Closure to "Discussion of 'Heat Transfer Mechanisms During Flow Boiling in Microchannels' " (2012, ASME J. Heat Transfer, 134, p. 015501)

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The interrelations among different nondimensional groups shown by M. M. Awad are quite correct. The insight provided by the author is very much appreciated.

The use of the correct nondimensional group is derived mainly from the physical interpretation of the underlying processes. Whenever possible, an underlying model based on force balance or some such similar approach is recommended. This will help in arriving at equations and correlations that are able to accurately represent the form of the interrelationships among variables. Such an approach was adopted by Kandlikar [1] in modeling the flow boiling CHF, resulting in the following equations from a force balance analysis at the liquid–vapor–solid contact line at the CHF condition.

$$F'_M = a_1(F'_{S,1} + F'_{S,2}) + a_2 F'_I + a_3 F'_\tau \quad (1)$$

In this equation, a_1, a_2, and a_3 are constants, and F' represents the forces per unit length of the contact line, and subscripts stand for the respective forces as follows:

M—evaporation momentum
S,1 and S,2—surface tension at the advancing contact line and the top of the bubble interface, respectively
I—inertia
τ—viscous

Dividing by the surface tension forces throughout and simplifying results in the desired relationship among the nondimensional groups of interest in this discussion.

$$\mathrm{K}_{2,CHF} = a_1(1 + \cos\theta_R) + a_2 \mathrm{We}(1 - x) + a_3 \mathrm{Ca}(1 - x) \quad (2)$$

where $\mathrm{K}_{2,CHF}$ represents the nondimensional group K_2 at the CHF condition, θ_R is the receding contact angle, and x is the vapor quality of the flow in the channel. As suggested by Awad, the Weber number may be replaced by the ratio $\mathrm{K}_2/\mathrm{K}_1$, but it may be better to retain the Weber number to clearly identify the contribution from the inertia term.

In analyzing the liquid–vapor interface during pool and flow boiling, there are four forces that have been identified to be of interest. These are evaporation momentum, surface tension, inertia, and viscous forces. The following six combinations emerge as nondimensional groups.

$$\frac{\text{Evaporation Momentum Force}}{\text{Inertia force}} = \mathrm{K}_1 \quad (3)$$

$$\frac{\text{Evaporation Momentum Force}}{\text{Surface tension force}} = \mathrm{K}_2 \quad (4)$$

$$\frac{\text{Evaporation Momentum Force}}{\text{Viscous force}} = \mathrm{K}_3 \quad (5)$$

$$\frac{\text{Inertia Force}}{\text{Surface tension force}} = \mathrm{We},\ \text{Weber number} \quad (6)$$

$$\frac{\text{Inertia Force}}{\text{Viscous Force}} = \mathrm{Re},\ \text{Reynolds number} \quad (7)$$

$$\frac{\text{Viscous Force}}{\text{Surface Tension Force}} = \mathrm{Ca},\ \text{Capillary number} \quad (8)$$

The nondimensional group K_3 has not been independently used yet, but it is relevant if the evaporation momentum and viscous forces are considered in a process. K_3 can also be represented as:

$$\mathrm{K}_3 = \mathrm{K}_1\mathrm{Re} = \mathrm{K}_2/\mathrm{Ca} \quad (9)$$

In summary, recognizing the evaporation momentum force as an important force during the boiling process opens up the possibilities of three new relevant nondimensional groups, K_1, K_2, and K_3. Any two of these groups can be represented by combining the third one with one of the other relevant nondimensional groups Re, We, and Ca.

Reference

[1] Kandlikar, S. G., 2010, "A Scale Analysis Based Force Balance Model for Critical Heat Flux (CHF) During Saturated Flow Boiling in Microchannels and Minichannels," Trans. ASME J. Heat Transfer, **132**(8), p. 081501.

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