Research Paper

Experimental and analytical study on liquid and vapor penetration of high-reactivity gasoline using a high-pressure gasoline multi-hole injector

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HIGHLIGHTS

- Penetration lengths for high-pressure GCI injector and GCI fuel were studied.
- Liquid penetration length was longer under high EGR condition.
- Penetration length regression models showed good agreement with experiments.

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ABSTRACT

Spray penetration length is an important parameter which is of great interest to both experimentalists and modelers. As it affects engine efficiency and emissions, measurement and prediction of spray penetration can significantly benefit engine optimization under various operating conditions. In this study, penetration length was investigated in a pre-burn constant volume combustion chamber using a gasoline multi-hole injector with high reactivity gasoline-like fuel designed explicitly for gasoline compression ignition (GCI) engines. Diffused back illumination (DBI) and shadowgraph were implemented for liquid and vapor phase penetration measurements, respectively. Different pre-burn gas mixtures are compared to investigate the influence of ambient gas properties on gasoline spray penetration under evaporating conditions. The liquid penetration under the gas composition of higher molecular weight tends to be longer. However, the vapor penetration showed insignificant effect under different gas compositions. Ambient gas temperature and gas composition were found to be an essential parameter for liquid phase penetration. Pressure difference was found to affect the vapor penetration length while its influence on liquid phase steady state penetration length at high ambient gas temperature is marginal. Statistical analysis was performed for both liquid and vapor phase penetration lengths, and a prediction model was developed with good agreement to the data under all test conditions.

1. Introduction

Gasoline compression ignition (GCI) engines have a high potential to increase engine efficiency and reduce emissions [1–3]. For manufacturers, development activities concerning designing and optimizing the new engine concept, CFD simulation is not only practical but also required [4]. Spray modeling contributes to one of the main uncertainties in engine CFD simulations [5]. Thus validation of spray models through experiments is of great importance for simulation fidelity.

Spray penetration length is a crucial characteristic which affects engine efficiency and emission performance. Over penetration might

cause impingement on the walls, thus leads to increased emission and reduced fuel efficiency while shorter penetration results in insufficient fuel-air mixing [6,7]. Optimization of spray penetration length for a specific engine combustion chamber geometry is mandatory to obtain optimum engine performance [8]. Therefore, spray penetration length is widely used for spray model calibration.

Many factors influence the transient behavior of spray penetration length. Commonly investigated parameters are injection pressure, ambient gas density, fuel properties, and nozzle geometry. For a diesel spray, predictive models for cold liquid jet penetration length were developed by researchers using single hole nozzles [9–11]. The work of Wang et al. [12] shows that single-hole diesel and bio-diesel spray

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Fig. 1. Schematic of pre-burn type Constant Volume Combustion Chamber (CVCC).

liquid penetration length at ambient room temperature is proportional to $t^{1/2}$ even at ultra-high injection pressure conditions. The correlation for vapor penetration length under hot conditions also has been established for the engine combustion network (ECN) spray D injector [13]. Payri et al. [14] developed models for diesel spray liquid and vapor phase penetration length at evaporative conditions. Dent [9] included ambient gas temperature's influence into liquid penetration correlation, but the model is a single equation for the entire injection duration. These correlations were developed based on single hole diesel spray, which does not fit with gasoline multi-hole sprays. Zeng et al. [15] developed empirical correlation by dimensional analysis for GDI spray penetration length at 1 ms after the start of injection. Reynolds number, Weber number and the density ratio of ambient gas to liquid fuel were included in the correlation while temporal information was not considered. Zhang et al. [16] further developed this model by including temporal analysis and divided the correlation into two zones based on the break-up time. However, the dimensionless correlations from previous works [15,16] were developed at room temperature conditions, and evaporation due to the influence of ambient gas temperature was not considered. Further, all these models were developed under the ambient environment of air for non-evaporative conditions and nitrogen (N_2) for evaporative conditions. This work fills the gap with developed regression models for both liquid and vapor penetration length, focusing on the volatile gasoline spray at evaporative conditions.

Payri et al. [11] compared liquid penetration length for a single-hole diesel spray in inert ambient gas N_2 and SF_6 environments, and it was reported that the penetration length in SF_6 was found to be longer than in N_2 . One reason reported was the difference in pressure drop, and the other was that more likely cavitation might take place with SF_6 ambient condition. This shows that there is an apparent influence of ambient gas composition on spray penetration. Exhaust gas recirculation (EGR) is used to reduce NO_x emissions in compression ignition engines [17]. By applying EGR, the exhaust gas displaces the fresh air entering the combustion chamber as a consequence the ambient gas composition is altered. It was recently reported that to achieve high gross indicated efficiency in GCI engines, high EGR up to 50% is used [18]. This indeed demonstrates that there is a need for understanding the spray penetration behavior under different ambient gas compositions. Therefore, in this study, the influence of ambient gas composition on spray tip penetration in both liquid and vapor phase at evaporative conditions has been studied, which was not reported earlier. Two different ambient gas composition was used to simulate no EGR condition

and high EGR conditions, respectively. Then a temporal regression model has been developed by taking into account for ambient gas density, temperature, pressure difference for different ambient gas compositions.

2. Experimental setup

2.1. Constant volume combustion chamber (CVCC) system

A constant volume combustion chamber was used to simulate high-pressure high-temperature engine related conditions, which is widely used by researchers for spray characterization [19–21]. It has the advantages of full control, well-specified boundary conditions, good optical access, and isolate the turbulence and swirl motions caused by the engine reciprocating motion. These advantages benefit not only for spray model development but also develop a fundamental understanding of the physical behavior of the spray event. The CVCC at KAUST Spray Lab is capable of handling 150 bar peak pressure. Pre-mixed gas preparation, pre-burn initiation, fuel injection activation, and high-speed imaging are automated through in-house LabVIEW program such that run to run variation due to the anthropic operation is minimized. The whole system is schematically shown in Fig. 1. Pre-burn gas components were firstly mixed in an accumulator and then pushed into the CVCC. The gas mixture was ignited by a spark plug such that high pressure and high temperature is formed. Due to heat loss, pre-burn gas product pressure and temperature will decrease with time. Then the injection is triggered with a carefully selected delay after spark ignition, such that a desired ambient gas pressure and the temperature is achieved. The injector is mounted horizontally, and two quartz windows of diameter ϕ 100 mm are installed orthogonal to the injector axis give access to optical diagnostics like shadowgraph and diffused back illumination (DBI).

2.2. Fuel injection system

A closed water circulation connected with a heat exchanger was provided around the injector body to control the fuel temperature. The injector used in this study is an Aramco customized ten holes solenoid injector specially designed for GCI applications. The maximum injection pressure is rated at 500 bar, which is much higher than that of commercial market GDI injectors. The injector's orifice diameter is 0.165 mm and spray designed included angle is 110° . National Instrument DIDS 2003 system is used for injector trigger to control the

Fig. 2. (a) Orientation of ten nozzle holes; (b) Front view of spray from Mie-scattering; (c) Side view from CAD model; (d) Side view from diffused back illumination (DBI) image.

Table 1
Properties of the studied GCI fuel from Saudi Aramco.

Properties	Value	Unit
RON	77	
Density @ 25 °C	707	kg/m ³
Kinetic viscosity	3.58×10^{-4}	Ns/m ²
Surface tension	1.96×10^{-2}	N/m
Final boiling point	180.9	°C

excitation duration. An air driven liquid pump is used to pressurize the fuel. The dynamic injection pressure is measured using a Kistler 4067E piezoresistive pressure sensor on the high-pressure line at 70 mm from the injector end similar to the ECN community [19]. The orientation of the ten plumes was arranged in such a way that two of the plumes are located at the central plane top and bottom, respectively, and the others are distributed symmetrically, shown in Fig. 2. The fuel used in this

study is high-reactivity gasoline with RON of 77 (GCI RON77) specially designed by Saudi Aramco for GCI applications. The properties of the fuel is shown in Table 1.

2.3. Imaging system

The optical alignment for vapor phase and liquid phase penetration length measurements are shown in Fig. 3. A high-speed monochrome Photron SA-X2 camera was used to capture spray event at 50,000 fps. Resolution for shadowgraph and DBI are 0.245 mm/pixel and 0.195 mm/pixel, respectively. The images were then post-processed with an in-house built MATLAB code. The flow chart in Fig. 4 shows the sequence of image post-processing. Background subtraction, noise removal, binarization, boundary detection, and calibration are the main steps to get the spray characteristics from images. Fig. 5 shows the intermediate images and final spray boundary output obtained following the procedure illustrated in the flow chart. Shadowgraph post-processing is similar, and the main difference is that background

Fig. 3. Optical set-up for (a) Diffused backlit illumination (DBI) and (b) Shadowgraph techniques.

Fig. 4. Flowchart showing the sequence of image processing.

subtraction is done with $frame(n) - frame(n - 1)$ to avoid interference on edge detection from the ambient gas flow.

According to SAE J2715 standard [22], spray penetration length of the GDI injector is defined as the distance along the injector axis between the farthest distant point on spray boundary and injector tip. Fig. 6 shows how spray (a) vapor and (b) liquid penetration lengths were defined, respectively in this work. The farthest point is marked as red¹, and a white line perpendicular to the injector axis goes through it. The distance of this white line from the injector nozzle outlet is defined as the penetration length. Each condition was repeated three times, and an averaged penetration length was used for further regression study.

3. Results and discussion

The influence of different factors such as ambient gas temperature, pressure, gas composition, and injection pressure was studied. The oxygen concentration after the pre-burn event was maintained to be zero to investigate spray characteristics under the evaporative and non-reacting conditions. Two different initial gas compositions were used for the pre-burn event as shown in Table 2. The two different gas

compositions are named as Gas No.1 and Gas No.2 and it will be used consistently throughout the paper from here on. The experimental test conditions are shown in Table 3. When different ambient gases were used, the ambient gas density and temperature were kept the same.

High reactivity gasoline of RON 77, specially designed by Saudi Aramco for GCI application, was used in this study. Fuel temperature was maintained at 90 °C throughout the experiments. Injector excitation duration was fixed at 1.75 ms for all cases. The rate of injection (ROI) is an essential input for CFD model validation and gives detailed information about the injection process. Bosch method [23] and momentum flux method [24] have been widely used for measuring ROI. The rate of injection and cumulative injection mass are measured at different injection pressures as shown in Fig. 7 by using momentum flux method. More details about the ROI measurements can be found in [25].

3.1. Penetration length

3.1.1. Effect of injection pressure

Fig. 8 shows the shadowgraph images for different injection

Fig. 5. Image post-processing sequence: (a) raw image, (b) masked image, (c) background subtracted and noise removed, (d) binary image, (e) boundary of spray, (f) pseudo color calibrated image.

Fig. 6. Definition of (a) liquid and (b) vapor penetration length.

Table 2

Two different initial gas compositions by vol. %.

Species	H ₂	C ₂ H ₂	O ₂	N ₂	CO ₂
Gas No.1	3	5	14	78	0
Gas No.2	3	5	14	14	64

pressures at 13.87 kg/m³ ambient gas density and 500 K ambient gas temperature. When injection pressure increases from 100 bar to 450 bar, vapor penetration length increases. This increase in the vapor

¹ For interpretation of color in Fig. 6, the reader is referred to the web version of this article.

Table 3
Experimental test conditions.

Parameter	value
Injection pressure (bar)	100, 300, 450
Ambient gas density (kg/m^3)	8.67 13.87
Ambient gas temperature (K)	800 500
Method	DBI, Shadowgraph
Initial gas composition (vol.%)	Gas No.1, Gas No.2

Fig. 7. Rate of injection and cumulative mass at different injection pressures [26] (back pressure 1 bar, duration 1.75 ms).

penetration length is due to the increase in momentum.

Fig. 9 shows the liquid phase DBI images for different injection pressures. It can be seen that the liquid penetration at an early stage, for instance, 0.1 ms aSOI, increases with injection pressure. However, at the later stage, for example, at 0.5 and 1 ms aSOI, liquid penetration length is almost the same for all the injection pressures. In the early stage, the momentum controls the liquid penetration length and velocity, but in the later stage, it is driven by evaporation. Droplet travels from nozzle to this steady state spray front and diminishes due to evaporation. At higher injection pressure, a shorter time is required for spray droplets to evaporate, because of the enhanced liquid break-up, and smaller droplets formation. A smaller droplet size leads to the bigger surface area to volume ratio, which leads to faster evaporation. Another reason could be the higher relative velocity to ambient gas, which also results in enhanced evaporation at higher injection pressures. Fig. 10 compares the influence of injection pressure on liquid and vapor penetration length. It is interesting to note that for the liquid phase, the impact of injection pressure on the quasi-steady state penetration length is marginal, which was also observed on ECN spray G [27].

3.1.2. Effect of ambient gas density and temperature

Fig. 11 shows a comparison between two different ambient gas conditions. Shaded error band represents the standard deviation of three repeats. At different injection pressures, the ambient gas conditions show similar effects. It is interesting to note that the vapor penetration for a case of the ambient density of $13.87 kg/m^3$ and the

ambient temperature of 500 K is shorter because of higher ambient gas density whereas, the liquid penetration is longer due to lower ambient gas temperature for all injection pressure cases.

3.1.3. Effect of ambient gas compositions

Fig. 12 shows the effect of ambient gas composition on liquid and vapor penetration for different injection pressure and ambient density and temperature. For vapor phase, spray penetration behaves almost the same for two different gases. For liquid phase, gas composition with higher molecular weight (Gas No.2) shows longer liquid penetration length similar to results found in literature [11]. The reason for the longer liquid penetration length under ambient gas with high molecular weight is that the ambient gas pressure is lower when the molecular weight is higher for the same density and temperature. Thus pressure drop on the nozzle is higher, which results in higher momentum. Fig. 13

shows the image comparison between the liquid and vapor phase penetration for injection pressure of 450 bar, ambient density of $13.87 kg/m^3$ and ambient temperature of 500 K. It can be seen that as explained earlier, the liquid penetration under high molecular weight ambient gas is longer than in the other gas composition. However, the vapor phase penetration shows no significant differences under both ambient gas compositions.

3.2. Prediction correlations

3.2.1. Vapor penetration

Fig. 14 shows the logarithmic plot of vapor penetration length with Time aSOI. Unlike the two zones separated by the so-called “transition time” or “break-up time” reported in literature [11,13,19], vapor phase penetration length in logarithmic scale shows excellent linear behavior in the entire injection duration. Thus a single prediction formula for entire injection duration is developed as shown in the following Eq. (1).

$$S_v(t) = k \cdot (\Delta P)^a \cdot t^b \quad (1)$$

where S_v is the vapor penetration length, t is the time after start of injection, k is a coefficient and it's a function of ambient gas density (ρ_a), and ΔP is the pressure difference ($\Delta P = P_{inj} - P_{amb}$, P_{inj} is the injection pressure and P_{amb} is the ambient gas pressure).

Table 4 shows that higher ambient gas density has a smaller coefficient $k(\rho_a)$, which is reasonable and matches with experiment results. Based on the correlation obtained in Eq. (1), comparison of prediction and experiment data are plotted in Fig. 15. It shows good confidence in

Fig. 8. Shadowgraph image sequences for different injection pressures of (a) 100 bar, (b) 300 bar, (c) 450 bar at ambient gas composition – Gas No.1; ambient density – 13.87 kg/m³, ambient temperature – 500 K.

the correlation.

3.2.2. Liquid penetration

Liquid penetration length in logarithmic scale (Fig. 16) shows that the curves are separated into two regions at a certain time, which is named as “separation time (t_1)” in this work. It should be noted that this “separation time (t_1)” is not the “transition time” or “break-up time” for cold jet mentioned in literature [11,13,19]. This separation point is due to the evaporation of liquid under high ambient gas temperature. For simplification, the regions earlier and later than separation time (t_1) are linearly fitted respectively. Separation time (t_1) advances with increasing injection pressure and increasing ambient gas temperature, similar trend was found by Payri et al. [28] for evaporative diesel spray. When the injection pressure is higher, droplet size formed are smaller thus droplet evaporates faster and the separation point advances. When the ambient gas temperature is higher, droplets also diminishes faster and leads to the advance of the separation point. Fig. 17 shows an example on how the t_1 is defined and penetration curve is piece-wise fitted. The same procedure is used for all the other data sets to arrive at the Eq. (2) and (3).

$$S_l = k_1 \cdot (\Delta P)^a \cdot t^b \quad t < t_1 \quad (2)$$

$$S_l = k_2 \cdot (\Delta P)^a \cdot t^b \quad t > t_1 \quad (3)$$

Fig. 9. DBI image sequences for different injection pressures of (a) 100 bar, (b) 300 bar, (c) 450 bar at ambient gas composition – Gas No.1; ambient density – 13.87 kg/m³, ambient temperature – 500 K.

where S_l is the liquid penetration length, t is the time after start of injection, k_1 is a coefficient and it's a function of ambient gas density (ρ_a) and ambient gas temperature (T_a), k_2 is a coefficient and it's a function of ambient gas density (ρ_a), ambient gas temperature (T_a) and ambient gas composition (Gas) and ΔP is the pressure difference ($\Delta P = P_{inj} - P_{amb}$, P_{inj} is the injection pressure and P_{amb} is the ambient gas pressure).

Eqs. (2) and (3) shows the correlation in the different regions separated by the separation point (t_1), and their corresponding coefficients are listed in Table 5. For the region before separation point, the two different ambient gases behave the same as it is shown in Fig. 12. Therefore, the gas component is not considered in the coefficient k_1 . But it includes the influence of ambient gas density and gas temperature. In this study, ambient gas density and temperature are not isolated, which requires further investigation in the future. For the region later than separation point, ambient gas compositions affect penetration length as the pressure drop on the nozzle is different with different gas compositions. Therefore, the coefficient k_2 is influenced by ambient gas density, temperature, and compositions.

The exponential “ a ” obtained in this study in the region earlier than separation point (t_1) is similar to the power of Weber number ($t \geq t_b$, $R \geq 12500$) reported by Zhang et al. [16], although the correlation developed by them is for cold jet, using a multi-hole diesel injector, and different fuel. The exponential “ b ” (0.646), is also similar to

Fig. 10. Influence of injection pressure on liquid and vapor phase penetration length. (a) Ambient gas composition – Gas No.1; ambient density – 8.67 kg/m³, ambient temperature – 800 K (b) Ambient gas composition – Gas No.1; ambient density – 13.87 kg/m³, ambient temperature – 500 K.

Fig. 11. Influence of ambient gas density and temperature for different injection pressures of (a) 450 bar injection pressure; (b) 300 bar injection pressure; (c) 100 bar and ambient gas composition – Gas No.1.

Fig. 12. Influence of ambient gas compositions for different injection pressures of (a) 450 bar injection pressure; (b) 300 bar injection pressure; (c) 100 bar and ambient gas densities of 8.67 and 13.87 kg/m³ and temperatures of 800 and 500 K respectively.

Fig. 13. Influence of ambient gas compositions on liquid and vapor penetration for injection pressure of 450 bar, ambient gas density of 13.87 kg/m³ and ambient temperature of 500 K.

Fig. 14. Vapor penetration length in logarithmic scale.

Table 4
Ambient gas density dependent coefficient, Eq. (1).

Eq. (1)	k	a	b
13.87 kg/m ³ , 500 K	4.9545	0.28	0.5514
8.67 kg/m ³ , 800 K	5.6532

Fig. 15. Comparison of prediction and experimental measurement for vapor penetration length.

Fig. 16. Liquid penetration length in logarithmic scale.

Fig. 17. Piece-wise fitting in logarithmic scale.

0.638 obtained in [16] for ($t \geq t_b$). This comparison between current study and study by Zhang et al. [16] shows that the results for $t < t_1$ obtained in this work is comparable with the zone ($t \geq t_b$) in literature. Fig. 18 shows the comparison between correlation prediction and experimental data. Black dots represents data earlier than t_1 and red dots for data later than t_1 . It shows good confidence of the correlation developed in this study for high injection pressure gasoline multi-hole injector.

Table 5
Coefficient for liquid penetration correlation.

Eq. (2)	Gas	k_1	a	b
13.87 kg/m ³ , 500 K	–	4.1779	0.318	0.646
8.67 kg/m ³ , 800 K	–	3.886		
Eq. (3)	Gas	k_2	a	b
13.87 kg/m ³ , 500 K	Gas No.1	8.3829	0.0903	0.1018
	Gas No.2	10.3112		
8.67 kg/m ³ , 800 K	Gas No.1	9.9752	0	
	Gas No.2	11.6373

Fig. 18. Comparison of prediction and experimental measurement for liquid penetration length.

Based on the correlation developed, comparison of penetration length between prediction and experiments are plotted for both liquid and vapor phase in Fig. 19. It shows an excellent agreement.

4. Conclusions

Influence of injection pressure, ambient gas condition, and ambient gas compositions are studied on spray liquid and vapor phase penetration using fuel and multi-hole injector specifically designed for GCI application. Ambient gas density exerted a similar influence on liquid and vapor penetration length. Higher ambient gas density led to shorter penetration length. This is due to the momentum exchange between spray and surrounding gas.

Higher injection pressure results in faster and longer vapor penetration length. Injection pressure affects liquid penetration only at an early stage. With higher injection pressure, spray penetrated faster to reach a steady state for the liquid phase. Momentum is the main cause of this phenomenon. But for liquid phase at quasi-steady state, penetration length does not change with injection pressure. Instead, the steady-state liquid penetration length is affected by ambient gas temperature, density and gas compositions.

The liquid penetration length was found to be longer in ambient gas composition of higher molecular weight. While the influence of increased CO₂ percentage on vapor penetration length was not observed. The mechanism of how gas compositions affect liquid penetration length should be further studied.

Correlations were developed for both the liquid and vapor phase penetration length with different ambient gas compositions. Two different regions caused by evaporation are distinguished for liquid penetration and piece-wise correlation was developed. Good agreement between correlation and the experimental results has been achieved. Ambient gas conditions should be expanded to find general correlations

Fig. 19. Comparison of penetration length versus time aSOI between experiment data and correlation prediction (100 bar, 300 bar, 450 bar injection pressure in each subplot).

for separation time t_1 , and further, isolate the influence of ambient gas density and temperature.

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