Optical detection of nano- and micrometer-scale particles in superfluid helium

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Synopsis Laser heated plasmonic copper nanoparticles were imaged in superfluid ^{4}He by high-speed photography using the shadowgraph and Schlieren techniques. In addition to the particle locations in the liquid, their sizes were determined online by employing the developed thermodynamic model. The method was validated against the particle size distribution data obtained independently by post-experiment atomic force microscopy. In the second part, the hydrodynamic response of superfluid helium to fast moving micron-sized metal particles was characterized. Various dynamic cavity shapes developing around the hot particles were captured and the observed geometries were rationalized by using the classical model of supercavitation as well as time-dependent density functional theory. In general, it was shown that the developed experimental method can be used to determine the optimal object shapes that minimize the hydrodynamic drag at a given velocity.

In the first part, the formation of gas bubbles around laser heated copper nanoparticles in superfluid helium at 1.7 K is described [1]. Due to the effective light capture by these plasmonic particles and the subsequent heat transfer into the surrounding liquid [2], the observed gas bubbles grow within *ca.* three microseconds to tens of micrometers in size (see Fig. 1). The shadowgraph and Schlieren imaging techniques using various nanosecond backlight sources were used to determine the spatial distribution of the nanoparticles in the liquid and the semi-stationary gas bubble radii were related to the parent nanoparticle size by using the developed thermodynamic model. The presented liquid phase particle size analysis was validated against post-experiment atomic force microscopy measurements of nanoparticles deposited from the liquid onto a solid substrate [1, 3]. This method allows to magnify metal nanoparticles in superfluid helium by a factor of *ca.* 1000 such that they can be detected optically.

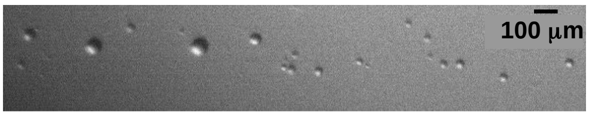

Figure 1. Gas bubbles formed around laser (355 nm; 8 ns pulse length) heated copper nanoparticles in superfluid helium at 1.7 K.

In the second part, the dynamics following laser ablation of a metal target (e.g., Ag, Cu) immersed in superfluid ^{4}He was studied by time-resolved shadowgraph photography [3, 4]. The delayed ejection of hot micrometer-sized particles from the target surface ("explosive boiling") into the liquid was observed indirectly by monitoring the formation and growth of gaseous cavities around the moving particles. The experimentally determined particle average velocity distribution appears similar as previously measured in vacuum but exhibits a sharp cutoff at the liquid speed of sound [5]. The propagation of the subsonic particles terminates in slightly elongated non-spherical cavities residing near the ablation target whereas faster particles reveal an unusual hydrodynamic response of the liquid. Based on the previously established semi-empirical model for macroscopic objects, the ejected transonic particles exhibit supercavitating flow to reduce their hydrodynamic drag [6]. Supersonic particles appear to follow a completely different propagation mechanism as they leave discrete and semi-continuous bubble trails in the liquid ("bubble chamber" [7]). The relatively low number density of the observed non-spherical gas bubbles indicates that only large micron-sized particles are visualized in the experiments. Although the unique properties of superfluid helium allow a detailed characterization of these processes, the developed technique can be used to study the hydrodynamic response of any liquid to fast propagating objects on the micrometer-scale.

Preliminary results from time-dependent density functional theory (DFT) calculations yield similar semi-stationary cavity geometries that were observed in the experiments. The cavity becomes elongated to minimize the hydrodynamic drag and the distinct tail structure was also faithfully reproduced by DFT as shown in Fig. 2. The hollow cone-geometry tail prevents the formation of turbulence in the wake by blocking vortex ring nucleation. In practical applications, similar constructions have, for example, been used to lower the hydrodynamic (air) drag on automobiles to reduce gasoline consumption. Since the gaseous cavities surrounding the ejected metal particles are significantly more flexible than the liquid around them, the presented method can be used to determine the optimal cavity shapes as a function of velocity, volume, and liquid viscosity.

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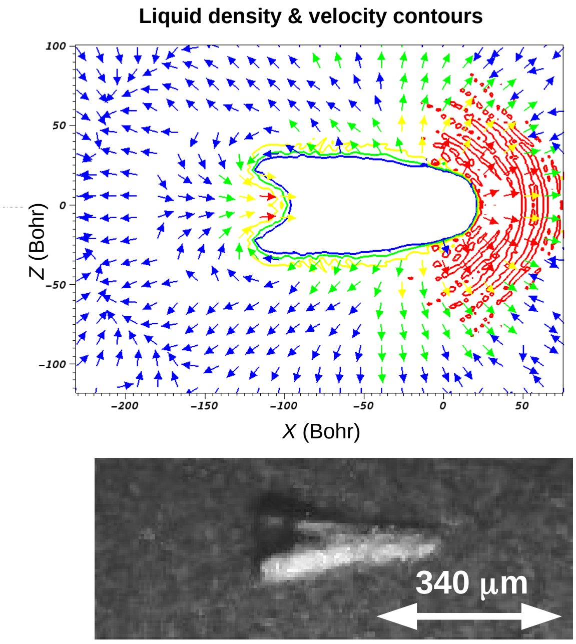

Figure 2. Upper panel: Liquid density contours and velocity field around helium gas bubble from density functional theory (co-moving frame). Lower panel: Experimentally observed cavity shape at 1.7 K.

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