International Journal of Multiphase Flow 000 (2018) 1–16

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Three-dimensional high speed drop impact onto solid surfaces at arbitrary angles

Radu Cimpeanu*, Demetrios T. Papageorgiou

Department of Mathematics, Imperial College London, London SW7 2AZ, United Kingdom

ARTICLE INFO

Article history:
Received 3 August 2017
Revised 20 March 2018
Accepted 18 June 2018
Available online xxx

Keywords:
Drop impact
Stagnation-point flow
Spreading
Splashing
Volume-of-fluid
Direct numerical simulations

ABSTRACT

The rich structures arising from the impingement dynamics of water drops onto solid substrates at high velocities are investigated numerically. Current methodologies in the aircraft industry estimating water collection on aircraft surfaces are based on particle trajectory calculations and empirical extensions thereof in order to approximate the complex fluid-structure interactions. We perform direct numerical simulations (DNS) using the volume-of-fluid method in three dimensions, for a collection of drop sizes and impingement angles. The high speed background air flow is coupled with the motion of the liquid in the framework of oblique stagnation-point flow. Qualitative and quantitative features are studied in both pre- and post-impact stages. One-to-one comparisons are made with experimental data available from the investigations of Sor and García-Magariño (2015), while the main body of results is created using parameters relevant to flight conditions with droplet sizes in the ranges from tens to several hundreds of microns, as presented by Papadakis et al. (2004). Drop deformation, collision, coalescence and microdrop ejection and dynamics, all typically neglected or empirically modelled, are accurately accounted for. In particular, we identify new morphological features in regimes below the splashing threshold in the modelled conditions. We then expand on the variation in the number and distribution of ejected microdrops as a function of the impacting drop size beyond this threshold. The presented drop impact model addresses key questions at a fundamental level, however the conclusions of the study extend towards the advancement of understanding of water dynamics on aircraft surfaces, which has important implications in terms of compliance to aircraft safety regulations. The proposed methodology may also be utilised and extended in the context of related industrial applications involving high speed drop impact such as inkjet printing and combustion.

1. Introduction

Since the days of Worthington (1876), the problem of droplet impact has offered the fluid dynamics research community exciting opportunities and challenges over the course of its history. For the first time in a systematic manner, in his book entitled *A study of splashes* (Worthington, 1908), Worthington makes use of early photographic technology (alongside careful sketchwork) to provide a comprehensive visual interpretation of splashing phenomena. The framework has since captivated the interest of theoreticians and experimentalists alike, as it incorporates one of the most invitingly simple geometrical configurations, while at the same time giving rise to diverse and rich phenomena of immense scope.

A plethora of application areas benefit from understanding the outcomes of droplet impact events. We emphasise in particular the role of droplet splashing (or absence thereof) in printing technologies (van Dam and Le Clerc, 2004; Jung and Hutchings, 2012), combustion (Moreira et al., 2010), granular material interactions at all scales (Thoroddsen and Shen, 2001; Marston et al., 2012), electronics (Kim, 2007) and spray-cooling in nuclear reactors (Sawan and Carbon, 1975). The design of superhydrophobic coatings in relation to droplet impact dynamics (Tsai et al., 2009; Deng et al., 2009) is yet another prime example of the widespread applicability of this canonical problem.

Recent reviews provide an excellent insight into the state-of-the-art in the field within each decade (Rein, 1993 in the 1990's, Yarin, 2006 in the 2000's and more recently Josserand and Thoroddsen, 2016). The area has witnessed a very strong surge in the past decade, fuelled in part by the development of progressively more powerful imaging technologies, with both frame rates and resolutions capable of capturing details beyond the scope of

* Corresponding author.
E-mail address: radu.cimpeanu11@imperial.ac.uk (R. Cimpeanu).
URL: http://www.imperial.ac.uk/people/radu.cimpeanu11 (R. Cimpeanu)

https://doi.org/10.1016/j.ijmultiphaseflow.2018.06.011
0301-9322/

previous equipment (see Thoroddsen et al., 2008 as well). Furthermore, the improvement of numerical algorithms and usage of high performance computing has enabled computational studies that complement and inform both experimental and analytical work. We focus particularly on the volume-of-fluid package *Gerris* (Popinet, 2003; 2009), which is one of the most popular open-source tools due to its strengths in dealing with interfacial flows on a range of very different scales. Comparisons with experiments, as well as analytical work have been consistently robust, be it in cases of liquid-liquid impact (Thoraval et al., 2012; Agbaglah et al., 2015) or impacts of liquid onto solid surfaces (Visser et al., 2015; Philippi et al., 2016; Wildeman et al., 2016).

In the case of normal (perpendicular) impact at low-to-moderate velocities (and depending on specific fluid properties), an axisymmetric assumption can be used in analytical and computational investigations. The reduction in dimensionality is a significant advantage that has led to very efficient (axisymmetric) computations and good agreement with experiments. Visser et al. (2015) for example, while innovating experimental technology enabling the time-resolved investigation of micron-sized drop impacts, have managed to conduct successful comparisons with direct numerical simulations at impact speeds of up to 50 m/s, a regime which is commonplace in combustion, inkjet printing or aircraft-related applications. In the respective scenario, the small drops spread onto the surface in what is known as pancaking motion, with the axisymmetric approximation remaining valid in the absence of splashing events.

In cases where spreading and later retraction rather than splashing occurs, the vast majority of efforts have been dedicated towards identifying quantities such as the maximal spreading radius (Stow and Hadfield, 1981; Clanet et al., 2004; Fedorchenko et al., 2005; Roisman, 2009; Schroll et al., 2010) and most recently Wildeman et al., 2016), as well as the resulting minimal film thickness, retraction dynamics and the role of the internal boundary layer - see Bartolo et al. (2005) and in particular Eggers et al. (2010) for a comprehensive investigation of the above.

At higher speeds however, there is still an ongoing debate as to how the splashing phenomena are first initiated, and the splashing threshold in particular. Up until the groundbreaking experimental investigation of Xu et al. (2005), there have been numerous attempts to characterise the transition from spreading to splashing dynamics in the classical impact problem in terms of drop-related parameters only (size, density, viscosity, surface tension coefficient, impact velocity). The Chicago group discovered, however, that decreasing the ambient air pressure may completely suppress splashing. As such, a host of additional modelling, experimental and numerical efforts have been initiated, with the work of Riboux and Gordillo (2014) proposing a model deducing a threshold splashing velocity as a function of a generalised set of key parameters containing the liquid density and viscosity, the drop radius, gas density and viscosity, the interfacial tension coefficient, as well as the nanometric mean free path of the gas molecules.

Once the drop splashes, there is very little attention dedicated to the ensuing dynamics, with the sizes and velocities of secondary drops being prohibitively small experimentally and computationally, although advances have taken place recently in terms of simplified models. In particular, Riboux and Gordillo (2015) have proposed a one-dimensional approach to predicting sizes and velocities of ejected droplets for $\mathcal{O}(1)$ mm sized impacting drops and low speeds, finding reasonable agreement with experiments.

As underlined by Josserand and Thoroddsen (2016), there are several exciting challenges lying ahead, two of which are of great importance in the context of the present work. First of all, gaining an improved understanding of splashing, particularly in difficult high speed conditions of industrial relevance, is moving more and more within reach, and further detailed investigation using the available tools is needed. Secondly, oblique impacts are rarely analysed (exceptions being Mundo et al., 1995; Sikalo et al., 2005; Bird et al., 2009) due to the additional flow complexity. Most often, qualitative rather than quantitative phenomena are explored in detail. The exceptions tend to focus on large scale effects at the level of the entire drop, as opposed to details at the level of the splashing itself and the interesting local structures arising. Both of these themes lie at the heart of the present work, which focuses on the modelling and computation of oblique three-dimensional drop impact in aerodynamic conditions.

In aircraft-oriented research and design involving drop impact, the relevant scales are often dictated by the size of the parts that are most affected by phenomena such as water impingement, retention and finally icing and its prevention. The wings or nacelles are several metres long, while computing accurate air flows around them requires domains that span tens of metres in all dimensions. This becomes highly prohibitive in terms of accurate resolution of the intricate and sensitive physical effects pertaining to drop impact, which often happen at sub-micron scales in the order of tens to hundreds of microseconds. As such, particle-trajectory calculations of various degrees of complexity have thus far proven to be the only tractable solution in industrial setting.

There are several important limitations of current models, as pointed out by Gent et al. (2000) in a relatively recent review:

- droplets are assumed to be spherical and non-deformable as they approach the solid surface, hence topological transitions such as the emergence of secondary drops either before or after impact are not considered;
- phenomena related to multiple drops such as collisions are completely ignored;
- aerodynamic drag, gravity and buoyancy are assumed to be the sole forces affecting the drop trajectories;
- whereas the local velocity of the air flow is embedded into the ordinary differential equations governing the updates in drop trajectories, the liquid mass is assumed not to affect the surrounding air flow;
- once on the surface, empirical models translate the drop contribution towards liquid film formation and its movement further downstream along the surface of interest.

Many of these assumptions become inaccurate in the context of the large supercooled droplets (larger than several tens of microns) found in the atmosphere. The difficulties outlined above have yet to be overcome, and most modelling is performed at a highly coarse-grained level (Potapczuk et al., 1993; Bragg, 1996; Rutkowski et al., 2003; Wright and Potapczuk, 2004; Wright, 2005; 2006; Honsek et al., 2008; Bilodeau et al., 2015), with semi-empirical relations of varying complexity being proposed in order to match with the rich but ultimately limited experimental data available by NASA experiments conducted by Papadakis et al. (2003, 2004). The focus here is primarily on the final water retention values rather than the more fundamental problem of the detailed impact process, making it ideal from an engineering standpoint but offering limited insight into the underlying physics. In the past few years, the group at INTA/Madrid (Vargas et al., 2012; Sor and García-Magariño, 2015) have looked in more detail into the deformation of large-scale drops prior to impact, with results that indicate regimes far more complex than captured by the typical assumptions mentioned above. Several studies focusing on recent numerical advances in the high speed regime ($>$ 50 m/s impact velocity) have emerged, particularly for impacts onto liquid, but also onto solid surfaces (Ming and Jing, 2014; Cheng and Lou, 2015; Guo et al., 2016; Cherdantsev et al., 2017; Xie et al., 2017). These offer exciting opportunities to study short timescale phenomena beyond the reach of traditional particle methods, however up to this point there have been few attempts to integrate the drop impingement