Research on Droplet spreading on Substrate Influenced by Droplet Flying Velocity

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Abstract

Droplet spreading characteristics on substrate make great effect on inkjet printing quality, but the ink viscosity, substrate surface parameters all and droplet flying velocity all affect droplet spreading on substrate. In this paper, we just research on droplet spreading on Substrate been influenced by droplet flying velocity from inkjet print-head to substrate. We set up numerical model of flying droplet based on moment equation and energy conservation equation, so that we can get theoretically result, then keep ink viscosity and substrate surface parameters invariableness, just change the droplet flying velocity, and from the analysis result, we find the relationship between droplet flying velocity and droplet spreading characteristic. From the experiment result, we amend the model for droplet, so that we get a correct numerical model for droplet spread, and in this model droplet velocity is the only variable.

Introduction

The process of droplet collide on the surface of substrate has important application in engineering such as ink jet printing, surface coating. The impact and spreading of droplet on a flat surface have been studied extensively in the literature from theoretical, computational and experimental point of view. The process includes droplet formation, droplet flying, droplet collision and droplet spreading. In drop-on-demand ink-jet printing, where the distance between nozzle and substrate is small, droplet ejection has been investigated theoretically in 1984 by Fromm[1]. In ink-jet printing, we know that the exit velocity can be obtained from high speed photography, or laser method, and the last method was developed in 1994 by Cartellier[2]. But in common experimental condition, the equipment is not always on hand, so we need some simple way to solve this problem. Fromm (1984) defined the behavior of a Newtonian liquid during droplet ejection in terms of the ratio of the Weber number to Reynolds number [3]. This ratio is thought to control droplet formation in ink-jet printers although experiment suggests that viscosity alone is a simpler guide to whether or not a liquid can be printed.

As droplet spreading be concerned, a number of difficulties have been encountered, including failure of droplets to bond to each other, formation of pores at the interface between droplets, and residual stresses in the finished part, many of the same problem have also been observed. Achieving good material properties in all spray deposition technologies requires careful control of droplet size, temperature and impact velocity. Some other way has been mentioned in literature to describing the model of droplet impact on solid substrate surface. Harlow and Shannon were the first to simulate droplet impact on solid surface. They used a "marker-and-cell" (MAC) finite-difference method to solve the fluid mass and momentum conversation equations, while neglecting the effect of viscosity and surface tension to simplifying the problom. Tsurutani et al. [4] enhanced the MAC model to include surface tension and viscosity effects, and also considered heat transfer from a hot surface to a cold liquid drop as it spread on the surface. Trapaga and Szekely [5] applied a commercial code, FLOW-3D [6], that uses the "volume of fluid" (VOF) method, to study impact of molten particles in a thermal spray process. Liu et al. [7] employed another VOF based code, RIPPLE [8], to simulate molten metal droplet impact. Pasandideh-Fard et al. [9] applied a modified SOLA-VOF [10] method to model the impact of water droplets in which varying amounts of a surfactant were dissolved to modify the liquid–solid contact angle. They extended the model [11] to include heat transfer and phase change, and simulated freezing of molten tin droplets falling on a stainless steel plate. Zhao et al. [12] formulated a finite-element model of droplets deposited on solid surfaces.

Droplet flying velocity calculation

For the common ink jet printing, the droplet flying vertically to substrate after jetted from nozzle, so the we need only calculate the vertical velocity, the horizontally velocity is zero. For the droplet, many parameters affect the flying speed; include droplet size, droplet mass and air pressure around the droplet. In this paper, we calculate the speed with common condition that the temperature is 20centgrade, the pressure is 69kPa, and the droplet diameter is 230μm with the density of 920Kgm-3.

In the vertical mode, we consume the initial speed is v_0 , then

$$y = v_0 t + \frac{1}{2} a t^2 \tag{1}$$

Where y is the droplet flying distance from the nozzle, t is the droplet flying time from the nozzle, a is the acceleration of the droplet. And then the equation of motion can be expressed based on the force equilibrium, as

$$ma = \vec{F}_g + \vec{F}_d + \vec{F}_c \tag{2}$$

In Equ.2, $\vec{F}_g$ is the gravitational force, $\vec{F}_d$ is the drag force and $\vec{F}_c$ is the Coulomb force due to interaction between charged droplets which occurs in continues ink jet printing. $\vec{F}_c$ can be neglected in this case because the droplets are not charged by the printer, and also the single droplet is applied.

Assuming the air drag on the droplet is similar to that for motion of a spherical particle in viscous fluid, we get the motion equation in vertical direction as follow.

$$m\frac{dv}{dt} = mg - 3\pi d\mu v \qquad (3)$$

Where v is velocity in the vertical axis, μis the viscosity of air, d is the diameter of the drop, in the vertical direction, solving Equ.3 give the relation between the initial velocity (v_0) and velocity (v) at time t

$$v = v_0 e^{((-3\pi\mu d/m)-1)t} \qquad (4)$$

Replacing m with $\frac{\rho\pi d^3}{6}$ in Equ.4, then

$$v = v_0 e^{((-18\mu/\rho d^2)-1)t} \qquad (5)$$

Where ρ=920Kgm^{-3} is the density of ink, and the viscosity of the air is $1.8\times10^{-5} Pas$, then set

$$v = v_0 e^{-t/\tau} \qquad (6)$$

And $\tau^{-1} = \frac{18\mu}{\rho d^2} + 1 \qquad (7)$

Where τ is designated as a relaxation time. We take different parameters of the droplet into Equ.7, and then the flying condition will changed. And from the result, we find that the flying condition can be separated to three steps: first, when the Reynolds number is bellow 0.2, the droplet is laminar; second, when the Reynolds number rang of 0.2-500, the droplet is semi-turbulent; at last, if Reynolds number exceeds 500, the droplet is turbulent.

If the drag force is concerned, the position of the droplet during flight can be calculated as follow [13]

$$y = -v_0 t - g\tau(t - \tau(1 - e^{-t/\tau})) \qquad (8)$$

From analysis above we can conclude that the velocity of the droplet is affected by droplet size, air viscosity, ink viscosity, ink droplet initial velocity and Reynolds number of the droplet. So that if we want to reduce the motion of the droplet before it touches the substrate, we can change the parameters above. At last from the Equ.8, we can also conclude that change the distance and the nipple can also change the motion.

Droplet spreading on substrate

The process of a droplet impact on the substrate is shown in Fig.1, a spherical droplet falls vertically to the substrate with uniform velocity, impinges onto a horizontal substrate at room temperature. The time, t, is measured from the instant when the drop first touches the solid surface, the density of air and ink are set to ρ_g and ρ_l respectively. The fluid is assumed to obey the Navier-Stokes equation, and in this paper, surface tension at free surface, the effect of gravity, viscosity, and wetting ability between liquid and substrate has been taken into account. The conservation equations are given by

$$\rho\frac{Dv}{Dt} = -gradp + \mu\nabla^2 v + \rho F \qquad (9)$$

and

$$\text{div}\, u = 0 \qquad (10)$$

Where t, v, p are time, velocity and pressure, μ ρ and Fare apparent fluid density, apparent viscosity and volume force, respectively.

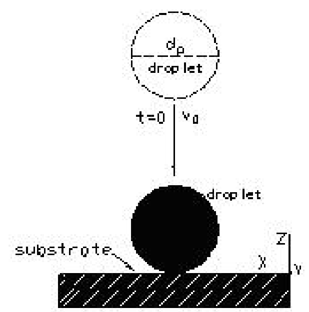

Fig.1 Schematic of the collision of a droplet on solid substrate

The conversation equation are dispersed and solved by a finite difference method. The computational domain is divided into numerous small cells. A staggered mesh is used where pressure, p, and density, ρ , are evaluated at the center. The fractional step method is used to solve the conservation equation [14]. The momentum equations are approximated and decomposed into three parts utilizing a forward Euler scheme in the unsteady term

$$\frac{\bar{v} - v^n}{\Delta t} + (v^n \cdot \nabla)v^n = 0 \qquad (11)$$

$$\frac{\tilde{v} - \bar{v}}{\Delta t} = \frac{\mu}{\rho}\nabla^2\tilde{v} + F^n \qquad (12)$$

$$\frac{v^{n+1} - \tilde{v}}{\Delta t} = -\frac{1}{\rho} gradp^{n+1} \qquad (13)$$

Where F is the volume force, n and n+1 represents two consecutive time stages, $\bar{v}$ and $\tilde{v}$ is intermediate velocities, Δt is time increment. And Δt is controlled by CFL (Courant-Friendriches-Lewy) condition for numerical stability given by

$$\Delta t = f_{CFL} \frac{1}{Max(\frac{|v_i|}{\Delta x_1})} \quad (14)$$

Where the CDL number, f_{CFL} can be set a value based on the experimental condition and Δx_1 is the mesh size. A non-uniform mesh system focusing on the region near the solid surface is used. The mesh in the z-direction is given by

$$z_k / d_p = \frac{\exp(k\Delta\zeta) - 1}{\exp(n_z\Delta\zeta) - 1}, \text{ k=0,1,2,3.......} \quad (15)$$

And

$$z_k = 2a_{k-1} - z_{k-2} \quad (16)$$

In which $\Delta\zeta$ =0.0012 and n_z represent time stages in z-direction, k denotes the mesh number. The mesh size in the z-direction increases upward with minimum mesh size located adjacent to the solid surface, because of the presence of a thin velocity boundary layer along the surface where the velocity gradient is large, and uniform mesh size are used in x-direction and y-direction.

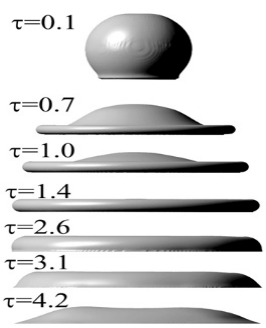

Fig.2 *Droplet spreading process simulated by computer*

The prediction spreading process is shown in Fig.2, we can include that grid convergence is of great importance. The most common way demonstrates grid convergence is to repeat a computation on a grid with more grid points. And from the model we can find that droplet velocity important to droplet spreading, the higher the velocity, the more serious the droplet spreading.

Conclusion

The flying process and spreading process are simulated by numerical models. Then we applied some typical parameters to test the models, from the simulation equation and test result, we can get conclusion as bellow.

Droplet flying velocity affected by droplet size, ink viscosity, ink density, droplet surface tension and air pressure. The acceleration of the droplet during flying process will reduce for the affect of parameters mentioned above.

The distance between jet nozzle and substrate affects the droplet velocity before it touch the substrate. With the increasing of the distance, the velocity increasing until the droplet separated to numerous small droplets.

The droplet spreading process can be simulated by the Fractional step method, and this method is based on conservation equation and Euler scheme, and the model can be simulated by computer if we give correct value to the parameters.

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