Splashing criterion when drop impacting on the liquid with liquid film

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Abstract. The paper considers a new method to combat the secondary drops ejecting into the gaseous medium when a single drop impacts the liquid surface. Possible increase in the critical Weber number when a discrete drop of liquid separates into the gaseous medium due to the stability loss of the Rayleigh jet has been shown experimentally. The degree of increase in the critical Weber number is commensurate with the ratio of the surface tension coefficients of liquids to the gaseous medium and can be estimated from the proposed analytical ratio.

1 Introduction

Single drop impact onto liquid film surface is an important aspect of a wide range of phenomena encountered in technical applications. This problem is complicated by variety of boundary and initial conditions (diameter, shape, velocity, drop trajectory, impact frequency, and properties of liquid and gaseous media). Depending on these conditions, after the moment of drop impact on the surface of the liquid, sticking, spreading, splashing or rebound of the drop may occur. At high impact velocities, low viscosity of the liquid or high density of the gaseous medium, so-called liquid coronas can form in the drop crater. Crown consists of a thin liquid layer with an unstable free edge at the top, from which numerous small secondary drops are ejected [1]. The release of secondary liquid droplets into a gaseous medium is a significant problem for many technical applications. For example, in the dehumidifier of a nuclear reactor, such secondary droplets of submillimeter size (which are very difficult to remove and are easily carried by the steam flow), due to the impact on the wetted inner surface, have a significant influence on the safety and efficiency of the reactor. In addition, the appearance of secondary droplets can cause a potential problem of pollution from the nuclear reactor operation.

The case when a drop and a liquid are identical substances is disclosed in sufficient detail by analytical, experimental and numerical works [2–8]. Based on the results of these studies, criterion relations using composite groups of dimensionless similarity numbers of the problem statement to describe the resulting action from drop impact of a different nature have been proposed. To date, the vector of scientific development of this topic is devoted to the research and formulation the theory of secondary drop formation, in

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particularity the Rayleigh-Plateau instability theory, which is confirmed by many studies [9-12].

Thus, we can conclude that the classical problem statement of the single drop impact on the calm liquid surface has been studied in sufficient detail, and the attention of modern researchers has been switched to the development of methods to combat the formation of primary and secondary drops. Basically, the essence of all methods is to change the properties of the liquid due to the use of polymer additives [13], increasing the pressure of the surrounding gaseous medium, or completely replacing the liquid with another one [14], for example, with a higher viscosity.

The present paper proposes a radically new approach in this direction - the artificial creation of a liquid film on the surface of a liquid. It is assumed that a significant difference in the values of the dynamic viscosity of the liquids in the film and in the tank will contribute to a significant decrease in the range of similarity numbers at which primary and secondary splashes occur.

2 Dynamics of droplet impact on liquid surface

2.1 Without liquid film at the interface

A falling drop of liquid has kinetic energy, and its magnitude is due to the action of gravity. Depending on the properties of the liquid and gas, the magnitude of kinetic energy, there can be four scenarios for the interaction of the drop and the liquid surface: 1) the drop touches the liquid and remains floating on the surface; 2) the drop touches the liquid and rebound the liquid; 3) the drop connects with the liquid without significant perturbations of the interfacial surface and smoothly penetrates into it; 4) upon contact with the liquid, the drop forms a crater at the interface, the further dynamics of crater leads to significant perturbations on the interface, the possible formation of a Rayleigh jet, primary and secondary splashes. The fact of formation of Rayleigh jet is known as the splash criterion of Rodriguez and Mesler [2].

The main but not the only criterion for the similarity of the regime of interaction between a drop and a liquid surface is the Weber number (We, relation (1)), which determines the ratio of the liquid inertia to the surface tension σ. According to [15], the We number can be represented as the square of the ratio of two time scales: the effects of surface tension τ₁ and of convective forces τ₂ (1).

$$We = \frac{\rho DU^2}{\sigma} = \left(\frac{\tau_1}{\tau_2}\right)^2 = \left(\frac{\rho D^3}{\sigma} \frac{U}{D}\right)^2$$

where D is the drop diameter, U is the average bulk velocity of the drop, and ρ is the liquid density. If τ₁<<τ₂, then the drop is easily deformed into a vortex ring in the liquid without splashing due to the large convective scale. If τ₁>>τ₂, the time to deform the drop is insufficient and it crashes into the liquid as a spherical body. For liquids close in viscosity to water (~1 cSt), the critical We number when splashes appear is about 60; for more viscous liquids (~1 cSt), the critical We number can be almost 1.5 orders higher [12].
2.2 With liquid film at the interface

When a second (film) liquid appears, this forms a film of a fixed thickness on the surface of the main liquid, the number of problem parameters increases significantly. To simplify, we introduce into consideration only parameters of the film liquid that are used in the We number - density $\rho_2$ and the coefficient of surface tension with air $\sigma_2$, as well as the dimensionless liquid film thickness $\beta=h/D$, where $h$ is the liquid film thickness.

The problem has two critical states in terms of $\beta$. For $\beta=0$, the criteria ratios must completely coincide with the classical problem of a droplet impact on a liquid surface without a liquid film. The second critical state $\beta=\beta_c$ occurs when a further increase in the thickness $h_c$ of the liquid film leads to self-similarity of the solution. Based on these conditions, the present paper proposes relation (2) for the critical value of the We number.

$$We = \left( \frac{\tau_1}{\tau_2} \right)^2 = \left( \frac{\rho_1 D \sigma_2 \beta + \sigma_2}{\sigma_1 (\beta+1) \sigma_2} \right)^2 = \frac{U^2 \rho_1 D (\sigma_1 \beta + \sigma_2)}{\sigma_1 \sigma_2 (\beta+1)},$$

where the subscript "1" means the main liquid, the subscript "2" means the liquid of which the film is composed.

3 Experiment statement

3.1 Experimental setup

Figure 1 shows an experimental setup. Interfacial boundary between liquid 1 (distilled water; $\rho_1=999$ kg/m$^3$, $\mu_1=1\cdot10^{-3}$ Pa·s, $\sigma_1=72.8\cdot10^{-3}$ N/m, $T=20^\circ$ C) and gas (atmospheric air; $\rho=1.2$ kg/m$^3$, $\mu=1.82\cdot10^{-5}$ Pa·s, $T=20^\circ$ C) is implemented in a Petri dish 3 with a diameter of 100 mm and a thickness of 50 mm. According to [12], the dimensions of such a reservoir are more than sufficient to level out the effects of interaction between the liquid and the walls of the reservoir. In experiments, in the presence of liquid film 2, the second liquid (oil; $\rho_2=919$ kg/m$^3$, $\mu_2=5.57\cdot10^{-2}$ Pa·s, $\sigma_2=33.1\cdot10^{-3}$ N/m, $T=20^\circ$ C) was added to the Petri dish, the film thickness was estimated from the known interfacial area and the measured weight of added oil. Droplets were generated using a syringe pump 4 with replaceable needles of various diameters.
Process of impacting of the drop was recorded with a monochrome high-speed camera Fastec HiSpec 5 with the frame resolution of $300 \times 300$ pixels, frame rate $f=5000$ 1/s. The camera was equipped with a Navitar 1''F/0.95 lens with 25 mm focal distance. A series of experiments were carried out at room temperature of the ambient air and liquids used. The reproducibility of the data was ensured by five repetitions of each experiment.

### 3.2 Experimental measurements

Dynamics of interaction of a drop and a liquid with a film is very similar to the process of drop impact on a liquid without a film (Fig. 2). This process includes the formation of a crater with its subsequent collapse, the formation of a Rayleigh jet. Depending on the parameters of the problem statement, secondary drops can form on the crown of the crater; the Rayleigh jet can lose stability also ejecting of secondary drops. However, two significant differences were found. First, the dynamics and hydrodynamic stability of the Rayleigh corona and jet are determined by the parameters of the liquid with the film. Due to this fact, the presence of the liquid film makes it possible to change the values of the critical hydrodynamic parameters at which secondary droplets are ejected. Secondly, the occurrence of a secondary Rayleigh jet between two liquids has been observed, which can lead to the formation of discrete separated droplets of the secondary (target) liquid in the primary one.

![Fig. 2. Dynamics of interaction of a falling drop and a liquid with a film at $\beta=1$ and We=45.](image-url)
Fig. 3. Dependence of the critical We number on the dimensionless liquid film thickness.

Estimation the value of the critical We number obtained from the results of video digital processing are in good agreement with the proposed analytical expression (2): an increase in the critical We number is commensurate with the ratio of the surface tension coefficients of liquids (Fig. 3). It should be noted that in the absence of a liquid film, the values of the critical We number are in complete agreement with the results of [2, 12].

In the case of the presence of a liquid film, an effect was revealed: with an increase in the droplet diameter, a more significant increase in the threshold number $\text{We}(\beta)$ occurs, at which secondary drops form. This fact can be explained by following: when plotting in the $\text{We}(\beta)$ coordinates, with an increase in the droplet diameter, the same value of $\beta$ corresponds to different thicknesses of the liquid film, the breaking of these films requires different energy.

4 Conclusions

The present obtained results show that as one of the possible measures to combat the secondary drops ejecting into the gaseous medium when a liquid drop impacts on the liquid surface, the method of artificial formation of a film from a liquid of lower density with a high coefficient of dynamic viscosity can be used. In this case, with a sufficient dimensionless thickness $\beta$ of the film, the conditions for the formation of secondary drops will be determined by the parameters of the liquid from which the film consists. On average, the degree of increase in the critical We number is commensurate with the ratio of the surface tension coefficients of liquids to the gaseous medium and can be estimated from the proposed relation (2). Also, according to the results of experimental studies, a possible formation of a second Rayleigh jet between liquids was revealed.

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References