Characteristics of Splash Formed by the Impact of Liquid Jet on a Thin Liquid Film

Tianyu Kang\textsuperscript{a}, Qin Qin\textsuperscript{*}, Xin Yao\textsuperscript{b}, Qingbo Yu\textsuperscript{c}

School of Metallurgy, Northeastern University, Shenyang, Liaoning 110819, China

\textsuperscript{*}Corresponding author e-mail: qinq@smm.neu.edu.cn, \textsuperscript{a}602737224@qq.com, \textsuperscript{b}yaoxin_0129@163.com, \textsuperscript{c}yuqb@smm.neu.edu.cn

Abstract. For rotary cup granulation, the splash may occur during liquid slag falls onto the cup, which increases the risk of operation. By performing experiments for three liquids with different properties, including water, 95\% ethanol and 30\% glycerol-water solution, the characteristics of splash formed by the impact of liquid jet on a thin liquid film were studied. The experimental results showed that increasing the impact velocity and diameter lead to intense splash, while increasing the viscosity and the surface tension reduced the scale of the splash.

1. Introduction

Rotary cup granulation is regarded as an important method to treat metallurgical waste residue [1], whose advantages include high recovery and low pollution [2, 3]. During the liquid slag falls onto the cup, unwanted splash increases the danger of the operation and damages the granulation effect. In order to ensure safe production, it is necessary to study the characteristics of splash. Splash formed by the liquid impact is a common phenomenon in production and life, such as painting, surface cooling, fuel atomization and the erosion of soil [4], which are effective applications of the research results on impact and splash control.

Morphology of the impinging liquid, especially the splash, has been the focus of investigation. Due to the influence of many factors such as impact velocity and surface tension, the situation of impact morphology is complicated. Fukai et al. [5] analyzed the process of deformation, spreading, oscillation and recoil in the experiment of drop impact on the solid surface, and established a theoretical model to explain the influence of inertia, viscosity, gravity, surface tension and wetting. Guo et al. [6] reported that, in the case of large \textit{we} number, the upward liquid sheet produced by drop impinging on the film bended inward, making a special bell-like spray. Cossali et al. [7] described the evolution of the crown in detail whose upward liquid sheet turned outward, and defined two forms of splash: the prompt spatter and the late splash. A large number of the mechanism and dynamics studies have been carried out on drop spreading and crown development [8–10], while the research of splash mainly focuses on the critical conditions for splash occurrence [11–13]. Overall, there are few studies on the characteristics of splash.

On the other hand, there has been a long history of studies of liquid impact since that Worthington [14, 15] presented the process of the drop impact on horizontal glass smoked and its "pattern", most of which used the drop as a simplified test subject. By contrast, the splash research with liquid jet as the
impact object is rare. Therefore, the purpose of this paper is to experimentally study the characteristics of splash formed by the impact of liquid jet on a thin liquid film.

2. Experimental set-up
In this study, the experiment was conducted to record the impact process of liquid jet, whose set-up schematic is showed in Figure 1. The liquid reservoir connected to an outlet tube was placed on the bracket. The liquid jet with an initial velocity $1.47 \text{ m} \cdot \text{s}^{-1}$ was produced under the control of valves.

Liquid jet diameter was changed by replacing tubes of different diameter from 4 to 10 mm. Adjusting the height of tube measured vertically from the impact plane to change the terminal impact velocity from 1.93 to $4.35 \text{ m} \cdot \text{s}^{-1}$.

![Figure 1. Schematic of experimental set-up.](image-url)

With the support of backlighting, the impact processes were visualized by a high-speed CCD camera with a Nikon-Nikkor lens at 1000 frames/s and $1280 \times 1024$ pixels. The computer was used to adjust the shooting parameters, control the shooting time and store the image data. The Motion Studio software was utilized to track splash droplets and obtain motion data, which was averaged in subsequent processing.

In order to explore the influence of surface tension and viscosity, water, 95% ethanol and 30% glycerol-water solution were selected as experimental liquids. The physical properties of experimental liquids acquired by the measurement or supplier are listed in Table 1.

| Physical Property                  | Water   | 95% ethanol | 30% glycerol-water |
|-----------------------------------|---------|-------------|--------------------|
| Surface tension $(\text{N} \cdot \text{m}^{-1})$ | 72.75   | 23.65       | 64.13              |
| Viscosity $(\text{Pa} \cdot \text{s})$ | 1.005   | 1.200       | 2.490              |
| Density $(\text{kg} \cdot \text{m}^{-3})$ | 998.2   | 795.0       | 1080               |

3. Results and discussions
Zhan et al. [16] presented that the splashing rate caused by a continuous jet was negligible whilst a large number of droplets was splashed when a broken jet impinged, which has been proved in this experiment.
3.1. Effects of impact velocity
Figure 2 shows the splash scale of water jet varied with impact velocity, the average splash time spacing decreased first and then stabilized (Figure 2(a)); the average number of splash droplets increased and its growth rate increased after the initial stage (Figure 2(b)); the average splash droplet velocity increased (Figure 2(c)). With the increase of impact velocity, the number of droplets generated by the broken jet was close to the upper limit that was reached by complete breakup of jet. Most of the droplets had enough kinetic energy to overcome the resistance and left more kinetic energy to splash, which made the splash more intense.

3.2. Effects of diameter
Figure 3 shows the splash scale of water jet varied with diameter, the average splash time spacing decreased (Figure 3(a)); the average number of spatter droplets increased first and then stabilized (Figure 3(b)); the average splash droplet velocity increased (Figure 3(c)). The jet flux increased with the diameter, which lead to an increase in the upper limit of broken droplet quantity accordingly. The kinetic energy of broken droplet also increased with the diameter, so that the degree of splash was intensified.

3.3. Effects of surface tension
95% ethanol with a small surface tension produced more broken droplets, and the increase in impact velocity caused the majority of droplets to splash, which resulted in a greater decrease in the average splash time spacing of 95% ethanol than that of water as shown in Figure 4(a).

With the increase of diameter, the average splash droplet number of 95% ethanol increased and then exceeded that of water (Figure 4(b)); the average splash droplet velocity of 95% ethanol was slightly higher than that of water (Figure 4(c)). Because the thin film and the droplet were both made of 95% ethanol with a small surface tension, the impact droplets needed to overcome small resistance in the period of deformation. And the droplets retained so much kinetic energy that they broke up violently during splash.

3.4. Effects of viscosity
The broken jet of 30% glycerol-water solution with a large viscosity produced additional satellite droplets. In the case of large impact velocity, these small satellite droplets also caused splash, which made the average splash time spacing of 30% glycerol-water solution less than that of water as shown in Figure 5(a).

With the increase of diameter, the average number of splash droplets of 30% glycerol-water solution increased steadily, although it was less than that of water (Figure 5(b)); the average splash droplet velocity of 30% glycerol-water solution was slightly lower than that of water (Figure 5(c)). Because the thin film and the droplet were both made of 30% glycerol-water solution with a large viscosity, the droplets needed to overcome large viscous resistance during deformation and were difficult to break during splash, reducing the scale of splash.
Figure 2. The splash scale of water jet varied with impact velocity: (a) splash time spacing, (b) Splash droplet number, (c) splash droplet velocity.
Figure 3. The splash scale of water jet varied with diameter: (a) splash time spacing, (b) Splash droplet number, (c) splash droplet velocity.
Figure 4. The splash scale varied with surface tension: (a) splash time spacing, (b) splash droplet number, (c) splash droplet velocity.
Figure 5. The splash scale varied with viscosity: (a) splash time spacing, (b) splash droplet number, (c) splash droplet velocity.
4. Conclusion

In this paper, the experimental subject was set as the liquid jet to analyze the characteristics of splash formed by impinging on the thin liquid film. The three indexes of splash time spacing, splash droplet number and splash droplet velocity were investigated. The experimental results showed that increasing the impact velocity and diameter led to intense splash, while increasing the viscosity and the surface tension reduced the scale of the splash.

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