Comparative investigation on macroscopic and microscopic characteristics of impingement spray of gasoline and ethanol from a GDI injector under injection pressure up to 50 MPa

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A B S T R A C T
Particulate Matter (PM) emissions from passenger vehicles have attracted considerable interest over the last decade. In order to reduce PM emissions, improving maximum injection pressure has been a developing trend for new generation GDI engines. However, comparing gasoline and ethanol impingement spray characteristics from a GDI injector under high injection pressure is still unclear. In this paper, a comparative investigation on both the macroscopic and microscopic characteristics of impingement spray from a GDI injector fuelled with gasoline and ethanol was performed under injection pressure up to 50 MPa, providing new findings to promote a more homogeneous air–fuel mixture and reduce PM emissions. The experimental results show that under the same $P\text{I}$ (injection pressure), rebound height of gasoline impingement spray is a bit higher than ethanol. $A\text{S}$ (spray area) of gasoline is slightly higher than that of ethanol under $P\text{I} = 10$ MPa. However, under $P\text{I} = 30$ MPa and $P\text{I} = 50$ MPa, $A\text{S}$ of gasoline is gradually exceeded by that of ethanol as time progresses. By increasing $P\text{I}$ to 50 MPa, the difference in $D\text{N}$ (diffusion distance of the near side) between gasoline and ethanol is greatly reduced, meantime $D\text{F}$ (diffusion distance of the far side) becomes weaker than ethanol. For both gasoline and ethanol, with the increase $P\text{I}$ from 10 MPa to 50 MPa, $V\text{N}$ (average normal component of droplet velocity) and $V\text{T}$ (average tangential component of droplet velocity) of incident droplets increase by around 1 m/s. Meanwhile, there is a slight decrease in the absolute value of $V\text{N}$ and $V\text{T}$ of reflected droplets. $D\text{SMD}$ (Sauter mean diameter of droplets) presents a significant decreasing trend with the increase of $P\text{I}$. Besides, a smaller $D\text{SMD}$ can be seen for the gasoline impingement spray compared to ethanol under the same $P\text{I}$.

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1. Introduction

As one anthropogenic aerosol in the ecosystem, Particulate Matter (PM) emitted by passenger vehicles has been a prominent uncertainty factor of climate change, owing to its influences on the incoming solar radiation and outgoing thermal radiation (Hughes et al., 2021; Zhang et al., 2022a). Moreover, regarding the impacts on human health, fine PM could penetrate into the alveoli and blood, potentially leading to some respiratory and cardiovascular diseases (Manisalidis et al., 2020). Hence, PM emitted by passenger vehicles has attracted considerable interest worldwide. Battery Electric Vehicle (BEV) and Fuel Cell Electric Vehicle (FCEV) are proposed as two major effective technologies. But their market shares are much lower than that of Internal Combustion Engine (ICE) vehicles, due to some drawbacks, such as price performance, recharging facilities, recharging time and cruising range (Guo et al., 2020; Inçi et al., 2021).

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Regarding the powertrain system of ICE vehicles, owing to the benefits for engine thermal efficiency, Gasoline Direct Injection (GDI) engine has been the most popular choice instead of Port Fuel Injection (PFI) over the last few decades (Attar et al., 2014; Luo et al., 2020; Chen et al., 2019; Li et al., 2022). However, compared to PFI engines, the relatively high PM emissions from GDI engines become worthy of more attention, particularly the Euro 6c standard released in 2017 further restricted the PM number of GDI-powered vehicles from $6 \times 10^{12}$ #/km to $6 \times 10^{11}$ #/km (Giechaskiel et al., 2019; Awad et al., 2020; Li et al., 2022).

The PM emission level of GDI engine is generally influenced by operating parameters, such as air–fuel ratio, spark timing, Exhaust Gas Recirculation (EGR), fuel injection timing and injection pressure. In order to reduce PM emissions, improving maximum injection pressure has been a developing trend for new generation GDI engines in recent years (Eitel et al., 2018). Hence, some researchers have commenced investigations related to GDI injector under the conditions of high injection pressure equal to or greater than 30 MPa (Hustedt et al., 2014; Kim et al., 2018; Lee and Park, 2020; Lou et al., 2022; Li et al., 2018; Luo et al., 2021; Chang et al., 2021; Zhang et al., 2022b; Montanaro et al., 2020; Migliaccio et al., 2020).

Hustedt et al. (2014) experimentally investigated fuel economy with varying injection pressure from 10 MPa to 40 MPa. It was found that increasing fuel pressure is good for the fuel economy of GDI engine, but the benefit is not obvious due to the growth of fuel consumption required by fuel pump. Kim et al. (2018) and Lee and Park (2020) studied the effects of injection pressure up to 50 MPa on combustion and emission characteristics of a GDI engine. It was confirmed that increasing injection pressure could considerably reduce gaseous and PM emissions. The maximum reduction in PM number, hydrocarbon and nitrogen emissions can be up to 93.6%, 34.5% and 35.6%, respectively. Lou et al. (2022) demonstrated that with the increase of injection pressure from 35 MPa to 50 MPa, the proportion of PM with a diameter below 23 nm is increased to more than 40% of total PM. Li et al. (2018) evaluated the macroscopic characteristics of ethanol spray from a GDI injector under injection pressure up to 50 MPa, by analysing spray development stages, cone angle, penetration, area and irregular ratio. Luo et al. (2021) and Chang et al. (2021) studied the microscopic characteristics of near-nozzle spray and the impinging spray from a GDI injector fuelled with surrogate fuels (n-heptane, toluene) with injection pressure up to 30 MPa. It indicated that the number of droplets with a diameter above 20 μm could be significantly decreased by increasing injection pressure from 10 MPa to 30 MPa. Zhang et al. (2022b) also carefully analysed the effects of iso-octane spray characteristics under cross-flow conditions with an injection of up to 35 MPa. It was found that with the increase of fuel injection pressure, both the spray horizontal penetration and area distributions could become uniform. Using experiment and simulation methods, Montanaro et al. (2020) and Migliaccio et al. (2020) studied the effects of ultra-high injection pressure up to 100 MPa on the spray morphology. It indicated that by increasing injection pressure from 40 MPa to 100 Mpa, the spray cone angle has a slight increase of 2 degrees.

As mentioned above, regarding the studies related to GDI injector under high injection pressure equal to or greater than 30 MPa, most previous researchers focused on GDI engine performance and spray characteristics. Few studies have investigated the effects of high injection pressure on impingement spray from a GDI injector. Furthermore, no investigation has systematically compared gasoline and ethanol impingement spray from a GDI injector under high injection pressure. Besides, biofuels have been a promising alternative and a hotspot, which have attracted great interest in the research domain of ICE (Huang et al., 2019a,b; Zhuang et al., 2020; Puricelli et al., 2021; Li et al., 2021a; Badawy et al., 2022, 2021). Particularly, owing to high content of oxygen, ethanol addition into engine combustion process could help reduce PM emissions, which has become a popular solution to achieve low-carbon emissions as the concern for the climate increased in recent years (Zhuang et al., 2020; Puricelli et al., 2021; Li et al., 2021a).

Hence, this paper aims to initially develop a theoretical framework for macroscopic and microscopic characteristics of impingement spray from a GDI injector fuelled under injection pressure up to 50 MPa, which is helpful to form a more homogeneous air–fuel mixture in GDI engines. Moreover, a comparison between gasoline and ethanol impingement spray characteristics was explored to provide new scientific perspectives and valuable references for further experimental and simulation studies.

2. Experimental setup and method

2.1. Experimental setup and procedures of macroscopic spray characteristics

The GDI injector used in this investigation is from a dual-injection Spark Ignition (SI) engine. As the orifice geometry and spray sketch presented in Fig. 1, the injector has five holes with a diameter of 0.174 mm. In this investigation, spray jets are numbered as jets “1” to “5”. The utilised fuels are commercial gasoline and absolute ethanol, which properties are listed in Table 1. Regarding the effects of fuel properties in the utilisation of common GDI engines, it would be better to increase the engine’s transient power response to use gasoline, which has a relatively low heat of vaporisation. With the advantages of low carbon content, ethanol is normally recognised as reducing the production...
of PM emissions during engine combustion process (Zhuang et al., 2020; Puricelli et al., 2021; Li et al., 2021a).

The comparative investigation on the macroscopic characteristics of gasoline and ethanol impingement spray was carried out via Schlieren technique, which has the advantage of getting the image of gas-liquid two-phase based on the differences of refractive index gradients (Allocca et al., 2016; Wu et al., 2018; Li et al., 2019). The whole experimental setup of macroscopic characteristics can be seen in Fig. 2. After connecting to a metal holder, injector can be adjusted and fixed to a specific distance and angle referring to a wall, which is a very flat aluminium alloy plate with a roughness of less than 0.4 mm.

Fuel injection pressure was selected to be 10 MPa, 30 MPa and 50 MPa, representing common, high and ultra-high pressures of GDI injector, respectively. The drive signal of fuel injection was transmitted from a programmable Electronic Control Unit (ECU), which could also synchronise injection with “768 × 768 pixels at 10 000 frames per second” images captured by a high-speed camera. Then, using MATLAB, the captured images were converted to grayscale, followed by image processing and calculation. In order to minimise the potential interference of suspended fuel droplets caused by the preceding injection, injection pulse width was set to be 1.2 ms, and the injection frequency was fixed to be a very low level of 0.1 Hz. The aluminium alloy plate was cleaned and restored thoroughly every five injections. Fuel was injected into an ambient condition of 293 ± 0.5 K and 0.1 MPa. An air extractor was used to eliminate the safety risks of experimental site. Besides, each condition should be repeated thirty times during the test to improve the measurement accuracy.

As shown in Fig. 3, based on the design of side-mounted injector of engine, injector’s orientation was set to be in an inclined direction in this investigation. The jets “2” to “5” hit the wall vertically, whilst jet “1” hits the wall at an inclined angle. The wall was located at a distance of 33 mm from the tip of injector. Moreover, to characterise the spray development and atomisation process from a macroscopic view, the parameterisation of impingement spray propagation is quite helpful and scientific. Therefore, some important parameters were introduced in this investigation. According to a reference line that is perpendicular from the injector top to the wall, $H_N$ and $H_F$ denote rebound height of the near side and far side for impingement spray, respectively. $D_N$ and $D_F$ each denote diffusion distance of the near side and far side. $A_S$ denotes area of impingement spray. $P_I$ denotes fuel injection pressure; $t$ denotes time After Start of fuel Injection (ASOI).

### 2.2. Experimental setup and procedures of microscopic spray characteristics

Regarding the investigation of microscopic characteristics of gasoline and ethanol impingement spray, the experimental setup mainly based on a Phase Doppler Particles Analyser (PDPA) system can be seen in Fig. 4.

Using a 1.3 W power argon-ion laser and a 180 MHz signal processor of the PDPA system, the measuring range of droplet velocity was set to be $-151.95$ to $238.77$ m/s with 0.01 m/s resolution. Meantime, the measurement of droplet diameter ranges from 0 to $236$ µm with 0.1 µm. As shown in Fig. 5, two measurement points (“A” and “B”) were selected at 4 mm above the wall. Point “A” was at the axis of injector, representing droplet behaviour in the central region of jet “1”. To better understand the droplet behaviour of impingement spray’s evolution, Point “B” was chosen at 10 mm to the right of Point “A”. Besides, in the PDPA test, $D_{50}$ denotes droplet diameter; $D_{30}$ denotes Sauter mean diameter of droplets; $D_{40}$ denotes the difference of $D_{30}$ between the conditions $P_{I_1}$ = 10 MPa and other $P_{I_2}$ (30 MPa, 50 MPa). $p_A$ denotes probability, $V_N$ denotes average normal component of droplet velocity; $V_F$ denotes average tangential component of droplet velocity. The positive direction of $V_N$ and $V_F$ was also defined as shown in Fig. 5.

For each test condition, in order to guarantee the measurement accuracy, data collection and analysis were from 20000 validated droplets, and the measurement should be repeated three times. The other experimental conditions and rules of microscopic characteristics investigation are the same with those of macroscopic characteristics.

### Table 1

<table>
<thead>
<tr>
<th>Fuel properties of gasoline and ethanol.</th>
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<tbody>
<tr>
<td><strong>Fuel type</strong></td>
</tr>
<tr>
<td>Chemical formula</td>
</tr>
<tr>
<td>Relative molecular mass</td>
</tr>
<tr>
<td>Gravimetric oxygen content (%)</td>
</tr>
<tr>
<td>Research octane number</td>
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<tr>
<td>Density (293 K) (kg/l)</td>
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<tr>
<td>Kinematic viscosity (293 K) (m²/s)</td>
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<tr>
<td>Surface tension (293 K) (mN/m)</td>
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<td>Boiling range (K)</td>
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<td>Low heating value (kJ/kg)</td>
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<tr>
<td>Density(293K)(kg/L)</td>
</tr>
<tr>
<td>Researchoctanenumber</td>
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<tr>
<td>Fueltype</td>
</tr>
<tr>
<td>Gravimetricoxygencontent(%)</td>
</tr>
</tbody>
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**Fig. 1.** The orifice geometry and spray sketch of the GDI injector used in this investigation.
3. Results and discussion

3.1. Macroscopic characteristics of gasoline and ethanol impingement spray

In order to completely understand the macroscopic characteristics, this section shows the results of $H_N$, $H_F$, $D_N$, $D_F$, and $A_t$ for both gasoline and ethanol with varying $P_I$. The maximum statistical time of the figures in this section is 3.0 ms ASOI, which is attributed to two factors. First, as the fuel injection pulse width was 1.2 ms, 3.0 ms ASOI can fully cover the relatively long time after the end of fuel injection. Second, the curves' trends in the figures are relatively stable near 3.0 ms ASOI and do not have apparent changes again.

In addition, the percentage changes in the figures of this section mean the change of gasoline concerning ethanol at the end of the statistical time. It shows the result of “the difference between the value of gasoline over ethanol” divided by “the value of ethanol” in percentage.

As $H_N$ shown in Fig. 6, the $t$ of reaching field boundary is advanced from around 2.8 ms ASOI to around 1.7 ms ASOI with the increase of $P_I$ from 10 MPa to 30 MPa. Then, the corresponding $t$ would be further advanced to 1.3 ms ASOI by increasing $P_I$ to 50 MPa. Regarding $H_F$ of 3.0 ms ASOI shown in Fig. 7, it improves from around 18 mm to around 27.3 mm by increasing $P_I$ from 10 MPa to 50 MPa. This is mainly because under higher $P_I$, the kinetic energy of spray droplets can be improved owing to the higher initial velocity. Based on the energy conservation law, the sum of droplets' kinetic energy and surface energy can be converted to energy dissipation and surface energy during the impingement process. Hence, the energy of rebound and splash for the droplets is enhanced, increasing the growth rate of $H_N$ and $H_F$. This would help promote the mixing of gasoline and air, reducing the possibility of PM emissions in GDI engines.

In addition, Figs. 6 and 7 demonstrate that under the same $P_I$, $H_N$ and $H_F$ of gasoline are a bit higher than those of ethanol. This can mainly be attributed to the difference in fuel properties between gasoline and ethanol. In the same condition of $P_I$ and height, initial velocity of droplets would be reduced with a higher fluid density according to Bernoulli’s principle stated in Eq. (1). Hence, compared to ethanol, the initial velocity of gasoline spray is higher owing to the lower fluid density.

$$\frac{1}{2} \rho_L v^2 + \rho_L g z + P = C$$  \hspace{1cm} (1)

Here, $\rho_L$ and $v$ is the mass density and flow velocity of the fluid, respectively. $g$ is the acceleration of gravity; $z$ is the height of a location above a reference plane; $P$ is pressure at the chosen point; $C$ denotes constant.

Figs. 8 and 9 present $D_N$ and $D_F$ of gasoline and ethanol with varying $P_I$. It can be seen that with the increase of $P_I$ from 10 MPa to 50 MPa, the difference in $D_N$ between gasoline and ethanol is

**Fig. 2.** Experimental setup of macroscopic impingement spray characteristics.

**Fig. 3.** Determination of parameters for macroscopic impingement spray characteristics.
which is the \( t \) of reaching field boundary for \( H_N \). With regards to \( D_F \) of gasoline, it is 0.27 mm or 0.45% higher than that of ethanol at 3.0 ms ASOI under \( P_I = 10 \) MPa. However, when \( P_I \) increases to 30 MPa and 50 MPa, \( D_F \) of gasoline becomes weaker, which is 1.81 mm and 2.9 mm lower than ethanol at 3.0 ms ASOI. This is mainly because the vortices around the boundary of gasoline impingement spray are a little stronger than ethanol, as shown in Fig. 10. The stronger vortices would have a negative effect on the growth of \( D_F \), owing to the increased kinetic energy for droplets moving toward inner inside of spray.

Fig. 11 shows \( A_S \) of gasoline and ethanol under different \( P_I \). For both gasoline and ethanol, the overall trend of \( A_S \) is ascending with the increase of \( P_I \). It indicates that the spread of fuel spray could be further prompted under high \( P_I \), thus it would be beneficial to enhance the air–fuel mixture homogeneity for GDI engines. Moreover, the comparison between gasoline and ethanol is quite different. Under \( P_I = 10 \) MPa, \( A_S \) of gasoline is slightly higher than ethanol, which is 1303.93 mm² and 1300.91 mm² at 3.0 ms ASOI, respectively. Under higher \( P_I \), \( A_S \) of gasoline is gradually
exceeded by of ethanol as time progresses. At 3.0 ms ASOI, $A_S$ of gasoline is 2.34% and 3.05% lower than ethanol under $P_I = 30$ MPa and $P_I = 50$ MPa, respectively. This is due to a combined impact of two reasons. One is that compared to ethanol, stronger vortices around the boundary enhance the kinetic energy for droplets moving toward inner inside of spray, which could slow down the growth of $A_S$. The other reason can be attributed to the lower kinematic viscosity of gasoline. As shown in Eq. (2), a larger $Re$ could enhance the instability of gasoline impingement spray, increasing violent breakup and negative effects on the $A_S$ expansion.

\[
Re = \frac{UD_d}{v}
\]  

Here, $Re$ is Reynolds number; $U$, $D_d$ and $v$ are each normal incident velocity, droplet diameter and kinetic viscosity.

3.2. Microscopic characteristics of gasoline and ethanol impingement spray

Figs. 12 and 13 present $V_N$ and $V_T$ at points “A” and “B” of gasoline and ethanol. It can be seen that the overall trends of $V_N$ and $V_T$ are generally stable by increasing $P_I$, but the changes of incident droplets and reflected droplets are a bit different. With the increase of $P_I$ from 10 MPa to 50 MPa, $V_N$ and $V_T$ of incident droplets increase by around 1 m/s for both “A” and “B”. However, there is a slight decrease in the absolute value of $V_N$ and $V_T$ of reflected droplets in the meantime. This is largely because that by increasing $P_I$, it would be easier for droplets to break down after impingement, increasing irregularity in the direction of reflected droplets’ movement. In addition, due to higher initial velocity of gasoline impingement spray, the absolute value of $V_N$ and $V_T$ of gasoline is a bit higher than ethanol under the same $P_I$. However, with the increase of $P_I$, the difference in velocity between gasoline and ethanol becomes very slight at “B”, which is similar to the corresponding variations and characteristics of $D_N$ and $D_F$ in Figs. 8 and 9.

Regarding the droplet size of “A” and “B”, two main features can be found in Figs. 14 and 15, which present both $D_{SMD}$ and $D_{Sub}$ of gasoline and ethanol. First, with the increase of $P_I$ from 10 MPa to 50 MPa, $D_{SMD}$ presents a significant decreasing trend at both “A” and “B”. For incident droplets, $D_{SMD}$ decreases from around 28 $\mu$m to around 10 $\mu$m. Meantime, $D_{SMD}$ decreases from around 18 $\mu$m to around 8 $\mu$m for reflected droplets. Second, under the same $P_I$, a smaller $D_{SMD}$ can be seen for the gasoline impingement spray compared to ethanol. These features can be further explained by $p_d$ of $D_d$. For example, from $p_d$ of $D_d$ of incident droplets at “A” shown in Fig. 16, it can be observed that compared to $P_I = 10$ MPa, the centralisation of $D_d$ moves towards smaller size under $P_I = 50$ MPa. The $p_d$ of $D_d$ above 20 $\mu$m decreases significantly to close to 0% under $P_I = 50$ MPa. Moreover, a bit higher $p_d$ of small $D_d$ can be found in gasoline compared to ethanol. The reason of these features can be attributed to that increasing $P_I$ would promote the spray breakup progress and produce a larger number of tiny droplets. Compared to low $P_I$, high $P_I$ could easily lead to better air–fuel mixture homogeneity, contributing to mitigate PM emissions from GDI.
4. Conclusions

An investigation was conducted to explore and compare the macroscopic and microscopic characteristics of gasoline and ethanol impingement spray from a GDI injector under injection pressure up to 50 MPa. This investigation provides theoretical perspectives for understanding impingement spray characteristics, which also benefits the model mechanisms establishment in numerical work. In the meantime, the investigation’s findings could contribute to forming a more homogeneous air–fuel mixture in GDI engines, further reducing PM emissions. The main conclusions can be summarised as follows:

1. Compared to ethanol, $H_N$ and $H_F$ of gasoline are a bit higher under the same $P_I$. By increasing $P_I$ to 50 MPa, the difference in $D_N$ between gasoline and ethanol is greatly reduced. Meanwhile, $D_F$ of gasoline becomes lower than ethanol at 3.0 ms ASOI.
(2) With the increase of $P_1$, the overall trend of $A_S$ is ascending for both gasoline and ethanol. As time progresses, $A_S$ of gasoline is gradually exceeded by ethanol under $P_1 = 30 \text{ MPa}$ and $P_1 = 50 \text{ MPa}$.

(3) For both gasoline and ethanol, with the increase of $P_1$ from 10 MPa to 50 MPa, $V_T$ and $V_I$ of incident droplets increase by around 1 m/s. Meanwhile, there is a slight decrease in the absolute value of $V_T$ and $V_I$ of reflected droplets.

(4) Compared to ethanol, a smaller $D_{SMD}$ can be seen for the gasoline impingement spray under the same $P_1$. By increasing $P_1$ from 10 MPa to 50 MPa, $D_{SMD}$ decreases from around 28 $\mu$m to around 10 $\mu$m for incident droplets. Meantime, $D_{SMD}$ decreases from around 18 $\mu$m to around 8 $\mu$m for reflected droplets.

In addition, to further establish the new framework about impingement spray characteristics of gasoline and ethanol from a GDI injector under high injection pressure. In future work, the effects of many other helpful injection parameters on impingement spray characteristics can be explored, such as injection duration, distance, angle, pulse frequency, etc.

CRediT authorship contribution statement

Xiang Li: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft.


Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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