Applied Energy 180 (2016) 598–606

Contents lists available at ScienceDirect

Applied Energy

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

Microscopic characterization of isooctane spray in the near field under flash boiling condition

Ziman Wang, Bo Wang, Changzhao Jiang, Hongming Xu *, Tawfik Badawy

School of Mechanical Engineering, University of Birmingham, Birmingham, UK

HIGHLIGHTS

- Ultra-high speed micro imaging technique was developed.
- Near field primary breakup characteristics of isooctane spray were investigated.
- The impact of flash boiling on primary breakup characteristics were probed.

ARTICLE INFO

Article history:
Received 25 April 2016
Received in revised form 26 July 2016
Accepted 27 July 2016

Keywords:
Primary breakup
Flash boiling
Superheating
Spray
Near field

ABSTRACT

The isooctane spray characteristics were experimentally investigated under flash boiling condition which represents the part load operating condition for modern gasoline engine. Various tests were carried out with back pressure ranging from 0.2 bar to 1 bar and ambient temperature varying between 20 °C and 100 °C. A long distance microscope together with an ultrahigh speed camera was employed to capture the spray development in the near field to study the primary breakup characteristics. The study was performed by using a diesel common rail injection system so that the influence of hydraulic force can be investigated. It was found that flash boiling led to dramatic radial propagation due to the explosion and collapse of the vapor bubbles, significantly boosting the atomization. The strength of vapor bubble explosion in the near field tended to be strongly affected by the flow regime in the nozzle. Besides, higher injection pressure led to larger cone angle during the initial injection stage but smaller cone angle during the quasi-steady stage due to the dominance of the hydraulic force.

1. Introduction

The fuel injection for modern GDI engine generally occurs during the intake stroke where the in-cylinder pressure is sub-atmospheric and the gas is quite warm, especially under hot idle condition [1,2]. At part load, the throttle is not fully open and the in-cylinder pressure may be lower than the vapor pressure of gasoline. Meanwhile, when the engine is fully warm, the cylinder head is quite hot and air sucked into the cylinder is heated. Two phases, namely, gas phase and liquid phase exist simultaneously when fuel is injected into such operating condition [3]. Generally, the phase transfer from liquid to vapor when liquid is heated under constant ambient pressure is defined as boiling. However, if the phase transfer occurs with constant temperature but lower ambient pressure, cavitation is expected [4]. When fuel is injected into this type of so-called flash boiling condition (the existence of both boiling and strong cavitation), the spray characteristics are quite different. This is because the depressurization leads to the collapse of spray, brings the plumes together and alters the desired direction of spray [4].

Flash boiling condition was reported to produce favorable combustible air/fuel mixture as the fuel pattern and spray atomization can be significantly improved [5]. This is mainly attributed to the explosion of the formed vapor bubbles, allowing the spray to propagate very quickly [2,3]. The large cone angle caused by the vapor bubble explosion leads to better fuel mixture since the plume becomes less dense. The appearance of flash boiling is thus expected to produce smaller droplets due to the aforementioned improved atomization and propagation [6]. Zhao [7] reported that for indolene, D32 was halved when fuel temperature varied from 20 to 90 °C with injection pressure of 11 MPa and ambient pressure of 0.1 MPa. This is explained by the occurrence of the flash boiling. However, when the back pressure was set to 0.6 MPa, only 1.9 μm reduction of droplet size was achieved with the rise of temperature from 20 to 90 °C. The HC was also reported to be lowered because of the reduced possibility of fuel impingement caused by the reduced plume velocity [8].

* Corresponding author.
E-mail address: h.m.xu@bham.ac.uk (H. Xu).

http://dx.doi.org/10.1016/j.apenergy.2016.07.115
0306-2619/

The near field primary breakup study under flash boiling is of great interest since this stage initiates the spray breakup and dominates the resultant secondary breakup and fuel mass distribution [9,10]. To obtain plume morphology development and spray behavior, long distance microscope with the help of lighting is generally employed [11–13]. Aleiferis et al. [4] experimentally studied the impact of various injecting factors, including ambient pressure, fuel temperature and fuel properties on the spray behavior in the near field during the quasi steady stage with a transparent injector. Fuel temperature varied between 20 and 90 °C while the ambient pressure was set to 0.5 and 1 bar. The low and high ambient pressures can represent the part load and WOT operating conditions. It was reported that the interaction between the boiling and cavitation considerably complicates the spray behavior. The rise of temperature led to reduced viscosity and surface tension but raised vapor pressure, boosting the growing rate of vapor bubbles. However, the frame speed of the employed Photron- APX camera in their study was 9000 fpm which was very low [4]. This low frame speed resulted in the loss of some very important information, especially during the initial spray developing stage.

The study on the primary breakup of gasoline spray under flash boiling condition at microscopic level is still very limited. The plume development during the initial stage obtained through ultra-high frame speed is unavailable. Besides, the interaction between flash boiling and cavitation at elevated pressure requires deep study. To address these unknown questions, a long distance microscope complete with an ultra-high speed camera was employed in the present study to investigate the plume behavior under various flash boiling conditions. A modern diesel common rail injection system was used so that the study could be carried out under high injection pressure which tended to be a trend for future gasoline engine. A single-hole diesel injector was also employed to eliminate the effects of interaction between plumes when a multiple-hole injector was used.

2. Experimental setup

The experimental setup for primary breakup is presented in Fig. 1. A high pressure vessel (pressure limit of 7 bar) with 2 inline glass windows (diameter of 10 cm) was employed. A cylindrical single-hole solenoid diesel injector with the nozzle diameter of 0.18 mm was used for the tests. The ambient temperature in the vessel was varied from 20 °C to 100 °C by using the 8 heaters located at the 8 corners of the vessel. The ambient temperature was kept stable with a close loop PID controller to control the 8 heaters with the feedback from a thermocouple. Meanwhile, the adoption of the vacuum pump allowed the ambient pressure to range between 0.2 and 1 bar and the ambient pressure could be monitored by the pressure gauge.

The optical setup includes an ultra-high speed camera, a long distance microscope, a lens and a 500-Watt xenon lamp. The frame speed of the camera was set to 1 million fps with the resolution of 312×260 pixel^2, giving extremely high temporal resolution (1 microsecond interval between two sequent images). The long distance microscope worked at the focusing distance of 18 cm, allowing an observation field of 1.8×1.46 mm for height and width respectively. This gave very high spatial resolution of 5.8 μm/pixel. The spray development process with detailed information which cannot be studied with traditional high speed imaging technique can be captured accurately by this ultra-high speed imaging technique. The lens was employed to focus the light at the injector tip so that the spray can be illuminated sufficiently when the ultra-high frame speed was used.

3. Test fuel and test conditions

To simplify the tests and quantify the fuel properties, isooctane rather than commercial gasoline was tested in the present study. The vapor pressure (Fig. 2) is of great importance for spray dispersion under flash boiling condition. When the ambient pressure is lower than the vapor pressure, isooctane transfers from liquid phase to gas phase. Other properties of isooctane are shown in Table 1.

To study the effects of flashing boiling condition on the spray collapse at the microscopic level, four tests under the injection pressure of 400 bar were carried out, which are A, B, C, and D as shown in Fig. 2. The injection duration was set to 1.2 ms, allowing the injector to fully open to study the quasi-steady state characteristics. For test point A with back pressure of 1 bar and ambient temperature of 20 °C, no flash boiling could be observed and this point is used as reference for the comparison with other test points. Point

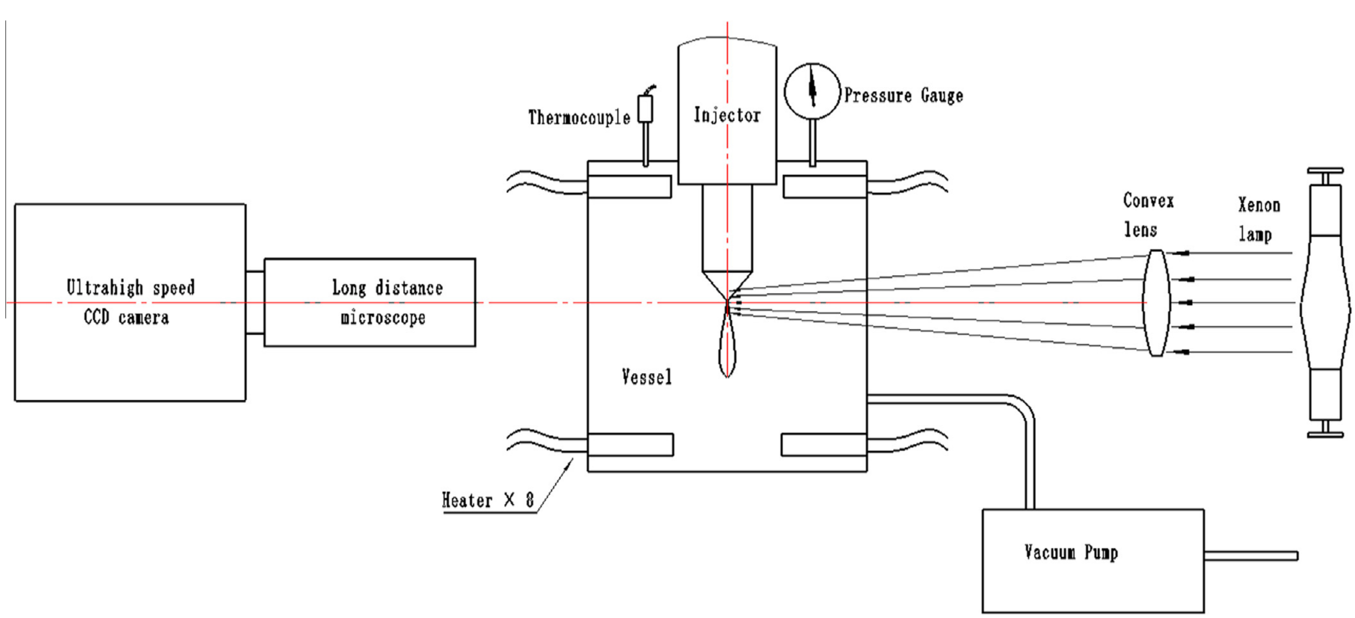

Fig. 1. Experimental setup.