International Journal of Advanced Technology in Engineering and Science
Vol. No. 11, Issue No. 12, December 2023
www.ijates.com
ijates
ISSN 2348 - 7550

Review of Nozzle Geometry's Impact on the Diesel Engine's Performance, and Emission Characteristics

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ABSTRACT

This review investigates the impact of injector nozzle geometry on fuel atomization, spray characteristics, and emissions in diesel engines. The findings reveal that a smaller hole diameter in the nozzle results in improved brake thermal efficiency (BTE) due to enhanced evaporation and atomization, leading to decreased brake-specific fuel consumption (BSFC) attributed to higher air-fuel mixing rates. Additionally, an increase in the number of nozzle holes leads to higher BTE, fuel evaporation, and enhanced combustion. Furthermore, decreasing the nozzle hole diameter lowers CO and hydrocarbon (HC) emissions, primarily due to enhanced fuel vaporization, better atomization, and reduced wall impingement. On the other hand, an increase in NOx emissions occurs with larger nozzle hole diameters, while smoke opacity rises with increasing nozzle hole size. Reducing the number of holes leads to slightly increased emissions, as smaller hole sizes facilitate more efficient mixture preparation and improved air utilization.

KEYWORDS:

NHD: nozzle hole diameter

BTE: Brake Thermal Efficiency

BSFC: Brake-Specific Fuel Consumption

D: Diameter

HOME: Honge Oil Methyl Ester

IOP: Injector Opening Pressures

POME: Palm Oil Methyl Ester

IJNHN: Injector Nozzle Hole Number

IP: Injection Pressure

ITE: Indicated Thermal Efficiency

ROME: Rise Bran oil Methyl Ester

CAOME: Canola Oil Methyl Ester

CRDI: Common Rail Direct Injection

IT: Injection Timing

PPRR: Peak Pressure Rise Rate

CD: Combustion Duration

ID: Ignition Delay

PP: Peak Pressure

HRR: Heat Release Rate

CO: Carbon Monoxide

HC: Hydrocarbon

NO_X: Nitrogen Oxides

RSME: Rubber Seed Oil Methyl Ester

HSU: Hartridge Smoke Unit

1. INTRODUCTION

The energy demand is on the rise due to the inadequate supply of nonrenewable fuels and the dangers of engine exhaust gas, emphasis has been placed on the usage of sustainable energy and alternative energy sources. To address these demands, the usage of renewable diesel fuels such as biodiesel and biofuels has increased. As a result, new ways of increasing the efficiency of the transportation engine and power generation must be introduced. Renewable energy sources have significant advantages over fossil fuels in providing brief energy.[1]. Diesel engines are constantly being improved to comply with ever-stricter emission regulations. Internal and external interventions are the two types of efforts that are being made to meet the statutory limits. Internal actions affect pollutant emissions from engines directly while external measures relate to exhaust gas after treatment. The nozzle design has a big impact on combustion and, as a result, on pollution and fuel consumption. As a result, they're crucial for engine performance and in-cylinder pollution control strategies. Nozzle characteristics, such as the number of holes, diameters of holes, cone angle, and hydraulic flow rate, are all within the limits of engine production optimization [2]. Nozzles are often used in many uses in engineering, primarily to produce sprays and jets. The attention of most research laboratory studies is on designing nozzles that produce a steady distribution with little turbulence strength at the end of the nozzle. Higher turbulence intensity can be ideal in mixing applications at the exit. [3].

1.1. Constructional Features of Fuel Injector Nozzle

When a diesel injector is opened, the nozzles open, and spray fuel is injected into the chamber or chamber for pre-combustion. The injector nozzles, one for each cylinder, are threaded or fixed into the cylinder head and are replaceable as a unit. The injector nozzle's tip has many holes so that diesel fuel can be atomized and sprayed into the cylinder. The diesel injector nozzle is made up of many components and the construction of the injector nozzle is shown in Fig. 1

Heat shield - It is the injector nozzle's outer casing that can have outside threads in the cylinder head for sealing.

Injector body–An injector needle valve and spring are housed in this portion of the nozzle, which threads through the exterior heat shield.

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ISSN 2348 - 7550

Diesel injector needle valve - When the injector body is closed, this precision-machined valve and the needle's tip lock against it. The combustion chamber is sprayed with diesel fuel when the valve is opened. On engines with computer-controlled injection, a computer-controlled solenoid controls this passage.

Injector pressure chamber- A machined cavity serves as the pressure chamber in the vicinity of the injector tip needle in the injector shell. Fuel is forced into this chamber by the injection pump pressure, which opens the needle valve.[4]

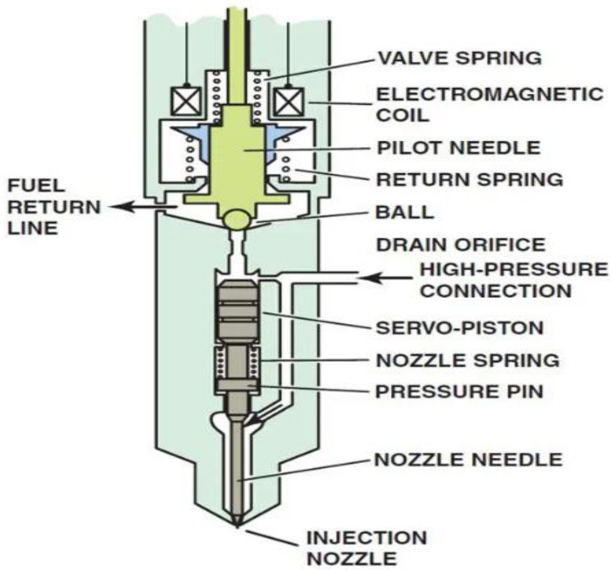

Figure 1 - Construction of fuel Injector [27]

2. RESULT AND DISCUSSION

2.1. Effect of Hole Diameter on Performance Characteristics

There are different hole diameters of size 0.20mm and 0.31mm used having 3 holes with diesel fuel. For a small hole size of 0.20 mm nozzle hole diameter (NHD), Due to better evaporation and atomization, BTE slightly increased. With 0.31 mm of greater NHD, the BTE was reduced as air-fuel was not mixed appropriately and the fuel droplet was increased. In the case of an NHD of 0.20 mm, due to high mixing rates of air-fuel, the BSFC decreases significantly. In higher NHD, due to poor atomization, the BSFC increases [5]. R Rajaraman studied the effect of varying NHD about the injector, including (5-hole x D 0.28 mm), (4 hole x D 0.28 mm), (3 hole x D 0.28 mm), (5 hole x D 0.30 mm), (4 hole x D 0.30 mm) and (3 hole x D 0.30 mm). The BSFC is greatly reduced for the case of a 0.28 mm NHD due to higher rates of air-fuel mixing. Because of de-prived atomization, the BSFC is rising with greater NHD [6]. Shehata researched the impact of varying nozzle hole diameters, it was found that the increase in NHD increases the BSFC because the average mean size diameter and the quantity of fuel injected have both increased. It has been noted that ignition delays are shorter the smaller the nozzle diameter. The shorter combustion owing to correct mixing is also demonstrated by the lower nozzle diameter. As a result, time and heat losses are reduced, resulting in greater thermal performance and lesser fuel consumption. BTE increases with the reduction of NHD because of, an increase in brake power and combustion efficiency Simultaneously, there is a decrease in the quantity of injected fuel [7]. A Tumbal studied the effect of NHD, he observed that the orifice size of the HOME introduced with a 4-hole injector increased from 0.2 to 0.3 mm. Proper air-fuel mixing occurs within the combustion chamber as the hole size is reduced from 0.3mm to 0.2 mm, resulting in better combustion and thus increased BTE [8]. R. Swamy studied the effect of different hole diameters for the 5-hole injector nozzle, he found that the BTE reduced from NHD 0.3mm to 0.2 mm for the diesel fuel with a 5-hole injector. When reducing the size of the holes, the combustion chamber experiences increased efficiency in mixing air and fuel, leading to improved Brake Thermal Efficiency (BTE) [9]. V. Yaliwal investigating the effect of nozzle diameter found in comparison to 0.2 mm and 0.3 mm injector nozzle operation, honge oil methyl ester (HOME)-producer gas using 0.25 mm hole size operation showed improved thermal efficiency. The chances for impingement of pistons and walls, smaller droplets with enough HOME penetration, and dispersion of spray in a gas mixture of the compressed air-producer can be minimized.

2.2 Effect of Number of Holes on Performance Characteristics -

The influence of BTE is investigated at various IOP and nozzle holes (3, 4, and 5), The highest BTE was observed at a pressure of 230 bar for the 4-hole nozzle of all the IOPs tested. The variation in the hole number on the injector does not affect the Brake Specific Fuel Consumption (BSFC), but it does increase the air-fuel mixing rate. With more holes on the injector, heat release rates rise during the mixing-controlled combustion phase as well as premixed combustion [10]. Mekonena studies the effect of POME for various injection hole numbers, the results show that with increasing injector nozzle hole number, the BSFC decreased, from 3 to 4 IJNHNs, at 200 bar IP. The higher quantity of holes has improved fuel atomization and increased the tiny biodiesel droplets injected. BSFC, on the other hand, increased with a further increase to IJNHN 5, there are fewer holes in IJNHN 3, which influences atomization and so increases BSFC, and more droplets of fuel in IJNHN 5 generates a shorter ignition delay time, which increases the possibility of non-homogeneous mixing and therefore increases BSFC. The BSFC was increased by 1.6% with 5 IJNHN. At IJNHN 4 with 212 bar fuel injection pressure (IP), the test fuel exhibited an average percentage decrease of 10.6% in BSFC compared to IJNHN 4 using 200 bar fuel IP [11]. B. Sudarshan investigates the performance of tire pyrolysis oil with a change in nozzle geometry, he found that BTE is higher for a 5-hole nozzle as compared to a 3 and 4-hole nozzle. The BTE for 3, 4, and 5hole nozzle are 26.9, 27.25%, and 27.32% respectively at 80% load. It is seen that BTE is high with a 5-hole injector nozzle. As the number of holes increases, greater BTE output has been seen [12]. R. Thirunavukkarasu experimentally examined the nozzle hole number effect with diesel engines, He observed that the performance of the nozzle hole has a significant impact on spray penetration. It was observed that when the load was 9 kg, the brake thermal efficiency increased. The reason behind this was a rise in nozzle hole numbers, which caused an increase in the air-fuel mixture. It can be seen, that as the hole numbers increases, the BTE rises, and The increase in the number of nozzle holes directly correlates with the increase in thermal efficiency. Due to a rise in air-fuel intermixture, fuel evaporation, and enhanced combustion due to an increase in nozzle holes. As a result, the ITE rises with a variety of holes. It may have been observed that the SFC for the 5-hole nozzle is lower than it is for the 1-hole nozzle and the 4-hole nozzle [13]. J. Patil studied the effect of rice bran oil biodiesel, it has been noticed that ROME runs at a lower BTE than diesel over the whole power range. In comparison to 3 and 5-hole injectors, diesel engines with 4-hole injectors have greater thermal efficiency. It might be a result of enhanced fuel mixture mixing and combustion. One notable finding is that the 4-hole nozzle has greater spray dispersion and fuel penetration than the 3 and 5-hole nozzles. The BTE for ROME operation with three, four, and five-hole injectors was determined to be 14.2, 16.1, and 18.2%, respectively When studying the impact of nozzle holes, R. Sharma found that the shape of the nozzle holes significantly affected the size and penetration of the spray droplets. The investigation revealed that larger nozzle hole sizes led to improved thermal efficiency due to enhanced air-fuel mixing, fuel vaporization, combustion, and heat release rates. As the number of holes increased, the BTE also increased. Consequently, using a smaller-sized nozzle hole at a given injection pressure resulted in superior performance, as it required increased injection pressure for total combustion, lower fuel consumption, and ultimately better BSF [15]. S. Wategave conducted a research study to assess the impact of different nozzle configurations (3, 4, and 5 holes) when utilizing non-edible oil methyl esters. The findings revealed that the highest Brake Thermal Efficiency (BTE) was attained using a four-hole nozzle setup, with each orifice having a diameter of 0.3mm. The improved BTE in this configuration can be attributed to enhanced atomization, favorable spray characteristics, and superior air mixing at higher injection pressures, which ultimately led to more efficient combustion. Consequently, the four-hole nozzle arrangement demonstrated the most optimal performance in the study [16]. M. Shivashimpi conducted a study to explore the impact of the hole numbers on brake thermal efficiency. The results demonstrated a direct link between the injector hole numbers and enhanced brake thermal efficiency. This relationship can be ascribed to better fuel mixing and more effective combustion made possible by the injector design's greater number of holes [17]. Investigating the impact of injector nozzle hole numbers on performance characteristics, V. Yaliwal's study revealed interesting results. In the view of diesel-producer gas operation, a BTE was found to be greater with a 3-hole nozzle, while for HOME-producer gas operation, the 4-hole nozzle exhibited the highest BTE. The observed result can be credited to the 4-hole nozzle's capability to achieve enhanced atomization, better spray dispersion, and precise fuel penetration when compared to both 3 and 5-hole nozzles. However, the 5-hole injector showed decreased BTE due to incomplete combustion resulting from the increased mass flow rate of liquid fuel directed into the combustion chamber. As a consequence, larger droplets were formed, which resulted in reduced liquid droplet momentum and injection velocity, thereby adversely affecting the combustion process [18]. S. Khandal conducted a study on the impact of HOME using different nozzle hole numbers. The test findings showed that increasing the number of holes from 3 to 4 resulted in a significant improvement in BTE. This improvement can be attributed to the larger size of injected biodiesel droplets at identical injection pressure.

As a consequence of the increased number of holes, the injected fuel (HOME) was better mixed with the surrounding air, resulting in an efficient fuel combustion process when utilizing the 4-hole injector [19]. N. Reddy conducted a study to explore The influence of nozzle geometry on engine performance using CAOME. The experimental findings indicate that utilizing a 5-hole nozzle leads to significantly higher thermal efficiency compared to using 3-hole and 4-hole nozzles. This improvement can be attributed to the enhanced air-fuel mixing proportion achieved with the 5-hole nozzle configuration [20]. M. Shivashimpi researched to analyze the impact of CRDI nozzle hole configuration on Brake Thermal Efficiency (BTE). A comparison between 6 and 7-hole injectors revealed that the 7-hole injectors give higher BTE for both diesel and POME fuels. The lower BTE observed with the 6-hole injector can be attributed to its higher penetration distance, as a result, there is more wall impingement and a larger mass flow rate per injector hole. In contrast, the 7-hole injector exhibited better BTE for diesel and POME fuels, as it allowed more fuel to impinge from the injector and greater pressure participation in the combustion process, and improved injection timing [24]. S. Narayanan studied the influence of kapok oil methyl ester and observed that an increase in IJNHN led to improved BTE. The increased hole number changed the injection angle, resulting in greater air-fuel mixing and, as a result, increased engine thermal efficiency. Additionally, with the rise in IJNHN, BSFC decreased, indicating higher efficiency in converting the fuel's chemical energy to brake power. This improved efficiency is due to improved air-fuel mixing under certain conditions [21].

2.3 Effect of Hole Diameter on Emission Characteristics

A 0.20 mm NHD aperture with diesel fuel significantly reduces CO emissions by improving atomization and vaporization. Lowering NHD enhances fuel efficiency, minimizing unburned hydrocarbons. Proper combustion, facilitated by reduced orifice, reduces HC emissions. However, 0.31 mm NHD increases HC due to inadequate atomization. NOX generation is influenced by fuel quality, oxygen content, cetane number, injection pressure, and atomization. Elevated NHD raises NOX emissions due to higher combustion chamber temperature while lowering NHD decreases NOX by reducing temperature despite incomplete atomization. Effective gasification and atomization at 0.20 mm NHD decrease smoke opacity, contrasting with increased opacity in larger orifice NHD due to inadequate atomization [5]. R. Rajaraman asserts that CO emissions result from incomplete combustion in a rich air-fuel mix. The 0.28 mm 4-hole NHD reduces CO emissions significantly with diesel and RSME, enhancing fuel vaporization and atomization. Larger NHD increases CO due to inadequate vaporization. Reducing NHD improves atomization, and efficiency, and lowers CO emissions. For 0.30 mm NHD, HC emissions rise due to inadequate atomization. NOx increases with 0.28 NHD and exhaust temperature. Increasing NHD improves spray characteristics and lowers NOx due to a cooler combustion chamber, evident in 0.30 mm 3-hole NHD [6]. M. Shehata's study on nozzle hole diameter impact on emissions shows increased diameter raises HC concentration due to larger droplets. Reducing diameter enhances atomization, shortening spray penetration and reducing HC emissions. A 0.25mm nozzle yields lower pressure, slower injection, and better fuel distribution, but also causes longer igniting delay and increased NOx. Larger nozzle diameters reduce CO concentration, improving fuel/air mixing and atomization, resulting in elevated levels of HC, CO, exhaust smoke, and decreased NOx compared to larger nozzles [7]. Reducing the orifice size from 0.3 to 0.2 mm in a 4-hole biodiesel injector, as studied by A. Tumbal, resulted in decreased HC and CO emissions due to reduced fuel impingement on the chamber walls. Conversely, larger holes led to greater HC and CO emissions, while NOx emissions decreased with larger holes, possibly due to improved combustion conditions and increased heat during premixed combustion [8]. R. Swamy's research highlights that reduced injector hole sizes enhance air-fuel mixing, improving combustion and reducing smoke opacity. Smaller holes result in lower CO and HC emissions due to reduced wall impingement. Conversely, larger holes accumulate fuel on chamber walls, increasing HC and CO emissions. Varied hole sizes also influence NOx emissions, with larger holes causing higher NOx due to improved combustion conditions and increased heat during premixed combustion. Smaller holes lead to lower NOx emissions, attributed to submissive combustion in the engine cylinder and lower heat during premixed combustion, resulting in a decrease in exhaust gas temperature. [9]. V. Yaliwal's study on nozzle diameter impact reveals that using a 0.25 mm diameter for HOME and producer gas results in 13% and 4.5% less smoke compared to 0.3 and 0.2 mm. Improved air-fuel mixing from compressed air and producer gas spray penetration reduces smoke, while a 0.25 mm hole size decreases HC and CO emissions. This is attributed to enhanced premixed combustion and a closer time of combustion (TDC). However, NOx levels increase by 9.1% and 22.5% compared to 0.2 and 0.3 mm holes, respectively, indicating more efficient combustion during premixed combustion. Overall, increasing nozzle diameter reduces NOx emissions in HOME-producer gas dual fuel systems. [18]. V. Kumbhar's study reveals the influence of nozzle hole size changes on HC and CO emissions across various diameters. Smaller nozzles reduce wall impingement, resulting in decreased HC and CO emissions. Larger nozzle diameters lead to inefficient combustion, elevated particle size, and increased HC and CO emissions. While smaller nozzles enhance atomization and raise cylinder gas temperature, larger ones lower overall in-cylinder temperature but achieve lower NOx emissions. [22].

2.4 Effect of Number of Holes on Emission Characteristics

Higher NOx levels are associated with a greater number of holes in biodiesels. The four-hole injector provides a greater mixture of air and fuel, leading to greater premixed combustion and higher NOx emissions. The IJNHN increased the CO emissions from the original 3 to 4. The CO decrease can be due to the additional effective use of the POME fuel with more nozzle holes. However, due to an increase in fuel inputs and excessive combustion caused by an increase in CO emissions to IJNHN5 [10]. At a 9kg load, R. Thirunavukkarasu noted reduced NOx emissions in a single-hole nozzle due to a smaller combustion portion and incomplete atomization. More nozzle holes increased NOx emissions, while four and five-hole nozzles led to greater premixed combustion and higher NOx emissions. CO2 emissions rose with nozzle holes, reflecting full combustion behavior. CO emissions decreased with load increase, and improved nozzle holes enhanced CO emission. HC emissions were minimal in a single-hole nozzle but decreased with 9kg loading due to enhanced atomization and proper combustion. [13]. according to S. Dong, the number of nozzle holes affects emissions, due to the lower combustion temperature, engine-out NOx emissions of dual-fuel combustion were reduced with fewer nozzle holes, while soot emissions increased somewhat while staying low. The number of nozzle holes was reduced, which resulted in a small increase in HC and CO emissions [23]. In J. Patil's investigation of Rice bran oil methyl ester (ROME), he found higher smoke opacity compared to diesel, attributed to ROME's lower calorific value, increased viscosity affecting spraying pattern, and denser molecular structure of fatty acids. ROME produced elevated HC and CO emissions compared to diesel, indicating incomplete combustion. The number of injector holes influenced emissions, with 4-hole injectors showing reduced HC and CO levels for ROME. NOx values were lower with 3 and 5-hole injectors, suggesting incomplete combustion with 4-hole injectors. Increasing hole number and size improved mixture preparation, lowering HC and CO, but raised NOx with higher combustion temperatures. [14]. R. Sharma investigated the impact of 3 and 5-hole injectors on DI engines, revealing that increased holes led to higher NOx emissions. The 5-hole injector's improved air-fuel mixing heightened premixed combustion, elevating NOx emissions. Enlarging the nozzle hole within limits decreased CO emissions. Enhanced atomization from 5-hole injectors reduced CO and HC emissions, with shorter igniting delays. Smoke opacity correlated with HC emissions, and increasing opacity linked to reduced nozzle hole and IP. [15]. A considerable decrease in HC emission is seen for the four-hole nozzle geometry for biodiesel due to better combustion, according to S. Wategave's investigation into the impact of hole density. Improved atomization will lead to a shorter ignition delay Four-hole nozzle geometry was identified to have lower HC emissions, followed by three-hole and five-hole nozzle geometries, in that order. This means that all tested biodiesels have enhanced atomization and adequate combustion, which is why there are fewer unburnt HCs with the four-hole nozzle. The same pattern is seen for CO emissions as well; the four-hole injector exhibits fewer CO emissions due to enhanced atomization and proper combustion of all biodiesels. Increased holes were associated with higher NOx emissions from all biodiesels. The 4-hole injector enhances the air-fuel mixture, which results in more premixed combustion and higher NOx emissions [16]. Shivshimpi investigated how the count of nozzle holes affected emission characteristics and discovered that the more nozzle holes there were in an engine running on Palm oil methyl ester (POME), the less smoke there was since there was more POME fuel being involved at greater injection pressure. For the 3, 4, and 5 holes in the CI engine, the POME smoke level at 240 bar, the quantities were 49 HSU, 47 HSU, and 46 HSU. Because of the abundant air and fuel mixer, the 5-hole nozzle shape produced less smoke than the other two. By using more nozzle holes while using POME biodiesel in the engine, there was a tendency toward lesser emissions of HC and CO. Because of enhanced combustion inside an engine powered by POME fuel, which results in fewer emissions of both HC and CO, the lowest emissions were recorded with a 5-hole nozzle. The number of injector holes typically increased for POME operation in the engine as a result of proper combustion. Due to the increased peak temperature in an engine using POME with 5 holes, a greater NOx is produced, which causes a decrease in POME viscosity [17]. R. Swamy investigated how nozzle geometry affects emissions and discovered that increasing the constant orifice of the injector nozzle (0.3 mm) resulted in more holes that had an impact on the degrees of smoke opacity. Reduced smoke was seen as a result of the 5-hole injector's improved air-fuel mixture combinations. Other injector holes (3 and 4) that improperly mixed fuel and air led to inefficient combustion, which raised smoke levels. Additionally, due to improved combustion, a considerable decrease in HC emission is seen with a 5-hole nozzle shape. The five-hole nozzle is discovered to have lower HC emissions than the three and four-hole nozzle geometries, respectively. Similar to HC emissions, there were observed tendencies for CO emissions as well, with 5-hole injectors producing less CO than 3 and 4-hole injectors. Due to faster combustion and higher cycle temperatures, increased injector hole count results in higher NOx emissions [9]. with various injector nozzle designs, V. Yaliwal examined the emission differences between diesel-producer gas and HOME-producer gas operation. In comparison to operation on two fuels with 4-hole and 5-hole injectors, diesel-producer gas operating with a 3-hole injector produced reduced smoke levels. It might be a result of the three-hole injector's improved oxidation and comparative superior fuel combination mixing. A four-hole nozzle produces reduced CO and HC emissions when used with producer gas and biodiesel. Inadequate combustion and the CO presence in the product gas may be to blame for this. This tendency is also caused by reduced combustion temperatures, pressures, and oxygen levels while the HOME-producer gas is being burned. Increased NOx levels in the exhaust were caused by HOME-producer gas usage with a four-hole injector nozzle. It might be the result of somewhat better fuel atomization and mixing of air and fuel, which results in an increase in temperature, heat release rate, and peak combustion pressure [18]. S. Khandal investigated the impact of transitioning from 3 to 4 holes on smoke density. A 4-hole injector enhanced combustion by improving liquid fuel-air mixing in the chamber, reducing HC emissions. Increasing holes from 3 to 4 lowered CO emissions due to higher heat release rate (HRR) accumulation. However, NOx increased, likely linked to elevated peak temperature and cylinder temperature during premixed combustion. [19]. With the aid of CAOME, N Reddy examined the impact of nozzle geometry. Because of the production of a standardized mixture of air and fuel, it has been shown that adding more holes to nozzles reduces smoke emissions. In addition, adding more holes causes a decline in HC and CO emissions, but growth in NOx emissions, with 5-hole injectors producing more of them [20]. S. Narayanan demonstrates that as the number of holes rises, CO emission falls. This is because an increase in IJNHN ensures that the air and fuel will mix better, improving the likelihood of full combustion. Additionally, with the addition of more nozzle holes, the NOx emission decreases as a result of a decrease in wall impingement caused by the rise in IJNHN. As the hole numbers grow, HC and smoke emissions exhibit a decreasing trend [21]. In a study by S. Lahane utilizing a diesel biodiesel blend, it was discovered that as the number of holes grew, smoke emissions reduced. The patterns for CO and HC emissions are also similar. While NOx emissions rise as the number of holes owing to more premixed combustion increases [25].

3. Conclusion:

The review highlighted the important role injector nozzle shape plays in diesel engines fuel atomization, spray characteristics, combustion process, and emissions.

- The small hole diameter shows slightly increased BTE due to better evaporation and atomization and decreased BSFC because of the rapid mixing rate of air-fuel so, a small hole diameter shows better performance as compared to a large hole diameter nozzle. It is observed that the BTE is increasing as the hole number increases, because of a rise in the air-fuel mixture, fuel evaporation, and enhanced combustion.

- The increased nozzle holes with smaller diameters give better BSFC due to the increased air-fuel mixture which completes the combustion.
- The smaller nozzle hole diameter leads to a slower rate of heat release due to slow burning in the premixed phase. Also, there is less delay when the nozzle hole diameter is smaller. because the combustion chamber's gas temperature has risen. Because of the lower combustion duration, the heat release rate also increases which is caused by a rise in the number of holes.
- Reducing the nozzle hole diameter **CO** emission is also reduced with the aid of a fuel combination that burns more efficiently. It improves the dispersion of fuel vaporization and improves fuel atomization for smaller nozzle hole diameters.
- Because a smaller diameter nozzle has less wall impingement than a larger nozzle, HC emissions are also reduced when nozzle hole diameter is reduced. Larger dimensions resulted in an increase in HC emissions due to a harsher reaction brought on by a lower combustion chamber temperature brought on by inadequate atomization and evaporation.
- As the nozzle hole diameter grows, NOx emission is reduced due to a lower combustion chamber temperature as a result of the exhaust gas temperature rising as a result of the nozzle hole diameter increase. The improved combustion conditions within the engine cylinder and greater heat generated during premixed combustion may be the cause of the lower NOX with the larger holes. Due to quicker combustion, greater temperatures reached in the cycle, and higher premixed combustion, NOx emissions rise along with the hole number, which causes a rise in combustion temperature.
- Smoke opacity increases with increasing nozzle hole diameter due to atomization, and this is inappropriate for the combustion chamber.
- Finally, as the number of holes was reduced emissions were slightly increased because smaller hole sizes may enhance air use will facilitate effective mixture preparation.

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