International Journal of Multiphase Flow 57 (2013) 151–158

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Vaporization of a liquid hexanes jet in cross flow

Jeongseog Oh [a,*], Jong Guen Lee [b], Wonnam Lee [c]

[a] Energy Efficiency Department, Korea Institute of Energy Research, Daejeon, Republic of Korea
[b] School of Aerospace Systems, University of Cincinnati, Cincinnati, OH, USA
[c] Department of Mechanical Engineering, Dankook University, Yongin, Gyeonggi, Republic of Korea

ARTICLE INFO

Article history:
Received 25 April 2013
Received in revised form 3 August 2013
Accepted 5 August 2013
Available online 17 August 2013

Keywords:
Jet-in-crossflow
Hexanes vapor concentration
Infrared laser extinction method
Lab-scale test section
Plain orifice-type injector

ABSTRACT

The vaporization characteristics of a liquid hexanes jet in a lab-scale test section with a plain orifice-type injector were experimentally investigated. The experimental measurements were carried out on the basis of the infrared laser extinction method using two He–Ne lasers (one at 632.8 nm and the other at 3.39 μm). The momentum flux ratio ($q_{F/A}$) was varied from 20 to 60 over 20 steps, and the supplying air temperature (T_A) was changed from 20 to 260 °C over 120 steps. The objectives of the current study were to assess the vaporization characteristics of a liquid hexanes jet and to derive a correlation between flow conditions and hexanes vapor concentration in a jet-in-crossflow configuration. From the results of the experimental measurement, it was concluded that hexanes vapor concentration increased with the increase of the momentum flux ratio and the supplying air temperature. An experimental correlation between flow conditions and hexanes vapor concentration (Z_F) was proposed as a function of the normalized horizontal distance (x/d_o), the supplying air temperature (T_A), the momentum flux ratio ($q_{F/A}$), the fuel jet Reynolds number (Re_F), and the fuel jet Weber number (We_F).

1. Introduction

The vaporization of a liquid jet in crossflow is an important subject, as this injection method is available to evaluate spray models in fundamental studies and has been widely used in the combustion process of industrial burners or air-breathing engines, such as gas turbines, ramjets, and scramjets. It is necessary to understand the vaporization process, because engine performance and emission characteristics depend on mixture distribution and the liquid jet in crossflow affects vaporization behaviors.

Jiang et al. (2011) reviewed the modeling of two-phase flow between liquid and gas in atomization and spray. They divided the spray process of liquid fuel from injection atomization into three regions: atomization, dense spray, and diluted spray. Each section includes blobs/ligament/droplets for the atomization region, ligaments/droplets for the dense spray region, and droplets for the diluted spray region.

Faeth et al. (1995) reported on the breakup mechanisms of a liquid jet. They divided the spray region into three parts: a dense spray region, primary breakup region, and secondary breakup regime. In a liquid column region, Wu et al. (1997) derived the experimental approximation of a droplet trajectory related to the fuel-to-air momentum flux ratio.

During the vaporization process, droplets are known to have two types of vaporization modes: steady-state and unsteady state (Gary and Kenneth, 1998). In steady state vaporization, the droplet diameter decreases with a well-known D^2-law. This steady state includes several assumption, i.e. diffusion controlled evaporation, pure species, spherical droplet, constant uniform droplet temperature, and no droplet heating. The droplet surface evaporates as time goes by, while the droplet core might remain cold (Balasubramanyam and Chen, 2008). On the other hand, during unsteady-state vaporization, conduction and internal recirculation occur in the droplet due to the heat transfer caused by the aero-thermal interaction. One of cases in unsteady vaporization is that the droplet core heats up below the boiling point. And, in another case of unsteady vaporization, the droplet core can suddenly burst if the droplet is superheated.

When a liquid jet is injected into a free-stream air flow, the primary droplets and ligaments break loose from the liquid column, and the secondary droplets are split from ligaments, satellites, or blobs. After the liquid breakup, droplets are vaporized on the surface due to heat transfer and interaction with the surrounding air. The concept of a liquid jet in crossflow is shown in Fig. 1. In the current study, the surrounding air Reynolds number at a test section inlet (Re_A) was ranged in 51,518–106,611 while the fuel jet Weber number at a fuel jet nozzle exit (We_F) was ranged in

* Corresponding author. Address: Energy Efficiency Department, Korea Institute of Energy Research, Daejeon 305-343, Republic of Korea. Tel.: +82 42 860 3479; fax: +82 42 860 3133.
E-mail address: jeongs5@kier.re.kr (J. Oh).

0301-9322/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijmultiphaseflow.2013.08.002

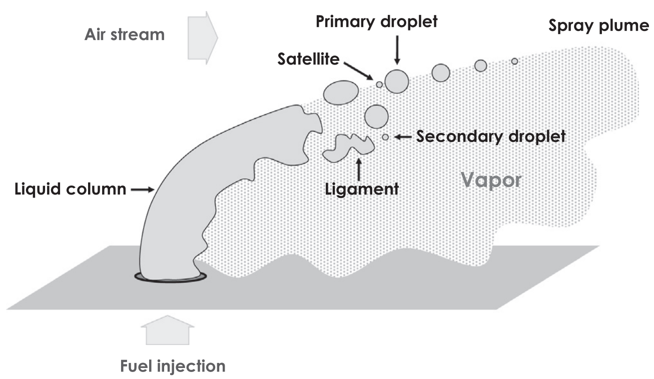

Fig. 1. Concept of a jet in crossflow.

1021–3062 which is responsible for a catastrophic breakup regime ($350 < We_F$).

Drallmeier (1994a,b) suggested the infrared extinction technique to measure hydrocarbon vapor concentration. Hydrocarbon vapor has C–H bond-stretching characteristics in the infrared region, which means that a laser beam is absorbed at certain frequencies. If the optical thickness of a non-absorbent wavelength is equal to an absorbent frequency, the hydrocarbon vapor concentration can be estimated based on the characteristics of laser extinction.

To measure the concentration distribution of liquid droplet vapor in a swirl type injector, Li et al. (2011) used the laser absorption–scattering (LAS) technique with Nd-YAG lasers. During the measurements, the ambient temperature and pressure were 500 K and 1.0 MPa, as an experimental condition. Two laser beams were used as light sources: ultraviolet light at 266 nm and visible light at 532 nm. The researchers found that the relative error of LAS was less than 8%.

In the current study, the vaporization characteristics of a liquid jet in a lab-scale test section with a plain orifice-type injector were experimentally investigated. The experimental measurement was carried out on the basis of the infrared laser extinction method. The hexanes vapor concentration was qualitatively measured; two He–Ne lasers were used to measure the reference beam (632.8 nm) and infrared (IR) emission (3.39 μm) intensity. The objectives of the present work were to study the vaporization characteristics of a liquid hexanes jet in cross flow and to derive an experimental approximation between flow conditions and hexanes vapor concentration in a lab-scale test section by using the infrared laser extinction method.

2. Experimental methods

A schematic of the experimental setup is shown in Fig. 2. The experimental facility included a lab-scale test section, lasers and optics, and a DAQ (data acquisition) system. The dimensions of the test section were 25.4 (width) × 25.4 (height) × 406.4 (length) mm, with two quartz windows mounted to allow optical access. Compressed air was supplied to the test section after passing through a heater with the power of 13 kJ/s. The fuel feeding line was connected from a vessel to an injector (injector outlet diameter, d_o = 0.259 mm). Hexanes were used as the fuel, comprising n-hexane 85%, methylcyclopentane, and hexane isomers. The flow rate of hexanes was metered by a rotameter. The momentum flux ratio ($q_{F/A}$) was varied from 20 to 60 over 20 steps, and the supplying air temperature (T_A) was changed from 20 to 240 °C in 110 steps (see Table 1).

To measure hexanes vapor concentration, an IR laser extinction technique was used (Drallmeier, 1994a,b). Two He–Ne lasers (LHX1, CVI Melles Griot co., Carlsbad, CA, U.S.A.) were used as light sources for simultaneous non-absorbing and infrared absorption measurements. One had a non-absorbing wavelength of 632.8 nm, and the other had an absorbing wavelength of 3.39 μm, which causes laser extinction due to the stretching of C–H bonds. The equation for the wavelength intensity ratio is

$$\frac{I}{I_0}(\text{at } 3.39\ \mu\text{m}) = \exp\left[-C_n \cdot l \cdot \frac{\pi}{4} \cdot \int_0^\infty Q_{sca} \cdot D^2 \cdot N(D)dD\right] \times \exp\left[-C_n \cdot l \frac{\pi}{4} \cdot \int_0^\infty Q_{abs} \cdot D^2 \cdot N(D)dD\right] \times \exp(-k_v \cdot P_v \cdot l) \quad (1)$$

where I is the signal intensity in an IR (infra-red) detector (3.39 μm), I_o is the standard signal intensity for normalization, I/I_o is the laser extinction intensity ratio, C_n is the number density of a gas molecule, l is the laser length along the line of sight, $N(D)$ is the line of sight averaged distribution of droplet diameter, k_v is the absorption coefficient of the fuel vapor, and P_v is the vapor concentration (Drallmeier, 1994a,b).

The optical thickness (τ) is calculated as follows:

$$\tau_{drop,3.39\mu m} = C_n \cdot l \cdot \frac{\pi}{4} \cdot \int_0^\infty Q_{ext} \cdot D^2 \cdot N(D)dD \quad \text{where} \quad Q_{ext} = Q_{sca} + Q_{abs} \quad (2)$$

where $Q_{ext}(D)$ is the extinction efficiency, $Q_{sca}(D)$ is the scattering efficiency, and $Q_{abs}(D)$ is the absorption efficiency; these were determined from Mie theory by the liquid phase refractive index of the drops at the characteristic wavelength.

The equation of a wavelength intensity ratio at 632.8 nm is

$$\frac{I}{I_0}(\text{at } 632.8\ \text{nm}) = \exp\left[-C_n \cdot l \cdot \frac{\pi}{4} \cdot \int_0^\infty Q_{sca} \cdot D^2 \cdot N(D)dD\right] = \exp(-\tau_{drop,632.8nm}) \quad (3)$$

where I is the signal intensity in a photo diode (632.8 nm).

From Eq. (1), the following relation can be deduced (Drallmeier, 1994a,b):

$$P_v = \frac{1}{k_v \cdot l_v} \cdot \left[-\tau_{drop,3.39\mu m} - \ln\left(\frac{I}{I_0}\right)_{3.39\mu m}\right] = \frac{1}{k_v \cdot l_v} \cdot \left[-\tau_{drop,632.8nm}\left(\frac{\tau_{drop,3.39\mu m}}{\tau_{drop,632.8nm}}\right) - \ln\left(\frac{I}{I_0}\right)_{3.39\mu m}\right] = \frac{1}{k_v \cdot l_v} \cdot \left[-\ln\left(\frac{I}{I_0}\right)_{632.8nm} \cdot R - \ln\left(\frac{I}{I_0}\right)_{3.39\mu m}\right] \quad (4)$$

where k_v is the absorption coefficient of the fuel vapor and l_v is the laser path way length in the fuel vapor.

If the optical thickness ratio (R) approaches 1 as the droplet diameter (D) becomes larger, the amounts of scattering and absorption intensity of both wavelengths are equal. The theoretical expression to calculate a vapor mole fraction (P_v) becomes

$$P_v = \frac{1}{k_v \cdot l_v} \cdot \left[-\ln\left(\frac{I}{I_0}\right)_{632.8nm} - \ln\left(\frac{I}{I_0}\right)_{3.39\mu m}\right] \quad (5)$$

That is, as the optical thickness ratio approaches 1,

$$R = \frac{\int_0^\infty (Q_{ext})_{3.39\mu m} \cdot D^2 \cdot N(D)dD}{\int_0^\infty (Q_{ext})_{632.8nm} \cdot D^2 \cdot N(D)dD} = \frac{(\tau_{drop,3.39\mu m})}{(\tau_{drop,632.8nm})} \to 1 \quad (6)$$

The laser extinction method is good for the quantitative or qualitative measurement of hydrocarbon fuel concentration in the gas-phase. However, this extinction method has limitations under the conditions of high pressure and dense droplet distribution, because the optical thickness ratio is no longer 1. In the current study, it