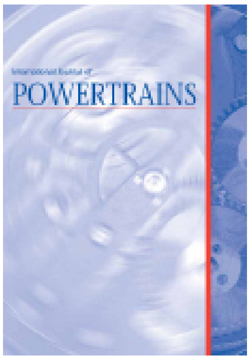


**International Journal of Powertrains**

ISSN online: 1742-4275 - ISSN print: 1742-4267
https://www.inderscience.com/ijpt

# Linking the performance of a compression ignition engine to physical indications of injector nozzle

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**DOI:** 10.1504/IJPT.2024.10060577

**Article History:**

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|---|---|
| Received: | 21 September 2022 |
| Last revised: | 07 October 2023 |
| Accepted: | 07 October 2023 |
| Published online: | 16 April 2024 |

# Linking the performance of a compression ignition engine to physical indications of injector nozzle

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**Abstract:** In the current study, the effect of aging of the injector nozzle during operation in an automobile engine was investigated by observing the optical imaging of the fuel spray pattern, engine dynamometer testing, and optical imaging of the nozzle sac. In this study, the spray breaks up length and the spray cone angle of four identical sets were compared. The different injector sets were brand new and from an engine of a vehicle that has done 40,000 km, 81,000 km, and 120,000 km. The investigation revealed that as the injector nozzle gets older, the spray cone angle gets reduced and the breakup length increases. Both the reduction of spray cone angle and increased breakup length can be attributed to poor atomisation quality. When the engine is running on old injectors, the fuel economy decreases and harmful emissions increase.

**Keywords:** diesel fuel; emissions; soot; fuel injection; spray cone angle; cavitation.

**Reference** to this paper should be made as follows: Perera, S.D.R. (2024) 'Linking the performance of a compression ignition engine to physical indications of injector nozzle', *Int. J. Powertrains*, Vol. 13, No. 1, pp.5–18.

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## 1 Introduction

Compression ignition engines are widely used in both the power generation and transport sector due to their relatively high thermal efficiency and reliability. The ability of the engine to operate on the wide-open throttle with a large amount of excess air during operation is an added advantage in terms of maintaining acceptable levels of exhaust emissions and reducing environmental pollution (Heywood, 1988). However, it is a common observation that diesel-powered vehicles emit excessive amounts of emissions under certain operating conditions. In a compression ignition engine, combustion and emission characteristics are influenced by the mixture formation and spray structure which determine the air and fuel mixture inside a combustion chamber of the engine (Stiesch, 2003). The fuel atomisation and mixture formation is characterised by parameters such as, nozzle geometry, injection pressure, the shape of the inlet port, etc. (Heywood, 1988; Wang et al., 2003).

To improve combustion performance and reduce particulate emissions, many researchers have investigated the characteristics of the spray behaviour and structure through experimental and theoretical approaches. If auxiliary systems of the engine function as expected, modern diesel engines used in the automobile industry are capable of operating for more than 250,000 km without engine overhaul. However, maintaining auxiliary systems such as the fuel injection system and its components which affect fuel efficiency and emissions is of prime importance for engine developers, manufacturers, and operators. Further, it is critical to maintain engine emissions within acceptable levels during the entire useful lives of engines.

Improved understanding of the trade-off among injector operating conditions, erosion risk, combustion performance, and emissions are of great importance in this regard (Nocivelli et al., 2019). There is a wealth of research information published relating to diesel fuel injection parameters that can be characterised to quantify the quality of spray, how air-fuel mixing occurs in a fraction of a second, etc. However, what happens to the spray, as the equipment gets older and eroded due to the interaction of liquid and gaseous phases on metal surfaces of fuel injection equipment is a subject that has not been offered prominence by researchers.

The prime objective of the present study is to investigate the effect of an aging injector nozzle on fuel atomisation, fuel economy, and emissions.

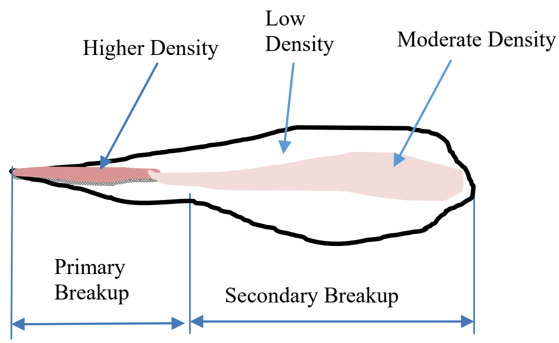
## 2 Literature review

Since the invention of compression ignition engines, many phenomena occurring in diesel engines have been successfully analysed by scientists. However, still there are certain phenomena occurring in a diesel engine fuel spray that is still not fully understood (Zhao and Ladommatos, 1998). A simple thermodynamic analysis reveals that the operating condition of a diesel engine lies at considerably higher pressure and temperature. In such conditions, there is a high probability for the injected diesel fuel to reach or exceed the thermodynamic critical point (Wensing et al., 2015).

A liquid spray can be characterised by the drop-size distribution, the drop-velocity distribution, the droplet density, the spatial distribution, and the drop of temperature (Dumouchel, 2008). Diesel fuel atomisation by means of spray breakup inside the combustion chamber is one of the main aspects of achieving complete combustion and improving the efficiency in compression ignition engines. The production of a liquid spray consists of two stages: primary breakup mechanism, and the secondary breakup mechanism. The primary breakup mechanism covers the early liquid flow deformation down to the production of the first isolated liquid fragments (Dumouchel, 2008). The fuel injection process is accomplished within a few milliseconds at high speed and pressure. Dumouchel (2008) described the presence of initial disturbances on the liquid–gas interface and a mechanism that allows some of these disturbances to grow leading to the breakup of the liquid flow. A complex mechanism including turbulence, cavitation, etc. facilitates the initial disturbance of the fuel when flowing through miniature orifices of the injector. However, as time goes on, erosion due to cavitation and other wear mechanisms, the initial disturbance process gets disrupted (Dumouchel, 2008).

Cheng et al. (2019) have carried out a study aimed at understanding the dynamics of diesel-like spray. They have observed a high density near the tip and a distribution gradient from the nozzle exit to the tip and that the spray near the outer edge has a significantly lower density. This is depicted in Figure 1.

**Figure 1** Variation of density in a fuel spray (see online version for colours)




Generally, optical methods are used to characterise the fuel atomisation process. Hiroyasu and Arai (1990) proposed the spray cone angle and primary breakup length to quantify the quality of atomisation. Many researchers have successfully used the spray cone angle to quantify the atomisation quality of diesel fuel injection systems (Zhao and Ladommatos, 1998; Hiroyasu and Arai, 1990). The spray cone angle is the angle that is formed by the outer boundary of the spray cone, taken from the injector exit hole. The motion of the spray tip and breakup length characterise the breakdown process. The breakdown of the fuel jet or the atomisation is characterised by the motion of the spray tip and breakup length.

Although breakup length has been identified as the length required to fully atomise the fuel which is one of the most important governing parameters, there is no clear way of identifying the breakup length practically. However, some empirical models have been proposed in the literature (Balachandran et al., 1994; Laryea and No, 2004). Yule and Filipovic (1992) have investigated the droplet velocity in order to investigate the breakup length experimentally. The penetration velocity during the breakup process is less compared to liquid exit velocity, as there is aerodynamic resistance on droplets of fuel.

## 3 Experimental investigation

The effect of aging of the injector nozzle during operation in an automobile engine was investigated. The study comprised of three stages as follows:

a optical imaging of the fuel spray

b engine dynamometer testing

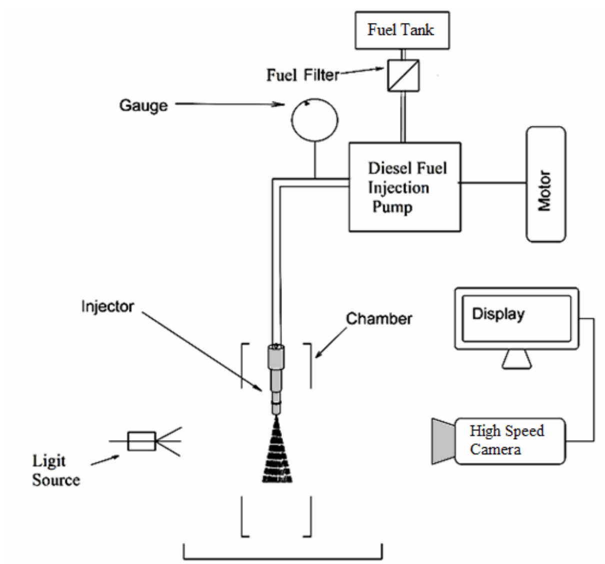
c morphology analysis of the nozzle sac.

A naturally aspirated, water cooled, four cylinder, four stroke compression ignition engine with indirect injection was used for the experiment. The engine had a bore diameter of 86 mm, stroke 85 mm and a compression ratio of 23:1. The fuel injection system comprised of a distributor-type injection pump with a fuel injector of single hole, pintle type nozzle.

### *3.1 Optical imaging of the fuel spray*

The experimental setup consisted of a spray chamber, a diesel fuel injection pump driven by an electric motor, an injector, a pressure gauge, a high speed camera with a digital screen and a recorder. A lighting system was used to illuminate the spray appropriately. Schematic diagram of the experimental setup is shown in Figure 2.

**Figure 2** The experimental setup used to quantify the fuel spray




In this study, the performance of three fuel injection nozzle with different performance histories was compared with a set of new nozzles. The three nozzles were from vehicles that have done 40,000 km, 81,000 km, and 120,000 km. All injectors were adjusted to open at 250 MPa gauge pressure. Fuel was injected and optical imaging was carried out at the atmospheric pressure.

All injectors were operated on the fuel injection test bench for 10 minutes prior to the testing. Images were taken for 50 injections for each test from which three random sets were selected from each injector for analysis. The formation of the spray for all four nozzles was analysed. As depicted in Figure 3, the spray for the new nozzle evolved over a period of 3 ms. When the evolution was analysed, there existed a point where the fuel began to break up in a similar pattern to the mode that is depicted in Figure 1. The transition from primary breakup to secondary breakup was clear. The secondary breakup show fine atomisation of the fuel. From Figures 3 to 6, fuel spray evolution is depicted at 0.3 ms intervals.

Figure 3 shows the evolution of the fuel spray pattern of the new nozzle. The image clearly depicts a larger spray cone angle and a clear breakup length. The maximum spray cone angle measured was 15 degrees throughout with a maximum deviation of ±0.5

degrees. The average breakup length and the penetration depth observed were 95 mm and 360 mm respectively. The maximum standard deviation of penetration depth and breakup length for consecutive repetitions was 12 mm and 16 mm, respectively.

**Figure 3** Spray evolution for the new nozzle (see online version for colours)

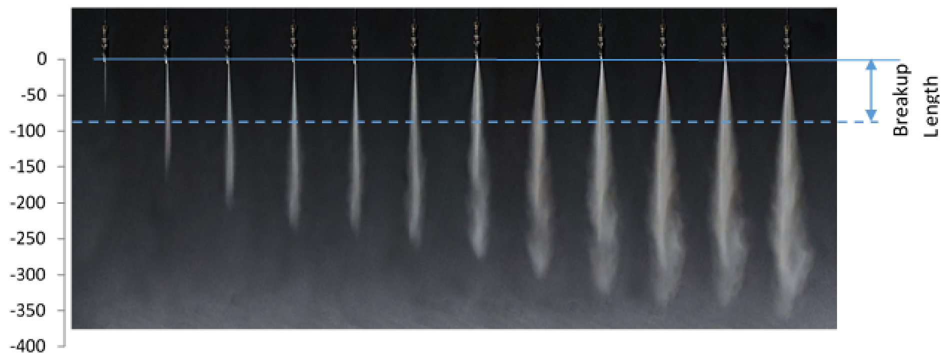



**Figure 4** Spray pattern for the 40,000 km nozzle (see online version for colours)

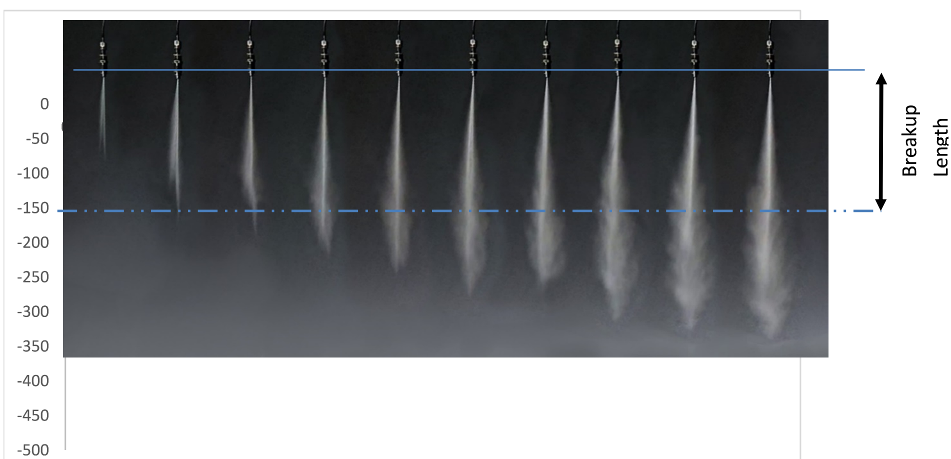



Figure 4 shows the evolution of the injection pattern of the 40,000 km nozzle. The image depicts a spray cone angle less than the one that was observed for the new nozzle. However an angle of 12 degrees with a maximum deviation of ±0.5 degree was observed throughout the injection stage. A clear breakup length could be seen. However, the breakup length was longer than that for the new nozzle. The average breakup length was recorded as 210 mm and the average penetration depth was 380 mm. the maximum standard deviation of penetration depth and breakup length for consecutive repetitions was 10 mm and 16 mm respectively.

Figure 5 shows the evolution of the injection pattern of the 81,000 km nozzle. The image depicts a smaller spray cone angle. The angle measured was 8 degrees with a maximum deviation of ± 0.5 degrees throughout the injection. A clear breakup length could be seen. However, the breakup length was longer than that for the 40,000 km nozzle. The average breakup length was recorded as 380 mm and the average penetration depth was 550 mm. The maximum standard deviation of penetration depth and breakup length for consecutive repetitions was 19 and 20 mm, respectively.

**Figure 5** Spray pattern of the 81,000 nozzle (see online version for colours)

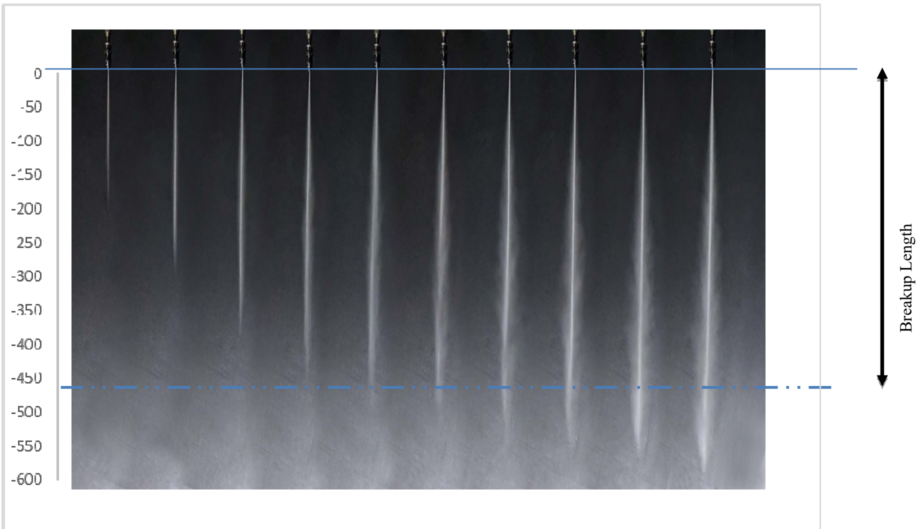
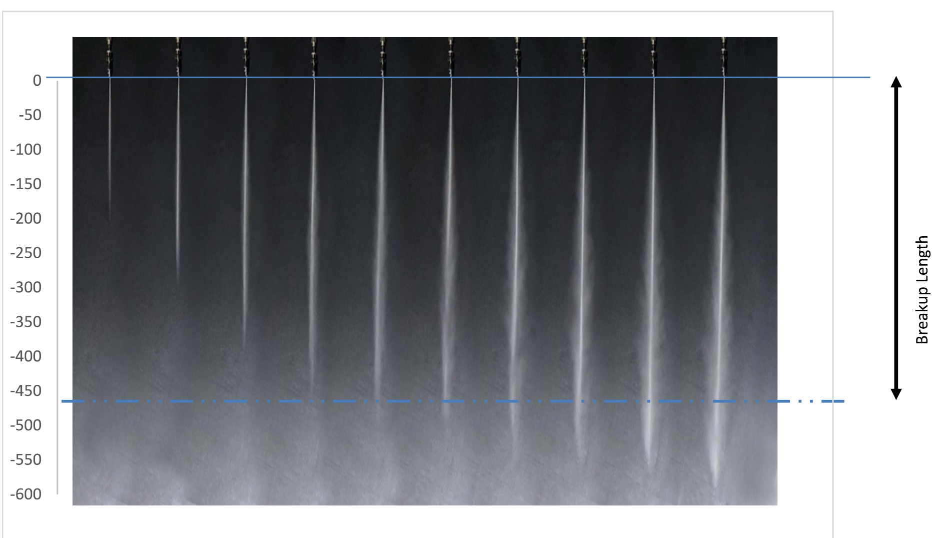



**Figure 6** Spray pattern of the 120,000 km nozzle (see online version for colours)




Evolution of the injection pattern for the 120,000 km nozzle is shown in Figure 6. The image depicts a small spray cone angle of 6 degrees with a maximum deviation of ±0.5 degrees throughout the injection. Referring to the breakup length defined in Figure 1, a long fuel-rich region could be seen. The end of the fuel-rich region was taken as the breakup length. A breakup length of 490 mm and a penetration depth of 570 mm were recorded. The maximum standard deviation of penetration depth and breakup length for consecutive repetitions was 25 mm and 22 mm, respectively.

Analysis of the variation spray cone angle with time for each injector did not change throughout the injection process. However, each injector had different spray cone angles with a decreasing value in line with aging. The variation of the spray penetration depth with time for each injector is summarised in Figure 7. The new injector and the 40,000 km injector had a shorter penetration depth compared to the 81,000 and 120,000 km nozzles. However, all four injectors have had their fully developed spray by 3 ms. The development of penetration depth of the 40,000 km nozzle over time was almost same as that of the new nozzle. The final penetration depth of the 81,000 km and 120,000 km nozzles reached far beyond the limit of the new nozzle. The penetration depth of the spray pattern observed for all four nozzles at the fully developed stage is shown in Figure 8. The breakup length is indicated by a horizontal line. Parameters observed for each injector are tabulated in Table 1.

**Table 1** Summary of parameters observed for the four nozzles

| *Nozzle* | *Nozzle mileage* | *Spray cone angle degrees* | *Breakup length mm* | *Penetration depth* |
|---|---|---|---|---|
| a | new | 15 ± 0.5 | 95 ± 12 | 360 ± 16 |
| b | 40,000 | 12 ± 0.5 | 210 ± 10 | 380 ± 16 |
| c | 81,000 | 8 ± 0.5 | 380 ± 19 | 550 ± 20 |
| d | 120,000 | 6 ± 0.5 | 490 ± 22 | 570 ± 25 |

**Figure 7** Spray penetration variation with time for different injectors (see online version for colours)

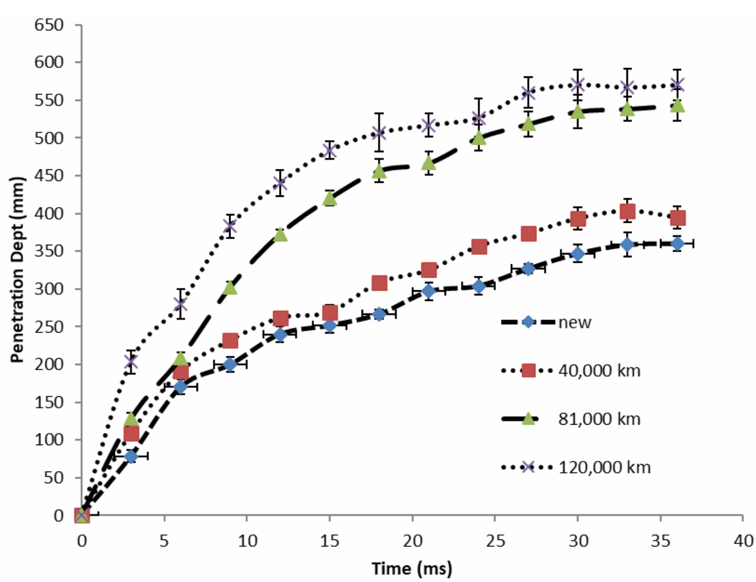
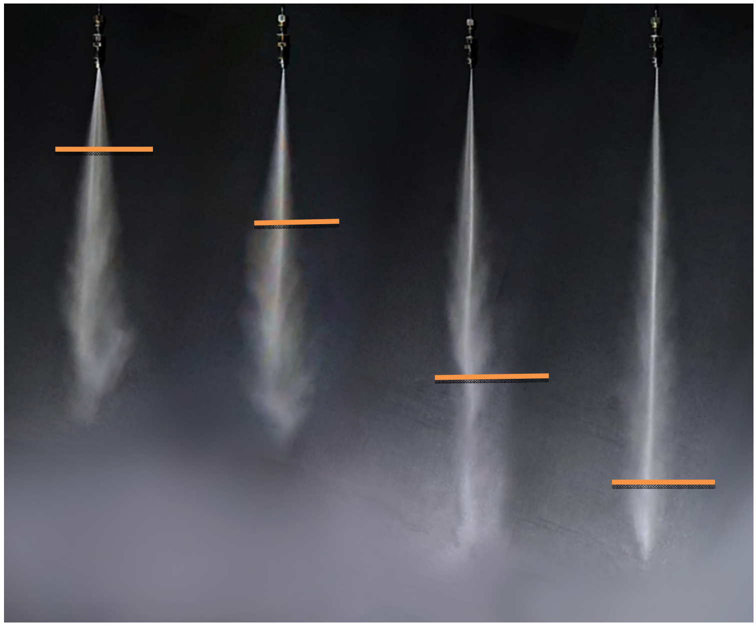


**Figure 8** Comparison of spray for all nozzles at the fully developed stage (see online version for colours)



(a) (b) (c) (d)

## *3.2 Engine dynamometer testing*

An experimental investigation into the power developed, fuel consumption, and emissions was carried out using an eddy current brake engine dynamometer. First, the engine dynamo meter was calibrated as per the manufacturer's specifications to read the speed and torque accurately. The torques was measured by means of a full bridge load cell. The coolant temperature out was maintained at 95°C and the coolant temperature in was maintained at 90°C throughout the experiment. Schematic diagram of the engine dynamometer setup is shown in Figure 9.

The torque was measured by means of a full bridge load cell. Exhaust emissions were measured using exhaust gas analysers that are capable of measuring CO and HC concentrations. The accuracy of CO and HC measurement was 1 ppm. In the test, the parameters of a new injector nozzle were compared with that of 40,000, 81,000 and 120,000 km nozzles.

The engine was tested at wide open throttle for a range of load and speed conditions. The engine dynamometer controller was capable of maintaining the required test conditions as per the user input in terms of speed and the torque. Knowing the torque reading of the load cell and the engine speed, the brake power was calculated. The repeatability and reproducibility of the experimental investigation was a crucial factor. The experiment was repeated three times and the variations of performance were assessed by means of percentage relative standard error. A comparison of performance parameters in terms of brake power, specific fuel consumption, HC and CO emissions for the four different injector nozzles are shown in Figures 10 to 14.

**Figure 9** Engine dynamometer setup

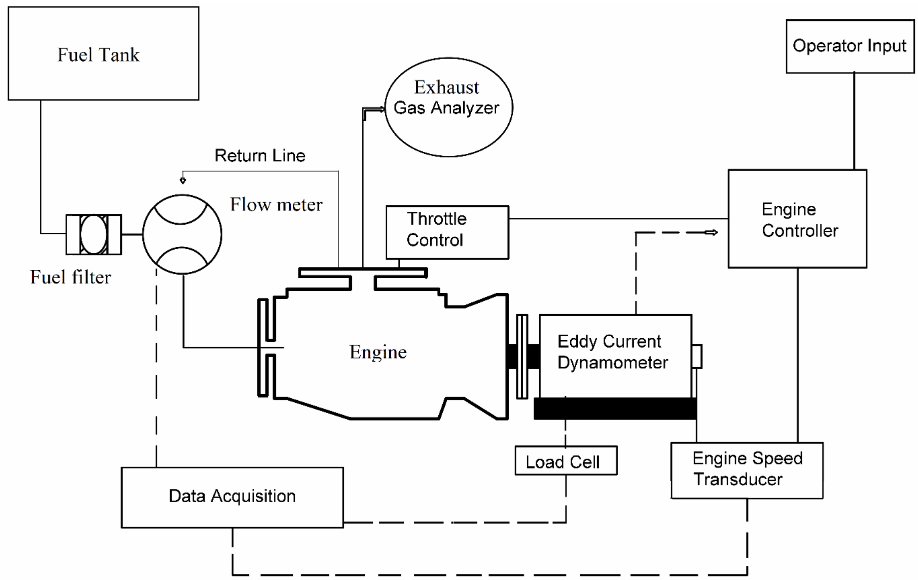
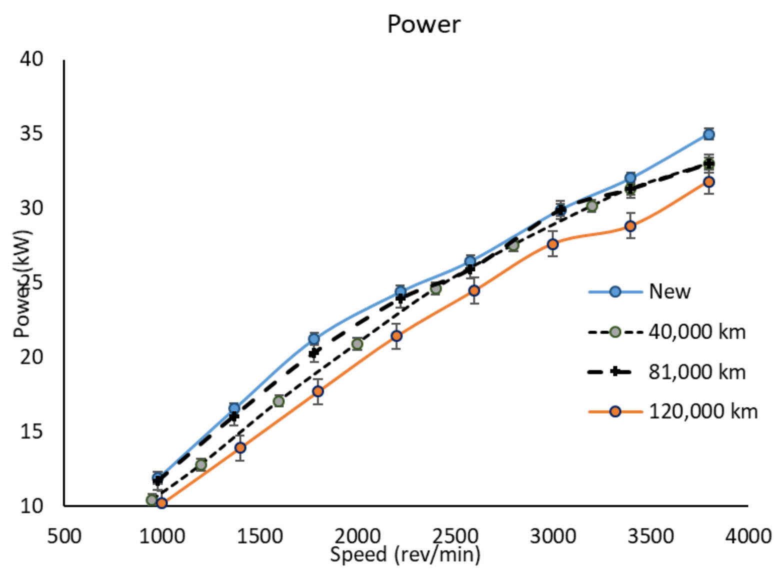
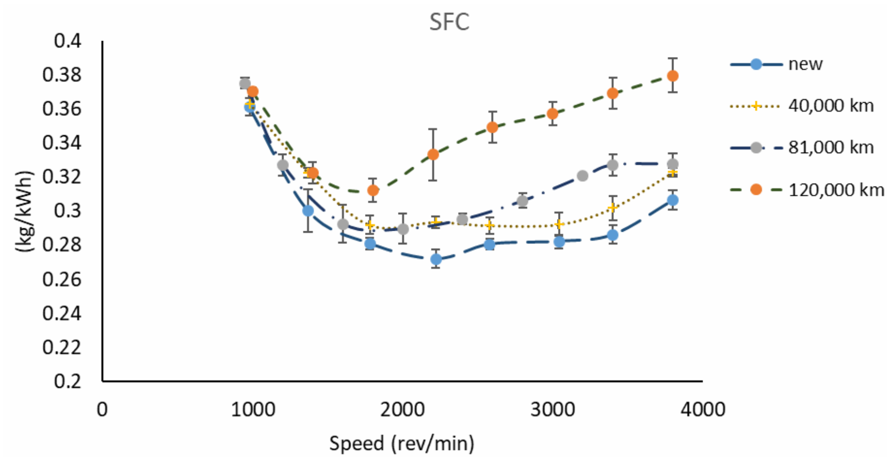



**Figure 10** Power comparison (see online version for colours)



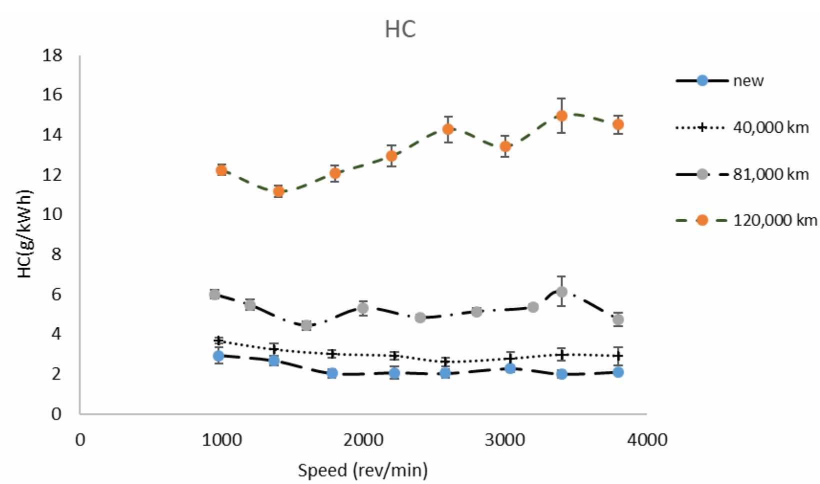

Graphical representation of engine dynamometer test results reveals a gradual reduction of power, an increase in specific fuel consumption, and HC and CO emissions with the aging of the injector nozzle. Figure 10 shows the variation of power developed by the engine for the selected four different injector nozzles. There was an average power drop of 2.69% for the 40,000 km, 6.42% for the 81,000 kW, and 10.87% for the 40,000 km nozzle, respectively. Further, a maximum deviation of 0.85 kW was observed for the 120,000 kW nozzle for repetitive experiments

**Figure 11** Fuel consumption comparison (see online version for colours)




The variation of specific fuel consumption for all four nozzles is presented in Figure 11. The lowest SFC was for the new nozzle throughout, whereas the highest SFC was recorded for the 120,000 km nozzle. The 40,000 km nozzle had a 3.3 % and the 120,000 km nozzle had 11.7 % increase in average specific fuel consumption compared to the new nozzle. Further, the 120,000 km nozzle had larger variations in repetitive experiments compared to the new and the 40,000 km nozzles.

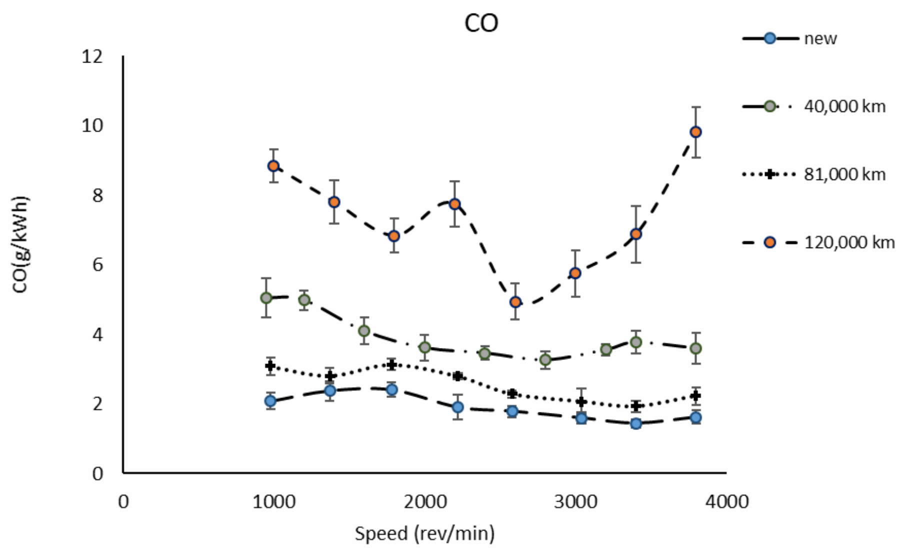
**Figure 12** HC emission comparison (see online version for colours)




When emissions are compared as shown in Figure 13, the new nozzle had 46.8%, 37.9% and 22.7% better CO emissions compared to the 120,000 km nozzle, 81,000 km nozzle, and 40,000 km nozzle, respectively.

As shown in Figure 12, when the HC emissions are compared, the new nozzle had 60%, 43%, and 24.8% lower HC emissions compared to the 120,000 km nozzle, 81,000 km nozzle, and 40,000 km nozzle respectively.

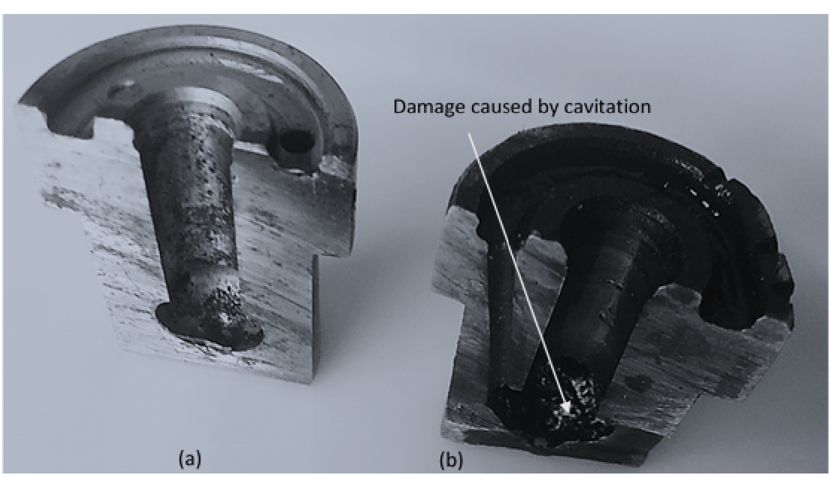
**Figure 13** CO emission comparison (see online version for colours)




## *3.3 Morphology analysis of the nozzle sac*

Even though the effect of aging of the injector nozzle on fuel atomisation quality and engine performance was analysed, what exactly happened to the nozzle itself was not revealed yet. For this purpose, an injector nozzle from the 120,000 km range was sectioned and compared with that of a new nozzle. The section of a new nozzle and an old nozzle are shown in Figures 15(a) and 15(b), respectively. The macroscopic investigation and comparison of the sac volume of the new nozzle and the old nozzle reveal severe destruction in the old nozzle.

**Figure 15** Sectioning of (a) a new injector nozzle and (b) a one from the 120,000 range (see online version for colours)



In a nozzle, at sharp edges, the streamlines are contracted due to the abrupt change in the flow direction. The boundary layer separates from the wall thus giving rise to a recirculation phenomenon (Mohan et al., 2014). The contraction due to the recirculation effect reduces the effective cross-sectional area of the fluid flow. The fluid is accelerated in this section thus reducing the pressure and creating ideal conditions for cavitation (Desantes et al., 2010).

Many researchers have observed that cavitation within the injector is required for better atomisation of fuel (Chaves et al., 1995; Sou et al., 2007). Nocivelli et al. (2019) have observed that a wider spray cone angle is obtained from a nozzle that is cavitating compared to a non-cavitating nozzle. Magnotti et al. (2021) has compared the non-eroded and eroded multi-hole fuel injectors for spray and combustion characteristics. They have observed that eroded injectors are prone to form richer mixtures thus increasing the soot emissions.

Cavitation has a strong influence on fuel atomisation, however, cavitation is followed by a gradual destruction of relevant metal surfaces. Figure 15 clearly depicts the serious destruction of the nozzle hole due to cavitation phenomena. It was observed that cavitation created a larger sac volume. Larger sac volume supports dribbling which increases HC and CO emissions (Koci et al., 2019).

## 4 Discussion

In compression ignition engines, combustion, and emission characteristics are influenced by the mixture formation and spray structure which determine the air and fuel mixture inside the combustion chamber of the engine. The mixture formation is characterised by the fuel injection parameters such as atomisation, nozzle geometry, injection pressure, the shape of the inlet port, etc. The production of a liquid spray consists of the primary breakup and the secondary breakup mechanism. A complex mechanism including turbulence and cavitation facilitates the initial disturbance of the fuel when flowing through miniature orifices of the injector.

The effect of aging of the injector nozzle during operation in an automobile engine was investigated. The study comprised of three stages: optical imaging of the fuel spray, engine dynamometer testing, and morphology analysis of the nozzle sac.

Four different injector nozzles that have done 40,000 km, 81,000 km, and 120,000 km were compared against a new nozzle. The spray of each injector at the fully developed stage is shown in Figure 6. Parameters observed for fuel spray for each nozzle revealed a reduction in spray cone angle and increased primary breakup length. The new nozzle had the shortest breakup length of 95 mm. The 40,000, 81,000, and 120,000 km nozzles had 210, 380, and 490 mm breakup lengths respectively.

The engine dynamometer test results shown in Figures 7 to 10 revealed that there was an average power drop of 2.69% for the 40,000 km, 6.42% for the 81,000 kW, and 10.87% for the 120,000 km nozzle respectively compared to the new nozzle. Further, there was an increase in specific fuel consumption, HC, and CO emissions with the aging of the nozzle.

The sectioning of the injector nozzle from the 120,000 km range shown in Figure 15 reveals severe destruction of the injector sac due to cavitation. Aging of the injector nozzle has a direct relationship with reduced fuel economy and increased emissions from compression ignition engines. Cavitation complements the fuel atomisation. However, cavitation deteriorates the injector fuel spray orifice and the sac. Eroded injector nozzles are prone to form richer mixtures thus increasing the soot emissions. The damaged orifice and the sac deteriorate the atomisation quality which prompts replacement of the injector nozzle periodically. As the injector nozzle gets older, a reduction in the spray cone angle was observed and increase in the breakup length was observed. Both the reduction of spray cone angle and increased breakup length could be attributed to poor atomisation quality. Due to cavitational damage, large sac volumes have been created. Larger sac volumes are capable of holding large quantity of fuel which favour dribble which increases HC and CO emissions.

## 5 Conclusions and future work

- In order to minimise the environmental pollution and fuel consumption, the engine manufacturers could recommend an injector nozzle replacement at scientifically established period of time.
- Industry could move towards alternative fuel atomisation mechanisms that could be achieved in the absence of cavitation.
- In order to prolong the lifetime of fuel injection components, further research is necessary to develop material that could withstand cavitation.

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