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Research Paper

Radial expansion of flash boiling jet and its relationship with spray collapse in gasoline direct injection engine

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HIGHLIGHTS

- Flashing sprays from single-hole and five-hole GDI injectors were studied.
- Relationship between spray collapse and radial jet expansion was revealed.
- Influence factors on radial jet expansion were examined in a wide condition range.
- Radial expansion of flashing GDI jets is dominated by $\Delta\mu$ and ambient resistance.

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ABSTRACT

In order to mitigate spray collapse and fully utilize the advantage of flash boiling injection in gasoline direct injection (GDI) engines, it is important to understand the flashing jet behavior and its relationship with spray collapse. In this study, n-hexane sprays discharged from a modified single-hole injector and the original five-hole injector were studied. The tests were carried out in a constant volume vessel with injection temperatures from 30 to 130 °C and ambient pressures (P_{amb}) from 20 to 101 kPa. By analyzing the relationship between the jet width and different parameters including superheat level, nucleation rate, and chemical potential of phase change ($\Delta\mu$), strong correlation was found between the jet width and $\Delta\mu \cdot P_{amb}{}^{-0.5}$, indicating the radial expansion of flashing jets was determined by chemical potential of phase change and ambient resistance. Beyond $20d_o$, the correlation was gradually weakened along the axis, as flash boiling process was finished. Besides, it was found that the extent of single-jet radial expansion was positively related to that of multi-jet spray collapse in the transitional collapse region. Therefore, to mitigate spray collapse, it is necessary to restrict the radial jet expansion, and generating external flashing jets is proposed as a practical approach to realize it.

1. Introduction

Flash boiling is a type of phase transition when a liquid is suddenly depressurized to a pressure lower than its saturation point. Flash boiling injection involves several physical processes such as nucleation, bubble growth, two-phase flow and atomization. Compared to subcooled liquid jets, flash boiling jets exhibit some favorable features such as improved atomization quality, shorter penetration length, as well as enhanced radial dispersion [1]. It has been found and applied in various industrial fields including automobile [2], spray cooling [3–5], desalination [6], and rocket propulsion [7].

Nowadays, gasoline direct injection (GDI) engine has become the mainstream power source of passenger cars. Because of the relatively high fuel temperature, flash boiling injection occurs frequently in GDI engines. It has been reported that up to 99% of injections during the 'New European Driving Cycle' were superheated in a mid-range car [8]. In GDI engines, multi-hole injectors are commonly used due to the feasibility in controlling fuel distribution. However, under flashing conditions, the multiple jets would collapse towards each other and even merge into one solid jet [9], which is called as 'spray collapse'. The occurrence of spray collapse could significantly change the fuel distribution and bring negative effects such as fuel-wall impingement [10–13], which is one of the main sources of soot formation [14] and super-knock [15].

In order to mitigate spray collapse and fully utilize the advantage of flash boiling injection in improving the atomization quality, the influencing factors of spray collapse has been studied intensively in the recent years [16–20]. Heldmann et al. [21] demonstrated that the

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Nomenclature

GDI	gasoline direct injection
d_O	inner hole diameter
P_{inj}	injection pressure
P_{amb}	ambient pressure
P_{sat}	saturation pressure
T_{inj}	injection temperature
R_p	superheat level
ρ_l	liquid density
σ	surface tension
m	molecular weight
R	gas constant
k_B	Boltzmann constant
N_A	Avogadro constant
v_l	specific volume of liquid
v_g	specific volume of gas
J	nucleation rate
ΔG^*	free energy barrier
X	indicator of nucleation rate
μ_l	chemical potential of liquid phase
μ_g	chemical potential of gaseous phase
$\Delta\mu$	chemical potential of phase change
ΔS	extent of spray collapse

occurrence of spray collapse is due to jet-to-jet interaction. Mojtabi et al. [22] revealed that superheat level and nozzle hole configuration are two key factors influencing the extent of spray collapse. Aori et al. [23] reported that spray collapse is more severe for nozzles with a symmetrical hole configuration and more holes. Aleiferis et al. [24] reported that with increased superheat level, the radial expansion of jets was enhanced and the spray collapse was intensified. The previous studies indicate that the extent of spray collapse is closely related to the radial jet expansion which enhances the jet-to-jet interaction. However, more quantitative analyses are necessary to yield practical approaches to mitigate spray collapse.

On the other hand, it is also important to characterize the flashing jets and figure out the influencing factors on the radial jet expansion. Indeed, massive studies have been carried out in the past to study the influencing factors on the radial expansion of flashing jets [25–29]. However, the injection pressure and nozzle geometry are much different to those of GDI injectors, which could cause significant difference in flashing jet behaviors [30–32]. Therefore, the conclusions in the previous studies can hardly be directly applied to GDI injectors, and studies based on real GDI injectors are necessary. However, only a few studies can be found so far studying the radial expansion of flashing jets using real GDI injectors or their real-size mockups. Serras-Pereira et al. [33] and Weber et al. [34] reported that the jet angle increased at higher injection temperature. Allocca et al. [35] reported that the jet angle increased at lower ambient pressures. Wu et al. [36] found a correlation between the superheat level R_p and the jet width at $20d_O$ from the nozzle exit, but the maximum injection temperature was only 85 °C, which is much lower than that of GDI engines [24].

The purpose of this study is to investigate the radial expansion of flashing jets and its relationship with multi-jet spray collapse. Hence, n-hexane jets discharged from a modified single-hole injector and the original five-hole GDI injector were studied in a constant volume vessel. The influencing factors on the radial jet expansion were examined over a wide range of conditions (injection temperatures from 30 to 130 °C, ambient pressures from 20 to 101 kPa). Besides, the relationship between multi-jet spray collapse and single-jet radial expansion was quantitatively analyzed. Based on the results, a novel approach to mitigate spray collapse was proposed.

2. Methodology

2.1. Experiment set-up

Fig. 1 shows the schematic of the experiment set-up. The tests were conducted in a constant volume vessel with two quartz windows mounted oppositely. The injector was mounted at the top of the vessel. The injection fluid was heated before entering the injector, and the injector was also heated to maintain the temperature. The two temperatures were kept identical and monitored by two thermocouples, respectively. Besides, the ambient pressure was realized by a centrifugal

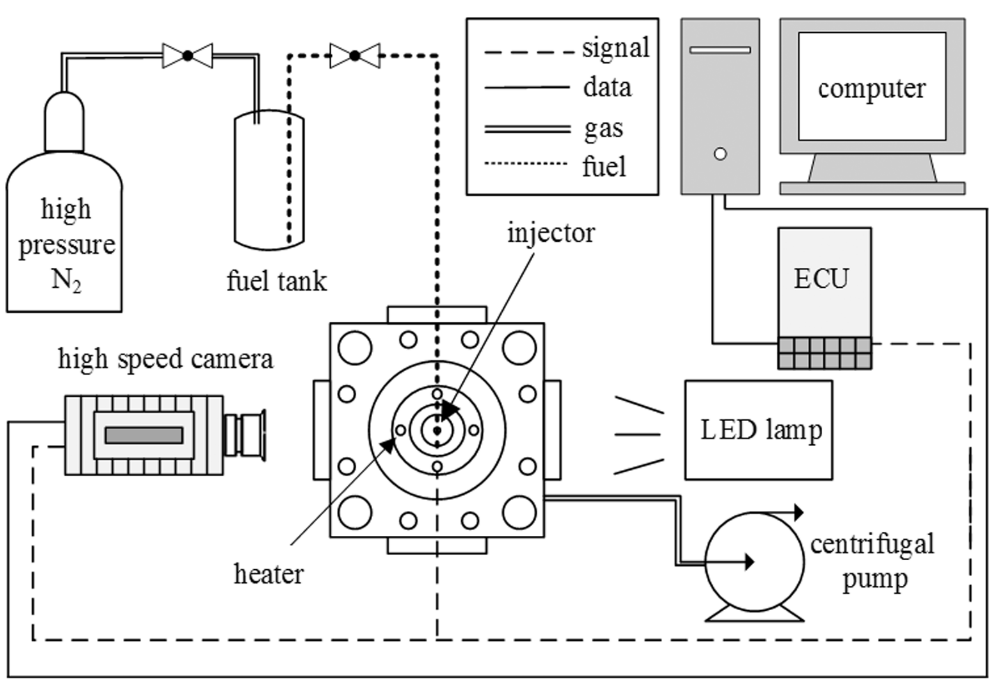

Fig. 1. Schematic of the experiment set-up.