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SPRAY CHARACTERISTICS OF A ROTATING FUEL INJECTOR IN A DIRECT INJECTION DIESEL ENGINE

Summary

Diesel engines are used extensively due to their higher performance, better fuel efficiency and low maintenance. Their major drawback is that they emit considerably higher NO_x and particulate matter. The fuel injection parameters and spray characteristics have a major role in combustion and emission formation. A conventional injector produces spray mainly along the axial direction, which results in the poor mixing of air and fuel. This study aims to overcome this poor mixing issue by developing a rotating injector by functionally modifying the existing three-orifice injector to enable injector rotation. A modified fuel injection system is developed to accommodate a rotating fuel injector with a sleeve. The rotating injector provides an angular momentum to the fuel, establishing a co-swirl motion to the fuel and modifying the spray characteristics. The spray images were observed using a high-resolution camera. A comparison and analysis of the spray characteristics were carried out using image processing techniques. A detailed comparison was made of a conventional injection system with two-, three- and five-orifice injectors, a Common Rail Direct Injection system, and a rotating injection system. OpenCV Python was used for spray edge detection, the colour thresholding of images, determining the spray angle, and cross-sectional fuel dispersion area calculations. The overall spray cone angle is greater for the Rotational Direct Injection system. The rotating injection spray was found to disperse over a wider angle, with an almost negligible air gap and over a greater cross-sectional area. The rotation of the injector reduces the local high concentration of the fuel, and the structure of the highly homogeneous fuel-air mixture.

Key words: *rotating injector, dispersion, co-swirl, air gap, spray cone angle*

1. Introduction

Diesel engines are energy efficient. They are an indispensable power source for several applications thanks to several inherent advantages such as higher brake thermal efficiency, their cost effectiveness, and higher compression ratio [1]. However, they have one major drawback: the amount of exhaust emissions of NO_x and particulate matter is greater for diesel engines than gasoline engines [1,2]. The major concern for almost every government and non-government agency is that the effect of air pollution is increasing at a rapid rate, owing to the huge increase in the number of vehicles throughout the world.

1.1 Air pollution and emissions

There are varieties of sources of air pollution, both anthropogenic and of natural origin [3]. Six common air pollutants referred to as "criteria" pollutants by environmental protection agencies are CO_2, lead, NO_x, ozone, particulate matter, and sulphur dioxide. Particulate matter, nitrogen dioxide, and ground-level ozone are generally known as the three pollutants that most significantly affect human health [4]. To improve air quality standards, regulations on emissions from mobile sources have become stringent all over the world over the last decade. The emission norms that are of prime importance around the world include the United States emission standards, European emission standards, and other standards based on specific country needs [5]. According to various reports, exhaust emissions from engines have undesirable effects on human health and the atmosphere [6].

1.2 Diesel engine emissions

The combustion of the air-fuel mixture in diesel engines has a significant effect on the concentration of NO_x and particulate matter (PM) [1,7-9]. NO_x and PM are traded against each other in many aspects of engine design [1]. The various factors that affect the formation of NO_x include the temperature of the burnt gas, the residence time, the amount of excess oxygen, the equilibrium concentrations of nitrogen and oxygen, and turbulence [10]. The formation of PM is very much influenced by the fuel-air ratio and the temperature. Various methods and techniques have been developed to reduce the emissions of NO_x and PM, such as early in-cylinder injection, port injection, exhaust gas recirculation (EGR), and homogeneous charge compression ignition (HCCI). Aftertreatment devices are used to reduce PM [11]. By lowering the local rich concentration of the mixture and by bringing down the peak combustion temperature, NO_x emissions can be reduced [12,13]. Low-temperature combustion (LTC) is an advanced combustion technology that increases an engine's thermal efficiency and even provides low emissions of NO_x and PM [14].The NO_x formation is higher because of the higher cylinder temperature, the longer ignition delay, and the non-homogenous nature of the fuel mixture [15-17]. All blends of biodiesel had lower CO emissions compared with diesel, which indicates better combustion due to the presence of inherent oxygen [18].

1.3 Fuel injection systems

The performance and emission formation in diesel engines primarily depends on the internal air-fuel mixture formation, which relies on an efficient fuel injection system [19]. Fuel injection systems are generally classified into direct injection (DI) and indirect injection (IDI) systems. Over the years, various injection systems and methods have been developed and are being used. Air blast injection is one of the earliest injection methods, where the fuel is blown into the cylinder by a blast of air. It suffered from being heavy and hence became unusable for road vehicles. The throttle body injection system is similar to carburetion, but it did not work with turbocharging. Direct unit injectors were developed during the 1950s and were used to inject fuel into the combustion chamber and they became common in the commercial diesel engine market. Certain unit injectors at full load can inject fuel at about 2000 bar. The CRDI system is a mixture of both a direct injection and multi-port injection system. The CRDI system uses a common rail to contain high pressure and inject the high pressurized fuel into the cylinders at a pressure of about 1500 bar. All these systems have a larger air gap between each spray and less distribution of fuel in the combustion chamber [20,21]. This flexibility, coupled with the possibility of cutting the injection into three to seven phases, allows more control over the combustion and exhaust after treatment processes, as they mostly depend on the air-fuel mixing and burning during and after the injection event [22].

Other injection techniques include distributor types and electronic controlling of fuel injection. Several nozzles were also developed over the years, such as the Pintle nozzle, the Pintaux nozzle, and solo-hole and multi-hole nozzles. Solo hole nozzles cannot disperse fuel over a wider angle, while a multi-hole nozzle requires high pressure when compared to single-hole nozzles [3]. In this work, we developed a new injection system which sprays without an air gap between the spray, with a high dispersion and a larger cone angle. The Bosch type injection meter was considered to indicate the exact injection rate, but the results show that the cause, the injector nozzle flow rate, and the effect, the subsequent pressure variation, are different in every test case. This is mainly due to the bulk modulus and damping of the system, including fuel compressibility, pipe deformation, etc. If the curves are closely examined, it can be concluded that neither the dynamics nor the quasi-steady state values match the nozzle flow rate [23].

1.4 Atomization and spray characterization

A liquid fuel jet disintegrates by the kinetic energy of liquid, by experience to high-velocity air, or by the mechanical energy applied outwardly through a rotary or vibratory device. The purpose of atomisation is to amplify the specific surface area of the fuel to attain high rates of mixing and evaporation. In a laminar jet, the growth of small turbulence leads to the breakup of the jet into drops with a diameter almost twice that of the jet, [24] whereas a turbulent jet can break up without the function of any external force.

The main function of atomizers is not only to break the liquid into drops, but also to disperse the drops uniformly and symmetrically in the surrounding gaseous medium. The concept of any given type of atomizer depends on the size and geometry of the atomizer, the physical properties of the detached phase such as the density, viscosity and surface tension of the fuel, and the physical properties of the continuous phase. The turbulence in liquid, the cavitation in the nozzle, and the aerodynamic interaction with the nearby air contribute to atomization. Various processes of atomization are proposed, such as drop breakup, jet disintegration, and liquid sheet disintegration. Numerous jet disintegration and breakup models were developed by earlier researchers based on various influencing parameter considerations [24-28]. There are three modes of jet disintegration [29]: rim disintegration, perforated-jet disintegration, and wave disintegration.

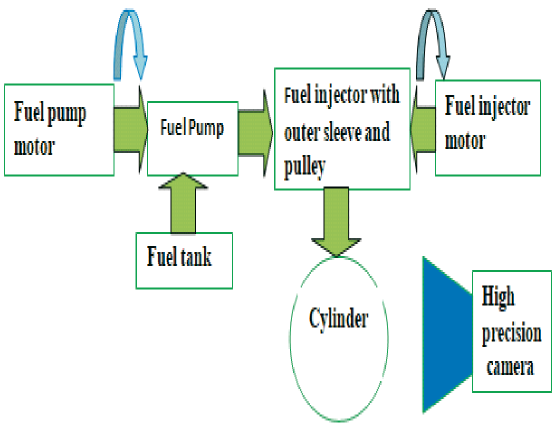
1.5 Spray properties

The combustion and emission from the diesel engine depend on the various spray & injection parameters. The atomization of fuel impacts the spray characteristics to a larger extent [30]. The effect of swirl and squish on the spray characteristics in turn affect the performance and emission of the engine [6]. Several microscopic and macroscopic qualities, including drop size distribution, velocity distribution, evaporation rate, spread or span of the spray, spray angle, penetration, drop size, velocity, and flow rate of the fuel, affect combustion and emissions formation.

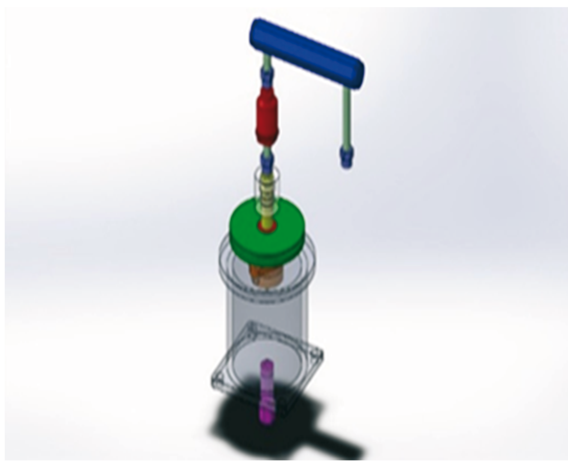
The spray edge is an illusion or imaginary line, and is defined at a point where the rate of mass flow or mass flux falls below a certain critical value. The degree of dispersion is given by the ratio of the amount of the spray to the amount of the liquid from which this spray develops. A high degree of dispersion indicates uniform distribution and a good atomization of fuel in the combustion chamber. Penetration may be defined as the maximum distance the leading edge of the spray reaches, and is governed by two opposing forces of the kinetic energy of the first jet of liquid, and the aerodynamic resistance of the nearby gas. A narrow spray has high diffusion when compared to the broad cone spray due to the influence of air resistance on the latter. A rotating injector produces shorter spray than a static one [31], resulting in reduced emissions [2]. The spray cone angle is defined as the angle between two straight lines drawn from the nozzle orifice to cut the spray edges at some particular distance from the atomizer. The spray profile can be defined by taking measurements of the spray width at more than a few axial locations. The spray cone angle is influenced by the nozzle dimensions, liquid properties, and the density of the ambient gas into which the liquid is sprayed. All existing injection systems give a narrow spray system when compared to a rotational system [31,32]. Drop size is usually characterized as the diameter of the fuel droplets, and a smaller drop size reveals good atomization of the liquid by the injector nozzle. Generally, a smaller drop size increases the evaporation rate [33]. Fine spray particles and a homogeneous mixture lead to better combustion and low emission [13]. A rotating injection system delivers a fine spray and helps to reduce NO_x emissions, and gives a marginal improvement in performance [27]. Drop size and velocity distribution are ways of converting drop level information into spray level information. The drop size and velocity distribution can be made in two sampling methods, namely spatial sampling and temporal sampling. The sprays are generally classified into solid cone sprays and hollow cone sprays, and the spray pattern is usually determined by the spray type and spray symmetricity, which are measured using both radial and circumferential pattern techniques. Various methodologies have been developed and used to analyse spray characteristics [31–34]. An appreciable reduction in HC, CO, and CO_2 emissions was observed in the three-fuel mixture concept with an increase in engine performance without raising its emissions [35] By choosing a proper combustion chamber and an intake air pipe that provides a proper value of air turbulence, the formation time of the air-fuel mixture may be reduced [36].

2. Experimental setup

A 3-hole injector was functionally modified to provide rotation to the injector, giving an angular momentum to the liquid fuel being injected to modify the spray characteristics by establishing a co-swirl motion to the fuel droplet. The experimental setup consists of a rotating injector, a sleeve to enable rotation to the injector, an optical cylinder, a fuel pump, a speed control drive unit, motors to drive the fuel pumps and to rotate the fuel injector, a fuel tank to contain the fuel, an overflow sleeve, tubes, pulleys, and belts. Fig. 1a shows the line diagram depicting the functionalities of the experimental setup, Fig.1b shows the CAD model of the overall setup, and Fig. 2 displays the overall setup with its parts.



a)



b)

Fig. 1 a) Line diagram depicting the basic functionalities of the setup. b) CAD model of the overall assembly

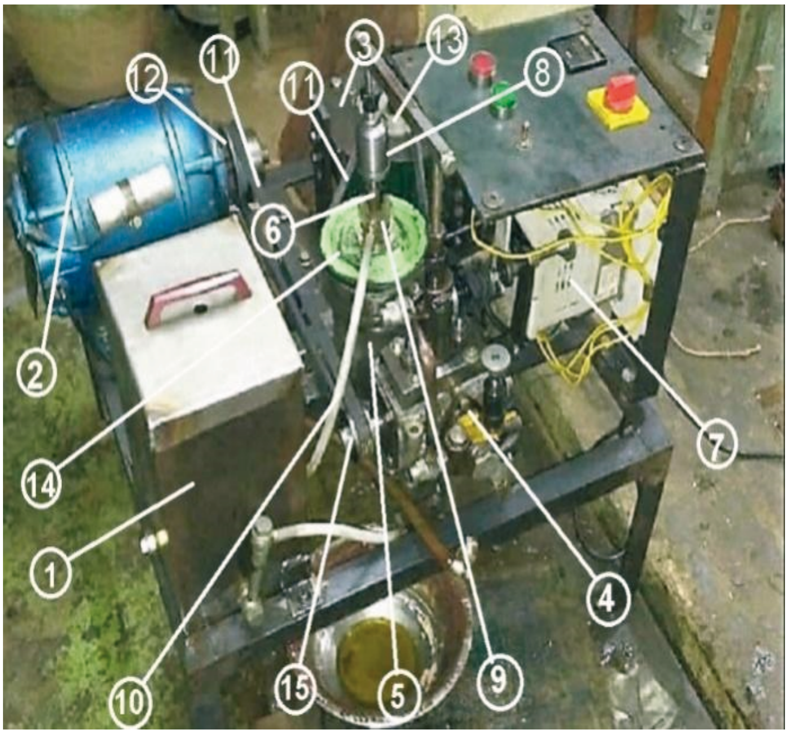


Fig. 2 Experimental Setup
1. Fuel tank; 2. Fuel pump motor; 3.Injector motor; 4. Fuel pump; 5. Optical cylinder; 6. Fuel injector; 7. Speed control drive; 8. Sleeve to enable rotation; 9. Overflow sleeve; 10. Overflow tubes; 11. Belts; 12. Fuel pump motor pulley; 13. Injector motor pulley; 14. Injector pulley; 15. Fuel pump pulley.

The diesel fuel is stored in the fuel tank and covered with a lid. The fuel is pumped and metered by a fuel pump and is delivered into the injector. The fuel pump is driven by a fuel pump motor which is connected to the fuel pump using a belt drive. The pumped diesel is delivered to the rotating injector through a high-pressure fuel rail. The rotating injector injects the required amount of fuel through the nozzle. The injector motor rotates the injector to provide a co-swirl motion to the spray of fuel being injected, the rotating speed being controlled by a speed control drive. The image of the injection spray with a rotating injector was captured using a high resolution camera and the spray characteristics were analysed.

2.1 Geometries of the nozzles

Table 1 Geometries of the nozzle

Sl. No.	Parameter	2-hole nozzle	3-hole nozzle	5-hole nozzle	CRDI nozzle
1	Injection pressure /bar	230	230	230	2200
2	Diameter of the nozzle hole /mm	0.3	0.3	0.31	0.2
3	Engine cylinder model diameter	87.5 mm			
4	Fuel used	Diesel			

Table 1 shows the geometries of the nozzle. The nozzle injection pressure 230 bar used a 2-, 3- & 5-hole nozzle and 2200 bar was used in the CRDI injector. The diameter of the nozzle hole is 0.3 mm, 0.3 mm, 0.31 mm and 0.2 mm of 2, 3, 5 & CRDI injectors, respectively. In the experimental setup, the engine cylinder diameter taken was 87.5 mm. The model of the cylinder with rail is shown in Fig.1b. Standard diesel fuel was used for this study. The rotating speed of the fuel injector was controlled using a variable frequency drive. The specification of the device is given in Table 2.

Table 2 Specification of the variable frequency drive

PARAMETERS	SPECIFICATIONS
Make	Larsen & Toubro
Model	LTVF – C10005BAA
Applicable motor	0.75 kW (HD)
Input	200-240V 1 Phase 50/60 Hz 11.0A
Output	0-INPUT V 3 Phase 0.01-400 Hz 5.0A

a) 2-hole nozzle b) 3-hole nozzle c) 5-hole nozzle d) CRDI injector e) RDI

Fig. 3 Injector used for the spray characteristics study

Figs. 3 a) to e) show the injector used for the spray characteristics study, All the fuel injectors have a different geometry, injection pressure, nozzle hole diameter, and length. All the conventional injectors are tuned to an injection pressure of 230 bar except the CRDI injector. The RDI injector was modified to achieve a 360 degree rotational motion.

2.2 Image processing methodology

The methodology used for this research work was image processing. Image processing is a technique used to obtain information from captured spray images. It is a core part of edge detection, the colour thresholding of images, determination of the spray angle, and calculation of the cross-sectional fuel dispersion area. OpenCV Python means Open Source Computer Vision. It is a famous tool for image processing tasks. The flow chart of the image processing is shown in Fig. 4 below.

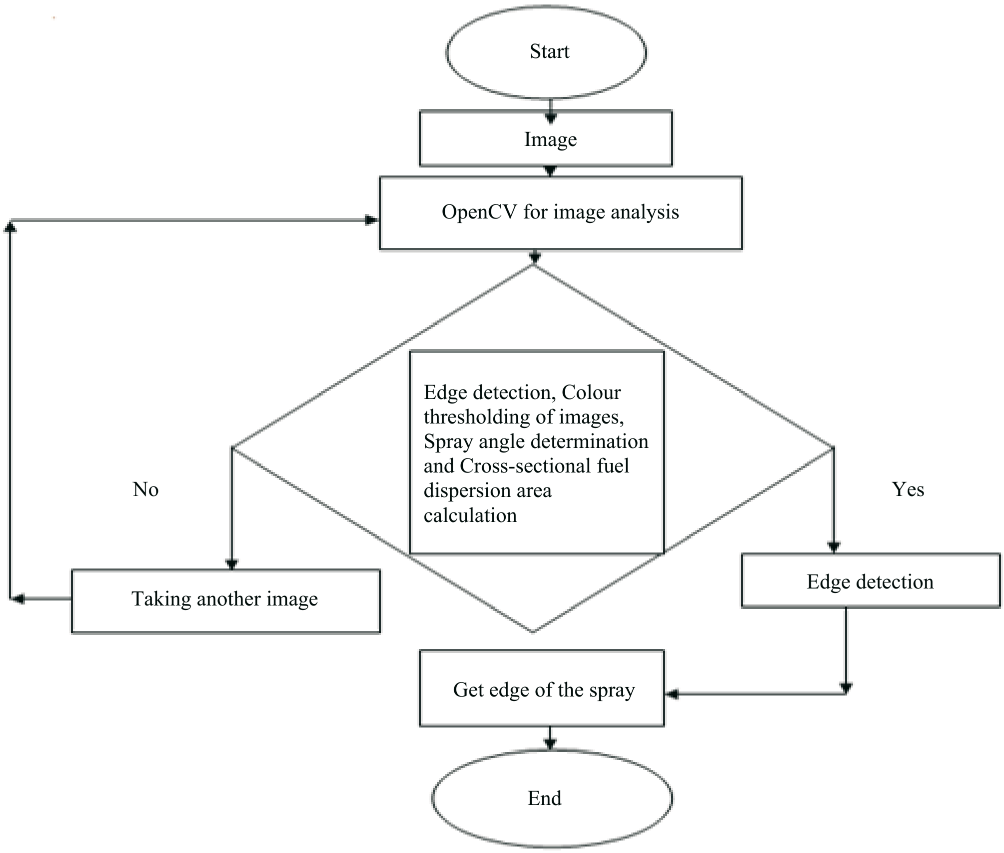


Fig. 4 Image processing flow diagram

The captured spray image is taken as an input for an analysis of edge detection, the colour thresholding of images, spray angle determination and cross-sectional fuel dispersion area calculations using OpenCV-Python. After a satisfactory result, the process ended. If a satisfactory result was not achieved, the processing was repeated until the best edge detection, colour threshold of images, spray angle determination and cross-sectional fuel dispersion area calculations were obtained. The sample coding used is given below.

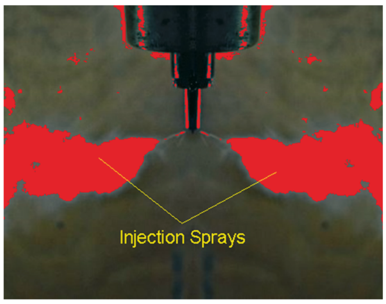
```
import cv10
# Read the original image
img = cv10.imread('test.jpg')
# Display original image
Cv10.imshow('Original', img)
Cv10.waitKey(0)
# Convert to grayscale
img_gray = cv10.cvtColour(img, cv10.COLOUR_BGR2GRAY)
# Blur the image for better edge detection
img_blur = cv10.GaussianBlur(img_gray, (4,4), 0)
# Sobel Edge Detection
sobelx = cv10.Sobel(src=img_blur, ddepth=cv10.CV_64F, dx=1, dy=0, ksize=5) #
Sobel Edge Detection on the X axis
sobely = cv10.Sobel(src=img_blur, ddepth=cv10.CV_64F, dx=0, dy=1, ksize=5) #
Sobel Edge Detection on the Y axis
sobelxy = cv10.Sobel(src=img_blur, ddepth=cv10.CV_64F, dx=1, dy=1, ksize=5) #
Combined X and Y Sobel Edge Detection
# Display Sobel Edge Detection Images
```

```
Cv10.imshow('Sobel X', sobelx)
Cv10.waitKey(0)
Cv10.imshow('Sobel Y', sobely)
Cv10.waitKey(0)
Cv10.imshow('Sobel X Y using Sobel() function', sobelxy)
Cv10.waitKey(0)
# Canny Edge Detection
edges = cv10.Canny(image=img_blur, threshold1=100, threshold2=200) # Canny Edge
Detection
# Display Canny Edge Detection Image
Cv10.imshow('Canny Edge Detection', edges)
Cv10.waitKey(0)
Cv10.destroyAllWindows()
```

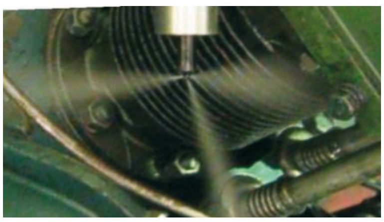
3. Results and discussion

A comparison of the sprays of fuel injection was made between a direct injection system with a 2-hole, a 3-hole and a 5-hole injector, a CRDI system with a five-hole injector, and a rotating injection system characterized by a three-hole injector. Tests were performed at an injection pressure of 230 bar for a 2-hole conventional system, a 3-hole conventional system, a 5-hole conventional injection system, an RDI system, and a rail injection pressure of 2200 bar for a CRDI system. The injector was rotated at a rotational speed of 750 rpm for the rotating direct injection system. Images captured at different orientations were taken to compare the different injection systems. The images were analysed using an open-source python package for image processing, OpenCV-Python, where the colour threshold was used to identify and detect the spray edges. Figs. 5a to 5e show the captured spray images, and Figs. 5a1 to 5e1 display the colour threshold images of different types of injection systems. The spray images of the five different types of injection are compared qualitatively and quantitatively to arrive at the results. A comparison is made of the following spray characteristics: spray cone angle, fuel spray dispersion, and spray pattern.

a) 2-hole injector

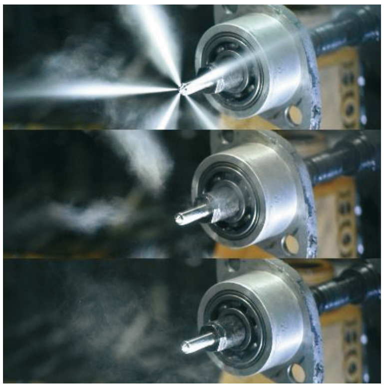


a1) 2-hole injector

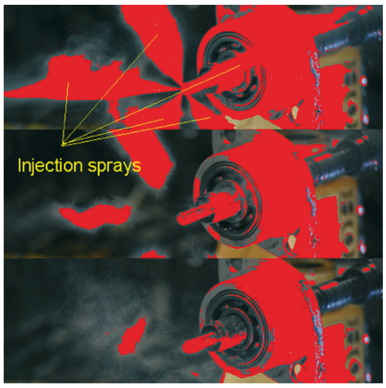


b) 3-hole injector

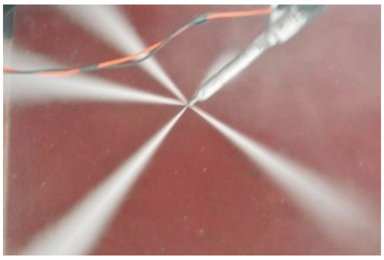
b1) 3-hole injector



c) 5-hole injector

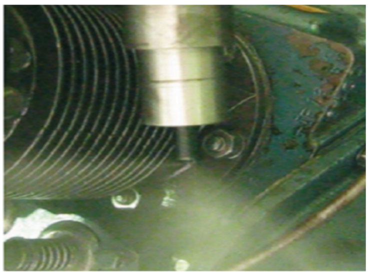


c1) 5-hole injector

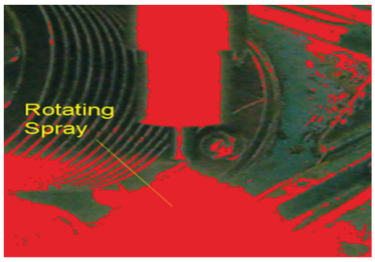


d) CRDI system

d1) CRDI system



e) Rotational injection system



e1) Rotational injection system

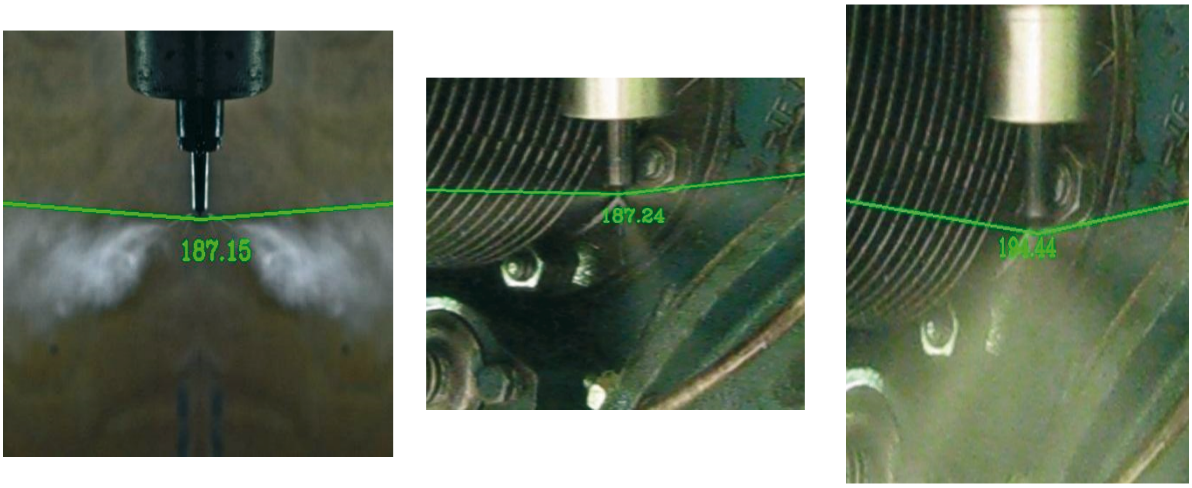
Fig. 5 Captured and colour threshold images of injection sprays: a-e) Captured images. a1-e1) Colour threshold images.

3.1 Spray cone angle

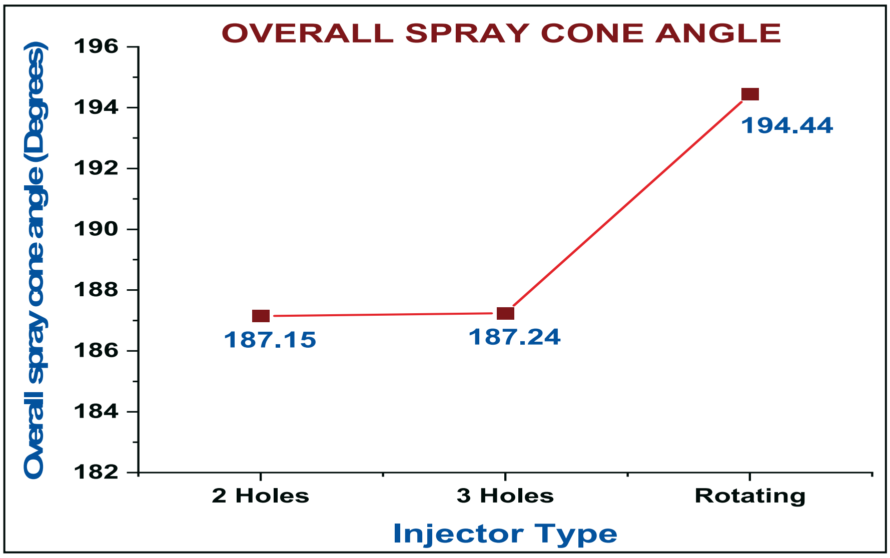
Two forms of cone angles are compared in this work: overall spray cone angle and spray jet cone angle.

3.1.1 Overall spray cone angle

The overall spray cone shape angle represents the angle made between the two extreme edges of a cone of spray developed by the fuel injection system. The overall spray cone shape angle was found and represented for 2-hole injection in Fig. 6a, 3-hole injection in Fig. 6b and rotating injection in Fig. 6c along with a graphical representation showing the trends in the difference of the overall spray cone angle among the various fuel injection systems in Fig. 6d plotted with injection types along the x-axis and the overall spray cone angle on the y-axis. The comparison reveals that the overall angle of the conventional 2-hole injection system and the 3-hole injection system are found to be nearly equal, with a variation of less than 1°. The comparison between the conventional system and the rotating system shows that the spray has been discharged over a larger cone angle in the RDI system than in a conventional type, where the difference is greater than 7°. This is due to the tangential components of velocity of the fuel drops emanating from the orifice, resulting in increased centrifugal action and improved interaction between the fuel and the air.



a) 2-hole conventional system b) 3-hole conventional system c) Rotating system

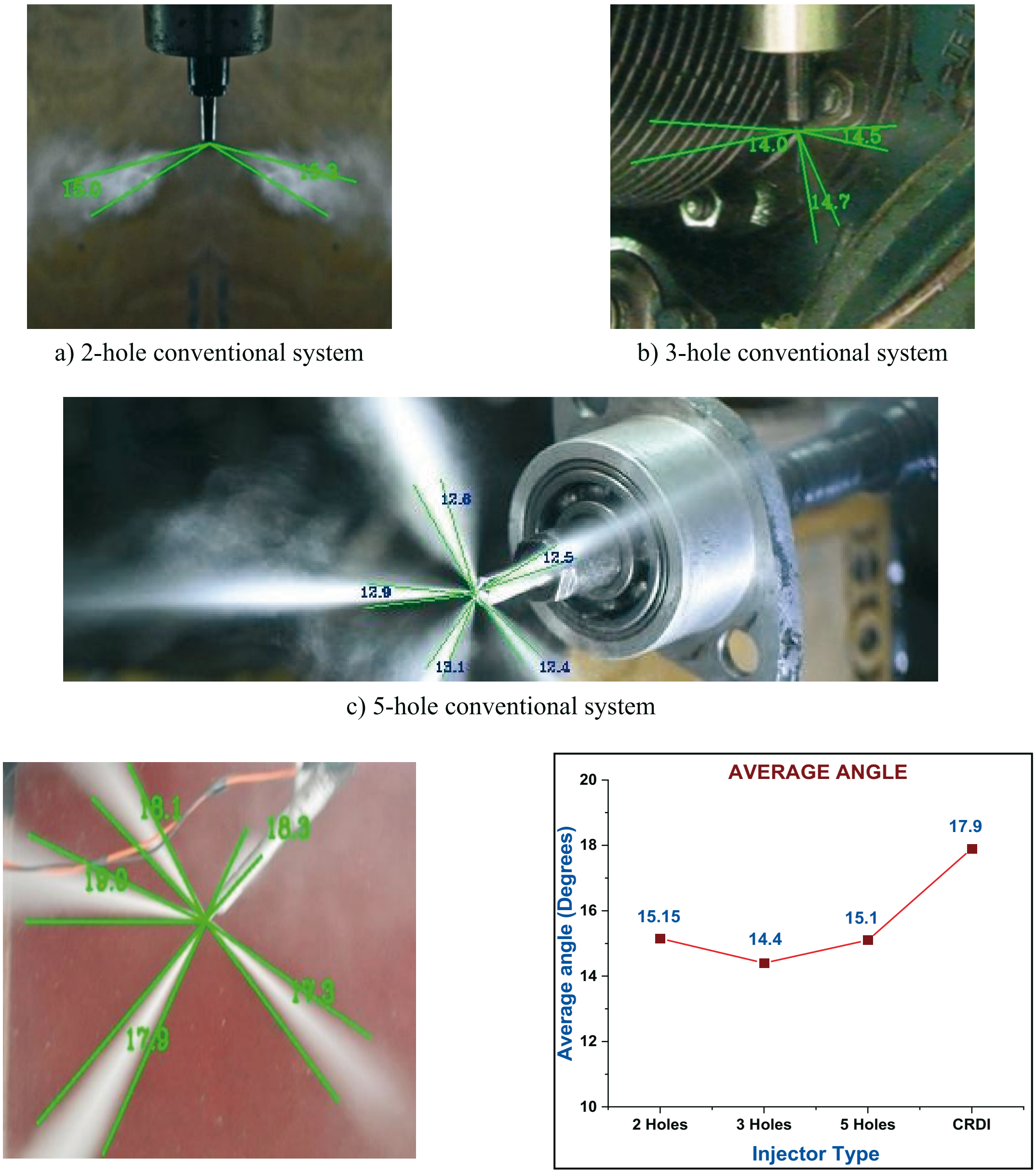


d) Comparison of overall spray cone angles

Fig. 6 Overall spray cone angles

3.1.2 Fuel spray jet cone angle

The fuel spray jet cone shape angle is the angle made by the cone of spray discharged from each orifice of a multi-orifice injector. A comparison is made between a 2-hole conventional injector, a 3-hole conventional injector, a 5-hole conventional injector, and a CRDI system. The spray jet cone angle was determined and represented for 2-hole injection in Fig.7a, 3-hole injection in Fig.7b, 5-hole injection in Fig. 7c, and a CRDI system in Fig.7d along with a graphical representation showing the trends in the variation of the overall spray cone angle among the various injection systems with injection types along the x-axis and an average spray jet cone angle on the y-axis in Fig. 7e. Each hole of a 2-hole conventional injector produces a spray jet cone of an average angle value of 15.15° with a deviation of about 0.15° which decreases to 14.4°±0.4° for a 3-hole injector and to 12.7°±0.4° for a 5-hole injector. The average value of the cone angles developed by the individual sprays of a CRDI system is 18.1°±0.9°.



a) 2-hole conventional system

b) 3-hole conventional system

c) 5-hole conventional system

d) CRDI system

e) Comparison of spray jet cone angles

Fig. 7 Spray jet cone angles

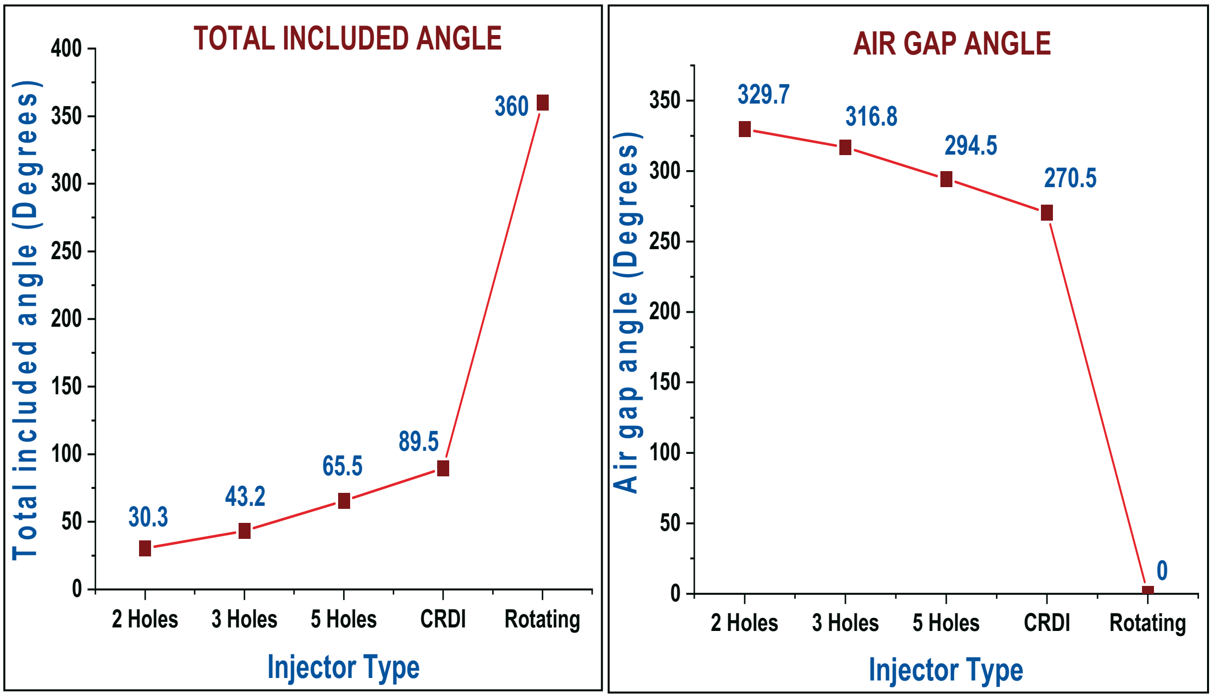
3.2 Fuel spray dispersion

The dispersion of the static injector spray is less in contrast to that of the rotating injection. This can be attributed to the increase in the interfacial area between the dispersed phase of the fuel and the nearby air in a rotating direct injection system due to the entrainment of air on both the outside of the spray and in between the spray sheath. The dispersion of the sprays is characterized in two ways in this work: air gap angle and area.

3.2.1 Air gap angle

The air gap angle is the sum of the angles of the air gap between the spray jets of the individual orifices. It is calculated as the complement of the total included angle, which is the total angle incorporated by all the jets of the spray discharged from the injector. Let θ_1, θ_2 represent the spray jet cone angles for a multi-orifice injector with 'n' orifices. Then the total included spray angle is given by $\theta_{T=}$ $\theta_1+\theta_2+\theta_n$ and the air-gap angle is given by

θ_{AG}=360 degree-θ_T. The total included angle of a rotating system is the highest with an angle of 360° with no air gap. Fig. 8a represents the total included spray angle plotted with injection types along the horizontal axis and the total included angle on the y-axis. Fig. 8b shows the air-gap angle of different types of injection taken along the x-axis and the air gap angle on the y-axis.

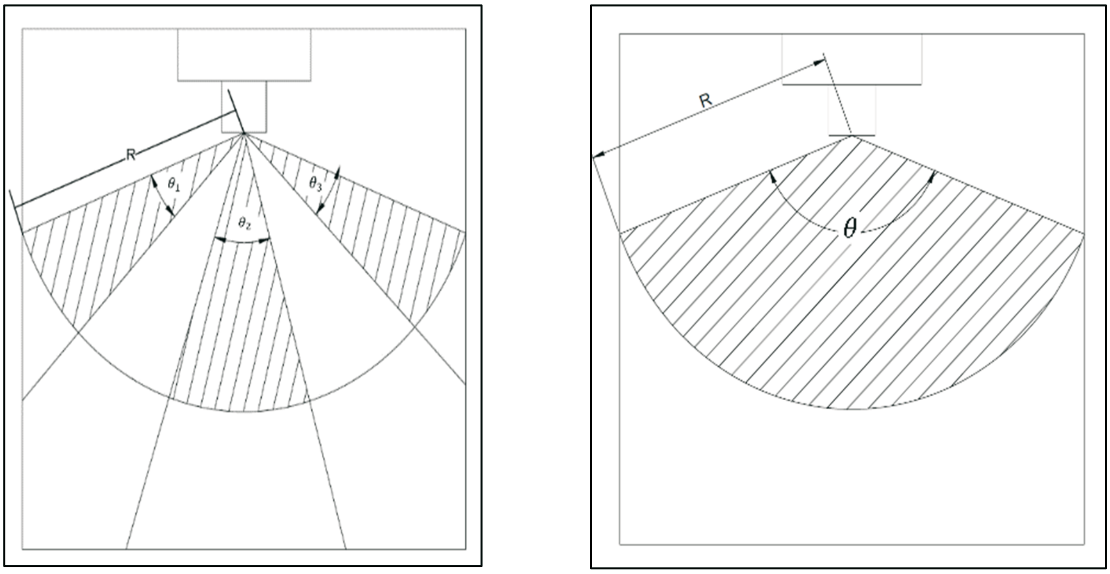


a) Total included spray angles b) Air gap angles

Fig. 8 Comparison of the total included spray angles and air gap angles

3.2.2 Area of spray

The area of cross-section occupied by the spray is studied between the nozzle orifices and a radial distance of R = 30 mm. Fig. 9 shows the section of the spray used to calculate the cross-sectional area of dispersion, while Fig. 9a illustrates a conventional multi-orifice injector and Fig. 9b displays a rotating injector. The hatched area reveals the CS area of the sprays for a radial distance of 'R' mm. The cross-sectional area of dispersion is $A=\theta/360\cdot\pi R^2$. For multi-orifice injection, the total area of cross-section is calculated as the sum of the CS area of the individual spray jets. The area of cross-section occupied by the RDI system is greater than the corresponding CRDI and conventional systems. Fig. 10 indicates the comparison between the areas occupied by the various injection systems plotted with the CS areas along the vertical axis and the different injection types along the horizontal axis.



a) Conventional multi-orifice injector b) Rotating injector

Fig. 9 Pictorial representation of the CS area of spray

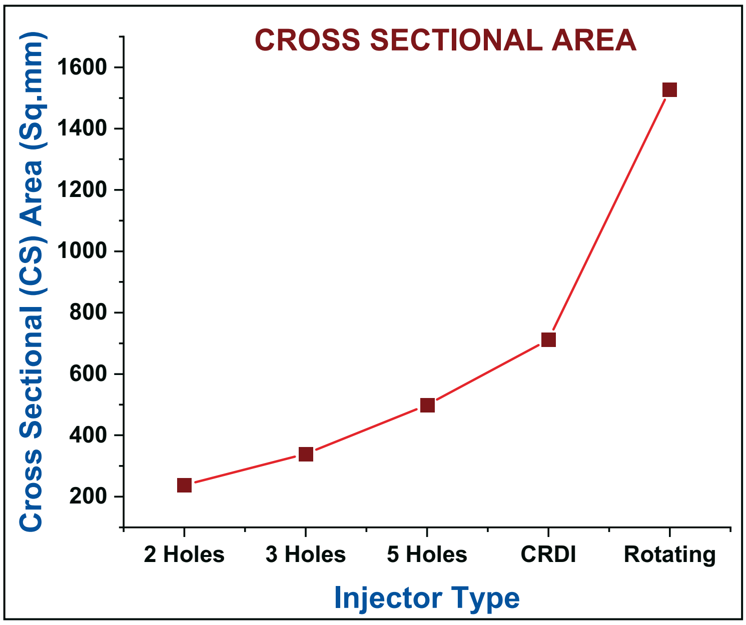


Fig.10 Comparison of the cross-sectional areas

3.3 Spray pattern

In the case of conventional injection, the spray pattern obtained from the images shows that the spray emerging from each of the orifices has a solid cone. When the injector is taken as a whole, it is found that the pattern is similar to a hollow cone, with the sprays appearing as the slant edges of the cone. Though the spray pattern of each of the orifice is of a solid cone pattern, the RDI system has a hollow cone spray with homogeneous distribution of the liquid diesel fuel droplets in the combustion chamber. The RDI system reduced the spray penetration depth and the fuel over a wider surface area. This is evident in the photographs due to the injector rotation and spray deformation shown in Figs. 5b, b1 and 5e,e1. The RDI spray length was reduced and the spray was distributed more widely, as shown in Fig. 6C.

4. Conclusion

A comparison was made of the spray characteristics of a conventional direct diesel injection system with 2-hole, 3-hole and 5-hole injectors, a CRDI system with five orifices, and a rotating direct injection system (RDI). The conclusions can be summarized as follows:

1. The increasing order of the overall spray cone angles is given by:
   5-hole <3-hole < 2-hole < RDI.
2. The average value of the cone angle of each of the spray jets from a multi-orifice nozzle is maximum for the CRDI system, which decreases as follows:
   3-hole <5-hole < 2-hole < CRDI ($14.4^{\circ}<15.1^{\circ}<15.5^{\circ}<17.3^{\circ}$).
3. The rotating spray disperses over a wider angle, without an air gap that occurs between the spray jets as in the case of multi-hole injectors. This establishes the capability of the system to discharge over a wider angle, resulting in increased liquid fuel-air interaction. The air gap angle increases as follows:
   RDI< CRDI< 5-hole<3-hole<2-hole ($0^{\circ}< 270.5^{\circ}<294.5^{\circ}<316.8^{\circ}<329.7^{\circ}$).
4. The rotating spray is uniformly dispersed over a greater cross-sectional area with a ratio of 2.14:1 for the CRDI system, 3:1 for the 5-hole injection system, 4.5:1 for the 3-hole injection system, and a ratio of 6.4:1 for the 2-hole injection system.
5. The interfacial area between the fuel spray and the surrounding air is found to be greater for the rotating system than the conventional system. This is due to the entrainment of air within the hollow cone of the injected spray and the interface between the liquid and the nearby air.
6. The spray pattern of a rotating spray is of a hollow cone pattern, when compared to the direct injection and CRDI systems, where the fuel spray pattern is of the form of the slant edges of a cone, where each spray jet is of a solid cone type.

Hence, the RDI system has a better overall spray cone angle and spreads the fuel widely throughout the combustion chamber without an air gap between the jets. It supports the better mixing with air and better combustion, and results in improved performance and reduced emission. It is a new technique to inject fuel in a C.I. engine.

The higher value of the overall spray cone angle is usually attributed to the tangential components of the velocity of the fuel drops emanating from the orifice, resulting in increased centrifugal action, thereby increasing its angle and the interaction between the liquid fuel drops and the continuous phase of air, which is absent in a conventional system, resulting in the lower value of the overall cone angle. The increased value of the individual jet cone angle of a CRDI system is due to the high injection pressure developed in the CRDI system. The value of the jet cone angles of a 3-hole injection system decreases from the value of a 2-hole injector. This is due to the reduction in the mass flow rate passing through each orifice, resulting in a reduced jet cone angle. The value of the total included angle of an RDI system is the highest, with a value of 360 degrees, although the value falls for other systems. The higher value of the included angle shows that a system of spray is discharged over a wide angle, ensuring the good dispersion of fuel droplets in the air, while the high value of the air gap angle establishes the inability of the system to disperse over a wider cone angle. The value of the area of the cross-section in the case of a rotating system means that it is discharged and dispersed over a wide area when compared to other systems. The pattern of dispersion of the spray with a hollow cone provides a greater area for interaction with the air, thus producing a good homogeneous mixture, reducing the local concentration of the fuel in the combustion chamber. It is evident that the rotating fuel spray helps in better mixing the fuel and air inside the combustion chamber [27].

The rotating fuel injector avoids the local concentration of the mixture. Hence, the RDI facilitates better combustion, an optimum peak heat release, reduced NO_X emissions, and improved performance.

Abbreviations

NO_X – Oxides of nitrogen
PM – Particulate matter
EGR – Exhaust gas recirculation
DI – Direct injection
θ_T – Total included spray angle
IDI – Indirect Injection
CRDI–Common rail direct injection
RDI – Rotating direct injection
θ_{AG} – Air gap angle

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