Closure to "Discussion: "Dynamics of Bubble Motion and Bubble Top Jet Flows from Moving Vapor Bubbles on Microwires" (Christopher, D. M., Wang, H., and Peng, X., 2005, Journal of Heat Transfer, 127, pp. 1260–1268)"

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Shekriladze points out that the pumping effect of the growing bubble (PEGB) model can also predict jet flows similar to those described in our results [1,2], which we have attributed to Marangoni flow. PEGB is caused by the evaporative reactive force due to vapor recoil, which is most significant along the bottom part of the bubble interface closest to the heated surface during the initial growth period. Shekriladze [3] points out that the PEGB is most significant during saturated boiling and is less important for subcooled boiling. He also expresses concerns about our assumptions for the accommodation coefficient and the steady-state analysis.

Vapor recoil, which is the physical mechanism for the PEGB model, will certainly affect the bubble shape and flow near the bubble base during the initial vapor bubble growth phase during nucleate boiling. This is because the very large temperature differences initially present near the bubble base result in very high initial rates of evaporation. However, our results pertained to relatively stable bubbles, long after they have reached an essentially stable size for relatively long periods of time (several seconds). By this time, the initially high temperature gradients are already drastically reduced by the large initial evaporation rates near the contact line. The vapor recoil is expected to push some flow out from underneath the bubble as the meniscus is pushed out by the vapor recoil pressure, but this effect would be small and limited to very early times. Anderson and Davis [4] noted that this effect is only significant very near the contact line in an evaporating droplet. Nikolayev and Beysens [5] made a similar observation for a growing vapor bubble. They showed that the vapor recoil pushes the receding contact line, thus modifying the interfacial curvature. These curvature changes would then most likely balance much of the vapor recoil pressure, in preference to the pressure in the liquid region being significantly increased. In addition, a gradient in the vapor recoil force along the interface would not create a similar gradient in the liquid region but would also likely change the interface curvature that would create a force to balance much of the vapor recoil force.

Shekriladze [3] also notes that the effect of vapor recoil is much lower in a highly subcooled environment. Since our experiments were conducted at typical subcoolings of approximately 40°C [2] or 60°C [1] in water and 30°C in ethanol [1], the vapor recoil effect would be expected to be insignificant for our conditions.

Shekriladze also questions the use of a steady-state analysis in our models. In numerous cases during the experiments done for this work, the initiation process for the bubble top jet flows was observed visually as shown by Wang et al. [2]. This initiation of the jet flows occurred after the bubble size had remained essentially constant; moreover, the bubble size continued to remain constant during and after the growth of the jet flows. These steady-state jet flows occurred long after the initial temperature gradient had been reduced so that they cannot be attributed to the vapor recoil effect. The jets continue to emanate from the moving bubbles for a relatively long time relative to the bubble growth time; thus, this phenomenon could be construed to be at steady state in the bubble's frame of reference. We believe, therefore, that the steady-state assumption was justified based on our experimental observations.

Shekriladze also questions whether the locations from which the jets leave the bubble are realistic. Very distinct pairs of jets were observed experimentally to develop around stationary, steady-state bubbles [2] and sometimes around moving bubbles [1]. As shown previously [6], the multiple jets were predicted by the Marangoni flow analysis and were found to emanate from more than one cold spot on the bubble interface in some cases. The jets form due to the complex flow of subcooled liquid up around the wire and the bubble. The main reason for this jet formation is that, for bubbles with diameters larger than or similar to the wire diameter, the upward flow of subcooled liquid from below the wire impinges on the bubble interface which is about even with or extends out beyond the wire, as shown in Fig. 1, causing relatively cold spots on either side of the lower half of the bubble (the exact location depending on the bubble size and the subcooling). These cold spots do not form on the top half of the bubble due to the lack of cooling flow impinging on the top surface. The cold spots on the lower parts of the bubble interface on the larger bubbles, therefore, serve as the sources for the multiple experimentally observed Marangoni jets.

Shekriladze's reference to the experiments of Betz and Straub [7] further corroborate the present results. In Ref. [7], the liquid velocities were measured near gas bubbles in various liquids with the liquid being driven against gravity by Marangoni flow. Betz and Straub characterized their results in terms of $\mathrm{Pe}=wB/\alpha$, where w is the tangential velocity, B is the bubble height that is essentially equal to the diameter for small bubbles, and α is the thermal diffusivity. Values of Pe in their work ranged from 150 to 200. For water, the bubble diameters were on the order of 0.1 mm [2], and for ethanol the diameters were approximately 0.2 mm [1]. A value of $\mathrm{Pe}=200$ would then give liquid velocities of 340 mm/s in water and 81 mm/s in ethanol, which agrees with the order of magnitude of the measured and calculated velocities based on Marangoni flow as the driving force [1,2]. Betz and Straub [7] as well as numerous other published studies by Straub and his colleagues concluded that the experimentally observed jet flows around gas or vapor bubbles [8], which were similar to the current observations for vapor bubbles, are due to Marangoni flow in the same manner as described in [1,2,6].

Shekriladze correctly states that the value of the accommodation coefficient continues to be a significant source of uncertainty that requires further investigation. As noted by Marek and Straub [9], the "evaporation and condensation coefficients of water obtained theoretically or experimentally scatter over a rather large range of more than two decades…". The small value of 0.03 for the accommodation coefficient used in the present work con-

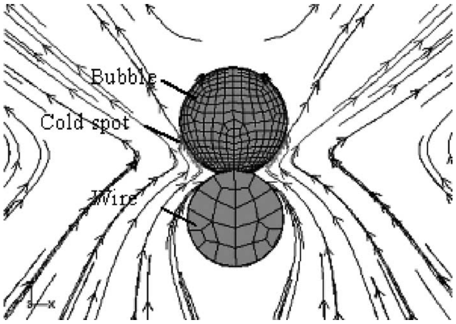

Fig. 1 Predicted pathlines for multijet flow

ducted in glass vessels is consistent with Marek and Straub's [9] additional comment that "even small contaminations of the surface significantly reduce the interfacial mass transfer…. Evaporation and condensation in glass vessels can be strongly hindered by the accumulation of dissolved glass components on the interface." Marek and Straub [9] referred to several studies that all confirm this strong reduction in the accommodation coefficient. The lowest value of the accommodation coefficient given in their review [9] was 0.002 for water in a glass vessel. Hickman [10] noted that the throttling due to evaporation into a saturated vapor rather than into a vacuum would significantly reduce the evaporation coefficient. Hickman also found that very high evaporation coefficients close to unity could only be obtained with moving liquid water in a vacuum where the surface is continually refreshed by the moving stream and the evaporating molecules are immediately removed by the vacuum. In our work, where the surface is not being refreshed as in a moving stream and was almost stationary for the stationary bubbles (except for the Marangoni flow along the interface), a value of 0.03 was adopted based on the comprehensive review of Paul [11] and Hickman's [10] statement (for nonflowing and nonvacuum conditions) that "the consensus, backed by different experiments, has been that not more than one molecule of water in 25, approaching the surface from either side, actually merges with the interfacial layer."

In summary, we contend that these additional results confirm our previous conclusions [1,2] that the experimentally observed jet flows around relatively long-lived, steady-state moving or stationary vapor bubbles in highly subcooled nucleate boiling result from Marangoni flow induced by the temperature gradients along the bubble interface. During the initial bubble growth transient, when the temperature gradients and evaporation rates are very high, the vapor recoil effect would influence the bubble shape, especially the microlayer shape near the contact line, and the liquid flow very near the base. At later times, when the vapor recoil effect is insignificant; the vapor recoil effect is not expected to produce the essentially steady-state jets observed in the experiments.

Acknowledgment

This project was supported by the National Natural Science Foundation of China (Contract No. 50476014).

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