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## ► To cite this version:

Kaitao Tang, Thomas Adcock, Wouter Mostert. Effects of Gravity on the Liquid Rim Splashing Behaviour. The 26th International Congress of Theoretical and Applied Mechanics, The International Union of Theoretical and Applied Mechanics, Aug 2024, Daegu (Korea), South Korea. <hal-04686348>

**HAL Id: hal-04686348**

**<https://hal.science/hal-04686348v1>**

Submitted on 4 Sep 2024

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## EFFECTS OF GRAVITY ON THE LIQUID RIM SPLASHING BEHAVIOUR

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**Summary** Motivated by splashing phenomena in breaking ocean waves, we numerically investigate the splashing process between two cylindrical liquid rims under the influence of gravity. We first propose scaling arguments relating the rim splashing configuration to the wave breaking scenario, and then examine the statistics of the splash drops in comparison with available wave breaking data. Finally, we discuss the effects of gravity on the rim splashing process. It is found that while gravity does not affect the transverse ligament merging cascade directly, it terminates the ligament merging cascade when the lamella sheet fully retracts, thus assigning great significance to transient effects in shaping the fragment statistics.

### SCALING ARGUMENTS

A deep-water surface wave with amplitude  $a_b$ , wavenumber  $k_b$ , surface tension  $\sigma$  breaking under gravity  $g$  can be characterised by two non-dimensional parameters: Bond number  $Bo_b \equiv \rho_l g / \sigma k_b^2$  and slope  $S_b \equiv a_b k_b$ . As the wave front overturns to reconnect with the sea surface below, a splash-up is produced which later merges with the wave bulk behind. The closure of the indentation space between these two structures leads to the ‘secondary splashing’ phenomenon, during which many small fragments are ejected upwards whose generation mechanism remains largely unknown [1]. To model this scenario, we consider two infinitely long cylindrical liquid rims with diameter  $d_0 = a_b$  aligned along the transverse direction as shown in Fig. 1a, which are set to travel towards one another at relative speed  $u_r = \sqrt{g/k_b}$ , estimated as the phase speed of the breaking wave. The gravitational field  $g$  is set perpendicular to the plane containing the two rims, and the Weber and Bond numbers of rim collision are related to the breaking wave parameters as follows:

$$We \equiv \frac{\rho_l u_r^2 d_0}{\sigma} = Bo_b S_b, \quad Bo \equiv \frac{\rho_l g d_0^2}{\sigma} = Bo_b S_b^2, \quad (1)$$

Thus the case of [1] where  $Bo_b = 500$  and  $S_b = 0.55$  corresponds to  $We = 280$  and  $Bo = 150$ . The rim Ohnesorge number  $Oh \equiv \mu_l / \sqrt{\rho_l d_0 \sigma}$  is here fixed at 0.01, as we focus on the inviscid limit. Since the initial splash-up during wave breaking features strong surface corrugations which have not yet been fully characterised, we also impose random transverse perturbations on the rim radii [1] characterised by  $\varepsilon_0$ , the non-dimensionalised characteristic perturbation amplitude; and  $N_{\max}$ , the highest wavenumber among the perturbation signal spectrum.

### FRAGMENT STATISTICS AND COMPARISON WITH WAVE BREAKING DATA

We conduct three-dimensional direct numerical simulations to solve this problem within the open-source Basilisk numerical library [2]. The fragment statistics are collected over a total period of  $T = 2.7\tau$ , where  $\tau \equiv \sqrt{\rho_l d_0^3 / 8\sigma}$  is the capillary timescale, to produce ensemble-averaged number density  $n$  and size distribution function  $N$ . A typical right-view simulation snapshot is shown in Fig. 1a, where a spreading lamella forms between the two rims, topped by growing ligaments which pinch off to form fragments of various sizes. Fig. 1b shows the fragment number density  $n$  as a function of their radius  $r$  for two different  $Bo$  values (0 and 125) and two different times ( $t = 0.09\tau$  and  $0.36\tau$ ), while  $We = 280$  and  $N_{\max} = 60$  for both cases. Vertical dashed lines showing the threshold of  $2\Delta_{10}$  are also added, above which the numerical results are considered fully grid converged. Finite  $Bo$  value does not lead to any significant modification of the fragment distribution, whose right tail shows a significant shift towards larger sizes as time elapses. Consequently, the slope of  $n$  at intermediate radius values becomes more gradual, which at  $t/\tau = 0.36$  can be described by a power-law decay of  $n \propto r^{-5/3}$ . The splash fragments are produced by the end-pinching of their parent ligaments which undergo a merging cascade at the same time; this ensures that the ratio between the fragment size and their parent ligament width scatters around 1.4 [3]. The insensitivity of  $n$  to  $Bo$  therefore suggests that gravity does not influence the essential dynamics of the ligaments topping the transverse lamella rim.

We also present in fig. 1c a comparison between the fragment size distribution function retrieved from our rim splashing simulations at  $t/\tau = 0.36$  and the wave breaking data taken from [4]. The results have been non-dimensionalised using the capillary length  $l_c \equiv \sqrt{\sigma / \rho_l g}$ . It is found that when the maximum initial perturbation wave number  $N_{\max} \geq 60$ , our size distribution functions within the radius range of  $0.1l_c \leq r \leq 0.5l_c$  match excellently with those of [1] and [4], although the break of slope in our distribution appears to occur at slightly larger  $r$  values ( $0.5l_c$ , which is around  $0.2l_c$  for [1] and [4]); which may be because the duration of rim splashing has not yet been fully matched with that of secondary splashing phenomenon in wave breaking. Our right tails within the range of  $r \geq 0.5l_c$  also match in slope with all wave breaking data, featuring a power-law exponent of around  $-6$ .

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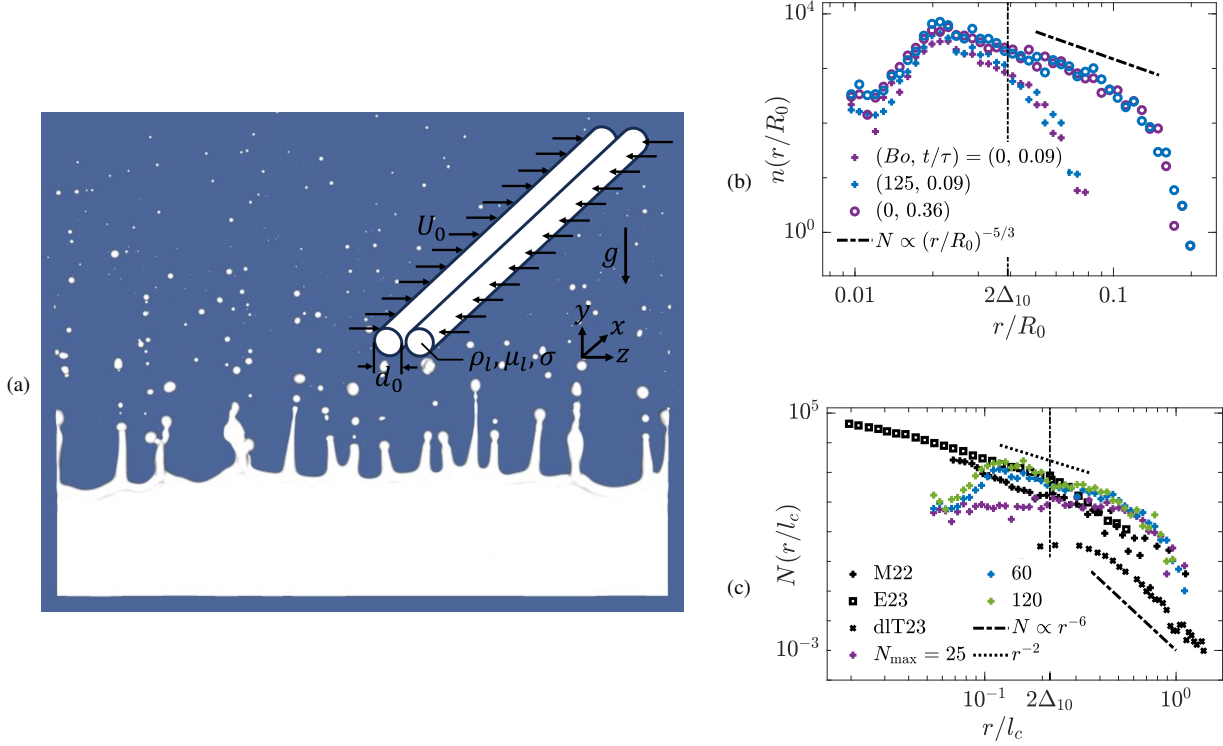


Figure 1. (a): Sketch showing the configuration of the liquid rim collision problem superimposed on a typical right-view simulation snapshot. (b): Evolution of the fragment number density  $n(r/R_0)$  for two simulation cases where  $Bo = 0$  and 125. (c): Comparison of our splash fragment size distributions  $N(r/l_c)$  at  $t/\tau = 0.36$  with available wave breaking statistics.

### GRAVITATIONAL EFFECTS ON RIM SPLASHING

The power-law exponents we observed in fig. 1c are much smaller than our previous results [3], where it is found to transit from  $-1/2$  to  $-7/2$  at large fragment sizes. While gravity does not affect the dynamics of ligament growth and merging, it causes the lamella and its bordering rim to decelerate and fall back, thus prescribing a finite lamella retraction timescale  $t_R$  when the ligament merging cascade is terminated abruptly, preventing production of larger splash drops and further evolution of the fragment size distribution. Consequently, for finite- $Bo$  splashing events, it is necessary to consider transient effects not covered in [3] when investigating fragment statistics, e.g., the evolving distribution of transverse ligament widths. Where  $Bo = 0$ , the bordering rim only experiences capillary deceleration and it is expected that at still later times, the exponent would reach the quasi-steady-state value of  $-1/2$  we theoretically predicted in [3].

This cutoff timescale  $t_R$  can be estimated by inspecting the kinematics of the lamella rim. When gravity is incorporated, we find that the evolution of its average vertical position  $y_{\text{rim}}$  features a free-fall motion superimposed on the capillary deceleration [3]. This is given as follows,

$$\frac{y_{\text{rim}}}{R_0} = 0.44\sqrt{We}\sqrt{\frac{t}{\tau}} - \frac{1}{8}Bo\left(\frac{t}{\tau}\right)^2. \quad (2)$$

By setting  $y_{\text{rim}} = 0$ , we arrive at  $t_R = 2.31We^{1/3}Bo^{-2/3}\tau$ , which equals  $0.6\tau$  for the simulation case of  $We = 280$ ,  $Bo = 125$  we presented in fig. 1.

### CONCLUSIONS

We have obtained novel simulation results of rim splashing under gravity, which shows promising agreement with both numerical and experimental wave breaking data. Our analysis also sheds light on the effects of gravity on rim splashing, and we are able to predict the cutoff timescale of fragment production under gravity, which serves as a stepping stone towards further theoretical analysis of the time-evolving splash fragment size distribution.

### References

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