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Normalizing study on the characteristic size of the stable cavity induced by a gas-jet penetrating into a liquid sheet

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ABSTRACT

Generating a stable cavity accompanying with a dry spot on the solid substrate by a gas-jet penetrating into a liquid sheet is commonly required in various industrial fields. In-depth study to the impact of the characteristic size of the stable cavity (i.e. the dry spot diameter) from the penetrating conditions is still lacked. In this paper, a series of experiments were carried out to study stable cavities created by vertical gas-jet penetrating into and rupturing a shallow liquid sheet (spread in a container with the thickness of 3–5 mm), in which a dry spot (a circular dry area after the liquid displaced) was produced on the solid flat substrate. The effects on the dry spot diameter by the penetrating parameters including nozzle diameter, liquid sheet thickness, gas flow rate and jet height were systemically studied. In addition, further dimensionless analysis was implemented on the experimental results to normalize the dry spot diameter with all penetrating parameters. To realize the normalization, a mechanical equilibrium model of the dry spot boundary line was built according to gas–liquid–solid interface action mechanism, and further simplified according to Young–Dupré law based on the experimentally monitored results of the cavity contact angle. Based on the simplified model, the ratio of dry spot diameter to jet height was expressed by a linear function of a combined dimensionless parameter of the Froude number and the ratio of nozzle diameter to jet height as normalization, where the slope of the function could be determined by curve fitting of the experimental results. The normalizing study on the characteristic size of the stable cavity in this paper can provide useful criteria for the jet controls in actual industry applications.

1. Introduction

Technologies based on gas-jet penetrating into liquid have been widely used in various industrial fields. It is considered as a method of gas-jet wiping to control the final liquid film thickness in film, paper and wire coating manufactures [1,2] and utilized as a common decarburizing technique in oxygen steelmaking to reduce the carbon content in the metal bath [3–5]. In addition, it is entitled as a novel sealing way to prevent the liquid between the lens and wafer from leaking in immersion lithography [6,7].

When a gas-jet penetrating into a deep liquid pool, an air cavity can be generated accompanying with the liquid surface deep depression [8]. This interesting phenomenon has attracted many researchers from fluid mechanics and physics areas to study on the penetrating cavity behaviors. Banks and Chandrasekhara [9] and Cheslak et al. [10] served as the pioneers have launched comprehensive researches on the cavity size (depth, width and peripheral lip height) by stagnation-pressure and weight displaced analyses and then proposed the dimensionless results with experimental verification. Subsequently, Ersson et al. [11] and Hwang and Irons [12] utilized PIV technology to reveal the flow field produced by a gas-jet impinging onto a liquid surface and validated the depth of surface deformation with fundamental theory. Based on the method of volume of fraction, Nguyen and Evans [13] numerically studied the diameter and depth of cavity in confined and unconfined liquid system. Olmstead and Raynor [14] and He and Belmonte [15] analyze the cavity deformation shape by the asymptotic solution derived from the conformal mapping method. Besides, Rosler and Stewart [16] found the cavity shape conformed to specified differential equation through developing the force balance at the liquid–gas interface. Moreover, to the dynamic motion behavior of this cavity, Berghmans [17,18] formulated a variational approach based upon the principle of minimum free energy to study the cavity stability, and proposed a critical stable boundary in theory which was in agreement well with experiments. Muñoz-Esparza et al. [19] numerically found the relationship between the cavity flap frequencies in horizontal and vertical under a certain ratio in the cavity oscillation.

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Nomenclature

b	intercept of fitting line	V_0	mean jet velocity at outlet of the nozzle (m/s)
c	coefficient	V_s	sound speed (m/s)
D	dry spot diameter (mm)	r	radial position from the jetting stagnation (m)
d	nozzle diameter (mm)	Re	Reynolds number
g	gravity acceleration (m/s^2)	Ma	Mach number
H	liquid sheet thickness (mm)	Fr	Froude number
H_c	critical liquid sheet thickness (mm)	ρ_G	density of gas (kg/m^3)
h	jet height (mm)	ρ_L	density of liquid (kg/m^3)
k	slope of fitting line	v	kinetic viscosity of air (m^2/s)
L	required minimum length for a fully developed turbulent flow (mm)	γ	gas–liquid surface tension (N/m)
		γ_{SL}	solid–liquid surface tension (N/m)
P	pressure distribution on the flat surface (Pa)	γ_{SG}	solid–gas surface tension (N/m)
P_L	liquid sheet static pressure (Pa)	θ	cavity contact angle (°)
Q	flow rate (L/min)	θ_s	static contact angle of the solid substrate (°)

A similar air cavity can be produced by a gas-jet penetrating normally into a liquid sheet with the thickness of several millimeters. Different from penetrating mode happened in deep liquid pool, the cavity here is induced by a gas-jet with sufficient momentum completely rupturing the liquid sheet and leaving a dry spot on the solid substrate. This is a distinct phenomenon has received a few attentional works for its important applications in coating and steelmaking industry as well. Taylor and Michael [20], López et al. [21] and Bankoff et al. [22] used the gas-jet impingement on a liquid sheet to produce a cavity accompanied with a dry spot on the substrate, and then focused on studying the stability and dynamic evolution (closing, staying and opening) of the dry spot with the theory model after withdrawing the gas-jet which is relevant to the crucial coating process. Benefited from this dry spot generated by a gas-jet impingement, Zou et al. [23] have developed an original mobile device to contactless measure the surface temperature of hot strips originally covered by a liquid sheet after run-out table cooling in steelmaking industry.

However, compared with gas-jet penetrating into a deep liquid pool, many cavity behaviors induced by a gas-jet penetrating into a liquid sheet still lacks in-depth study in general. One of them is the impact of the characteristic size of the stable cavity (i.e. the dry spot diameter) from the penetrating parameters (including nozzle diameter, liquid sheet thickness, gas flow rate and jet height), which in fact is extremely important for cavity behavior control. It can provide bases for the jetting flow rate and height control in contactless measurement of the strip surface temperature in steelmaking [23], and also for air-knife strength control in sealing of immersion liquid [6,7], etc.

In this paper, an experiment setup was designed to conduct parametric study on the characteristic size of the stable cavity (i.e. the dry spot diameter), which implemented by a vertical gas-jet penetrating into and rupturing a shallow liquid sheet (spread in a container with the thickness of 3–5 mm) on the solid flat substrate. Further dimensionless analysis was then implemented on the experimental results to normalize the dry spot diameter with the penetrating parameters, including nozzle diameter, liquid sheet thickness, gas flow rate and jet height. For the normalization, a mechanical equilibrium model of the dry spot boundary line was built according to gas–liquid–solid interface action mechanism, and further simplified according to Young–Dupré law based on the experimentally monitored results of the cavity contact angle. Based on the simplified model, the ratio of dry spot diameter to jet height was expressed by a linear function of a combined dimensionless parameter of the Froude number and the ratio of nozzle diameter to jet height as normalization, where the slope of the function could be determined by curve fitting of the experimental results. We believe the normalizing study in this paper can provide useful criteria for the jet controls in actual industry applications.

2. Experimental setup

An experimental setup as shown in Fig. 1 was specially developed to study the characteristic size of the stable cavity under different penetrating conditions, i.e. different nozzle diameters, liquid sheet thicknesses, gas flow rates and jet heights. The air provided by the compressor passed through a mass flow controller and jetted out of a flat tipped needle, finally penetrated normally into the liquid sheet which was spread in a rectangle glass container (length of 250 mm, width of 250 mm and height of 50 mm) to generate a cavity. The penetrating parameters of the nozzle diameter d, jet height h and gas flow rate Q are listed in Table 1. The nozzle diameter d was variable by replacing the standard flat tipped needle which was mounted on the lifting platform. The mass flow controller (Alicat-10-KM1178) was employed to adjust the flow rate Q with an accuracy of 0.8% in reading scale and 0.2% in full scale. The width of the container reached more than 200 times of the nozzle diameter to minimize the reflected waves from the container lateral walls [16]. Thus, the liquid spread in this big container can be deemed infinite and called as liquid sheet due to the relevant studies about this mentioned in the introduction. In addition, the increment of liquid sheet thickness due to the formed cavity can be neglected.

Before experiments, the jet height h vertically from the nozzle to the solid substrate of the container was adjusted by a lifting platform with the maximum scale of 20 mm and an accuracy of 0.01 mm. If the jet height set to a lower value in experiments, the cavity cannot be stably existed as well as accompanied by a few droplets splattering from the liquid sheet. Thus, a serial of suitable jet heights were qualified to generate the stable penetrating cavity shown in Table 1. A high speed video camera (Phantom M320S) fitted with a Nikon 50 mm lens was used to capture the images of the stable cavity. Images were captured at a speed of 1000 frame/s. Non-flickering backlighting was produced by a high-intensity lamp with a thin paper as a diffuser.

Experiments were carried out at the temperature of 20 ± 1 °C and the environment pressure of 101.3 kPa. Clean air with the density of $\rho_G = 1.2$ kg/m^3 was used as the gas for jetting and purified water with the density $\rho_L = 998$ kg/m^3 was employed to form the liquid sheet. Two dimensionless parameters Reynolds number $Re = V_0 d/v$ and Mach number $Ma = V_0/V_s$ (displayed in Table 1) were also employed to express the gas flow jetting out of the nozzle. Here, V_0 is the mean jet velocity at outlet of the nozzle which