Title: Experimental and numerical investigations of high-speed jets ensuing from interacting cavitation bubbles

Abstract

A distinctive feature of the fluid dynamics is the possibility of the coexistence of a vapor phase with the liquid phase. Such formation and disappearance of vapor bubbles in a monophasic liquid due to local pressure depression below vapor pressure caused by flow variation or energy concentration is known as cavitating flow. In cavitating flows, plenty of nuclei are available for the inception of cavitation bubbles. These bubbles can grow and collapse violently in an inertial manner and may liberate energy in the form of high-pressure waves and temperatures, produce intense shock waves, and emit visible light upon implosion.

Cavitation research is vital in various domains, from naval hydrodynamics to health and energy sciences. Cavitation offers both pros and cons. Some deleterious consequences encountered in practice are vibration, noise, erosion, and an increase in hydrodynamic drag, which may reduce the efficiencies of pumping machinery and alter the flow pattern. Cavitation can also reduce the precision of flow measuring devices and cause severe erosion damage due to intense localized pressure waves. On the other hand, the benefits are for many applications in medicine (for example, the comminution of kidney stones during shock wave and laser lithotripsy, drug delivery), low-cost graphene manufacturing, waste-water treatment, cleaning, and nanoparticle generation utilizing sonochemistry, and so on.

Most of the aforementioned cavitation applications include many tiny bubbles that appear as clusters, filaments, and vapour clouds. This dissertation begins by describing the behavior of a vapor cloud and the various flow patterns it creates in a micro-diaphragm (i.e., micro-orifice). The formation of a cavitation cloud appears to promote turbulence and mixing dynamics in a micro-diaphragm.

The dynamic behavior of individual bubbles within the vapor cloud with mutual interactions, on the other hand, is more complex than that of a single isolated bubble. An interacting bubble-pair is a unit that may be used to comprehend the physical insight of their interactions in a vapor cloud. Therefore, later, the complex dynamics of interacting cavitation bubbles and the underlying sling-shot mechanism of ensuing high-speed liquid microjets are revealed in this dissertation using state-of-the-art experimental techniques and high-fidelity direct numerical simulations.

Here, the experiments are conducted by systematically varying the distance between the bubble centers (i.e., the locations of the two laser-induced optical breakdowns) and the delay between their time of generation. Whereas the open-source software OpenFOAM is employed to describe the numerical modelling of interacting cavitation bubbles utilizing the Finite Volume Method (FVM) in conjunction with the Volume of Fluid Method (VOF). Significant advantages of this approach include its capacity to mimic compressibility phenomena (like shock waves) and its adaptability when the underlying topology needs to be changed.

We provide a comprehensive analysis of the dynamics of interacting collapsing bubbles in various geometric configurations. We demonstrated that the presence of a nearby rigid surface develops an anisotropy in the surrounding liquid medium. This propels a microjet of liquid at high speed towards the wall. To further comprehend their potential use in the cryo-comminution of polymeric materials and plastic waste remediation, the shearing action of these resulting liquid jets, traveling at hundreds of meters per second, has been assessed at cryogenic temperatures and different over-pressure values. The results are validated with the experimental data available in the literature.

Finally, a strategy for evaluating the potential of high-speed microjets and their controlled, precise, and directional deployment in a needle-free injection technique has been established.

This work will benefit researchers conducting experimental and numerical studies of interacting cavitation bubbles in room temperature and cryogenic fluids to determine their promising applications.

Keywords: Cavitation, Interacting bubbles, Microjet, Sling-shot, Mechanical shearing, Cryogenic, Plastic recycling, Needle-free injection