International Journal of Heat and Mass Transfer 127 (2018) 244–254

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Analysis of evaporation characteristics and heat transfer for flash-boiling sprays

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ARTICLE INFO

Article history:
Received 4 December 2017
Received in revised form 23 June 2018
Accepted 4 July 2018

Keywords:
Liquid temperature
Vapor concentration
Heat transfer
Flash-boiling spray
LIEF

ABSTRACT

In order to improve engine thermal efficiency with reduced emissions, substantial studies have been carried out to improve the atomization and evaporation of fuel sprays, as well as fuel-air mixing in the engine cylinder. It has been found that flash-boiling spray is an effective way to achieve these goals. To further understand the evaporation characteristics and hear transfer phenomena between flash-boiling sprays and ambient gas, liquid temperature and vapor concentration of flash-boiling spray were measured quantitatively using laser induced exciplex fluorescence (LIEF) technique. The effects of fuel temperature, ambient pressure and superheated index (P_a/P_s) on the evaporation characteristics and heat transfer of fuel spray were investigated. The experimental results demonstrate that compared with non-flash-boiling spray, the rapid evaporation of flash-boiling spray leads to a higher vapor concentration along the center line. Meanwhile, the remarkable amount of energy absorbed from liquid phase of flash-boiling spray results in a faster liquid temperature decrease along the center line. When hot fuel is injected into cold environment, increasing fuel temperature leads to an increase of heat transfer from fuel spray to ambient gas because of the higher temperature difference between them. On the other hand, increasing ambient pressure decreases the evaporation rate of fuel spray due to the higher P_a/P_s. As such, the energy absorbed for fuel evaporation from liquid phase of spray is decreased, the heat transfer from fuel spray to ambient gas is increased.

1. Introduction

In recent decades, spark-ignition direct-injection (SIDI) engines have been studied worldwide because of their higher fuel economy, faster dynamic response, and lower hydrocarbon emissions during cold start, compared with port-fuel-injection (PFI) engines [1]. Since the fuel is directly injected into the combustion chamber, the quality of fuel-air mixture and combustion processes are governed by fuel spray characteristics. Therefore, promoting the spray atomization and evaporation is an important way to improve the fuel economy and reduce the hydrocarbon emissions for SIDI engines [2].

It has been reported that flash-boiling is effective to promote spray atomization and evaporation [3–8]. Flash-boiling occurs when liquid fuel is injected into an environment below its saturation pressure, as such the fuel will instantaneously evaporate as it enters the environment. Flash-boiling can be observed at many part-load, throttled conditions in SIDI engines due to the low combustion cylinder pressures [4,9]. Because of nucleation, growth, and explosion of vapor bubbles, flash-boiling sprays exhibit significantly different characteristics compared with non-flash-boiling sprays. To describe spray characteristics under flash-boiling conditions, Zeng et al. [5] successfully used the superheated index (P_a/P_s) defined as the ambient-to-saturation pressure ratio, which was similar to the superheated degree in principle, to study flash-boiling spray generated by a multi-hole injector. In existing literature, extensive studies have showed that flash-boiling spray exhibits a larger cone angle of an individual spray plume, smaller droplet sizes, and a faster evaporation rate [3,5,10–14]. In addition, it has been reported that flash-boiling sprays can improve the performance of direct injection (DI) engines in the aspect of combustion stability, fuel economy and emission reductions [15–17].

The process of flash atomization and vaporization is clearly described as the subsequent occurrence of nucleation, bubble growth, breakup through bubble disruption, and droplet evaporation, but unfortunately, the prediction and control of such phenomena is still hampered by the unavailability of validated theoretical models for each sub-process [18]. Distinctive heat and mass transfer characteristics are the keys to further investigate

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.023
0017-9310/

the evaporation mechanism of flash-boiling spray and provide a reliable and consistent experimental database for assessing the accuracy of model predictions and their range of validity. In order to understand the heat and mass transfer process, accurate temperature and mass concentration measurements of the flash-boiling spray are necessary. Among diagnostics techniques, laser-induced fluorescence (LIF) is one of the widely applied techniques to measure the liquid temperature of spray [18–20]. For instance, Vetrano et al. [18] utilized LIF technique to investigate liquid temperature of fuel spray with rhodamine B as the tracer. Their results demonstrated that the liquid temperature of fuel spray transitioned very rapidly to equilibrium under flash-boiling conditions. It is worth noting that due to the coexistence of liquid and vapor phases, it is challenging to distinguish the required fluorescence signals of liquid phase and vapor phase from an evaporating fuel spray. Therefore, the vapor concentration could not be properly measured by conventional LIF techniques because the liquid-phase temperature measurement could be affected by the fluorescence signal from the vapor phase, especially under flash-boiling conditions where a significant amount of vapor is expected.

To separate the fluorescence signal of liquid phase from that of vapor phase, laser-induced exciplex fluorescence (LIEF) was developed with two dissolved tracers [21–24]. Zhang et al. [25] investigated the vapor concentration and liquid temperature of flash-boiling spray with a multi-hole injector using LIEF. They found that the vapor was concentrated along the centerline of the multi-hole spray due to the spray collapse. This is because the high liquid temperature region was located along the centerline and vicinity of spray tip as the spray collapses, resulting in high vapor concentration and vortex structure under the flare flash-boiling conditions. However, due to the plume-to-plume interaction and collapse of multi-hole fuel spray under superheated conditions, the physical mechanism of flash-boiling spray itself was not fully explained. Besides, the temporal characteristics and heat transfer of flash-boiling spray were not investigated in Zhang et al. 's study.

To resolve these issues caused by the multi-hole injector setting, a single-hole injector is applied to further investigate the flash-boiling spray in this current study. An experimental study on heat transfer and evaporation characteristics of flash-boiling spray with a single-hole injector was implemented to understand the physics behind flash-boiling. Vapor concentration and liquid temperature distributions were measured quantitatively at various conditions using laser-induced exciplex fluorescence technique. In this study, heat transfer between fuel spray and ambient gas is investigated to further understand the effect of interaction between spray and ambient gas during spray evaporation. The heat transfer phenomena can provide us more information to build up an accurate flash-boiling spray heat transfer model. In addition, effects of fuel temperature and ambient pressure on liquid temperature, vapor concentration and heat transfer are studied. Based on quantitative analysis, this research aims to provide a deeper insight into the complex evaporation characteristics of flash-boiling sprays.

2. Methodology

2.1. Laser induced exciplex fluorescence (LIEF) technique

LIEF technique, in which two tracers are added into an optically transparent base liquid, is an extended application of traditional LIF methods [23]. The two tracers used in LIEF are known as the monomer (M) and ground-state exciplex forming molecule (G), respectively. The fluorescence signal from excited monomer (noted as M^*) is collected to represent vapor concentration, while that emitted due to the photochemical reaction of M^* and G is used to trace the liquid phase. More details of LIEF technique can be found elsewhere in the references [21–25].

The laser-induced fluorescence intensity at a wavelength λ can be expressed as [19]:

$$I = K_{opt,\lambda} K_{spec,\lambda} V_c I_0 C e^{\beta_\lambda / T} \tag{1}$$

where K_{opt} and K_{spec} are two constants related to the optical system arrangement and spectral properties of the tracer, V_c is the measuring volume, I_0 is the incident laser energy, C is the concentration of fluorescent tracer, β is a constant interpreted as a spectral temperature sensitivity coefficient, and T is the temperature of fluorescent tracer. In an oxygen-free environment, the quenching process has a negligible impact on the fluorescence intensity of the fluorobenzene (FB)/diethyl-methyl-amine (DEMA)/n-hexane mixture used in this study [23]. Therefore, the fluorescence intensity from the vapor phase (I_{vapor}) can be simplified to:

$$I_{Vapor} = K_{vapor}(\lambda_1, T) C \tag{2}$$

If the vapor coefficient factor (K_{vapor}) is well calibrated under a known temperature, the vapor concentration can be measured quantitatively.

For the liquid temperature measurement, two fluorescence signals of liquid phase at different wavelength are recorded to calculate the fluorescence intensity ratio ($R(T)$) which can be expressed by [19,25]:

$$R(T) = \frac{I_{\lambda_2}}{I_{\lambda_3}} = \frac{K_{opt,\lambda_2} K_{spec,\lambda_2} V_c I_0 C e^{\beta_{\lambda_2}/T}}{K_{opt,\lambda_3} K_{spec,\lambda_3} V_c I_0 C e^{\beta_{\lambda_3}/T}} = K_0 e^{\frac{\beta_{\lambda_2} - \beta_{\lambda_3}}{T}} \tag{3}$$

As a reference condition T_0 is chosen to calibrate the constant coefficients in Eq. (2), Eq. (3) can be further simplified as:

$$In\left(\frac{R(T)}{R(T_0)}\right) = \left(\beta_{\lambda_2} - \beta_{\lambda_3}\right)\left(\frac{1}{T} - \frac{1}{T_0}\right) = \Delta\beta\left(\frac{1}{T} - \frac{1}{T_0}\right) \tag{4}$$

Then, the relationship between fluorescence intensities and temperature of liquid phase can be obtained after $\triangle\beta$ is calibrated with a known fluorescence ratio $R(T_0)$.

2.2. Calibrations of liquid temperature and vapor concentration

In this study, as mentioned, fluorobenzene (FB) and diethyl-methyl-amine (DEMA) are chosen as the tracer pair, and the base fuel is n-hexane. The volume fractions of FB, DEMA and n-hexane are 2%, 9% and 89%, respectively. Since these components have similar boiling points (BP), as shown in Table 1, the chosen fuel mixture has a good co-evaporation characteristic [26]. The fluorescence spectra of vapor and liquid phases of n-hexane/FB/DEMA mixture excited by 266 nm laser are shown as solid curves in Fig. 1 [23]. Three band-pass filters were used to detect the fluorescence signals from vapor and liquid fuel, and their transmission characteristics are also presented as dashed curves in Fig. 1. Detailed selection procedures and recommendations of fluores-

Table 1
Experimental specification and conditions.

Parameter	Specification
Injector	Single-hole, L/D = 2.5
Fuel (BP @101 kPa)	2% FB (356 K), 9% DEMA (338 K), 89% n-hexane (341 K)
Injection pressure (P_{inj}, MPa)	10
Ambient pressure (P_a, kPa)	40, 80, 100
Fuel temperature (T_f, K)	318, 338, 358
Ambient temperature (T_a, K)	298 ± 1
Injection duration (ms)	1.0 (2.09 mg)