Journal of Heat Transfer Discussion

## Consecutive-Photo Method to Measure Vapor Volume Flow Rate During Boiling From a Wire Immersed in Saturated Liquid[1]

**J. R. Thome[2].** The consecutive-photo method presented by the authors is not a new technique as claimed but actually dates back quite awhile. The only difference is that Ammerman and You have used a relatively low-speed digital camera (240 frames/s) rather than a true high-speed cine camera (speeds of 4000 frames/s or more). Numerous researchers utilized high-speed cine cameras to obtain bubble growth data for isolated bubbles in the 1960s and 1970s, e.g., refer to the two-volume book *Boiling Phenomena* by van Stralen and Cole published in 1979. In particular with respect to the consecutive-photo method, Thome and co-workers (Preston et al., 1979; Thome and Davey, 1981) presented a detailed description of how they applied a computerized image analysis system to measure of a large number of consecutive bubbles departing from the same boiling site (up to 30 bubble growth cycles per cine film with each bubble image divided into numerous segments to determine its profile with departure frequencies up to 120 bubbles/s) and thus compiled an extensive database with both individual and statistically averaged bubble growth rates, bubble departure diameters and bubble departure frequencies for liquid nitrogen, liquid argon, and also their mixtures at a variety of wall superheats. The corresponding volumetric vapor flow rates were later published in the ASME *Journal of Heat Transfer* (Thome, 1982) together with analysis of their influence on the bubble evaporation and cyclic thermal boundary layer stripping heat transfer mechanisms, work which lead to an analytical model of bubble growth and departure in a mass transfer model for predicting pool boiling coefficients in mixtures (Thome, 1981; Thome and Shock, 1984). Thus, while I am pleased to see renewed interest in the fundamentals of nucleate pool boiling, let's not neglect the past work of others.

### References


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### Authors' Closure[3]

As early as the 1930s, Jakob and Linke (1933) used high-speed photography (500 fps) to study the fundamental aspects of boiling, including bubble departure diameter and frequency from a single nucleation site. By the 1950's, Westwater and his co-workers (1955, 1960) were examining single-site departure diameter and frequency as well as nucleation site density using film speeds of up to 5000 fps. Throughout this period in history, it was generally believed that latent heat removal in boiling contributed insignificantly to the total heat flux. In 1964, however, Rallis and Jawurek were among the first to recognize the importance of the latent heat contribution. They used single-site bubble frequency and departure diameter measurements along with nucleation site densities to calculate vapor volume flow rate departing from a wire for various heat fluxes. These vapor flow rates resulted in latent heat contributions as high as 80 percent of the total nucleate boiling heat flux. During the 1960s and 1970s, numerous researchers used high-speed photography to measure single-site bubble departure diameter and frequency, as well as bubble growth rates.

Around 1980, Thome also was using high-speed photography (up to 4000 fps) to measure single-site, boiling bubble growth rates, departure diameters, and departure frequencies. At this time, the current method of obtaining bubble diameter was to manually measure bubble chord lengths in each successive photographic frame. Thome and his co-workers (Preston et al., 1979; Thome and Davey, 1981) introduced a computer-aided method for measuring these bubble chord lengths which automated the previous manual measurement technique. This time-saving method enabled the analysis of up to 800 frames per hour. In 1982, Thome went on to publish the vapor volume flow rate data resulting from these measurements. With these data, he was able to calculate a single-bubble latent heat contribution. He then used a semi-empirical method to estimate the per-bubble sensible heat contribution and compared it with the latent heat value.

In 1998, the present authors introduced a consecutive-photo method for measuring the vapor volume flow rate departing from a wire during boiling. Instead of examining characteristics of a single nucleation site, this method measures the vapor volume flow rate from all nucleation sites simultaneously. Because this method does not focus on a single site, it also enables the experimental evaluation of the sensible energy contribution in nucleate boiling.

[1] by C. N. Ammerman and S. M. You and published in the Aug. 1998 issue of the ASME Journal of Heat Transfer, Vol. 120, pp. 561–567.

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Dr. Thome states that he and his co-workers have previously developed a photographic method for measuring boiling parameters and implies that this method is similar to the consecutive-photo method we introduced. While the consecutive-photo method utilizes high-speed photography and digital image processing, we believe it is different from the method of Thome and his co-workers based on the following comparisons:

- The photographs shown in Preston et al. (1979) indicate that approximately 100 frames are analyzed per bubble growth cycle using Dr. Thome's method. This results in the analysis of approximately 3000 frames at each heat flux to obtain the vapor volume flow rate. Our method requires the analysis of only eight frames per heat flux.
- Dr. Thome's method for measuring vapor volume flow rate is only valid for the partially developed nucleate boiling regime (Thome and Davey, 1981). Our method is valid in the partially developed, fully developed, and film boiling regimes.
- Dr. Thome's method examines bubbles growing from a single nucleation site. Our method examines bubbles departing from multiple cavities over the heated surface simultaneously.
- Dr. Thome's bubble diameters are measured while the bubble is still attached to the heated surface (Preston et al., 1979). Our diameter measurements are performed after bubbles have departed.
- To obtain vapor volume flow rate, Dr. Thome's method requires individual bubble departure frequency as well as bubble volume (Thome, 1982). Our method does not require bubble departure frequency. We measure vapor volume that passes a control line above the heated surface per unit time.
- Dr. Thome computes the per-bubble sensible heat contribution semi-empirically by assuming the bubble influence area is twice the bubble departure diameter (Thome, 1982; Thome and Shock, 1984). In our method, the sensible heat contribution can be obtained from our experimental measurements without using the bubble influence area assumption.

Dr. Thome states that many researchers before us have used high-speed photography to perform fundamental investigations of boiling, thus implying that we have neglected the past work of others. We realize, however, that we were not the first to use photographic methods to measure boiling parameters. We cited individual references which are closely related to our work. In addition, we stated the following in the second paragraph of our paper:

> Other investigators ". . . have employed various photographic techniques to determine key boiling parameters such as bubble departure diameter, departure frequency, and nucleation site density. These investigators have presented experimental results of these key boiling parameters and most have used them to calculate contributions to total heat flux from a heated surface. Despite their merits, however, the methods used by these investigators require the analysis of a large number of individual photographic frames at each heat flux."

Finally, we are pleased that others are taking an interest in our work. We would like to thank the Editor of the *Journal of Heat Transfer* for making this open exchange of ideas possible.

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