{--- (9)}$$

According to literature, [11] The first theoretical model to predict nozzle flow under cavitation was proposed by Nurick [12]. According to Nurick [12], the final discharge taking into consideration the total losses should include friction, Borda-Carnot, and turbulence losses.

For the point b,

$$\dot{V}_b = \frac{\dot{m}}{A_b} \text{--- (10)}$$

Therefore, eq (9) can be written as,

$$C_d = \frac{\dot{V}_b}{\sqrt{2\rho(P_i - P_B)}} \text{---- (11)}$$

From continuity,

$$V_c A_c = V_b A_b \text{ --- (12)}$$

Let us define a parameter C_c as the ratio of effective cross section

$$C_c = \frac{A_c}{A_b} \text{--- (13)}$$

From 12, it can be written as;

$$C_c = \frac{V_b}{V_c} \text{--- (14)}$$

From Bernoulli's equation

$$P_i = P_c + \frac{1}{2}\rho V_c^2 \text{--- (15)}$$

$$\frac{P_i - P_c}{\frac{1}{2}\rho} = V_c^2$$

Substituting V_b from eq (14),

$$\frac{P_i - P_c}{\frac{1}{2}\rho} = \left(\frac{V_b}{C_c}\right)^2 \text{---(15)}$$

From eq (9) and eq (15),

$$\frac{P_i - P_c}{P_i - P_b} = \left(\frac{C_D}{C_c}\right)^2$$

Or

$$\sqrt{\frac{P_i - P_c}{P_i - P_b}} = \left(\frac{C_D}{C_c}\right) \text{---(16)}$$

The part within the square root in equation 16 is named as Cavitation number. Cavitation number is used to characterize the degree of which the nozzle internal is filled with vapor. When the cavitation number is higher than its critical value, super cavitation appears [10]. Based on mass flow measurements, Nurick [12] proposed cavitation inception. There is a linear relationship between mass flow and cavitation number until a certain value of cavitation number is reached. Beyond this particular point, the cavitation disappears. The point is called the critical cavitation number. A close analysis of the cavitation number reveals that it increases when the upstream pressure is decreased or when the downstream pressure is increased. Under low K values, the discharge coefficient depends only on the cavitation number. The pressure conditions needed to arrive at this stabilization point are named as critical cavitation conditions. The flow in this condition is known as choked flow directly affects discharge coefficient (Cd).

In the determination of cavitation number, geometry parameters do not involve; it is defined using dynamical parameters only. In literature, two main methods have been used to experimentally investigate the cavitation phenomena in diesel fuel injectors [13]. One being near nozzle observations, the other is observations through a transparent representative model. Even though a considerable number of researchers have observed cavitation in the sac volume [14,15], a strong emphasis has not been given to the material degradation taking place within the injector nozzle itself, specifically, the sac volume and its vicinity.

The current investigation is based on observations of a real-life injector, which was subjected to cavitation and comparison of its features with that of a new one. In a previous research Nicholas Mitroglou et al. [15] have highlighted the necessity of such research as follows "Upon start of injection, cavitation is found to form in the needle seat area. Although the well-known cavitation erosion in such areas manifests the existence of cavitation, direct visualization in this location in real-size injectors has not been reported previously."

Experimental

A diesel fuel injector nozzle from a naturally aspirated water cooled, four cylinder four stroke Compression Ignition Engine was selected for investigation. The Engine is of indirect injection, distributor type mechanical fuel injection with a bore of 86 mm and stroke of 85 mm. The compression ratio of the engine was 23:1. The injector was single hole pintle type with a sac volume. The injector under investigation was from a vehicle that has done 120,000 km from the same set of injectors. The used injector was compared with a new similar type of an injector during the investigation. The needle and nozzle sac volume were characterized by optical macrography. The hardness of the case of the injector nozzle was 732 HV and the hardness of the core was 521 HV. Material composition of the injector is given in Table 1. Both the new and the old injectors were sectioned. The observations are shown in Figure 2. The microstructure of the material is shown in Figure 2. A fine microstructure consisting of martensite and austenite matrix was observed. A comparison of sac volume of the old nozzle and the new nozzle is shown in Figure 3. Figure 3 clearly depicts enlarged and severely eroded sac in the old nozzle compared to that of the new nozzle. The sac volume with the injector needle in place for the old and the new nozzle are shown in Figure 4.

Table 1: Material composition of the injector material.

Element	C	Si	Cr	Mn	Fe
Composition by Weight	3.75	0.33	1.37	1.52	Balance

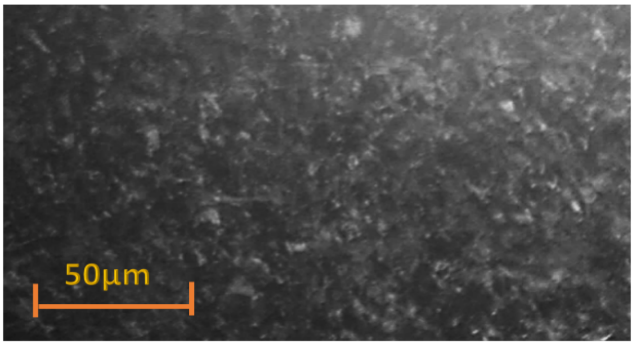

Figure 2: Microstructure of the nozzle material.

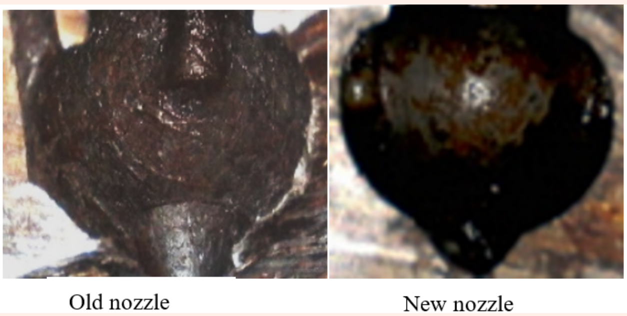

Figure 3: Sac volume of the old nozzle and the new nozzle.

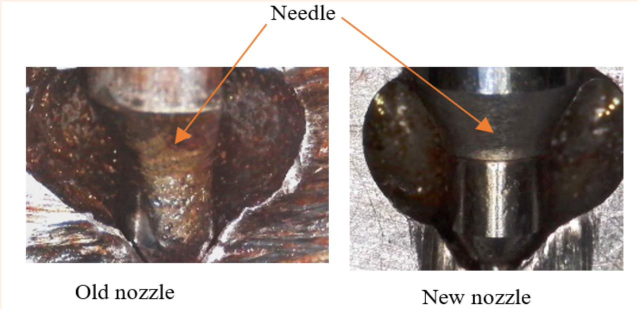

Figure 4: Sac volume with the injector needle for old and new nozzle.

Figure 4 compares the needle condition and the condition of the needle seating area of the old nozzle and the new nozzle. Figure 4 clearly depicts the expected surface finish and the clearance of the manufacturer in new nozzle. The kind of cavitation erosion taking place in the sac and the needle seating area of the old nozzle can be compared with the new one to understand the extent of cavitation damage occurring in an injector nozzle over a period of time. The injector spray orifice is shown in Figure 5 for the old and the new nozzle. The new nozzle had an average diameter of 1000 µm and the old nozzle had an average 1100 µm nozzle spray hole diameter.

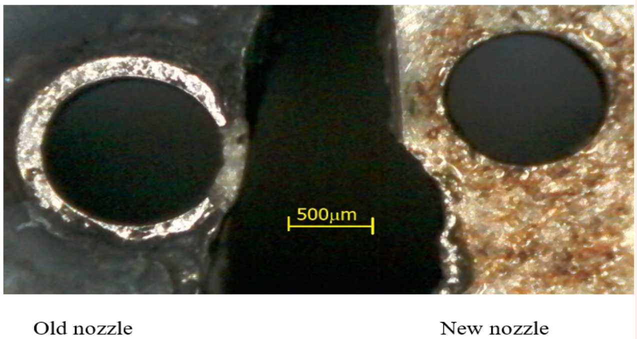

Figure 5: Injector nozzle orifice.

The experimental setup consisted of a spray chamber, a diesel fuel injection pump driven by an electric motor, an injector, a pressure gauge and a collector. Schematic diagram of the experimental setup is shown in Figure 6. Four injector nozzles, which have done zero mileage (new), 40,000 km, 81,000 km and 120,000 km were tested. They are being identified as injector A B C and D respectively in the text. All injectors were adjusted to open at 250 MPa gauge pressure. Fuel was injected and optical imaging was carried out at the atmospheric pressure. The mass flow was measured by the amount of fuel collected on the collector. The fuel density was 820 kg/m^3 and the kinematic viscosity at 40 C was 2.24 mm^2/s.

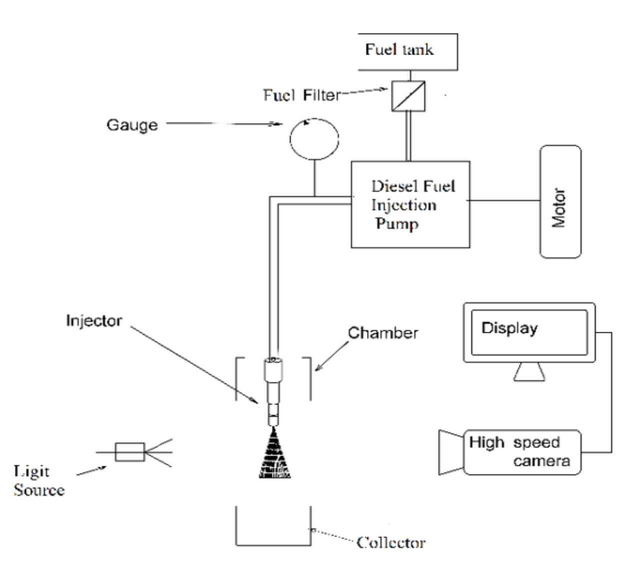

Figure 6: Experimental setup [7].

For steady-state analysis, only mass flow rate values averaged while the needle is fully open are needed [7]. For the current study, the mass flow was measured by collecting the amount of fuel injected for 50 strokes. The Start of injection and end of injection were recorded from the high speed camera. Dumouchel C [13] has categorized the production of a spray into three main steps, namely, the ejection of a liquid flow, the primary breakup mechanism and the secondary breakup mechanism. The ejection of the liquid flow was quantified by the initial exit velocity. The variation of mass flux with exit velocity for the four injector nozzles tested are shown in Figure 7. The figure depicts that both the exit velocity and mass flux are increasing with aging of the injector. However, the variation of the velocity becomes stabilized after some time. The injector C and D had almost the same velocity whereas the mass flux continued to increase. The time for breakup is analyzed in Figure 8. The injector A (new) had the shortest time to reach the breakup. The breakup time gradually increases until the injector C. from C to D, the graph depicts that the breakup time has become stable. The extent of cavitation damage was analyzed by replicating the sac volume of sectioned injector nozzles shown in Figure 3. The outcome is shown in Figure 8.

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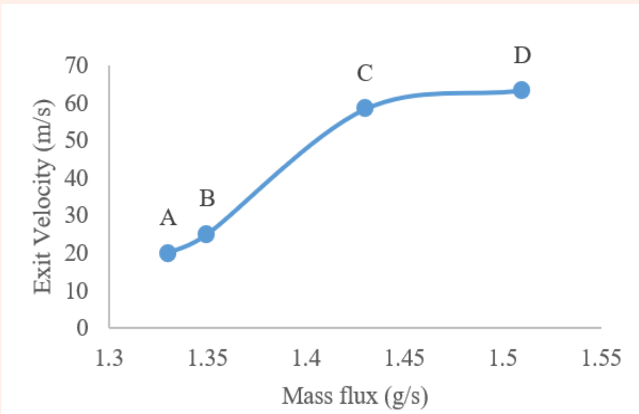

Figure 7: Mass flux with exit velocity before breakup.

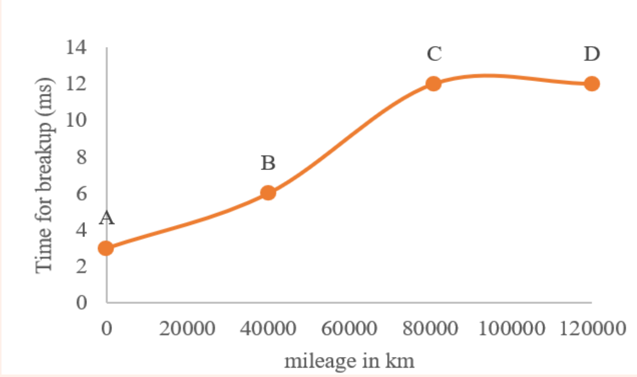

Figure 8: Time for breakup with mileage of nozzle.

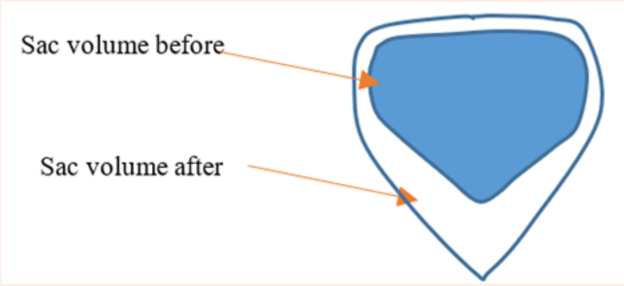

Figure 9: Variation of the sac volume before and after the cavitational erosion.

Discussion

Many researchers have reported the cavitation effect on the fuel exit nozzle of the diesel fuel injector [14,15]. However, a strong emphasis has not been given to the material degradation taking place within the injector nozzle itself, specifically, the sac volume and its vicinity. Macêdo et al. (2015) have reported a failure of a diesel fuel injector predominantly due to cavitation erosion [9]. The current investigation is based on observations of a real-life injector, which was subjected to cavitation and comparison of its features with that of a new one.

Mingrui et al. [14] & Mitroglou et al. [15] in experimental investigations carried out using transparent nozzles have observed that cavitation bubbles are formed in the nozzle sac volume near the needle when the needle valve opens. Material parameters including the hardness, microstructure and chemical composition of the injector nozzle under investigation has been carried out. The reciprocal value of the maximum instantaneous erosion rate is identified as the cavitation resistance rate [16]. Hattori & Kitagawa [16] have studied the cavitation resistance of metals. They have observed that erosion resistance of carbon steel increases proportionally with hardness and developed a mathematical relationship between hardness and erosion resistance of carbon steels. The relationship is expressed as

$$ER = 5.8 \times 10^{-7} \times HV^{2.4} \text{ --- } (17)$$

Submitting values in eq (17),

$$ER = 5.8 \times 10^{-7} \times 732^{2.4} = 4.34\ \mu m/h$$

Based on the relationship given by equation (17) the cavitation resistance for the injector nozzle under investigation is 4.34 μm/h. As per data given in [8], this value is quite high. In addition to hardness, there is a strong relationship of surface roughness on the cavitation formation [17]. In experiments conducted by Mingrui Weia et al. [14] the total duration of an injection lasted 1000 μs. They have noted that cavitation bubbles are formed in the nozzle sac volume near the needle when the needle valve opens and at about 200 μs, the cavitation has almost disappeared at nozzle sac volume. Nicholas Mitroglou [15] have reported cavitation presence and location inside the sac volume of the nozzle.

Microscopic imaging revealed that the nozzle spray orifice diameter of the old injector nozzle had a 10% enlarged diameter compared to the new one. Further enlarged and severely eroded sac was observed in the old nozzle compared to that of the new nozzle. The needle and the needle seat were severely eroded due to cavitation in the old injector nozzle. The extent of damage was evident when compared with that of the new one [18]. The spray initiation and evolution with mass flow rate was examined experimentally. The experimental setup consisted of a spray chamber, a diesel fuel injection pump driven by an electric motor, an injector, a pressure gauge and a collector.

Four injector nozzles, which have done zero mileage (new), 40,000 km, 81,000 km and 120,000 km were tested. They are being identified as injector A B C and D respectively. The variation of mass flux with exit velocity for the four injector nozzles show that both the exit velocity and mass flux are increasing with aging of the injector. The increase of both the exit velocity and mass flux can be attributed to the increased diameter of the injector spray orifice in old injectors due to erosion. The time for breakup was analyzed. The injector A (new) had the shortest time to reach the breakup. The breakup time gradually increased with aging. The breakup should happen early as possible for proper atomization of fuel. This analysis clearly indicate the poor atomization quality of old injectors due to severe cavitation erosion

Conclusion

a. Severe cavitation erosion is taking place in the sac volume and the needle seat area of diesel fuel injectors due to cavitation.

b. The cavitation erosion enlarge the nozzle spray orifice diameter and the sac volume of the old injector nozzles

c. The erosion and creased spray orifice diameter could increase the exit velocity and mass flux of fuel

d. As the damage increase due to cavitation, the time for breakup increases. This will deteriorate the fuel atomization quality

e. The investigation revealed that the cavitation has a strong influence on the degradation of diesel fuel injectors.

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