Droplet Electro-Bouncing in Low-Gravity

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Abstract

We investigate the dynamics of spontaneous jumps of water droplets from electrically charged superhydrophobic dielectric surfaces during a sudden step reduction in gravity level. In the brief free-fall environment of a drop tower, with a non-homogeneous external electric field (with strengths 0.39-2.36 kV/cm) arising due to dielectric surface charges, body forces acting on the jumped droplets are primarily supplied by polarization stress and Coulombic attraction instead of gravity. This electric body force leads to a droplet bouncing behavior similar to well-known phenomena in 1-g, though occurring for much larger droplets ($\sim$ 0.5 mL). We show a simple model for the phenomenon, its scaling, and asymptotic estimates for droplet time of flight. The droplet net charge, estimated to be on the order of 1E-9 C, is field induced rather than by contact charging at the (PTFE coated) hydrophobic interface. In 1-g, for Weber numbers > 0.4, impact recoil behavior on a super-hydrophobic surface is normally dominated by damping from contact line hysteresis. However, at the low Bond and Ohnesorge numbers occurring in free-fall, the droplet impact dynamics additionally include electrohydrodynamic surface wettability effects. This is qualitatively discussed in terms of trends in coefficients of restitution and dimensionless contact time.

1 Introduction

Our terrestrially born intuition about how liquids flow is easily confounded in a low-gravity environment. This should come as little surprise, as we are creatures evolved at the bottom of a steep gravity well; gravity is natural to us. However when the magnitude of the gravity body-force becomes small, other forces come into play in fluid dynamics which are otherwise negligible, relatively speaking, under normal circumstances in 1-g. This 1-g cognitive bias leads to a plethora of problems which are both trivially easy to solve in 1-g, and which despite decades of study continue to elude solutions in a low-gravity context. One example of these problems is the so-called "phase separation" problem of separating a gas phase from a multi-phase flow (or the reverse case) without the aid of gravitational buoyancy. Sans buoyancy otherwise mundane activities such as venting a gas or settling a liquid in a tank become problematic. Trapped bubbles can vapor lock ECLSS (Environmental Control and Life Support), power, or propulsion systems. Issues of phase separation have so bedeviled human endeavors in space that an entire Apollo Saturn 1B mission (AS-203) was earmarked to study them. This problem has for some time motivated a quest for substitute body forces, and the present work follows in that august tradition.

When asked to name one of the biggest challenges to living in space, Astronaut Suni Williams replied that it is removing and dealing with bubbles in fluids systems.

> "... multiphase systems and thermal transport processes are enabling for proposed human exploration by NASA." - 2011 Decadal Survey

> "When the influence of gravity on fluid behavior is diminished or removed, other forces, otherwise of small significance, can assume paramount roles." - NRC Report to NASA, 2003

Un-terrestrially large droplets are produces by a huge array of mechanisms in a low-gravity environemnt.

Comprehensive list? of electrostatic applications particular to low-gravity:

- Spacecraft charging due to space environment. Surface charging largely due to low energy electrons (3-50 keV) which do not penetrate the surface of the spacecraft external stureture. This deposited charge accumulate and can lead to significant potential differences between different parts of a spacecraft. Deep dielectric charging occurs when higher energy charged particles penetrate the surface of a dielectric material, which can also lead to large potential differences if the dielectric leakage is lower than the external charging rate. The ultimate sources of these charges are trapped charged particles of the van Allen radiation belts, galactic cosmic rays, and the solar wind. Which space environemts have higher charging risks, propellant deopt locations. Venting, droplets.

- Active (but solid-state) phase seperation for ECLSS multiphase flows, especially high void-fraction flows (dish washing, laundry, waste solids drying, food processing, Sabatier CO_2 reaction, possibly in vapor-compression cycle condensers). Phase separation is critical to high reliability and low power gas-liquid systems for used in thermal control and life support. Phase seperation for other disperse droplet flows include electrostatic droplet seperators for high-efficiency Rankine cycle turbines. Removal of satellite droplets produced during pippetting during wet-lab research outside of a glovebox environemnt aboard ISS.

- Electrostatic levitators for containerless processing, droplet combustion experiements. Containerless creatio, and collection of monodisperse spheres (dielectrics or conductor; the chargeing mechanism will vary).

- Electrospray-based fire suppression systems.

- EHD (dielectrophoretic) augmentation of convection (electroconvection, an analog of natural convection due to a dielectric permititivy gradient, which is a function of fluid temperature, int he presence of a body force field analog, in this case an electric field) and condensation heat transfer. Boiling heat transfer by promotion of bubble detachment and prevention of dryout (e.g. as a substitute for bouyancy).

- EHD heat pipes, which substitude an electrode structre for the capillary wicking structure of a conventional thermocapillary heat pipe can evade the wicking limit. Problematically restricted to the use of insulating dielectric liquids (which usually have relatively low thermal conductivity), but offer advantages in highly-reliable priming, bubble rejection, flow control, and low viscous losses.

- Dielectrophoretic settling of cryogenic propellants (in both total and partial communication configurations), slosh baffling, vent screening, mitigation of vapor pulltrough (and concomittent minimization of propellant residuals at burnout). Reduction in heat transfer by collecting propellants away from tank walls, reducing boiloff losses.

- High temperature liquid droplet radiators with electrostatic collection.