SPRAY MEASUREMENT USING OPTICAL LINE PATTERNATOR

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ABSTRACT In high-pressure environment, the high density of the droplets leads to attenuate both the incident laser beam and the emitted signals. For the quantitative measurement, the intensity of the attenuated signal should be corrected. Therefore, Optical Line Patternator (OLP) was applied to get the original distribution of the spray at high ambient pressure. Because OLP uses laser beam instead of laser sheet to scan the spray, the noise effect of multiple scattering, caused by increasing number density of droplet in high-pressure environment, is also reduced significantly. The line image of Mie-scattering was captured simultaneously in the path of each laser beam by using CCD camera. The transmission that was calculated the fraction of the intensity of incident laser beam and the attenuated intensity after traversing spray region, was measured by using a photo-diode. The distribution of attenuation coefficient in the spray was obtained by processing the transmission and Mie-scattering intensity of incident laser beam and the attenuated intensity after traversing spray region, was measured by using a photo-diode. The distribution of extinction coefficient from Mie-scattering from laser-induced fluorescence signal. OLP is expected as a suitable method that can investigate the characteristics of relatively large spray under the high-pressure environment such as liquid rocket engine.

Keywords: Spray, Imaging Technique, Extinction, High Ambient Pressure, Patternation

1. INTRODUCTION

The effective atomization of liquid fuel is important to provide high combustion efficiency and low pollution emission in most combustion systems [1]. Generally, the small mean drop size of liquid fuel leads to high heat generation per volume, and improve the combustion efficiency. However, if the fuel drops become too small, combustion may not occur at desired position. In addition, the distribution of drops may change the mixing efficiency of liquid fuel. These spray characteristics during atomization and mixing process can cause combustion instability in a large combustion system, such as, liquid rocket engine. Therefore, it is important to determine the global spray characteristics quantitatively in the development of the practical combustion systems.

For decades, spray researches have used mechanical patternator that have an array of tubes or sections to collect liquid in spray flow field, and optical diagnostic techniques, such as, Malvern particle analyzer, PDPA. Recently, planar laser techniques have been developed, for example, an optical patternator can determine the planar distribution of fuel mass and drop size rapidly by analyzing the spectral images of spray excited by laser sheet. However, a great number of drops in high ambient pressure cause severe errors in measurement due to incident laser attenuation, signal attenuation and multiple scattering. Therefore, it is difficult to obtain the reliable results with optical techniques in high ambient pressure like rocket engine combustor.

Recently, several groups have proposed the correction methods concerning these errors. As for the attenuation of the incident laser sheet, bidirectional excitation method has been used [2]. Talley et al. [3] used sequential illumination of the spray by counter-propagating laser sheets assuming only that extinction would occur according to Beer’s law. Sick et al. [4] discussed the bidirectional illumination and the sequential illumination method to address the attenuation of the incident laser beam. In addition, the non-uniform attenuation of the signal is also important, and the attenuation of the laser induced fluorescence (LIF) signals on their path should be quantified through the spray [3, 4]. Sick et al. [4] measured the quantity of attenuation for LIF signals through sprays using a laser dye cuvette, and tried to address the signal attenuation. When the light can be scattered by droplets several times in succession before it emerges from the dense spray (i.e. multiple scattering), even the very simplest law of scattering for the individual particles leads to complex mathematics [5]. Most imaging methods have assumed that the photons reaching the detector have been scattered only once, and few papers have been published on multiple scattering problems in three-dimensional geometries, such as, two-phase flows [6]. Brown et al. [7] have proposed that the optical patternation method, which probes the spray with a swept beam instead of a laser sheet, minimizes the opportunity for multiple scattering.

In this study, we used a laser beam to minimize the multiple scattering effects in high ambient pressure. The transmission of laser beam passing through spray was also used to quantify the attenuation of incident laser and emitted signal. Mie-scattering images were captured by CCD camera, and processed with simple reconstruction algorithm to determine the structure of a whole spray. Optical line patternator using the transmission of incident laser beam and the image recorded by CCD was applied to a solid-cone type spray in the atmospheric pressure condition. The result was compared with other planar laser technique to confirm the accuracy of measurement. Optical line patternator was also applied to characterize a liquid rocket injector in high-pressure condition.

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2. EXPERIMENTAL METHODS

2.1 Measurement Principles

The intensity of the incident laser beam, $I_0$, is attenuated exponentially within a dense spray region due to high number of droplets. After the beam passes through the spray region, the transmission ($I/I_0$) can be expressed as follows according to Beer’s law [8]:

$$I = I_0 \exp[-\gamma(x, y)ds]$$  \hspace{1cm} (1)

The attenuation coefficient, $\gamma$, is dependent on various parameters, such as the wavelength of incident light, the optics arrangement, the optical properties of medium where incident light is passing, and so on. For droplets significantly larger than the wavelength of incident light, the attenuation coefficient can be assumed to be proportional to the square of the droplet diameter [9]. When neglecting the effect of multiple scattering, the attenuation coefficient can be expressed as a function of number density of droplets, $N$, the cross-section of droplets in a spray where existing high number of droplets. Therefore, the droplet surface area per unit volume in a spray region can be obtained from the attenuation coefficient [10].

$$\gamma = c_{ext} \int N(D)D^2 dD$$  \hspace{1cm} (2)

where, $c_{ext}$ is the coefficient dependent on the efficiency of attenuation.

The intensity of Mie-scattering signal, $G$, is also assumed to be proportional to the droplet surface distribution [11, 12].

$$G = c_i I \int N(D)D^2 dD$$  \hspace{1cm} (3)

where, $c_i$ is the coefficient that is dependent on the efficiency of scattering phenomenon and detection system characteristics. If we can obtain the intensity distribution of Mie-scattering signal in a spray field by using optical detection system, such as, CCD camera, then we can determine both the distribution of attenuation coefficient and the droplet surface distribution.

As shown in figure 1, the intensity of incident laser beam is attenuated when passing through a spray region, and the intensity of Mie-scattering signal is also reduced due to high number of droplets between a measuring plane and a CCD camera. Assuming that the attenuation coefficients have the same value at each lattice dividing a spray field, the distribution of attenuation coefficients in a whole spray can be calculated from the measured transmittance and the intensity of Mie-scattering signal.

$$\sum_{i=1}^{n} \gamma_{i,j} L_{i,j} = -\log\left(\frac{I_{0,j}}{I_{0,i}}\right)$$  \hspace{1cm} (4)

$$(\frac{c_s}{c_{ext}})I_0 exp\left[-\sum_{h=1}^{i-1} \gamma_{h,i} L_{h,i}\right] \gamma_{i,j} = G_{i,j}$$  \hspace{1cm} (5)

where $L_{i,j}$ is determined by the spacing of incident laser beam and the size of pixels of CCD camera for analyzing spray images. $I_0/I_{0,i}$ is the transmission when the incident laser beam passes through $j$-th row of grid, and can be obtained by measuring the intensity of incident laser beam with a photo detector. $G_{i,j}$ is the intensity distribution of Mie-scattering signal. The signal attenuation is assumed to be negligible, and the extinction of incident laser beam is