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BRIEF COMMUNICATION

STUDIES IN BUBBLE EVAPORATION BY STROBOSCOPIC PHOTOGRAPHY

Y. LERNER, A. SONN and R. LETAN
Department of Mechanical Engineering, Ben-Gurion University of the Negev, Beer Sheva, Israel

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INTRODUCTION

Very little is experimentally known on the dynamics of multi-bubble systems, such as boilers or condensers. To gain more insight into the governing mechanism, appropriate techniques have to be adopted or developed. In that direction the present work has been conducted. Namely, a photographic technique although not new, but also not yet fully exploited, has been adopted to sprays of evaporating bubbles, in measurements of instantaneous sizes and velocities. These could in turn be used to determine instantaneous heat transfer coefficients in the investigated complex system.

Considerable information is available on evaporation and condensation of single bubbles (Jacobs 1979, Sideman 1964, Mori 1976). More limited is the literature published on change of phase measured in sprays (Chigier 1974).

Numerous techniques applied to measurements of sizes and velocities were described in the literature and thoroughly reviewed by Somerscales (1974) and Goldschmidt (1978).

Among the visual techniques, photography was rather common in two-phase research. Both, still cameras and movie cameras were extensively used. In numerous systems a still camera and interrupted illumination can be used to record successive events on a single photographic plate. In such cases, the method is superior to cinephotography. That has been demonstrated by Temkin (1972), Kintner (1961) and Calderbank (1956) in studies of single bubbles and droplets. However, with respect to sprays and dispersions the method seems to be the most suitable to measure velocities (Chigier 1974, Abuaf 1974). For sizing and concentrations of sprays at steady state, again the still camera is preferable, because of its simplicity.

PHOTOGRAPHIC STUDIES

The investigation focussed on bubbles which increased in size from 0.3 to 3.0 mm, and varied in velocity within the range of 5–40 cm/s. The experimental apparatus consisted of a vertical test column, 0.09 m in diameter and 1 m long. Liquid Freon-113 was injected into the water filled column, through a 0.3 mm nozzle at the bottom of the column. The freon droplets on their way up evaporated into bubbles at 45–60°C and atmospheric pressure.

The photographic equipment consisted of a 35-mm camera, Asahi Pentax Sla, having a 1 : 2/55 lens. An Agfa Pan ASA No. 100 film was used. The stroboscope used for interrupted illumination was a Type 1538 A strobotac, with a flash duration of 1.2 μs at frequencies of 670–4000 fpm, and 0.8 μs in the range of 4000–25,000 fpm. Illumination, shutter speed, stroboscopic frequency, and other related variables were tested.

Backlight was applied for sizing, where single image photographs and sharp boundaries of bubbles were sought for. For velocity measurements, interrupted illumination by stroboscope was used to produce multi-image trajectories of bubbles. Cross illumination was found to yield the clearest trajectories, which appeared as a train of bright spots against a dark field. These spots were counted, length of the trajectory measured and the bubble velocity calculated.

For sizing, the camera shutter was set to its highest speed of 1/1000 s. In velocity measurements, the shutter speed was adjusted to produce the appropriate length of trajectories.

With single bubbles the trajectory has no limitations of length (Temkin (1972). The shutter speed is low, and adjusted accordingly. As the concentration of bubbles in a spray increases, the trains have to become shorter, to avoid overlapping of upper trains. Presently, the shutter speed of 1/30 s was selected to draw 0.07–1.3 cm long trajectories, within the velocities range of 5–40 cm/s.

The frequency required for illumination has to produce a clear sequence of countable images. The operational range can be defined by the overlapping fraction of an image. The frequency, f, to be selected relates to bubble velocity, u, and to the exposed portion ΔD, of images in a train:

$$f = \frac{u}{\Delta D}. \qquad [1]$$

To conduct trajectory tracking, and image counting in trains of tangential and half-overlapping images, requires $\Delta D = D - 0.5\,D$, where, D, is the bubble diameter. Therefore, for small bubbles, 0.3 mm in diameter, rising at a velocity of 5 cm/s, the required frequencies were 10,000–20,000 fpm. For larger bubbles, 3.0 mm in diameter, rising at a velocity of 40 cm/s the range of frequencies was 8000–16,000 fpm. Thus, the operational range of frequencies for the present spray appeared to be 10,000–16,000 fpm, producing tangential trains of small bubbles, and half-overlapping trains of the largest bubbles. These calculations fitted well with the experimental evidence, as illustrated in figures 1–4.

In sizing, horizontal and vertical diameters of bubbles, and the bubble location in the column were measured. Bubble sizes at any vertical location were averaged, and the mean diameter, D, plotted vs that location, H, as shown in figure 5.

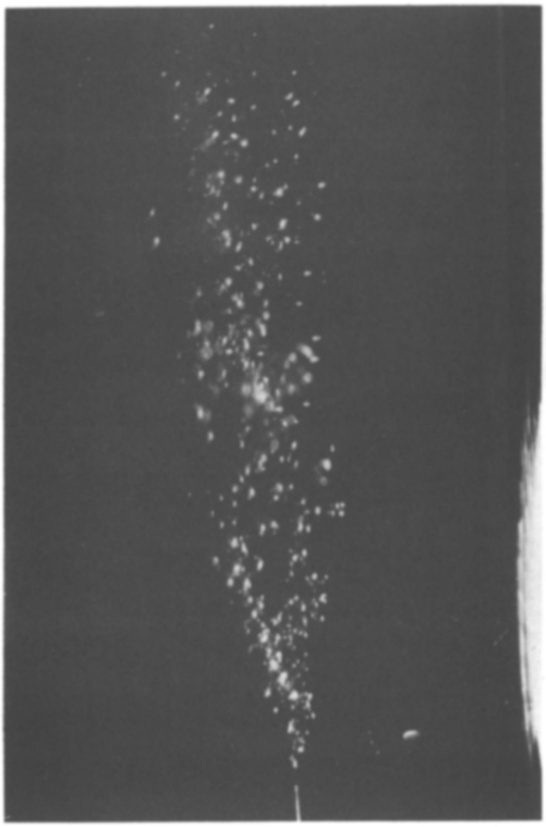

Figure 1. Stroboscopic illumination of a spray—5000 fpm.

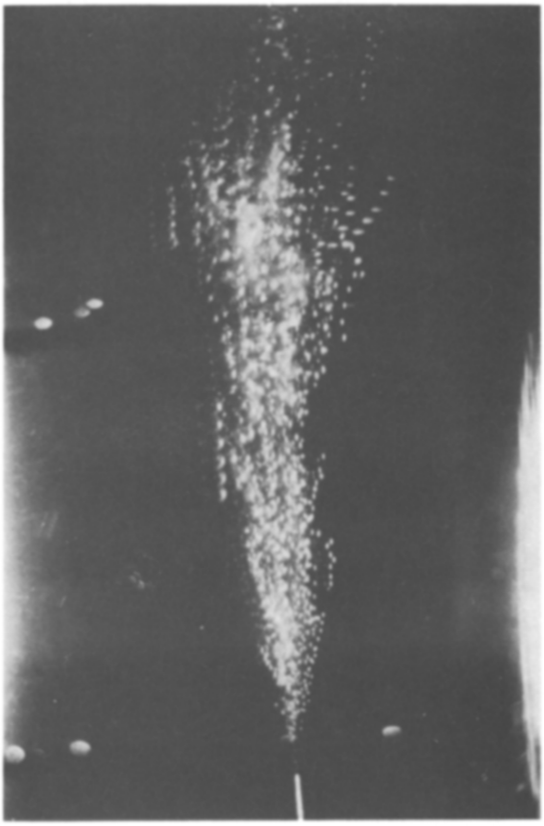

Figure 2. Stroboscopic illumination of a spray—8000 fpm.

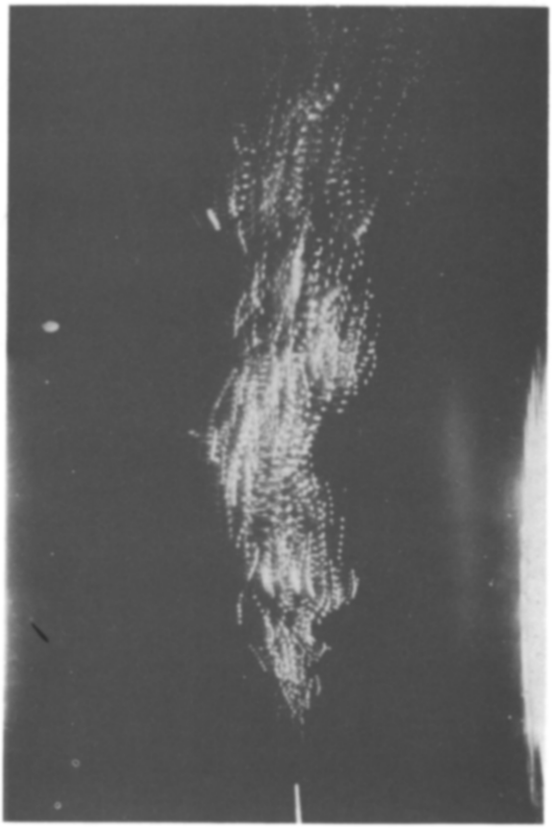

Figure 3. Stroboscopic illumination of a spray—14000 fpm.

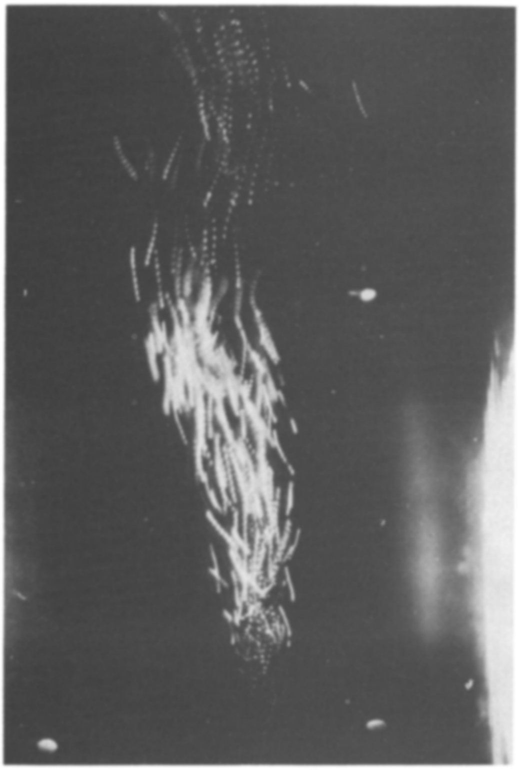

Figure 4. Stroboscopic illumination of a spray—20,000 fpm.

For velocity, the length, ΔH_i, of a trajectory of 4–6 images was measured, and the number of images, n_i, counted. At a frequency of illumination, f, the bubble velocity, u_i, at the center of the measured trajectory was obtained as,

$$u_i = \frac{\Delta H_i}{(n_i - 1)} \cdot f. \qquad [2]$$

The height of the trajectory above the injection nozzle was taken as the vertical distance between the nozzle and the center of the measured trajectory.

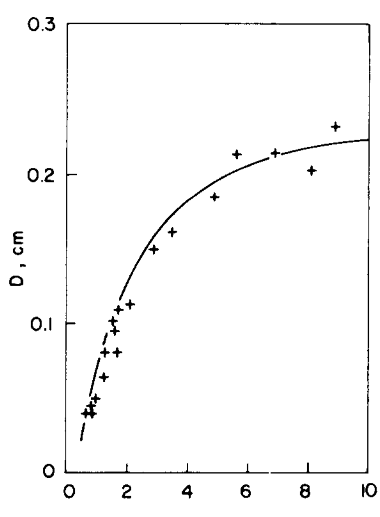

Figure 5. Average diameter of bubbles vs distance from nozzle.

The calculated individual velocities at any vertical location were averaged, and the mean velocity, u, plotted vs that location, H, as shown in figure 6.

HEAT TRANSFER COEFFICIENTS

The photographic method, herein described, permits measurement of instantaneous bubble sizes, and velocities in sprays. Therefore it may serve as a tool to the determination of instantaneous heat transfer coefficients in direct contact boilers.

Let us consider the variables involved in determining heat transfer rates to an evaporating bubble. The instantaneous heat transfer coefficient referred to the instantaneous surface of the bubble is expressed as,

$$h = \frac{Q/\Delta t}{A \cdot \Delta T} \qquad [3]$$

where Q is the heat transferred to the droplet-bubble of surface, A, within a time interval of, Δt. ΔT, is the temperature difference between the heating medium and the saturation temperature of the evaporating fluid.

Substituting for, Q, A and Δt, leads through differentiation to,

$$h = \frac{\rho_G \cdot h_{LG}}{2\Delta T} \cdot u \cdot \frac{\mathrm{d}(D)}{\mathrm{d}(H)} \qquad [4]$$

where ρ_G is vapor density, h_{LG}, heat of vaporization, $\mathrm{d}(D)/\mathrm{d}(H)$, is the slope of the experimentally measured curve of, D vs H (figure 5), and, u, the measured instantaneous velocity at the same height, H (figure 6).

The heat transfer coefficient may be presented against the vapor quality, x, expressed as,

$$x = \frac{(D/D_0)^3 - 1}{(\rho_f/\rho_g) - 1} \qquad [5]$$

where D_0 is the initial diameter of the evaporating droplet, and, ρ_f, the liquid density.

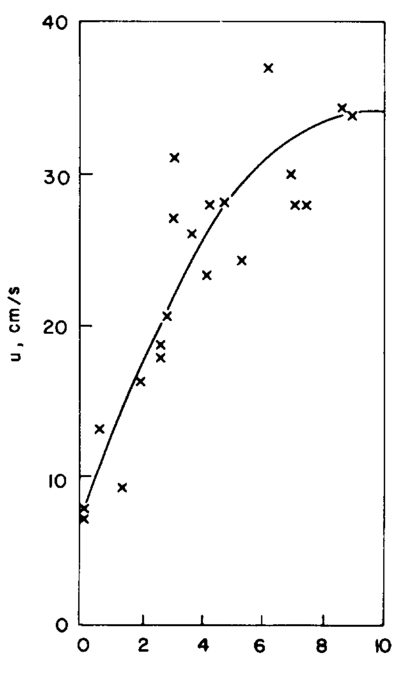

Figure 6. Average velocity of bubbles vs distance from nozzle.

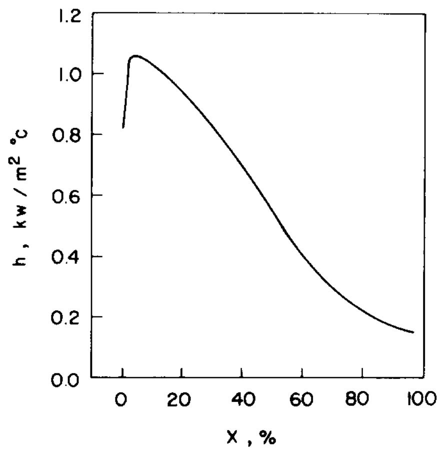

Figure 7. Instantaneous heat transfer coefficient vs vapor quality.

To demonstrate the viability of the technique an experiment was performed at: $\Delta T = 4.2°\text{C}$, $D_0 = 0.3$ mm, $h_{LG} = 143.8$ kJ/kg, $\rho_L = 1505$ kg/m^3, $\rho_G = 7.5$ kg/m^3. A photograph of single-image bubbles provided data for the curve of, D vs H, of figure 5. Bubble trajectories, photographed at 14,000 fpm (figure 3), yielded the curve of, u vs H, of figure 6. Then, both curves were computer fitted to polynoms, and the computerized data were employed to provide, h, by [4], vs x, by [5], as shown in figure 7.

This example shows the applicability of the photographic method to sprays in general, and to evaporating sprays in particular. The work does not report heat transfer data. It only illustrates how to use the experimental photographic results in heat transfer research.

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