Accelerated condensation in an ultrasonic field

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Direct-contact condensation of vapor bubbles rising in a subcooled liquid is dramatically enhanced using pulsed ultrasonic actuation. The acoustic waves from this actuation ($f = 1.7$ MHz, $\lambda = 0.9$ mm) produce a large acoustic radiation pressure or force on the interface of the bubble owing

FIG. 1. Condensation of a train of vapor bubbles in the (a)–(f) absence and (g)–(l) presence of pulsed ultrasonic actuation. Frames (a)–(f) show the formation of a liquid jet and a toroidal vapor volume following bubble detachment from the orifice. Frames (g)–(l) show enhanced condensation effected by the pulsed ultrasonic actuation in frames (h)–(j) that leads to a similar liquid spear and the ejection of liquid droplets inside the vapor bubble. DOI: <https://doi.org/10.1103/APS.DFD.2016.GFM.P0044>

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to a mismatch in the liquid-vapor acoustic impedance. This force causes a localized interfacial deformation of the bubble that leads to the formation of a subcooled liquid jet and atomized droplets inside the vapor volume. The effect of these motions on bubble condensation is investigated using a periodic train of vapor bubbles (12.5 Hz, $T_{\text{bubble}} \approx 80$ ms) produced by the injection of water vapor from an orifice submerged below a pool of subcooled liquid water at 93.5 °C. The acoustic beam is directed vertically downwards towards the center of the orifice to impact the vapor bubble from above. Figure 1 shows the condensation processes in the vapor bubble in the absence and presence of the pulsed ultrasonic actuation imaged at 8000 fps.

The detachment of a vapor bubble from the orifice in the absence of actuation [Fig. 1(a)] is dominated by a surface-tension-driven pinch-off process at the lower liquid-vapor interface. Pinch-off leads to the formation of a liquid jet or “spear” that protrudes into the vapor volume from below [Figs. 1(b) and 1(c)]. The liquid spear penetrates the entire bubble volume to contact the upper liquid-vapor interface, which leads to the formation of a vapor torus [Fig. 1(d)]. This unstable shape ultimately leads to the final collapse and condensation of the vapor bubble [Figs. 1(e) and 1(f)].

This “natural” surface-tension-driven liquid spear is mimicked using pulsed-modulated ultrasonic actuation (pulse length = $0.25 T_{\text{bubble}}$) triggered during bubble formation at the orifice [Fig. 1(g)]. The presence of the actuation in Figs. 1(h)–1(j) is shown using superimposed schlieren images of the acoustic wave fronts. The actuation leads to the formation of a liquid spear at the upper liquid-vapor interface and the formation of a vapor torus [Fig. 1(k)] that is similar to the bubble topology in the absence of actuation. However, the acoustically driven bubble torus forms earlier [Figs. 1(d) and 1(k)] and collapses faster [Figs. 1(f) and 1(l)]. In addition, focusing of the acoustic beam within the liquid spear leads to the formation of capillary waves on the spear and the ejection of O (1–100 μm) droplets into the vapor volume [droplet impingement on the outer liquid-vapor interface is visible; Fig. 1(j)]. Both of these effects contribute to an increase in the heat transfer area and the total heat transfer rate. Thus, the use of pulsed ultrasonic actuation leads to complete bubble condensation much closer to the ejection orifice. This significantly smaller characteristic condensation length could be exploited in new designs of highly compact condensers.

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