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Experimental study of vortices and cavities from single and double drop impacts onto deep pools

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ABSTRACT

In the present work, experimental investigations of single and double drop impacts into a deep pool of the same liquid are presented. For the first time, vortex interactions of two synchronised spherical drops of equal size are presented and compared to the evolution of undisturbed vortex rings generated by single drop impacts. High-speed images show novel and not yet documented vortex structures. The results show that vortex rings can be generated for drop Weber numbers well above the boundaries given in the literature, but with a different structure. Reynolds numbers of the relaminarised vortex rings depend on the presence of an outer vortex ring and are found to be significantly lower, if this structure was suppressed.

1. Introduction

The impact of a single drop onto a solid or liquid layer has been widely investigated for more than a century. Such an interest comes from the joining of a very basic identification of the problem (which allows a precise and rigorous formalisation), a remarkable amount of outcoming phenomena, a large range of important technical applications and – last but maybe not least – an unquestionable aesthetic appeal [1,2]. Drop impacts are involved everywhere a spray is used (coating, painting, cooling, fire suppression systems, internal combustion engines), plus many other applications that span from ink-jet printing, agriculture (irrigation and pesticide shedding), mitigation of the effect of rain on aircrafts and wind turbines (with the related icing problems), on conservation of cultural heritage (against erosion and corrosion), pollution and microbial transports, forensics analysis of blood stains. Furthermore, the phenomena taking place after the impact of liquid drops on liquid surfaces are of great interest in geophysics and soil mechanics: Ferreira et al. [3] have shown that the motion of the fluid after the impact of the drop on a thick liquid layer is responsible for an increase in soil erosion, since the receding part of crater evolution produces upward fluid motion that lifts the underneath soil [4]. In geophysical impact studies, the estimation of air–sea heat and mass transfer is expected to improve the predictions of local carbon budget and cyclone development in the tropical region [5]. These scalar transfers are affected by the underlying fluid flow behaviour.

In the general case, drop impact is first of all a multiphase (solid if present, one or more liquids, surrounding gas) fluid dynamics problem, with the addition of heat and mass transfer if temperature or concentration play a significant role, e.g. for hot or cold drops or surfaces or for drops impacting onto a chemically different liquid. In the latter cases, the problem becomes also a multiphysics one.

Inertial, viscous and capillary forces merge their effects so that, despite the apparent simplicity of the problem, the resulting phenomena are extremely complex and varied. The most used classification of drop impacts distinguishes first of all between impacts onto dry and wet surfaces, the latter case being then further subdivided in impacts onto thin liquid films, thick liquid films and deep pools. The influence of the solid surface is different in each, and it should be absent by definition for drop impacts into deep pools.

Depending on the drop kinetic energy, the surface characteristics and temperature, the impact onto solid surfaces may produce different outcomes: deposition, splash, fragmentation, bounce, spread and rebound [6–9].

When a drop impinges on the free surface of a deep liquid layer, the interface is deformed by the impact and coalescence, splashing and crater formation may take place (cavity and crater are commonly used as synonyms). Droplet impacts on a wavy liquid

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Nomenclature

D	Drop diameter [m]
D_h	Horizontal drop diameter [m]
D_v	Vertical drop diameter [m]
w	Drop velocity [m/s]
ρ	Density [kg/m^3]
μ	Dynamic viscosity [kg/(m s)]
g	Gravitational acceleration [m/s^2]
σ	Surface tension [N/m]
We	Weber number [-] $We = \rho D w^2/\sigma$
Fr	Froude number [-] $Fr = w^2/(gD)$
Re	Reynolds number [-] $Re = \rho D w/\mu$
L	Distance between drops impact points [m]
L^*	Dimensionless L [-] L/D
S	Sphericity [-]
t	Time [s]
l	Diffusion length [m] $\sqrt{4\mu t/\rho}$
z_C	Crater depth [m]
z_V	Vortex depth [m]
z_b	Vortex plane depth [m]
a	Vertical vortex dimension [m] $2(z_V - z_b)$
b	Horizontal vortex dimension [m]
f_{camera}	Acquisition frequency [Hz]
t_m	Time of maximum crater penetration [s]
$w_b(t)$	Vortex plane velocity [m/s] $(z_b(t) - z_b(t-1)) f_{\text{camera}}$
Re_b	Vortex Reynolds number [-] $Re_b = \rho b w_b/\mu$

film evidencing that the cavity becomes asymmetrical [10]. Crater formation and evolution may then show manifold characteristics like bubble entrapments [11], trampoline phenomena [12], ejecting thick jets [13,14], micro-jetting [15] and vortex rings generation [16–18].

During the impact, air – from a thin, circular sheet trapped between drop and free surface [19,20] – is transported in the receiving liquid [21].

Vorticity develops during crater formation and as the drop spreads over the cavity [21]. When the crater recedes a vortex ring may detach and travel through the deep liquid. As the complexity of this phenomenon had made analytical and even numerical solutions not viable in the past, experiments have historically been the primary tool of investigation. These experiments were focused on the structure and evolution of the vortex ring generated by a falling single droplet from heights of a few centimetres. Quantitative information about vortex ring diameter, translational velocity and Reynolds number of the vortex ring were reported [16,22–24]. Primary and secondary vortex rings structures were evidenced and their characteristics were found to be very sensitive to pool and ambient temperature, as they affect both surface tension and viscosity. An outer vortex ring was reported to be generated at crater edge during the expanding phase and a central one at the crater tip at the beginning of its receding phase [21,25]. Furthermore, the shape of the droplet at the moment of impact has a significant influence on the penetration of the vortex ring structure: prolate-shaped drops produce more penetrating vortex rings then oblate-shaped ones [16]. The conjecture about the existence of an upper limit on Weber number ($We = \rho D w^2/\sigma$, where ρ is the density, D the diameter, w the velocity of impinging drop at impact and σ the surface tension) for the generation of vortex structures is widely accepted, and different limits are reported. A constant limit of vortex inhibition is stated in terms of a "critical" Weber number of 64 in [26], while Oguz and Prosperetti [27] claim the existence of a boundary which limits the conditions for vortex ring formation. Such boundary is defined in terms of a power law correlation $We = 41.3 Fr^{0.179}$, where the Froude number is $Fr = w^2/(gD)$

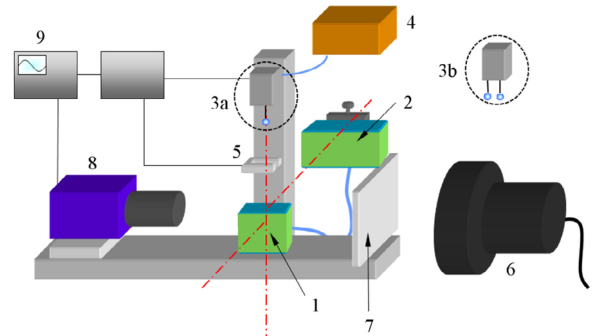

Fig. 1. Experimental setup; the deep pool (1) is connected to an auxiliary pool (level pool) (2) mounted on a vertical micrometric stage. Falling drops, produced by a droplet generator (3) allowing the production of either a single drop (3a) or two synchronised drops (3b), fed by a reservoir (4), are detected by a light sensor (5). A continuous light (6) is diffused (7) and needed to record high speed images on the camera (8) mounted on a tilt, rotating and movable micrometric stage. The components are controlled and synchronised (9).

and g is the standard acceleration due to gravity. Recent investigations [21,28] reported vortex ring formation exceeding the thresholds quoted above; but these vortex rings are characterised by a different structure.

To the authors' best knowledge, the study of vortex generation by impinging drops was previously limited to single drop impacts, due to the increased complexity of the phenomena with multiple drop impacts. This study is aimed at extending the investigation on vortex generation and evolution to double drop impacts where the interaction between the two processes leads to a complex vortex evolution characterised by a different behaviour than the one observed with single drop impacts. Three different characteristic Weber numbers – below, near to and above the aforementioned "critical" Weber number of 64 suggested in [26] – were chosen for a comparative study of flow fields generated by single and double drop impacts.

Results contribute to extend the knowledge of single drop impact in deep pool towards the investigations of binary impacts of two synchronised droplets. Additionally, the experimental studies for the given range of Re and We of binary drop impacts are unedited benchmark data sets for challenging numerical simulations.

2. Experimental procedure

Drop impact experiments were performed by a high-speed visualisation technique with continuous back-light illumination. The experimental setup is sketched in Fig. 1.

Millimetric-size deionised water droplets are produced with an on-demand droplet generator [29], which allows the synchronous detaching of two drops of equal size. The generator is composed of a pressurised chamber, calibrated needles with adjustable distance and a precise flow regulation system that allows regulating, in coordination with an imposed detaching frequency, the volume of the drops. An electro-mechanical component generates a pressure wave which propagates through the pressurised liquid to the needles tips where the droplets are pending, causing their simultaneous detachment. The droplet was pigmented by instant coffee powder solution of well known rheological behaviour [30] with a concentration of 1% (wt%). Effect on crater evolution was studied for different concentration in a previous work [21]. If coffee powder dissolved completely without leaving any type of residue was not known, but it is expected to be of sub-micrometric size. The highly industrialised production process guaranties a constant rheological behaviour of different charges. After their simultaneous detaching from the needles, the drops are accelerated by gravity and impact into a pool filled with water. The pool is made by a glass cubic