# BUBBLE PRODUCTION OCCURRING ON THE PERIODIC IMPACT OF VISCOUS DROPS 

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#### Abstract

By modulating the pressure upstream of a nozzle trains of drops are produced which impact the thin layer of liquid formed by the spreading of the previous drops on a glass block. The spreading flow was observed from below through the glass block with a CCD camera. For certain conditions a very regular production of bubbles is observed. The origin of the bubbles is not at the site of drop impact but at the position where the splash crown normally appears. However the phenomena occur below the splashing limit, i.e. no drops are ejected back from the surface. The impact parameters of the drops size and velocity as well as drop frequency together with the fluid parameters were varied and two non-dimensional correlations are presented corresponding to the onset of bubble production and to their disappearance. In the first case an abrupt transition occurs and large bubbles appear. A characteristic Weber number is derived for the phenomenon. With increasing Weber number the number of bubbles increases smoothly whilst the bubble size decreases until they disappear. The phenomenon is strongly dependent on the viscosity of the liquid.


## Introduction

The impact of drops on a thin layer of liquid on a solid surface is a very common phenomenon, for instance the fall of raindrops on puddles or the impact of paint droplets on the paint coat during application. In the later case the quality of the coating depends strongly on the outcome of the impact. Ideally, the paint droplets should adhere to the paint film already present on the substrate, spread and be incorporated into the film. However, for certain impact parameters gas is entrained into the liquid layer in form of small bubbles. In the case of water the lifetime of these bubbles is not very long in comparison with the time scale of spreading of the drop. However, for viscous liquids like paint it can be much longer. The rheological properties of most paints range from Newtonian to shear-thinning, but in all cases the viscosity is by about two orders of magnitude larger than the one of water. This means that once bubbles are present in the paint layer they need a long time to disappear. For some applications the paint is heat cured in an oven (automotive) immediately after spraying. If the bubbles have not disappeared when this process starts then they can yield a rough finish of the paint.
This paper is a first step in trying to understand how and under which conditions bubbles appear in a film impacted by drops.

## Experimental Set-up

Typically drop impact is studied from a side view. However, in the present case a view from below is better adapted for the phenomena under study, Figure 1. A periodic chain of drops is produced by a nozzle where the upstream pressure is modulated by a piezo-electric transducer resulting in a small modulation of the jet surface. The Rayleigh instability of the jet amplifies the waves until the jet breaks up into drops. The drops then pass a perforated mirror. This mirror reflects the light from LED 2 onto the area of investigation on the glass surface. From below a CCD camera records the images of the film phenomena, e.g. Figure 3. Camera 1 is used to measure the size and velocity of the drops, Figure 2. Stroboscopic illumination was used for these pictures, whilst for camera 2 only a single flash per image was applied.

## Liquid Influx



Figure 1. Set-up of the apparatus

## Results

Figure 3 shows the case of drop impact without bubble production. Figure 4 shows the large number of bubbles that are produced. The incoming drop can be seen as a black circle in the middle of the image. It is surrounded by a transparent area, which is free of bubbles. Around this area an interrupted white circle can be seen. This corresponds to the crown produced by the expanding liquid of the drops, see e.g. [1]. This crown does not splash, but the bubbles are produced here The bubbles propagate very slowly together with the film flow outside of the crown. Due to the curvature of the liquid surface outside of the crown the light is deflected and does not reach the camera. Further away from the crown the surface is flatter and the bubbles can be seen. They appear to be coming from singular points at the periphery of the crown. Basically at each point of the crown one bubble is produced per drop impact. This can be seen more clearly on Figure 5. In this case the train of drops was not quite perpendicular to the glass surface and the bubbles are only produced on one side of the impact area. Further work is necessary to elucidate the details of the mechanism of production.


Figure 2. Train of drops


Figure 3. Drop impact without bubble production


Figure 4. Drop impact with bubble production


Figure 5. One sided bubble production

Figure 6 shows a series of pictures taken for a constant pressure drop across the nozzle, i.e. constant drop velocity and total volume flux but varying drop frequency and therefore drop size. This series documents the smooth transition to bubble production. Analyzing the sequence of images it is can be observed that with increasing drop frequency the size of the bubble diminishes and their number increases. There is a certain point where the formation of bubbles ceases. This is called the smooth transition.

One of the objectives of the work was to obtain mathematical correlations in non-dimensional form which determine the region where bubbles are formed and disappear. The main problem in obtaining a correlation is that the film thickness on the wall could not be measured. This problem was circumvented by using the diameter of the crown together with the continuity equation to derive the film velocity at the position of the crown. Three non-dimensional numbers are used for these correlations: Reynolds, Weber and a modified Strouhal number all using a derived film thickness as a characteristic length scale. Based on the same assumptions as Yarin and Weiss [1] the film thickness is proportional to a viscous length scale:

$$
\begin{equation*}
h_{f i m} \propto(v / f)^{1 / 2} \tag{1}
\end{equation*}
$$

The Weber number is defined in this case as:

$$
\begin{equation*}
W_{e}=(\rho / \sigma) f^{5 / 2} D_{\text {drop }}{ }^{6} D_{\text {crown }}{ }^{-2} v^{-1 / 2}, \tag{2}
\end{equation*}
$$

and the film Reynolds-number as :

$$
\begin{equation*}
R_{e}=(1 / 6) f D_{\text {drop }}^{3} / D_{\text {crown }} / V \tag{3}
\end{equation*}
$$

where $\rho, \sigma, v$ are the fluid density, surface tension and viscosity and f is the drop impact frequency.
The modified Strouhal number used is defined as:

$$
\begin{equation*}
S t r_{m}=f D_{\text {crown }} / u_{\text {drop }} \tag{4}
\end{equation*}
$$

By varying the drop frequency (modulation frequency of the piezoelectric transducer), the drop velocity and size as well as the liquid parameters (density, viscosity and surface tension) the following correlations were found for the existence of bubbles:
for the onset (abrupt transition):

$$
\begin{align*}
& W e \geq 3.5 \mathrm{Str}_{m}^{0.35} \mathrm{Re}^{2.36}  \tag{5}\\
& W e<8.53 \mathrm{Str}_{m}^{0.62} R e^{2.36}
\end{align*}
$$

and for the upper limit:
(smooth transition)
In both cases the viscous effects are dominant. This explains why these phenomena can not easily be observed for low viscosity liquids.

## References

[1] Yarin, A.L.; Weiss, D. A., Impact of drops on solid surfaces: self-similar capillary waves, and splashing as a new type of kinematic discontinuity, J. Fluid Mech., 283, 141-173, 1995

$\mathrm{f}=3,096 \mathrm{kHz}$

$\mathrm{f}=3,511 \mathrm{kHz}$

$\mathrm{f}=3,872 \mathrm{kKz}$

$\mathrm{f}=4,249 \mathrm{kHz}$

$\mathrm{f}=6,092 \mathrm{kHz}$

$\mathrm{f}=7,079 \mathrm{kHz}$

$\mathrm{f}=8,262 \mathrm{kHz}$

Figure 6. Images documenting the smooth disappearance of bubbles for increasing drop frequency, constant drop velocity and total volume flux.

