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Effect of velocity profile of impinging jets on sheet characteristics formed by impingement of two round liquid jets

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ABSTRACT

The characteristics of a liquid sheet formed by the impingement of two round liquid jets are analyzed theoretically. Since the velocity profile of the impinging jet greatly affects the sheet characteristics, the sheet characteristics are analyzed using round impinging jets with uniform or parabolic velocity profiles. The calculated sheet shape is compared with the results of theoretical analyses reported in previous studies. The effects of the velocity profile of impinging jets on the sheet characteristics are shown theoretically. Experiments are conducted in order to verify the theoretical analysis using short and long nozzles. The sheet contour is determined by two mechanisms, i.e., the force balance at the periphery between the liquid inertia and the surface tension, and the unstable wave growth. A critical condition in which the sheet disintegrates as a result of the unstable wave growth is newly proposed. The predicted sheet shapes agree somewhat with the results of experiments using short and long nozzles. The predicted sheet breakup lengths calculated using the newly proposed critical condition agree well with the results of these experiments. The predicted sheet velocity distributions exhibit slightly smaller values compared with measurements reported in previous studies.

1. Introduction

For both boost and orbit transfer, the impinging-jet injector is commonly used in small bipropellant liquid rocket engines because of its simple fabrication and good spray and mixing characteristics. For a high-pressure boost engine with liquid oxygen and kerosene, the impinging-jet injector with a like-on-like configuration is widely used because of its good mixing and combustion performances. In this configuration, two liquid jets with the same properties impinge on one another at a certain impingement angle to form a thin liquid sheet. The liquid sheet thins with the radial distance from the impingement point, and the fluctuation of the liquid sheet continues to increase until reaching the breakup point, at which the liquid sheet disintegrates into large liquid clumps and then disintegrates into finer droplets downstream.

A number of researchers have experimentally and theoretically investigated the impinging jet injector. Fukui and Sato (1971) measured the sheet thickness and sheet velocity distributions in the case of normal impingement using the interferometric and PIV methods. Tokuoka and Sato (1977) measured the sheet thickness and sheet velocity distributions in the case of oblique impingement using the same methods to those used by Fukui and Sato. They also theoretically analyzed the liquid sheet flow using the uniform and parabolic velocity profiles in the impinging jets. And they compared the measurements with their analysis, and pointed out the importance of the velocity profile in impinging jets at the determination of a sheet shape. Lourme (1986) performed cold flow experiments on the spray characteristics of the like-on-like injector under a wide range of chamber pressures and deduced an empirical equation of mean drop size. Hautman (1991) also performed cold flow experiments on the like-on-like doublet injector and deduced the empirical equation of mean drop size as a function of the liquid and gas properties and the impingement velocity. Ryan et al. (1995) experimentally and theoretically investigated the atomization characteristics of impinging liquid jets and proposed a sheet disintegration model based on two existing theories. They deduced empirical equations of breakup length and mean drop size from their theoretical analysis and measurements. Lai et al. (1999) experimentally investigated the spray characteristics of like-doubled impinging jet atomization under a wide range of impingement angles. They clarified that the mean drop size decreases sharply with increasing impingement velocity in the low-impingement-velocity regime and decreases slightly in the high-impingement-velocity regime. Choo and Kang (2000) measured the thickness distribution of a liquid sheet formed by two impinging jets by the interferometric method and compared the measurement results with existing theoretical predictions. Strakey and Talley (2000) measured the spray characteristics of an impinging jet injector at high back-pressure. They reported that the Linear

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Stability Theory overestimates the breakup length of the liquid sheet at low gas densities, and the mean drop size is mildly dependent on the chamber pressure for a back-pressure of less than approximately 3 MPa. Recently, Bush and Hasha (2004) and Bremond and Villermaux (2006) analyzed the sheet flow generated by oblique impingement of laminar liquid jets. They considered the effect of thick rim on the periphery of a sheet and the velocity profile in the impinging jets. Choo and Kang (2007) also analyzed the sheet flow using the uniform and parabolic velocity profiles in the impinging jets, and compared their analysis with their measurements.

In most of the studies mentioned above, the Reynolds number of impinging jets is small, and the sheet flow seems to be laminar. In this condition, the edge of a liquid sheet is determined by the force balance between capillary force, sheet inertia and centrifugal force of a liquid flowing in a rim. On the other hand, in the practical use like a rocket engine injector, the Reynolds number is higher. In this condition, the sheet flow seems to be turbulent and the growth of a unstable wave on a sheet surface becomes dominant in a sheet breakup. Furthermore, in previous studies the length-to-diameter ratio of the liquid injection nozzle was large enough to guarantee the developed velocity profile at the nozzle exit. In some practical uses the liquid injection nozzle with small length-to-diameter ratio must be used. However, there are few experimental analyses that treat effects of the velocity profile in the impinging jet cross-section on the sheet characteristics.

In the present study, the sheet characteristics are analyzed theoretically based on the impingement of round liquid jets with uniform or parabolic velocity profiles. At the determination of a sheet shape the growth of a unstable wave on a sheet surface was considered besides the force balance. Moreover, the sheet shapes were measured experimentally using liquid injection nozzles with small and large length-to-diameter ratios to clarify effects of the velocity profile in the impinging jets, and the experimental results were compared with the predictions.

2. Theoretical analysis

2.1. Liquid sheet flow

Hasson and Peck (1964) theoretically analyzed the liquid sheet flow formed by two impinging jets. Ibrahim and Przekwas (1991) theoretically analyzed the liquid sheet flow using the initial sheet thickness hypothesis reported by Naber and Reitz (1988). Bush and Hasha (2004), Bremond and Villermaux (2006) and Choo and Kang (2007) theoretically analyzed the liquid sheet flow using the parabolic velocity profile in the impinging jets. Bush and Hasha and Bremond and Villermaux considered the effect of a rim on the sheet periphery at determining the sheet shape. In the present study, the liquid sheet flows produced by the impingement of two round jets are analyzed theoretically, expanding the theoretical analysis by Tokuoka and Sato (1977).

Prior to the theoretical analysis, the following assumptions were made:

(1) The axial velocity profile in the cross-section of a liquid jet is a uniform or parabolic distribution, and the radial velocity in the cross-section is neglected.
(2) The liquid in a liquid sheet flows radially from the stagnation point, and the velocity profile across a liquid sheet is uniform.
(3) The effects of a surrounding gas and gravity on the liquid sheet flow are ignored in the analysis of the liquid sheet flow.
(4) The liquid velocity is constant along the streamline in the liquid sheet from the stagnation point to the periphery of the liquid sheet. However, the velocity loss occurs during the impingement. Tokuoka and Sato (1977) compared calculations with measurements while varying the velocity coefficient, which indicates the ratio of the liquid velocity in the sheet to the impingement velocity and concluded that the calculations showed the best agreement with measurements when the velocity coefficient is 0.8. Therefore, in the present study, the velocity coefficient, φ, is assumed to be 0.8.
(5) The liquid flowing at a minute angle $d\alpha$ in the cross-section of a liquid jet flows at the same angle $d\alpha$ in the liquid sheet.
(6) The centerline of the liquid jet does not lie on the streamline passing through the stagnation point in a liquid sheet, as shown in Fig. 1. The distance between these two lines is expressed as εa, where a indicates a minor semi-axis of a liquid jet with an elliptical cross-section. The displacement rate, ε, is calculated by the momentum conservation equation before and after impingement in the liquid injection direction (see, e.g., Tokuoka and Sato, 1977).

The coordinate system used in the theoretical analysis is shown in Fig. 1. Considering the momentum conservation before and after

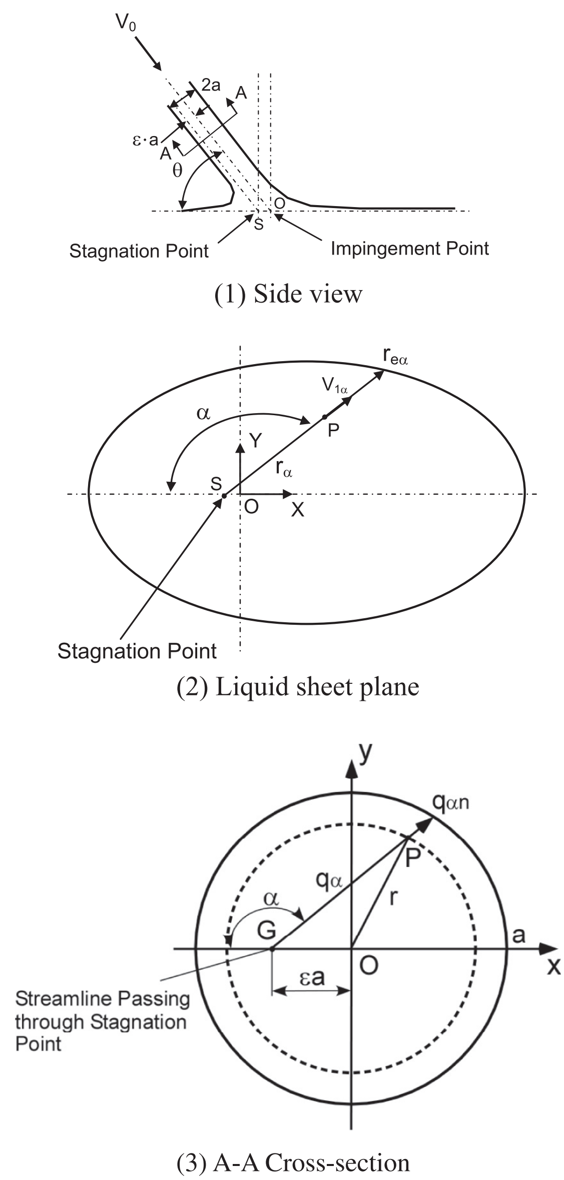

Fig. 1. Coordinate system.