International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
IJIREV
Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021

INTERNATIONAL JOURNAL OF INNOVATION AND INDUSTRIAL REVOLUTION (IJIREV)
www.ijirev.com

EVALUATION OF GASOLINE DIRECT INJECTION SPRAY MORPHOLOGY FOR VARIES INJECTION PRESSURE USING DISCRETE PHASE MODEL (DPM) APPROACH

Nuraqilah Zahari[1], Bukhari Manshoor[1*], Izzuddin Zaman[1], Reazul Haq Abdul Haq[1], Mohammad Fahmi Abdul Ghafir[1], Mohd Rosdi Salleh[2], Rio Marco Rathje[3], Christin Rothe[3], Mohd Nizam Ibrahim[4]

[1] Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA
Email: Hd230015@student.uthm.edu.my, bukhari@uthm.edu.my, izzuddin@uthm.edu.my, reazul@uthm.edu.my, fahmi@uthm.edu.my
[2] Automotive Research Center, Politeknik Sultan Mizan Zainal Abidin, KM 08 Jalan Paka, 23000 Dungun, Terengganu, MALAYSIA
Email: rosdi.salleh@psmza.edu.my
[3] Institute for Regenerative Energy Technology (in.RET), Nordhausen University of Applied Sciences, Nordhausen GERMANY
Email: rio-marco.rathje@hs-nordhausen.de, christin.rothe@hs-nordhausen.de
[4] Maxpirations (M) Sdn Bhd, Sura Gate Commercial Centre, Dungun, Terengganu, MALAYSIA
Email: nizam@maxp.com.my
[*] Corresponding Author: bukhari@uthm.edu.my

Article Info:

Article history:
Received date: 29.01.2025
Revised date: 12.02.2025
Accepted date: 17.03.2025
Published date: 30.03.2025

To cite this document:

Zahari, N., Manshoor, B., Zaman, I., Haq, R. H. A., Ghafir, M. F. A., Salleh, M. R., Rathje, R. M., Rothe, C., & Ibrahim, M. N. (2025). Evaluation Of Gasoline Direct Injection Spray Morphology For Varies Injection Pressure Using Discrete Phase Model (DPM)

Abstract:

Gasoline fuels are a primary fuel that is used widely in engine applications. However, it has contributed to carbon dioxide and particulate matter which led to greenhouse gas emissions. Researchers have conducted many studies to overcome this emission and improve engine fuel injection. These include altering the injection timing, optimizing the fuel-air mixture, and developing advanced technologies such as direct and multi-point injection systems. This study uses the Computational Fluid Domain approach to analyze the spray pattern and characteristics of gasoline direct injection into an engine chamber at different injection pressures. This simulation setup using Ansys Fluent will apply the discrete phase model and a realizable k-epsilon viscous model. The injection pressure varies at 40 bar, 120 bar, 200 bar, and 300 bar. From this simulation study, the high injection pressure of up to 300 bar produces more extended spray penetration and finer droplet atomization. The results demonstrated that direct fuel injection with high injection pressure can contribute to better fuel-air mixing and reduce carbon emissions.

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021

Approach. *International Journal of Innovation and Industrial Revolution, 7* (20), 330-343.

DOI: 10.35631/IJIREV.720021

Keywords:

Gasoline Fuels, Computational Fluid Domain (CFD) Study, Discrete Phase Model (DPM), High Injection Pressure

Introduction

Internal combustion engines (ICE) remain a dominant technology in transportation, particularly for lightweight vehicles such as cars and motorcycles. The primary fuels for these engines are petroleum-based, including gasoline and diesel, which contribute significantly to carbon dioxide and particulate matter emissions, leading to greenhouse gas accumulation and air pollution (Zhu et al., 2023). To reduce this problem, researchers and the automotive industry have explored alternative technologies, including hybrid vehicles, electric cars, hydrogen fuel cells, and biofuels. However, due to their efficiency and widespread use, spark-ignition internal combustion engines play a crucial role in modern transportation (Duronio et al., 2020). One key area of research in improving gasoline engine performance and reducing emissions focuses on fuel injection systems. The gasoline direct injection (GDI) system has emerged as a critical innovation, allowing for more precise fuel delivery and better combustion efficiency. Injection parameters, such as ambient pressure and temperature, significantly influence fuel spray characteristics. For instance, increasing the ambient pressure in the engine chamber reduces spray penetration due to more excellent axial resistance experienced by fuel droplets (Chintagunti and Agarwal, 2024). This insight is crucial, as optimizing the spray length and distribution directly impacts the engine's performance and reduces emission levels.

Understanding fuel spray dynamics is vital for improving injection system performance. Researchers have conducted experimental studies to analyze key spray characteristics such as penetration, droplet size distribution, and spray angle. Advanced optical techniques, such as Schlieren imaging and Laser-Induced Exciplex Fluorescence (LIEF), have been widely used to visualize transient spray behavior (Chang et al., 2020). While these experimental methods provide valuable insights into vapor-phase spray dynamics, they have limitations, including high costs, time constraints, and challenges in capturing detailed spray morphology under high-pressure and high-temperature conditions. To address these challenges, Computational Fluid Dynamics (CFD) simulations have become an essential tool in spray research. CFD allows for detailed investigations of internal injector flow, fuel spray formation, and droplet interactions with surrounding air. The Discrete Phase Model (DPM) simulates individual droplet trajectories, atomization, evaporation, and breakup processes. By complementing experimental studies, CFD provides a cost-effective and efficient means of analyzing fuel spray behavior under various injection conditions.

This study uses CFD simulations to investigate the impact of varying injection pressures on the spray morphology of gasoline direct injection (GDI) systems. By analyzing injection pressures of 40 bar, 120 bar, 200 bar, and 300 bar, the study focuses on key parameters such as spray penetration, droplet size distribution, and atomization quality. Understanding these parameters is crucial for optimizing GDI systems to enhance fuel efficiency and reduce emissions in modern gasoline engines.

International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
IJIREV
Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021

Literature Review

Spray Formation and Atomization

Spray atomization can be defined as converting bulk liquid into droplets as it exits the end of the nozzle injector. It can be categorized into two parts of atomization: primary and secondary, as shown in Figure 1. Primary atomization occurs as the spray exits the nozzle and experiences a rapid pressure drop. This is caused by turbulence and the formation of cavitating bubbles near the injector orifice. Then, secondary atomization occurs due to the aerodynamic forces acting on the surface of the liquid droplets, and this process is further influenced by the surrounding air turbulence (Khan et al., 2024). In cases where different fuels are mixed, cavitation within the injector nozzle can be influenced by the fuels' varying physical properties, such as surface tension, viscosity, and saturation pressure. This phenomenon is crucial in spray breakup and mixture formation (Chintagunti and Agarwal, 2024).

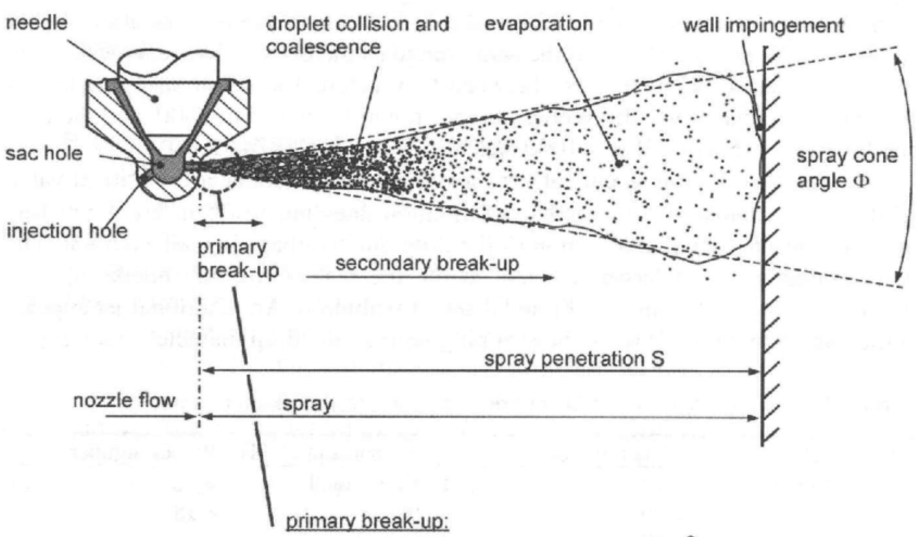


Figure 1: Spray Atomization Process

Source: (Khan et al., 2024)

Factor Influence Spray Atomization

Several factors influence spray atomization, including fuel properties, ambient conditions, injector configuration, and injection pressure.

Fuel Properties

A fuel's density, viscosity, and surface tension significantly affect spray formation. Gasoline, for example, has varying densities depending on its temperature and composition. At 15°C, gasoline density ranges from 710 to 770 kg/m³, according to the U.S. Environmental Protection Agency (Anon, 2008). The viscosity of gasoline at 293 K is 0.71 mm^2/s, while the surface tension of gasoline at 293 K is 0.22 mN/m (Li et al. 2023). High density and viscosity tend to produce larger droplets during spray breakup. However, these effects can be mitigated by blending gasoline with fuel additives to enhance atomization.

Ambient Pressure and Temperature

When fuel is injected into the engine chamber, the spray absorbs heat from surrounding gases, influencing evaporation and fuel-air mixing. Higher ambient pressure increases air density, intensifying aerodynamic forces acting on fuel droplets. This results in smaller droplet sizes

International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
IJIREV
Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021
and improved spray atomization (Chintagunti & Agarwal, 2024). Similarly, higher ambient temperatures enhance fuel evaporation, which alters droplet breakup dynamics and fuel-air mixture formation (Chang et al., 2022).

Injector Configuration
Injector design and operation significantly impact spray characteristics. According to (Pielecha, 2022), injection rate shaping reduces the linear spray range by approximately 50% and the radial range by about 40% during the initial injection phase. As the needle opens wider in the second phase, these ranges increase. This variability allows for more precise control over the spray, reducing the area affected in the early injection stages. In addition, it can help improve fuel atomization control by delaying the full opening of the injector. This leads to an increase in fuel flow.

Injection Pressure
High injection pressure will result in the production of finer droplets. In pressure homogenization, increased pressure accelerates the fluid velocity through a narrow orifice hole, facilitating turbulence and producing smaller droplet formation. Studies have demonstrated that turbulent flow conditions are crucial in determining the droplet size distribution, in which high pressure leads to the more effective breakup of the disperse phase, producing smaller droplets in size (Mutsch et al., 2021). Moreover, high injection pressure ranges from 350 to 700 bar increased spray penetration and spray plume area (Viscione et al., 2024).

Experimental Methods and Limitations
Experimental studies commonly use Schlieren imaging and Laser-Induced Exciplex Fluorescence (LIEF) to capture transient spray behavior (Chang et al., 2020). While these methods provide valuable insights into spray dynamics, they have significant limitations, including high costs, time constraints, and difficulty capturing detailed spray morphology under high pressure and temperature conditions.

Role of CFD in Spray Analysis
Computational Fluid Dynamics (CFD) has become a powerful tool for investigating fuel spray dynamics. CFD simulations provide detailed insights into internal injector flow, spray formation, and droplet-air interactions. The Discrete Phase Model (DPM) is particularly useful in modeling droplet trajectories, atomization, evaporation, and breakup processes. Compared to experimental techniques, CFD offers cost efficiency, greater flexibility, and the ability to analyze high-pressure conditions that are challenging to replicate experimentally. By complementing physical experiments, CFD enhances understanding of spray behavior and informs optimization strategies for fuel injection systems.

Research Gap and Study Objective
Despite extensive research on spray formation, limited studies have explored the impact of varying injection pressures on gasoline direct injection (GDI) spray morphology. Understanding how injection pressure affects spray penetration, droplet size distribution, and atomization quality is crucial for optimizing fuel efficiency and reducing emissions. This study aims to bridge this gap by analyzing injection pressures of 40 bar, 120 bar, 200 bar, and 300 bar using CFD simulations. The findings will provide valuable insights into optimizing GDI systems for improved engine performance and lower emissions.

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021

Methodology

Simulation Workflow Overview

The methodology of this study is based on the CFD simulation approach using Ansys Fluent software. It focuses on the Discrete Phase Model (DPM) approach to track the discrete individual droplets in the fluid domain. Fig. 2 below shows the flowchart of this simulation study. Firstly, the problem statement and research objective of this study are identified. Some literature review about this study is conducted to find the previous research related. Then, the 3D geometry model is obtained and designed using DesignModeler Ansys fluent. The mesh is generated and the boundary condition is assigned to the model. After that, the simulation setting is set up in Fluent by defining the physical setting like the model used and assigning boundary conditions type. This will be explained in the section below. Next, the solution method used is the Pressure Implicit with Split-Operator (PISO) algorithm with second-order discretization. The simulation is run, and the initial result is recorded. If the percentage error is more significant than 5%, the GIT Test will be conducted which the model need to be remeshed by altering the mesh size. Then, after doing the GIT test, the simulation will be conducted with a suitable mesh size, and the result will be finalized.

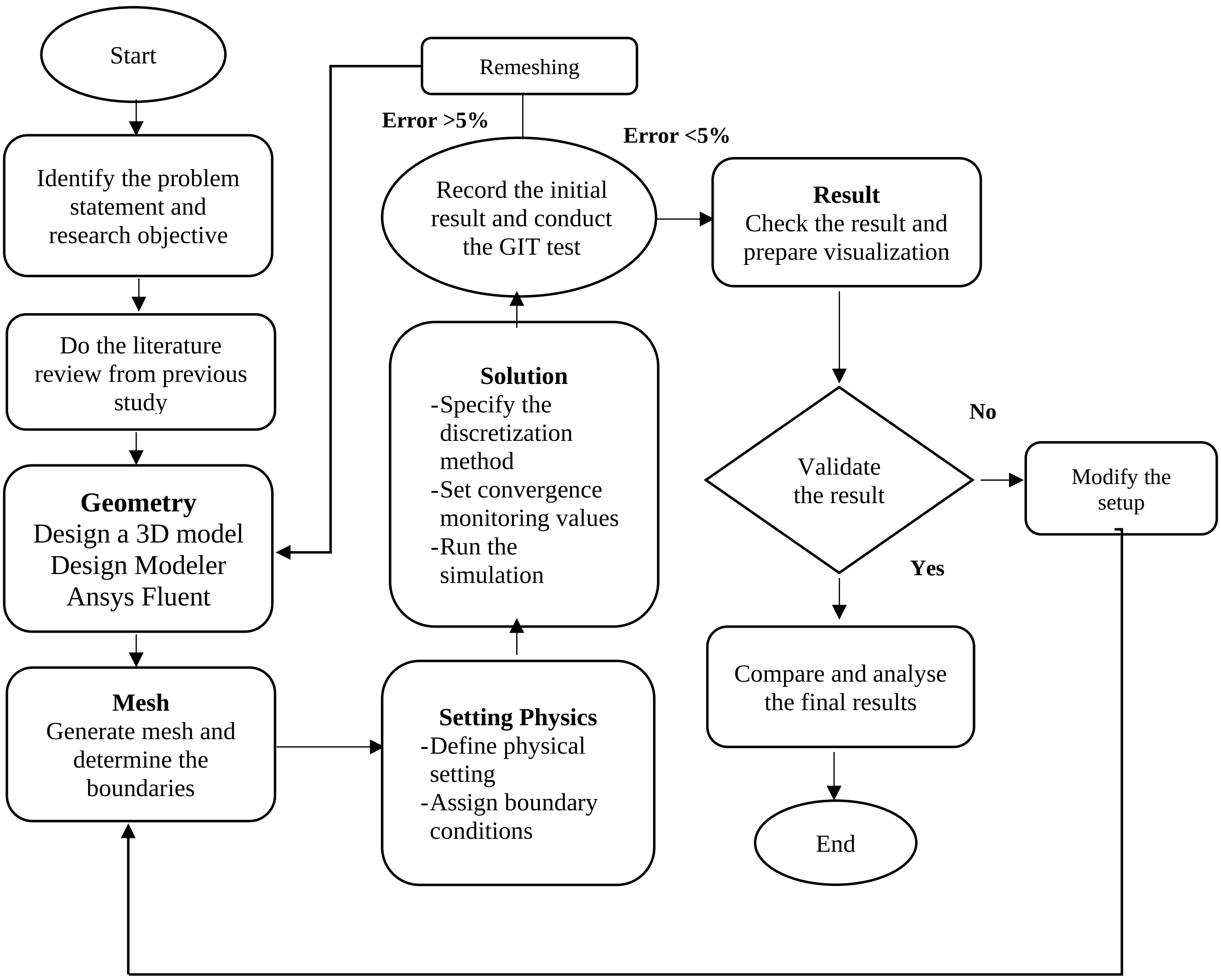


Figure 2: The Flowchart of The Simulation Study

Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021

Geometry Design

The geometry model, which represents a Gasoline Direct Injection (GDI) combustion chamber, is designed as a cylindrical body with a diameter of 140 mm and a height of 280 mm. It is created using the Design Modeler tools of Ansys Fluent in the 3D domain. Figure 3 below shows the parameters of the model, which represent a combustion chamber.

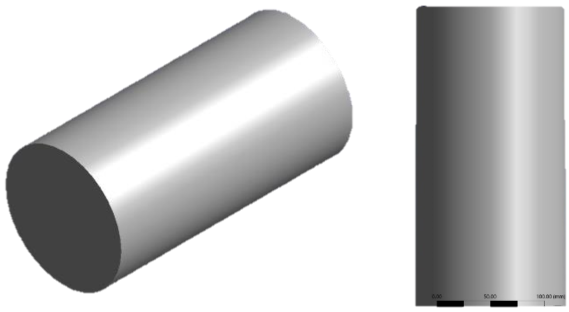


Figure 3: The Geometry Model Used in The Study

Meshing

Mesh is one of the important stages that must be determined before running the simulation. Figure 4 shows the hexahedral mesh shape of the full-body cylinder with face meshing and the section plane of the cylinder. The method of meshing used is multizone which help to obtain the hexahedral mesh shape. The hexahedral or structured nodes of mesh shape can provide smooth trajectories for tracking the spray particles. The face meshing is applied to the upper wall and outlet to avoid poorly aligned elements near the curved surfaces.

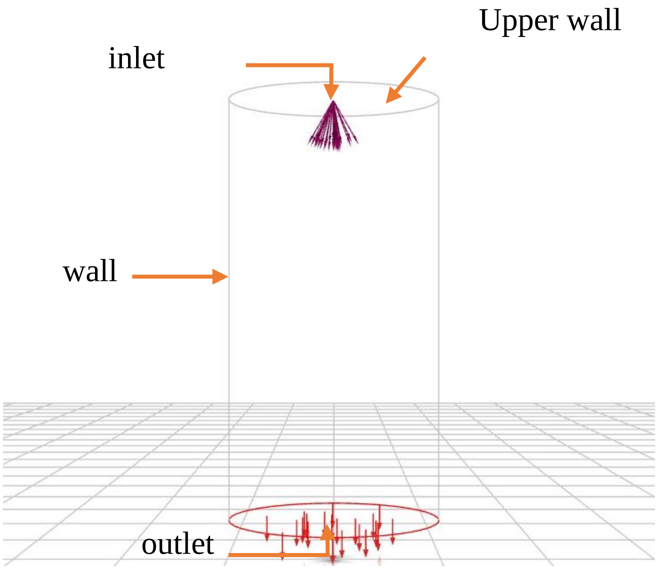
(a) (b)

Figure 4: The Mesh of Model (a) Full Body Cylinder (b) Cross-Sectional of Cylinder

Boundary Conditions

The model's boundary conditions include an inlet, outlet, upper wall, and wall. The inlet is located at the top surface of the cylinder with a diameter of 0.2 mm, while the outlet is at the bottom surface of the cylinder. The wall represents the cylinder boundary, as shown in Figure 5. The inlet boundary condition is set as an injection point with varying injection pressures of 40 bar, 120 bar, 200 bar, and 300 bar. This range is chosen to study the impact of different fuel injection pressures on spray characteristics. The outlet boundary condition is set to 0 bar to simulate atmospheric conditions and allow the spray to exit freely, ensuring realistic spray dispersion. The discrete phase model (DPM) is configured with escape boundary conditions at

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021
the outlet, enabling fuel droplets to leave the domain without reflection and closely replicating real-world spray behavior. At the upper wall and cylinder wall boundaries, a no-slip condition is applied, ensuring that the velocity of the fluid relative to the wall is zero. This condition is essential to account for wall interactions and boundary layer effects, which play a significant role in fuel-air mixture formation and combustion dynamics.



(a)

Figure 5: The Boundary Conditions Consist of Inlet, Outlet, and Wall

Simulation Set Up and Parameters

The simulation is performed using Ansys Fluent version 2024 with a similar setup to previous work (Payri et al., 2021). As we simulate the jet gasoline spray in the chamber, the flow in internal combustion engines is turbulent, which solves the system of closed motion equations and energy conservation. The turbulence kinetic energy k and its dissipation rate ε are obtained with two equations. The Realizable k-ε turbulence model is widely adopted in internal combustion engine simulations (Lewandowski et al., 2024). The Discrete Phase Model (DPM) tracks the discrete phase of spray. The spray breakup model is modeled with instability Kelvin-Helmholtz (KH) and Rayleigh-Taylor (RT). The instability KH is the mechanism close to the nozzle, known as the liquid jet's primary breakup. The RT instability originates from the acceleration normal to the density gradient. It is also known as a secondary breakup. As the liquid ligaments decelerate by a drag force, the RT instability grows on the trailing edge of the droplet (Wadekar, Yamaguchi, and Oevermann 2021). The dynamic drag model is applied to observe variations in the drop shape. The temperature of gasoline fuel is constant and set to 293 K. This simulation's ambient pressure and temperature are fixed to 101325 pa and 300 K, respectively. The type of jet injector used in this simulation is a plain orifice atomizer, as it consists of the simple nozzle with a narrow opening and is suitable for high injection pressure. The total number of streams is set to 2000 to represent the spray more accurately. The orifice diameter is 0.2 mm, and the orifice length is 1 mm. The injection point is located at the top center of a cylinder with coordinate (0,0,0) mm. The detailed DPM injection setup is shown in Table 1. The material properties of gasoline fuel are also listed in Table 2.

International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021

Table 1: DPM Injection Setup

Type of injector	Plain Orifice Atomizer
Number of Streams	2000
Fuel Temperature (K)	293
Ambient Pressure (pa)	101325
Ambient Temperature (K)	300
Orifice diameter (mm)	0.2
Orifice length (mm)	1
Breakup	KH-RT

Table 2: Gasoline Properties

Chemical Formula of Gasoline	C8H18
Density (kg/m³)	751
Specific Heat (J/kg K)	2420
Viscosity (kg/ms)	5.29e-07
Droplet Surface Tension (N/m)	0.021

The mass flow rate of gasoline fuel can be calculated by using the equation below:

$$\dot{m} = V \times A \quad \textbf{(1)}$$

Where v is the initial velocity of injected gasoline calculated from injection pressure. The equation to calculate initial velocity as follows:

$$V = \sqrt{\left(\frac{2 \times P_{inj}}{\rho}\right)} \quad \textbf{(2)}$$

The mass flow rate of gasoline for each injection pressure is tabulated in Table 3 below:

Table 3: Mass Flow Rate of Gasoline for Different Injection Pressure

	P_{inj}= 40 bar	P_{inj} = 120 bar	P_{inj} = 200 bar	P_{inj} = 300 bar
Mass flow rate (kg/s)	0.003242	0.005616	0.007250	0.00888

Before running the simulation, the solution method needs to be specified. In this study, the governing equation is solved by a finite volume method using a Pressure Implicit with Split-Operator (PISO) algorithm. A second-order discretization is used to obtain higher accuracy in capturing the flow variable precisely across the computational method. The simulation is run by a smaller time step size of 5 x 10^{-5} seconds. This helps to visualize the spray process accurately. The total time to run the simulation is 0.01 seconds as the real time to capture the spray in engine chamber.

Grid Independence Test (GIT)

This study uses a base mesh size of 2.0 mm as the starting point for this simulation. A total of 947100 elements are present in this coarse base mesh size. Grid Independent Test (GIT) was carried out to ensure a precise and valid result in the CFD processor by maintaining the GIT as low as possible without affecting the result. This step is done before the verification process.

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021
The Grid Independence Test runs six simulations with different mesh element sizes from 2.0 mm to 1.62 mm. Then, the average velocity is obtained for each simulation to calculate the percentage error. After the percentage error is consistently below 5%, the suitable mesh will be selected to run the simulation with different injection pressures. Table 4 shows the result of the comparison of percentage error. From the table, a 1.72 mm element size with 1460480 elements was chosen due to the medium mesh size. Hence, it had been considered the most reliable and suitable element size. Other than that, 1.62 mm of element size is determined as fine mesh size with the total elements 1741072. In addition, element size significantly impacts the simulation result of fluid flow as it challenges accurately modeling the mass and momentum coupling between gas and liquid phases while maintaining the validity of the underlying dispersed phase assumption (Viscione et al., 2024).

Table 4: Grid Independence Test

Element sizes, mm	No. of nodes	No. of elements	Ave. velocity (m/s)	Absolute Error	Percentage Error (%)
2.0	969516	947100	70.53	-	-
1.8	1293052	1265628	71.75	1.22	1.7
1.77	1388960	1360404	71.77	0.02	0.04
1.72	1490596	1460480	72.17	0.39	0.54
1.68	1641192	1609212	72.2	0.03	0.05
1.62	1774974	1741072	72.31	0.11	0.15

Result and Discussion

After conducting the simulation with various injection pressures, from 40 bar to 300 bar, the spray characteristics, including spray pattern, spray penetration, and droplet size distribution of spray droplets, were analyzed. The results displayed that variations in injection pressures affect the spray characteristics.

Spray Pattern and Penetration

The spray pattern of gasoline spray is visualized in the post-processing of Ansys Fluent software. Figure 6 shows the analysis of the gasoline spray pattern at different injection pressures: 40 bar, 120 bar, 200 bar, and 300 bar. From the result, we can analyze that as the gasoline spray exits the hole of the injector, the conical shape of the spray is formed. At a higher injection pressure of 120 bar to 300 bar, the spray penetration is extended to near the bottom of the cylinder. In addition, the higher injection pressure can improve the atomization of the spray, which leads to producing finer droplets and improved fuel-air mixing.

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021

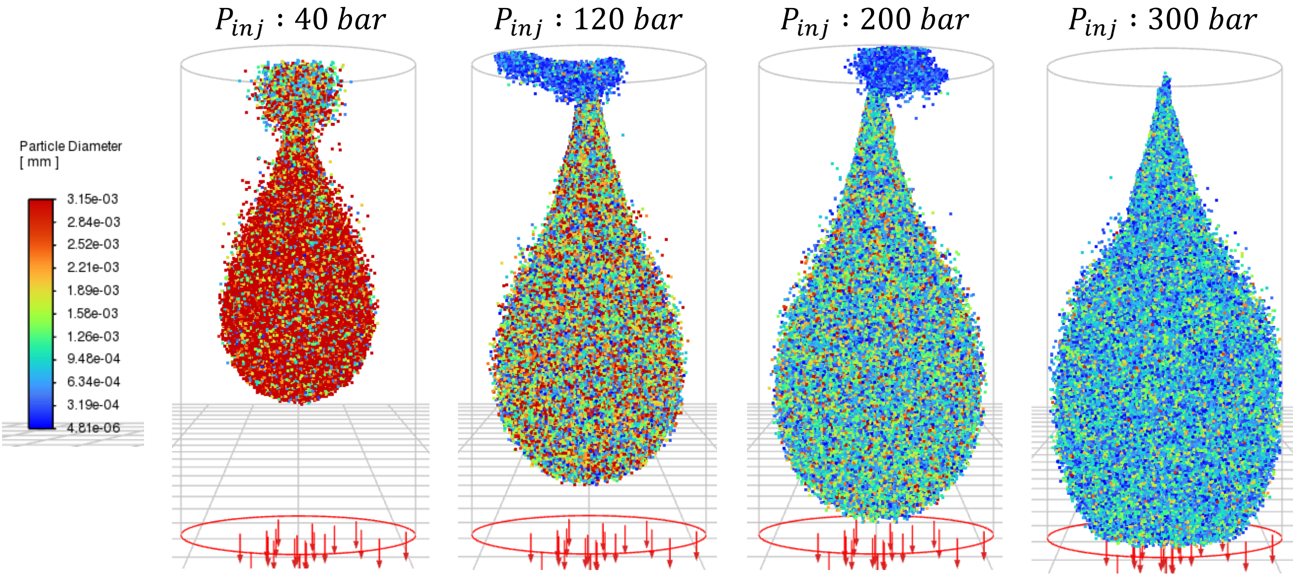


Figure 6: The Spray Pattern of Gasoline Fuel at Different Injection Pressure

The spray penetration can be defined as the distance from the hole injector to the end of the spray (Pelé et al. 2023). Several factors, such as injection pressure, ambient pressure, temperature, the size of the injector hole, and fuel properties, can influence it. In this study, we analyzed the spray penetration of gasoline spray by varying the injection pressure from 40 bar to 300 bar. With a total injection time of 0.01 s, it can be observed that the spray penetration is longer at a high injection pressure of 300 bar, reaching approximately 268.8 mm. Figure 7 below shows the graph of spray penetration of gasoline spray at injection pressure from 40 bar to 300 bar. Increasing the injection pressure (to 300 bar) results in higher force fuel injection and higher injected fuel velocity. Thus, the spray enters the combustion chamber faster, resulting in lower emissions and more efficient fuel mixing with air. The spray penetration at low injection pressure is reduced as the injected fuel has a low velocity with a short penetration of around 193.47 mm compared to high pressure. This slower penetration can also result in unmixing fuel with air, leading to potential increases in emissions.

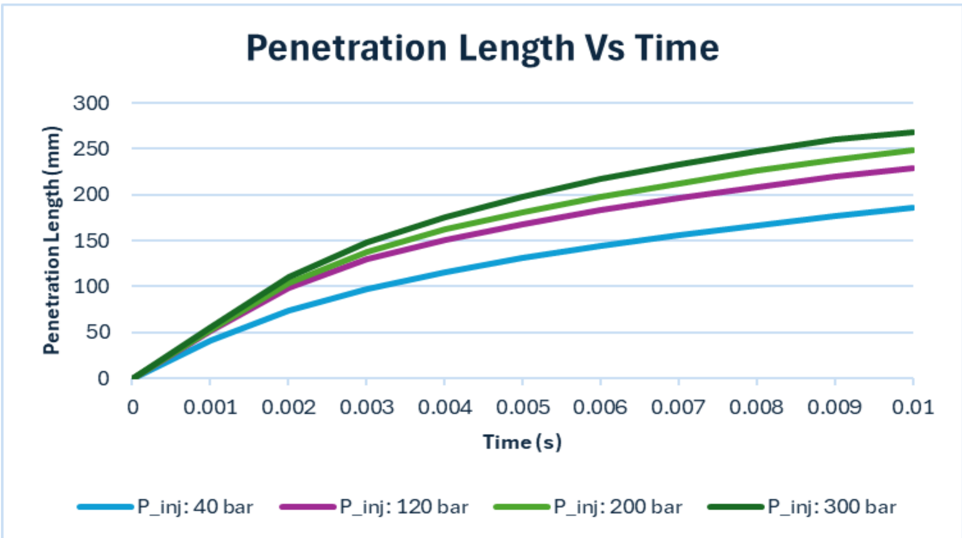


Figure 7: The Graph of Penetration Length Versus Time at Different Injection Pressure

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021

Droplet Size Distribution

The droplet size distribution of spray is important in achieving better fuel efficiency. The Sauter mean diameter, D32, is the average particle size distribution. Figure 8 compares the gasoline spray's Sauter diameter, D32, at various injection pressures. From the graph in Figure 8, the high injection pressure of 300 bar has a smaller range of DPM Sauter diameter, which is approximately 0.00037 mm. The droplet size decreases as the injection pressure increases up to 300 bar. This is because a higher injection pressure will promote the finer atomization of the spray. As the gasoline fuels exit the injector, the high pressure provides more energy to overcome the surface tension of gasoline fuel. Surface tension is the tension of the fluid interface, which is in contact with vapor pressure (Song et al., 2021). It is also a force that holds liquid molecules together, so as the high injection pressure is applied, it will break down this force and produce tiny droplets. In addition, the small droplet size can increase the evaporation rate and lead to more complete fuel-air mixing. Therefore, it can reduce the formation of soot and unburned hydrocarbons, resulting in lower pollutant emissions. The overall droplet size is expressed in the table below.

Table 4: Droplet Size at Different Injection Pressure

Injection Pressure, bar	Sauter Mean Diameter, mm
40	0.00188
120	0.000752
200	0.0005
300	0.00037

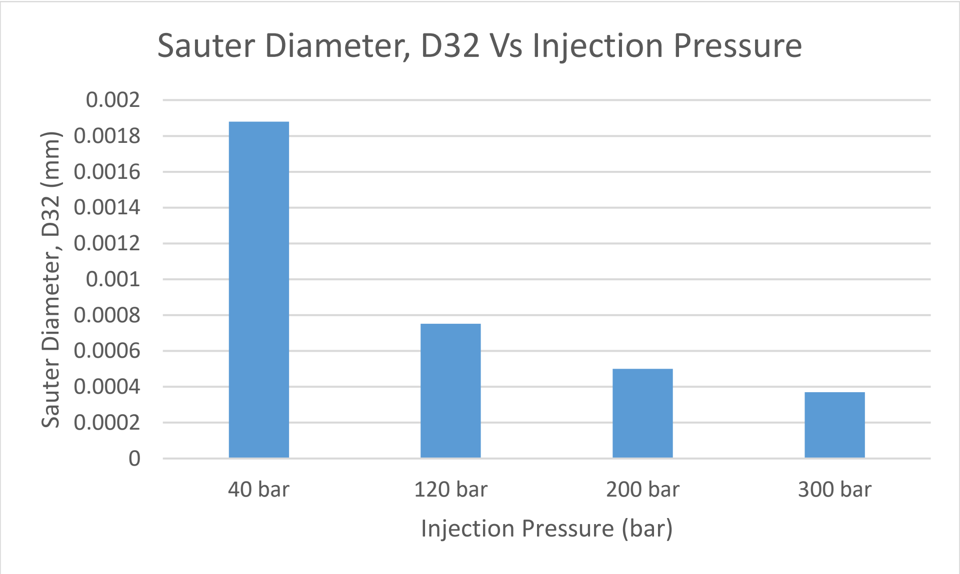


Figure 8: The Comparison of Sauter Diameter, D32 between Different Injection Pressure

Figure 9 shows the difference in contour of the Sauter diameter of the gasoline spray pattern of different injection pressures at time 0.01 s. At lower injection pressure, the range of DPM Sauter diameter is more significant than at higher injection pressure. This indicates that fuel droplets produce larger sizes at lower injection pressure due to low atomization efficiency. Low injection pressure results in low kinetic energy and will cause the breakup of gasoline liquid into smaller droplets to become less effective.

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021

Conversely, the higher kinetic energy at increased injection pressure promotes better atomization efficiency, producing more uniform spray and smaller droplet sizes. This higher atomization will result in better fuel-air mixing and reduce incomplete combustion or soot formation.

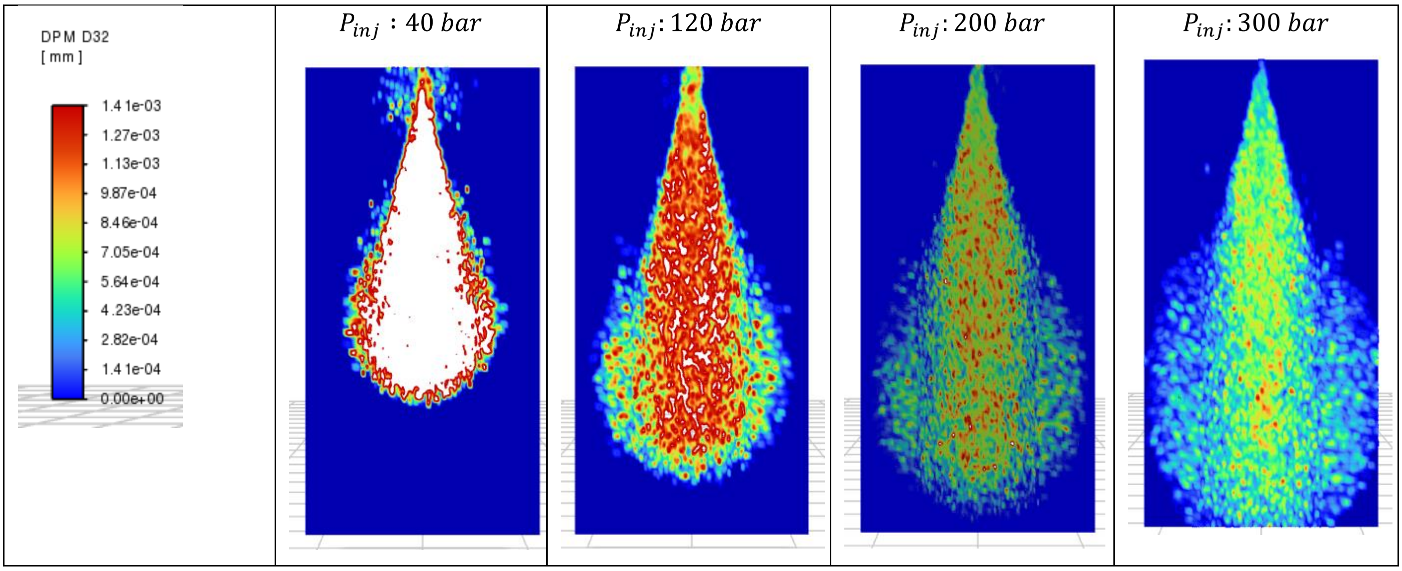


Figure 9: The Contour of Sauter Diameter of Gasoline Spray between Different Injection Pressure

Conclusion

In conclusion, using CFD simulations, this study investigated the effects of varying injection pressures on the spray morphology of gasoline direct injection (GDI) systems. The results demonstrate that higher injection pressures (up to 300 bar) significantly enhance spray penetration, atomization, and droplet size distribution, improving fuel-air mixing and combustion efficiency. These findings highlight the potential of high-pressure GDI systems in reducing emissions and enhancing engine performance. Higher injection pressures promote finer fuel atomization, resulting in smaller fuel droplets and improved fuel-air mixing. This more homogeneous mixture improves combustion, leading to more complete fuel burn, directly translating to better fuel efficiency and increased engine power output. The improved atomization and better spray penetration with higher injection pressures allow for better utilization of the combustion chamber, helping to reduce fuel consumption, lower unburnt hydrocarbon emissions, and significantly decrease particulate matter formation. Despite the study's insights, certain limitations, such as simplified geometry and constant ambient conditions, should be addressed in future work. Further experimental validation and exploration of injector durability at high pressures are also recommended to complement the findings. Additionally, studies on the impact of fuel properties and ambient conditions could provide a more comprehensive understanding of spray dynamics. Overall, this work contributes to developing advanced fuel injection systems, paving the way for more efficient and environmentally friendly internal combustion engines.

Acknowledgments

This research was supported by the Ministry of Higher Education (MOHE) through the Fundamental Research Grant Scheme (FRGS/1/2022/TK08/UTHM/02/14), Vot K434. We

Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021
also want to thank the Universiti Tun Hussein Onn Malaysia via sabbatical leave scheme, the Institute for Regenerative Energy Technology (in.RET), Nordhausen University of Applied Sciences and Maxpirations (M) Sdn Bhd for supporting data and technical advice.

References

Anon. 2008. Gasoline Properties Over Time.

Chang, Mengzhao, Ziyoung Lee, Sungwook Park, and Suhan Park. 2020. "Characteristics of Flash Boiling and Its Effects on Spray Behavior in Gasoline Direct Injection Injectors: A Review." Fuel 271.

Chang, Mengzhao, Young Soo Yu, Sungwook Park, and Suhan Park. 2022. "Spray Dynamics and Atomization Characteristics of Multi-Hole GDI Injectors under Flash Boiling Conditions." Applied Thermal Engineering 200. doi: 10.1016/j.applthermaleng.2021.117626.

Chintagunti, Sam Joe, and Avinash Kumar Agarwal. 2024. "Effect of Ambient Pressure on Macroscopic and Microscopic Spray Characteristics of Gasoline-Diesel Blends for Gasoline Compression Ignition Engine Applications." Applied Energy 376. doi: 10.1016/j.apenergy.2024.124106.

Duronio, Francesco, Angelo De Vita, Luigi Allocca, and Michele Anatone. 2020. "Gasoline Direct Injection Engines – A Review of Latest Technologies and Trends. Part 1: Spray Breakup Process." Fuel 265:116948. doi: 10.1016/J.FUEL.2019.116948.

Khan, Sadique, Mudassir Masood, Mario Medina, and Fahad Alzahrani. 2024. "Advancing Fuel Spray Characterization: A Machine Learning Approach for Directly Injected Gasoline Fuel Sprays." Fuel 371. doi: 10.1016/j.fuel.2024.131980.

Lewandowski, Michał T., Michał Pasternak, Morten Haugsvær, and Terese Løvås. 2024. "Simulations of Ammonia Spray Evaporation, Cooling, Mixture Formation and Combustion in a Direct Injection Compression Ignition Engine." International Journal of Hydrogen Energy 52:916–35. doi: 10.1016/J.IJHYDENE.2023.06.143.

Li, Xiang, Xuewen Zhang, Peiyong Ni, Rohitha Weerasinghe, Yiqiang Pei, and Zhijun Peng. 2023. "Insights into the Spray Impingement Process from a Gasoline Direct Injection Fuel System Fuelled with Gasoline and Ethanol." Journal of the Energy Institute 110. doi: 10.1016/j.joei.2023.101331.

Mutsch, Benedikt, Felix Johannes Preiss, Teresa Dagenbach, Heike Petra Karbstein, and Christian J. Kähler. 2021. "Scaling of Droplet Breakup in High-Pressure Homogenizer Orifices. Part II: Visualization of the Turbulent Droplet Breakup." ChemEngineering 2021, Vol. 5, Page 31 5(2):31. doi: 10.3390/CHEMENGINEERING5020031.

Payri, Raul, Pedro Marti-Aldaravi, Rami Abboud, and Abian Bautista. 2021. "Numerical Analysis of GDI Flash Boiling Sprays Using Different Fuels." Energies 2021, Vol. 14, Page 5925 14(18):5925. doi: 10.3390/EN14185925.

Pelé, Ronan, Pierre Brequigny, Camille Hespel, Jérôme Bellettre, Christine Mounaïm-Rousselle, Christine Mounaïm, Rousselle Spray, R Pelé, P. Bréquigny, C Hespel, J Bellettre, and C Mounaïm-Rousselle. 2023. Spray Characteristics and Vaporization Process of Ammonia-Ethanol Blends with a Current Bosch GDI Engine Injector.

Pielecha, Ireneusz. 2022. "Fuel Injection Rate Shaping and Its Effect on Spray Parameters in a Direct-Injection Gasoline System." Journal of Visualization 25(4):727–40. doi: 10.1007/s12650-021-00823-6.

Song, Minyung, Karen E. Daniels, Abolfazl Kiani, Sahar Rashid-Nadimi, and Michael D. Dickey. 2021. "Interfacial Tension Modulation of Liquid Metal via Electrochemical Oxidation." Advanced Intelligent Systems 3(8). doi: 10.1002/aisy.202100024.

International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
IJIREV
Volume 7 Issue 20 (March 2025) PP. 330-343
DOI 10.35631/IJIREV.720021
Viscione, Davide, Valerio Mariani, Stefania Falfari, Gian Marco Bianchi, Vittorio Ravaglioli, Giacomo Silvagni, Alessandro Montanaro, and Luigi Allocca. 2024. "Unconventional Gasoline Spray Injection Events: Compared Evolution of Experimental Data and Numerical Simulations." Fuel 355. doi: 10.1016/j.fuel.2023.129438.

Wadekar, S., A. Yamaguchi, and M. Oevermann. 2021. "Large-Eddy Simulation Study of Ultra-High Fuel Injection Pressure on Gasoline Sprays." Flow, Turbulence and Combustion 107(1):149–74. doi: 10.1007/s10494-020-00231-0.

Zhu, Jizhen, Dezhi Zhou, Wenming Yang, Yong Qian, Yebing Mao, and Xingcai Lu. 2023. "Investigation on the Potential of Using Carbon-Free Ammonia in Large Two-Stroke Marine Engines by Dual-Fuel Combustion Strategy." Energy 263. doi: 10.1016/j.energy.2022.125748.