Double droplets simultaneous impact on liquid film

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Abstract. The evolution of double droplets simultaneously impinging on flat liquid film are obtained with CLSVOF method (Combined Level Set and VOF). The impinging velocity, liquid film thickness, and the horizontal distance between the two droplets were investigated to analyze the factors that affect the evolution.

NOMENCLATURE:

\( \vec{u} \) velocity vector
\( \rho \) density
\( p \) pressure
\( \delta \) surface tension
\( \kappa \) total curvature of the interface
\( T \) temperature
\( S \) source term
\( \phi \) distance function
\( g \) gravitational constant
\( t \) time
\( \vec{n} \) interface normal vector
\( \mu \) dynamic viscosity
\( t^* \) non-dimensional time
\( h \) liquid film thickness
\( h^* \) dimensionless film thickness
\( d \) initial droplet diameter
\( v \) droplet velocity before impact
\( We \) Weber number
\( Oh \) Ohnesorge number
\( Re \) Reynolds number
\( r \) droplet radius

1. Introduction
Drop impact phenomenon is an important and common process in industry, such as ink jet printing, liquid drops impact on turbine blades, oil drops impact on walls of the combustion chamber in diesel engines, spray coating and cooling, plasma spraying, drops impact on outer surfaces of heat transfer tubes in falling film evaporators, as well as liquid atomization and cleaning. In nature, erosion of soil, dispersal of spores and microorganisms, rain drops falling onto ground and wings of aircrafts also...
involve drop impact. For most applications, a thin liquid film can be formed on the solid surface after drop impact, then the subsequent impact target becomes a liquid film rather than a solid surface. Thus, the phenomenon of drop impact on a liquid film should be paid more attention.

Some experimental results on droplet impact on the liquid film have been obtained by using high-speed camera. Hu Hai Bao did experiments to investigate the process of droplet impact on micro groove, and found the maximum diameter changing characteristics. Guo experimentally investigated the phenomena of spray formation, splashing and especially the bell spry after a droplet impacted onto a liquid film. Rioboo experimentally observed three typical outcomes, depending on the impact speed, after the impingement: deposition, crown formation without splashing and splashing. Cossali conducted experiments of the droplet impact on films, and the results showed that the upper external diameter was consistently smaller than the lower external diameter, and the evolution of the crown height depended on \( We \), whereas its growing velocity and the crown thickness evolution were almost independent of \( We \). Motzkus carried out an experimental investigation on the influence of different parameters such as liquid properties, impact droplet properties and the thickness of liquid film on the emission of airborne particles produced by the impact of millimeter-size droplets onto a liquid film. Computational simulation on this thesis emerged later than the experimental observation, but it developed rapidly with the development of the computer technology. Lee proposed the two-dimensional level set (LS) method for the interface tracking of the two-phase flow to simulate the impingement process numerically. The results showed that, the crown spread more strongly as the drop impact velocity and film thickness increased. Guo concluded that the kinetic energy of the droplet was the main reason that led the spray and splash. When the thickness of the liquid film increased, the splash is weakened. However, if only the Weber number and the Reynolds number were close, the fluid flow caused by the droplet impact was similar. Shen simulated droplet impact on curved surfaces with lattice Boltzmann method, and they analyzed the effects of impact speeds on the droplet impacting dynamics. Cossali and Vander Wal associated splashing with the production of satellite drops separating from the crown liquid sheet after the impact, which were named as secondary drops. Pasandideh-Fard established the numerical model for heat transfer process after single droplet impact on solid surface. H.Fujimoto experimentally investigated double droplets continuously impact on solid surface with different temperatures. T.Minamikawa numerically and experimentally studied double droplets continuously impact on heated surface, they found the results are in agreement. Sivakumar experimentally investigated the droplets impact on liquid films during spraying, compared the results with single droplet and discussed the interaction of multi-droplets.

Though there are many studies on the drop impact phenomenon, from the information above mentioned, it is found that there is few researches particularly focused on the evolution characteristics during double droplets simultaneously impact on very thin films. Therefore, in the present study, we mainly demonstrate the evolution characteristics after double droplets simultaneously impinging on flat liquid film. And the effects that affect the evolutions are discussed.

2. Numerical Method

The evolution after droplet impact on liquid film is a complex two phase flow process with deformation of the interface between liquid and gas, resulting in great difficulty for the simulation of the two-phase flow. The key problem is to capture the interface effectively. CLSVOF combines VOF method and Level Set method, where Level Set function is used to accurately compute the curvature and the normal vector to the interface while the VOF function is used to reconstruct the interface and conservation is guaranteed.
In the VOF method, the volume fraction $\alpha$ is introduced throughout the whole computational domain. $\alpha$ is defined as:

$$\alpha = \frac{\text{volume of the liquid}}{\text{total volume of the control volume}}$$

(1)

When the control volume is full of liquid, $\alpha = 1$, and $\alpha = 0$ as the control volume is full of gas. The interface lies within control volume with a volume fraction of $0 < \alpha < 1$. Governing equation of the volume fraction can be written as:

$$\frac{\partial \alpha}{\partial t} + \vec{u} \cdot \nabla \alpha = 0$$

(2)

In the LS method, in order to track the interface between the gas and liquid, a signed distance $\phi$ is used which is defined as the distance from the interface, and the interface is described as the regions with $\phi = 0$. Governing equation of $\phi$ is described as follows:

$$\frac{\partial \phi}{\partial t} + \vec{u} \cdot \nabla \phi = 0$$

(3)

The continuity and Navier-Stokes equation for the incompressible flow and the energy conservation equation can be given in Eq.(4) to Eq.(6).

$$\nabla \vec{u} = 0$$

(4)

$$\frac{\rho \partial \vec{u}}{\partial t} + \rho \nabla \cdot (\vec{u} \vec{u}) = -\nabla p + \nabla \cdot [\mu (\nabla \vec{u} + (\nabla \vec{u})^T)] - \sigma \kappa \delta(\phi) \nabla \phi + \rho g$$

(5)

$$\frac{\partial (\rho \phi)\nabla T}{\partial t} + \rho \phi \nabla \cdot (U T) = \nabla \cdot \left( \frac{\lambda}{c_p} \nabla T \right) + S$$

(6)

where, $\kappa$ is the interface curvature, which is calculated by using the following equation:

$$\kappa = \nabla \cdot \frac{\nabla \phi}{|\nabla \phi|}$$

(7)

and $\delta(\phi)$ is distance function and defined as:

$$\delta(\phi) = \begin{cases} 1 + \cos(\phi/a) & |\phi| < a \\ 2a & |\phi| \geq a \end{cases}$$

(8)

where $a = 1.5w$ and $w$ is the minimum size of the cell.

The interface normal vector $\vec{n}$ can be calculated by Eq.(9).

$$\vec{n} = \frac{\nabla \phi}{|\nabla \phi|}$$

(9)

When the moving interface is tracked, the interface profile always becomes vague or generates oscillations due to numerical dissipation, so it is necessary to reconstruct the interface for each time step. In the CLSVOF method, values of both the VOF function and the LS function are used. Namely, the VOF function provides the size of portion that the interface may pass through, and the interface normal vector in Eq.(9) calculated by LS function determines the direction of the interface.

3.0 Simulation Results and Discussion

3.1 Physical model

The double droplets with same size, whose center distance is $Sh$, simultaneous impact the liquid film with the same velocity, and the time when the bottoms of the droplets initially contact the film is taken as initial time $t=0$, as shown in figure 1. The velocity at initial time is $V$, and the thickness of the liquid film is $h$. Both the droplets and the film are water, and the viscosity and surface tension are constants. The simulation region is $50\text{mm} \times 20\text{mm}$, and the mesh number is $1000 \times 400$. 
3.2 Results and discussion

Figure 2 is the evolution after 2mm double droplets with the 4mm horizontal spacing simultaneous impact 1.2 mm thickness liquid film with the velocity of 0.5m/s, 1.0 m/s and 2.0 m/s respectively. It can be seen from 2(a) that when the impacting velocity is smaller, the area and height of spray are smaller. Both the sprays produced by the two droplets impact expand outward and meet at the middle of the impacting point. Then laminar jet is formed along the intersection line. The laminar jet is higher than the sprays around it. There are several wave crests for the around sprays (3ms), which are lower than the central laminar jet. That means slight fluctuation is caused by the collision. The height of the central laminar jet is about 2.42 times to the height of the surrounding sprays. When the velocity is 1m/s, compared to figure 2(a), figure 2(b) shows with the rise of impact velocity, the spray diameter and height increase, the time when the sprays produced by the two droplets meet at the middle of the double droplets turns earlier, and the laminar jet becomes higher. For the bigger impacting velocity contributes to the faster convergence of the droplet and the film, so a set of sprays with obvious crests are formed at 3 ms. The height of laminar jet along the intersection line is 2.63 times to the height of its surrounding sprays. From figure 2(c) it can be seen that when the impacting velocity is up to 2m/s, after double droplets impact, two crown sprays are formed going around the two impact points. The top of sprays quickly breaks up into many small droplets. Laminar jet is formed along the spray intersection line after the two crown sprays impact, and time when this jet forms is much earlier than that of the smaller velocity, just as shown in figure 2. It is obvious that for velocity 2m/s the laminar jet can be found at 0.8ms, while for velocity 1m/s, it is at 2ms that the jet is obvious. For velocity 0.5m/s, even at 3ms the height of the jet is far smaller than other two conditions. In figure 2(c), the height of laminar jet along the intersection line is about 1.68 times to that of surrounding sprays, and finally the top of the laminar jet also breaks up into many small droplets.

![Figure 2. The evolution after double droplets simultaneous impact liquid film at different impact speed (Sh=2D)](image-url)
Figure 3 is the pressure distribution after double droplets simultaneous impact on liquid film with the velocity of 2m/s. It indicates at the neck regions there are four pressure stagnation fields. The pressure within the stagnation area is much higher than the atmosphere. So great pressure gradient is created from inner to free surface, which causes the jets upward and outward at the neck. With the outward movements of both the droplets, the pressure gradient decreases gradually at both sides, while in the middle area, the two droplets meet and collide, and pressure stagnation point is produced at the impact point (0.8ms) where the pressure is higher. Because of the bigger pressure gradient to the free surface, the upward jets are produced at the interaction of the two droplets. The surrounding fluid goes into jet area constantly, and the laminar jet goes higher and higher. The kinetic energy of the liquid gradually transforms into potential energy of the jet. In the area of impact point, that is non-neck region, because of the smaller pressure difference between the inner fluid and the free surface, no jet appears, and this part of fluid enters into the jet area as supplement, so the film layer of this area is becoming thinner and thinner.

![Figure 3. Pressure distribution after droplets simultaneously impact liquid film](image)

Figure 4 is the evolution after 2mm double droplets with the 6mm horizontal spacing simultaneous impact 1.2 mm thickness liquid film with the velocity of 0.5m/s, 1.0 m/s and 2.0 m/s respectively. Compare figure 4 with figure 2, we can see that for the big horizontal spacing, the time sprays needed to meet is longer after two droplets impacting on the liquid film. The evolution difference is more obvious when the impacting velocity is bigger. Just as shown in the figure 4 (c), there exists hollow between the top and the bottom of the converged crown sprays in the middle of two droplets. In figure 4(a), when the velocity is as small as 0.5m/s, the sprays are just meeting at 2ms, while in figure 4(b), at that time the central jet has formed. In figure 4(a) the height of the central jet is equivalent to that of surrounding sprays. In figure 4(b) when the impacting velocity is increased to 1.0m/s, the time when sprays form is earlier than that in figure 4 (a). The sprays meet, collide and converge with each other and move upward. As shown in figure 4(b), the height of spray is 1.76 times to that of surrounding sprays at 3.0ms. When the impacting velocity is increase to 2.0m/s, splashing occurs quickly after two droplets impacting on the film simultaneously. The splashing sprays collide earlier at the higher position, furthermore, the spray on the bottom also collide, just as shown in figure 4(c) at1.0ms. As the result, an upward velocity normal to the wall is produced, which makes the fluid continues to move upward. In addition, the collision at higher position also brings upward movement, that makes part of liquid break away from surface tension and secondary droplets are produced. The height of the jet at the intersection is equivalent to that of surrounding sprays.
Figure 4. The change of the spray after double droplets simultaneously impact liquid film at different impact speed \( \phi = 30 \). 4. Conclusions

The solidification phenomenon of PCM in the horizontal trapezoidal cavity is studied using CFD. The effect of various aspect ratios, cold wall temperature, PCM’s initial temperature, cavity tilt angle, and Grashof number on heat transfer rate in PCM is investigated. The results of this numerical study lead to the following conclusions:

1. Solidification time is significantly decreased with the increase of the aspect ratio; e.g., the trapezoidal cavity with an AR=1.8 requires almost 17% lesser solidification time than that of the square cavity (AR = 1.0) having the same internal area. Therefore cavity aspect ratio can be used as a controlling parameter to improve the heat transfer rate.

2. The decrease of the cold surface temperature \( T_c \) decreases the solidification time significantly (nearly 50%) for the case where \( T_c \) was reduced from -5 to -10 °C but relatively less significant for other cases in the square cavity as well as trapezoidal cavity.

The theoretical prediction in this paper is hoped to be a useful guide for experiments dealing with the study of effectiveness of aspect ratio of trapezoidal cavity filled with PCM in improving the heat transfer rate.
5. Conclusions
CLSVOF method is applied to simulate the evolution after double droplets simultaneously impinging on flat liquid film. The conclusions are as follows:

1) After double droplets simultaneously impinging on flat liquid film, there are sprays produced by both droplets. They expand outward and meet at the middle of the impacting point, as the result, the laminar jet is formed along the intersection line, which is higher than the surrounding sprays.

2) The impact velocity affects the evolution a lot after double droplets simultaneously impinging on flat liquid film. The spray diameter and height increase with the rise of impact velocity and the laminar jet becomes higher. The times that the height of the laminar jet to the height of surrounding sprays depend on the impact velocity. At higher impact velocity, the time when the sprays produced by the two droplets meet at the middle of the double droplets turns earlier.

3) The horizontal distance between double droplets affects the evolution a lot after double droplets simultaneously impinging on flat liquid film. When the horizontal distance is big, the time when the two sprays meet caused by double droplets impact is later than that when the distance is small. Furthermore, for big impact velocity both the tops and bottoms of the two sprays meet and converge, and there exists hollow between the top and the bottom of the converged crown sprays in the middle of two droplets. However, for the small impact velocity, there is not this phenomenon.

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