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Characteristics of liquid upwash formed on a splash plate

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ABSTRACT

The present study attempts to clarify the characteristics, i.e., the sheet thickness and sheet velocity, of a liquid upwash formed by the oblique impingement of two equal liquid jets on a splash plate. Moreover, the results are compared with those obtained by the theoretical analysis derived in the previous paper. First, the equations of sheet thickness and sheet velocity of the upwash were derived using the theoretical analysis developed in the previous paper. Second, the upwash thickness and velocity were measured by the electric resistance method and the PIV method, respectively. Finally, the predictions of the upwash thickness and velocity obtained by the theoretical analysis were compared to the measurement results, and the validity of the theoretical analysis was verified.

1. Introduction

The phenomenon whereby a liquid jet impinges on a solid wall is observed in terms of liquid jet impingement cooling and in the combustor of an internal combustion engine. The splash plate atomization that issues the liquid sheet on a solid wall into the atmosphere and generates fine droplets after free liquid sheet fragmentation has been used in a small combustor, because this requires no auxiliary machine, such as a compressor, and easily generates fine droplets. In the cases of liquid jet impingement cooling or preparation of a fuel spray, multiple liquid jets are generally impinged on the solid wall in order to broaden the cooling area or increase the fuel flow rate. In these cases, adjacent liquid sheets on a solid wall impinge upon each other, and the liquid sheet normal to the solid wall generates an upwash. In the case of liquid jet impingement cooling, the liquid lumps and drops scattered around have an adverse influence on cooling equipment. Since the upwash is generally thicker than the liquid sheet on a solid wall, coarse droplets are generated by the disintegration of an upwash. Therefore, for the case in which splash plate atomization is used for the fuel injector, the upwash formation is anticipated to have an adverse effect on the fuel spray characteristics. Thus, the upwash formation and its characteristics have a significant influence on the performance of cooling equipment or a fuel injector.

Splash plate atomization, which generates fine droplets by issuing a free liquid sheet into the atmosphere, where the sheet is generated by the impingement of a liquid jet on a splash plate, has been widely investigated (Ashgriz, 2011). Inamura and Tomoda (2004) developed a new fuel injector that applies splash plate atomization and measured the spray characteristics of the new fuel injector. Inamura et al. (2004) theoretically analyzed the liquid sheet flow on a solid wall due to the impingement of a liquid jet on a splash plate and experimentally measured the sheet thickness distribution. Finally, they compared the sheet thickness distribution calculated by the theoretical analysis and the measurements and verified the theoretical analysis. Ren and Marshall (2014) experimentally investigated splash plate atomization under a large-Weber-number condition. They deduced a semi-theoretical equation for mean droplet size and verified this equation through measurements.

The phenomenon whereby two gas jets impinge on the ground and generate a gas upwash is observed during takeoff and landing of a VTOL (Vertical Take-Off and Landing). Since the gas upwash greatly influences the attitude stability of a fuselage, a number of studies have theoretically and experimentally investigated the generation of an upwash and its effect on attitude instability in the field of aeronautics (Jenkins and Hill Jr., 1977; Siclari et al., 1981; Rizk and Menon, 1989). However, despite its importance, as mentioned above, few studies have investigated liquid upwash. Kate et al. investigated the normal impingement of two equal liquid jets on a solid wall and phenomenologically discussed the formation of a liquid upwash (Kate et al., 2007). They also investigated the normal impingement of two unequal jets. Inamura theoretically analyzed the formation of a liquid upwash by oblique impingement of two equal liquid jets on a solid wall (Inamura, 2016). Moreover, he compared the upwash formation conditions and upwash shape

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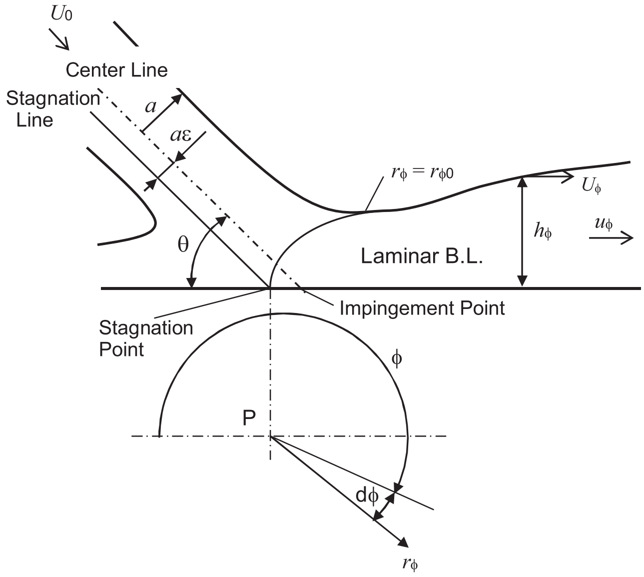

Fig. 1. Symbols and coordinate system.

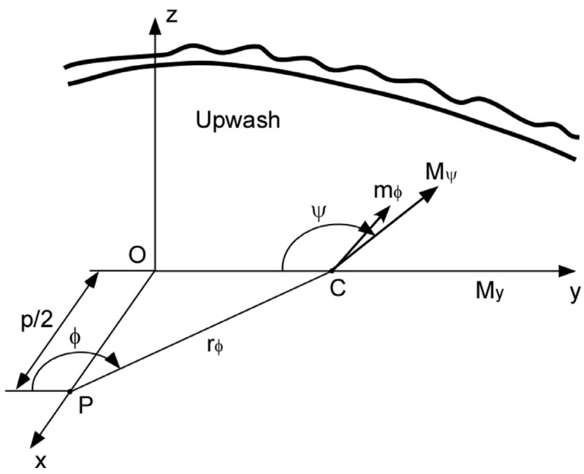

Fig. 2. Momentum of the upwash sheet.

predicted by the theoretical analysis to the measurements and verified the validity of the theoretical analysis.

Although the characteristics of an upwash formed by the liquid jet impingement on a solid wall are very important from the point of view of liquid atomization, they remain unclear at present. In the present study, the characteristics of a liquid upwash formed by the oblique impingement of two equal liquid jets on a splash plate were theoretically and experimentally investigated. First, the equations of the sheet thickness and velocity of an upwash were theoretically deduced. Second, the sheet thickness and velocity of an upwash were measured experimentally. Finally, the upwash thickness and its velocity distributions predicted by the theoretical analysis were compared with the measurements, and the validity of the theoretical analysis was verified.

2. Theoretical analysis of upwash formation

According to the theoretical analysis reported in the previous paper (Inamura, 2016), the sheet thickness and velocity of a liquid upwash generated by the oblique impingement of two equal liquid jets on a splash plate were deduced. Prior to the theoretical analysis, the following assumptions of the previous paper are established:

1) The liquid flows in an impinging jet and liquid sheet on the splash plate are two-dimensional and laminar.
2) The velocity distribution across the liquid jet is uniform.
3) The liquid sheet flows radially from the stagnation point on the splash plate, and the liquid flow in the circumferential direction can be ignored.
4) On the splash plate, the laminar boundary layer develops in the liquid sheet from the stagnation point (see Fig. 1).
5) The effects of the airflow and gravity on a liquid sheet flow and upwash flow can be ignored.
6) The velocity distribution across an upwash is uniform.
7) The x-component of the momentum of both liquid sheets is transferred to the z-component in an upwash after the impingement (see Fig. 2). The y-component of the momentum of both liquid sheets is transferred to the y-component in an upwash. At the impingement of two liquid sheets on the splash plate, momentum loss due to impingement occurs in only the z-direction, and the y-component of the liquid sheet momentum is maintained after impingement. The momentum loss coefficient Cimp in the z-direction was assumed to be 0.85 based on the comparisons between the calculations and measurements of the upwash shape.
8) The effect of a hydraulic jump generated at the periphery of a liquid sheet on the upwash can be neglected.
9) The liquid velocity in an upwash is constant along the stream line.

In assumption 7), the coefficient C_{imp} was assumed to be 0.9 in the previous paper. However, in the present study, C_{imp} is taken as 0.85 based on careful examinations.

After a liquid jet impinges on a splash plate, the laminar boundary layer develops along the stream line from stagnation point P (see Fig. 1) and reaches the liquid surface at $r_f = r_{f0}$. According to the previous paper, r_{f0} is expressed by the following equation (Inamura et al., 2004):

$$r_{\phi 0}{}^* = \frac{0.564}{(4\pi)^{1/3}} \left(A \cdot B^2\right)^{2/3} \tag{1}$$

where A and B are constant and are defined as

$$A = \frac{\sin\theta}{\sin^2\phi + \cos^2\phi \cdot \sin^2\theta} \tag{2}$$

$$B = \pm\varepsilon\sqrt{\frac{\sin^2\theta}{\tan^2\phi + \sin^2\theta}} + \sqrt{1 - \frac{\varepsilon^2\tan^2\phi}{\tan^2\phi + \sin^2\theta}} \tag{3}$$

in which θ, ϕ, and ε indicate the impingement angle, the azimuthal angle, and the coefficient of the gap between the center line and the stagnation line of a liquid jet, respectively (see Fig. 1). Here, ε is given as follows (Hasson and Peck, 1964):

$$\varepsilon = \cos\theta \tag{4}$$

The sign of the first term in the right-hand side of Eq. (3) depends on the azimuth-position in the cross section of an impinging jet (Inamura et al., 2004).

The dimensionless radial distance from the stagnation point, $r_\phi{}^*$, and the thickness of a liquid sheet on the splash plate, $h_\phi{}^*$, at the azimuthal angle, ϕ, and the jet Reynolds number, *Re*, are defined as follows:

$$r_\phi{}^* = \frac{r_\phi}{a} \cdot \frac{1}{\mathrm{Re}^{1/3}} \tag{5}$$

$$h_\phi{}^* = \frac{h_\phi}{a} \mathrm{Re}^{1/3} \tag{6}$$

$$\mathrm{Re} = \frac{Q}{a\nu_l} \tag{7}$$