Fuel 232 (2018) 308–316

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

# Near-nozzle spray dynamics of 6-hole GDI injector under subcooled and superheated conditions

Jeeyeon Jeon[a], Seoksu Moon[b,a,*], Kiyotaka Sato[c], Takeshi Nagasawa[c]

[a] National Institute of Advanced Industrial Science and Technology, Japan
[b] Inha University, Republic of Korea
[c] Mazda Motor Corporation, Japan

ARTICLE INFO

*Keywords:*
Flash-boiling spray
Near-nozzle spray
Spray dynamics
Bubble dynamics
X-ray phase-contrast imaging

ABSTRACT

The flash boiling of fuel sprays can occur in engines when the fuel is injected into the ambient gas which pressure is lower than the saturation vapor pressure of the fuel. Recently, the flash boiling has attracted many engine researchers' interest due to its superior spray atomization performance. It has been discussed that the formation of the flash boiling sprays is governed by the bubble dynamics in the fuel such as bubble nucleation, growth, and burst. However, the detailed bubble dynamics and its effects on near-nozzle spray dynamics have remained a mystery due to great difficulties in the observation of flow characteristics inside and near the nozzle. The current study investigates the near-nozzle dynamics of flash boiling sprays from a 6-hole gasoline-direct-injection injector using an X-ray imaging technique. Various $R_p$ (ratio of saturated vapor pressure to ambient gas pressure) conditions were applied by altering the ambient pressure under the fixed fuel temperature. The results showed that the flash boiling did not alter significantly the emerging flow velocity at the nozzle exit. The center of flash-boiling sprays did not decelerate in the near-nozzle region while that of the subcooled spray showed a gradual deceleration. The radial velocity of the flash boiling sprays increased at the edge of the spray as $R_p$ increased while that in the spray center was near zero regardless of $R_p$ condition. The radial velocity of the flash boiling spray was solely governed by $R_p$ regardless of injection pressure while that of the subcooled sprays was altered by the injection pressure. Based on the results, the initial formation mechanism of the flash boiling sprays and the associated bubble dynamics were thoroughly discussed.

## 1. Introduction

Flash boiling is a violent boiling phenomenon that occurs when a liquid is present at a pressure lower than the saturation pressure of the liquid. In modern gasoline-direct-injection (GDI) engines, the flash boiling spray can be observed easily during the engine operation. When the heated up fuel is injected into the cylinder at the intake stroke, in which the pressure inside the cylinder is lower than the saturation pressure of the fuel, the injected fuel generates the flash boiling spray. In these days, as the flash boiling spray is treated as one of the strategies that can improve the spray atomization in modern GDI engines, many researchers have studied the flash boiling spray phenomenon in the engine [1,2]. Also, it has been reported that the promoted atomization of the flash boiling spray can improve the combustion and reduce engine-out emissions [3].

It is known that the higher the degree of superheat, the more favorable to generate the flash boiling sprays. The degree of superheat is defined as the difference between the fuel temperature ($T_f$) and the fuel boiling temperature ($T_{sat}$), as described in Eq. (1).

$$\Delta T = T_f - T_{sat} \tag{1}$$

There is another parameter that indicates the degree of superheat, which is the ratio of the saturation vapor pressure of the fuel ($P_{sat}$) to the ambient pressure ($P_{amb}$), as described in Eq. (2).

$$R_p = \frac{P_{sat}}{P_{amb}} \tag{2}$$

If $R_p$ is larger than 1 or $\Delta T$ is larger than 0, the condition is called as 'superheated condition' which can generate flash boiling sprays. If $R_p$ is less than 1 or $\Delta T$ is less than 0, the condition is called as 'subcooled condition'. $R_p$ and $\Delta T$ can be replaced each other since the saturation pressure is a function of fuel temperature. The larger these parameters, the more favorable to generate the flash boiling spray [4]. In this study, $R_p$ is used as the indicator of the degree of superheat.

It has been found from previous studies that if a flash boiling spray is generated, the dispersion angle becomes wider and the droplet size

* Corresponding author at: 100 Inha-ro, Nam-gu, Incheon 22212, Republic of Korea.
*E-mail address:* ss.moon@inha.ac.kr (S. Moon).

https://doi.org/10.1016/j.fuel.2018.05.147
Received 14 February 2018; Received in revised form 24 April 2018; Accepted 29 May 2018
0016-2361/ 

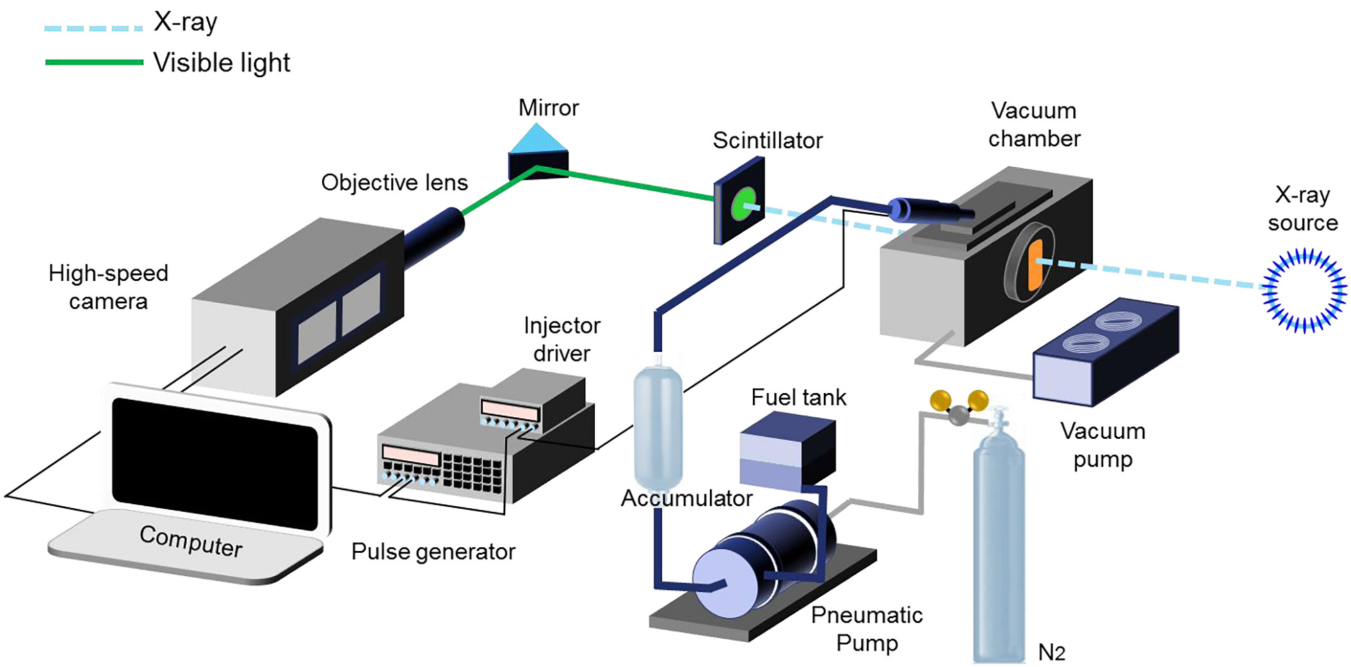


**Fig. 1.** Setup for the X-ray phase-contrast imaging.

becomes smaller compared to subcooled sprays [5–7]. When $R_p$ becomes larger, these characteristics become more apparent. This is due to the bubble dynamics involved in the liquid in the flash boiling condition. In the superheated condition, as the ambient pressure is less than the saturation pressure of the liquid, bubbles are created inside the liquid. It is known that the generated bubble increases through the phase transition of the liquid fuel, and then bursts when the surface tension of the liquid cannot overcome the expansion of the bubble. The bubble burst results in a larger dispersion angle of the spray and better atomization [8,9]. Especially, as the $R_p$ increases, it is known that the generation, growth and burst of bubbles become more active. Various models have been applied to simulate the bubble dynamics and flash boiling spray formation in detail. The models are composed several reasonable sub-models, such as bubble nucleation, growth and heat transfer during the growth process, which play a major role in the flash boiling process. However, regarding the bubble burst, which affects the spray dispersion and atomization, still, it is unclear when the bubble breaks down, and how it affects the spray formation. Some models assume that the bubble is broken when the void fraction of the liquid reaches a critical value [10]. Other models define the characteristic length, where the bubbles explode when the disturbance of the bubble diameter due to the bubble growth is greater than the characteristic length [11,12]. This phenomenon is supposed to occur inside the nozzle or near the nozzle, but the process has not been unveiled so far.

To clarify how the bubble bursts and affects the spray formation, many researchers have studied the behavior of the bubbles inside or near the nozzle and the relation of the bubble dynamics and initial flash boiling spray formation outside of the nozzle. Observation and quantification of bubble dynamics were made possible using transparent nozzles. Some studies have quantified the dependency of $R_p$ on bubble number density using the transparent nozzle [13–15]. Other studies have reported about the bubble burst in a single droplet under various ambient pressure and fuel temperature conditions [16]. However, despite many researchers' efforts, it is still difficult to observe the initial formation process and detailed dynamic structure of flash-boiling sprays near the nozzle exit, except the macroscopic shape of the spray. It is due to the limit of classical optical observation methods which suffer from severe absorption and scattering from the optically dense near-nozzle sprays.

The current study analyzes the near-nozzle dynamics of 6-hole GDI injector sprays under various flash boiling and subcooled conditions using an X-ray imaging technique. Based on the data of spray dynamics, the effects of the bubble dynamics on the initial flash boiling spray formation in the near-nozzle region were discussed. For the investigation, one subcooled spray, one transitional spray and three flash boiling sprays at different $R_p$ conditions were applied. The current study is divided into the two parts: one is the effects of $R_p$ on near-nozzle spray dynamics, and the other is the analysis of the spray spreading angle. In the spray dynamics part, the emerging flow velocity at the nozzle exit and the axial and radial velocity distribution of subcooled and flash boiling sprays will be compared. In the spray spreading angle part, the parameters that govern the spray spreading angle near the nozzle exit will be discussed. At last, the initial formation mechanism of the flash boiling sprays and the associated bubble dynamics were thoroughly discussed based on the results.

## 2. Methods and experiments

### 2.1. X-ray phase-contrast image (XPCI)

In this study, the X-ray phase-contrast image (XPCI) technique was used for the measurements. The XPCI is an imaging technique that uses X-ray which has an atomic level wavelength and ultra-short pulse duration. In the study of optically dense spray near the nozzle, the use of conventional laser sources (visible or ultraviolet light) causes severe scattering and absorption of the light which makes it difficult to obtain the morphology and dynamics information inside the spray. On the other hand, using X-ray which has an ultra-short wavelength (high energy) can pass through the dense spray region without severe scattering and absorption.

When the X-ray passes through the spray, some portion of the X-ray photons is absorbed by the spray. In the meantime, the phase-shift of the X-ray beam also occurs. The incident and phase-shifted X-ray beams interact each other at the boundary of liquid features in the spray and generate the interference fringe pattern. The XPCI records the interference patterns formed at the boundaries of liquid features as well as the intensity attenuation from the liquid features. The detailed information of the XPCI technique can be found in previous studies [17].