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# Experimental characterisation of sprays resulting from impacts of liquid-containing projectiles

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## HIGHLIGHTS

- Detailed characterisation of sprays resulting from the impacts of water-filled metal projectiles on a hard wall.
- Experimental measurements of spray speed, direction and droplet size.
- Detailed analysis of overall spray evolution.
- The spray characterisation information can be used in CFD analyses of aircraft impact fires.

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## ABSTRACT

Modelling and analysing fires following aircraft impacts requires information about the behaviour of liquid fuel. In this study, we investigated sprays resulting from the impacts of water-filled metal projectiles on a hard wall. The weights of the projectiles were in the range of 38–110 kg, with 8.6–68 kg water, and the impact speeds varied between 96 and 169 m/s. The overall spray behaviour was observed with high-speed video cameras. Ultra-high-speed cameras were used in backlight configuration for measuring the droplet size and velocity distributions. The results indicate that the liquid leaves the impact position as a thin sheet of spray in a direction perpendicular to the projectile velocity. The initial spray speeds were 1.5–2.5 times the impact speed, and the Sauter mean diameters were in the 147–344 μm range. This data can be used as boundary conditions in CFD fire analyses, considering the two-phase fuel flow. The overall spray observations, including the spray deceleration rate, can be used for validating the model.


## 1. Introduction

Aircraft impacts have been included in the safety analyses of nuclear power plants (NPP) for a long time, but only recently have these analyses assumed the impact of a large commercial aircraft. The impact of such an aircraft can cause damage to the safety-related structures and components through mechanical impact and fire. Three different modes of influence can be identified in aircraft impact-induced fires: the first mode is a large fireball, caused by the ignition of the aircraft fuel cloud erupting from the breaking fuel tanks. The diameter of the fireball can be tens of metres and it lasts for a few seconds. The second mode of influence is the combustion of residual fuel as a pool fire in the vicinity of the impact location. The size and burning rate of the pool fire depend on the geometry and the properties of the surfaces below the pool. The duration of the pool fire depends on the amount of aviation fuel that did not burn in the initial fireball, the pool burning rate and the possible fire suppression activities. The third mode of fire influence is the penetration of aviation fuel inside the plant through existing openings, or mechanical damage caused by perforated aircraft components. Even if the mass of the penetrated fuel was relatively small, it would cause a rapid ignition of existing internal fire loads, such as electrical cables. Experimental data and simulation capabilities of the high-speed fuel dispersal mechanisms are needed to develop engineering methods for protection against aircraft impact-induced fires.

Tieszen (1997) has summarised and classified the major fuel dispersal processes in the context of an aircraft crash as follows: the first stage is fuel leakage from the ruptured tank due to the inertial and gravitational forces. Because the deceleration of the plane

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occurs very rapidly and the impact forces are enormous, the fuel spills out from the ruptured tanks and disperses to surroundings. The next stage is known as the primary break-up phase, where the liquid break-up and atomisation begins, due to the destabilising processes of aerodynamic drag and turbulence within the liquid core. The primary break-up phase is followed by the secondary break-up phase of flying droplets. Due to the interphase momentum transfer from the droplets, the surrounding air is accelerated to a speed that is close to the speed of the spray, and the droplets are decelerated correspondingly. Depending on the speed of a droplet relative to the surrounding gas, the secondary break-up can produce droplets of different sizes. The size distribution resulting from the break-up process can be either uni- or bi-modal in nature. The size and velocity distributions have an influence on the transfer distance of a droplet cloud. The rest of the liquid stream and partially atomised droplets may impact the targets or fall down due to gravitational forces. Flying structures and fragments of the aeroplane also affect the fuel dispersal processes.

Very few publications are available on full-scale aircraft crash tests including fuel. Early test series by FAA and NACA using belly-landing aircraft demonstrated that fuel spilled from ruptured tanks, forming a fine mist (droplet) cloud that can be ignited by several sources (Pinkel et al., 1953; Ahlers 1977; Johnson and Garodz, 1986). Experiences from numerous real crash incidents, such as the '9/11' terrorist attacks on the World Trade Centre September 11, 2001, support this observation. Furthermore, a film footage analysis of aircraft crash fireballs has indicated that these flame balls are very similar to the fireballs resulting from boiling liquid expanding vapour explosions, i.e. BLEVEs (Luther and Müller, 2009). However, none of the analysed accidents included impact on a rigid vertical structure, such as modern NPP.

Most of the published studies involving high-speed impacts of liquids have focused on the fracture and deformations of solid surfaces. The fate of the liquid has been investigated mostly in the length scale of an individual droplet impacting a surface, serving the purposes of process industry and manufacturing technologies, such as spray coating. In his work concerning droplet impacts on rigid surfaces, Knežević (2002) defined 'high-speed' droplet impact as an impact causing at least 5% compressibility in the liquid. This was obtained if the impact speed was in the order of 100 m/s or higher. The properties of the splash have in general been found to depend on the properties of the liquid and the target, air pressure and the initial speed prior to the impact. The velocity of the splashing droplets has been found to be several times higher than the impact velocity (Yarin, 2006). Field et al. (1989), for instance, made observations of 10–32 mm droplets hitting various rigid surfaces at a speed of 110 m/s, producing splashing jets with initial speeds of between 670 and 1170 m/s and splash angles (angle between wall tangent and splash direction) of between 10 and 19 degrees. They observed that a harder target material generally leads to smaller splash angles and higher spray speeds than softer materials.

Experimental scenarios that are qualitatively closer to the aircraft impact are often related to the crashworthiness of the vehicle fuel tanks. Fasanella and Jackson (2001) reported on a drop test of an aircraft fuel tank at speed of about 10 m/s. Anghileri et al. (2005) used various numerical tools, validated through drop tower tests, to investigate the liquid-structure interaction within a tank during impact on the ground. The aim of these studies was to ensure that the fuel tanks can withstand impacts at moderate speeds. They did not increase our knowledge of the fate of fuel in case of tank rupture.

Sandia National Laboratories have conducted a crash test where a Phantom F-4 aircraft carrying 4.8 tonnes of water was hit into a reinforced concrete target at a velocity of 215 m/s (von Riesemann et al., 1989; Muto et al., 1989; Sugano et al., 1993). Unfortunately, the liquid dispersal processes were not measured and documented in detail because the main aim of the tests was to study the impact forces versus time. However, the liquid spread process can be seen in the video clips taken from the test (Fig. 1). According to the video material, the initial liquid discharge velocity was about 280–330 m/s, i.e. 1.3–1.55 times the impact velocity. The liquid spread pattern seems be quite symmetrical, except the sideward direction. The spread direction calculated from the wall plane was about $0–30^{\circ} \pm 10^{\circ}$ ($0^{\circ}$ is along the wall plane, $90^{\circ}$ is directly backwards). The final size (diameter) of the cloud was 60–80 m.

Jepsen et al. (2009) investigated the usability of various experimental methods for the diagnostics of high-speed liquid dispersion. In addition to the numerous small-scale tests on individual drops, they discussed the use of photometric, PIV and PDPA measurements in a large-scale water-slug test with a water-filled 1.2 m diameter aluminium cylinder hitting a concrete wall at 105 m/s. The photometrics showed that the initial speed of the radially spreading cloud of water was slightly higher than the impact speed (110 m/s). The cloud in their experiment reached distances of 30–40 m from the impact point. A large-scale PIV, based on the high-speed video images, showed peak velocities of about 250 m/s, i.e. substantially higher than the values shown by photometrics. A PDPA measurement of the residual spray indicated a size distribution in the range of 6–13 μm, which was concluded to be a result of the secondary break-up or atomisation processes, expecting the break-ups mainly in the bag break-up regime. PDPA measurements did not succeed in capturing the droplets of the primary spray.

BLEVE-induced fireballs are traditionally analysed using analytical and empirical formulas (Abbasi and Abbasi, 2007). Such formulas can also be used in the analysis of aircraft impact fires and explosions. In order to take into account the geometrical aspects and details of the event dynamics, it is necessary to use computational fluid dynamics (CFD) tools for the analysis. Using the CFD tools for the task has three major challenges: the first is to collect the necessary input data for prescribing the boundary conditions for the aviation fuel spray. The second challenge is the development of numerical tools with a verified capability to simulate the extremely dynamic reactive flow involving several different length scales. The need to validate the simulation methods and tools forms the third challenge, because the experimental data on impacts with fuel-filled projectiles is not available. The validation must therefore be performed independently for different parts of the modelling methodology, using water-filled projectiles to validate the spray formation and transport calculations, for instance.

The purpose of this work is to contribute to the first and third of the above-mentioned challenges by characterising experimentally the liquid spray resulting from a high-speed impact of a liquid-containing projectile against a hard wall. The intended use of the results is the generation of model inputs and validation data for the CFD simulations of aircraft impact fires. The work has been done in the context of VTT's IMPACT experiments (Kärnä et al., 2004; Lastunen et al., 2007). The paper by Silde et al. (2011) provided an overview of the liquid experiments, but as the experimental methods have been improved from earlier attempts, they will be presented here in detail. The next section describes the experimental methods. The third section presents the experimental results in a form that can be utilised as model inputs (droplet size distribution, initial spray velocity) and validation (spray deceleration). Finally, some concluding remarks will be given.

## 2. Experimental methods

### 2.1. Impact facility

The facility for impact testing was designed and constructed in the early 2000s in the wake of the 9/11 terrorist attacks. The facility