Comment on "Flow and heat transfer of liquid plug and neighboring vapor slugs in a pulsating heat pipe" by Yuan, Qu, & Ma

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The modelling of the oscillating or pulsating heat pipe (PHP) becomes more and more popular subject of the engineering research. Several works appeared very recently, in particular [1, 2] appeared this year. Their starting point is the work [3]. The modelling approach used in all these works describes the liquid plugs and the vapor bubbles separately as control volumes. The equations are written separately for each of them. The equations for the vapor control volume are especially important since the bubbles act as elastic springs that provide the oscillating behavior. I address here only the vapor energy balance equation because it is written differently in [1] and in [2, 3]. I aim to show that the form used by Yuan et al. [1] is erroneous.

The change of the total internal energy of the vapor control volume V is

$$d(mu) = \delta Q - pdV + hdm, \qquad (1)$$

where m is the vapor mass, u is the internal energy per unit mass, p is the vapor pressure, h is the vapor enthalpy per unit mass and δQ is the heat received by the heat exchange with the exterior or generated by viscous friction. The differentials mean here the change of a quantity during the time dt. The term hdm is usual for open systems that can exchange the mass dm with the surrounding. Eq. (1) is well known in the classical thermodynamics, e. g. when describing the discharge of a pressurized vessel [4]. Because of the weak heat conduction of the vapor, δQ is generally small and is neglected in [1, 3]. It is accounted for only in [2]. It will be omitted below for the sake of clarity.

All above works use the ideal gas assumption, so that the following expression holds for the internal energy:

$$u = c_v T + A. \qquad (2)$$

Here c_v is the specific heat capacity at constant volume, T is the temperature in K, and A is an arbitrary energy that fixes the reference state. A is usually omitted in the literature because it never enters the dynamic equations. By using (2) and the ideal gas equation $pV = mRT$ (R: universal gas constant, Jkg^{-1}K^{-1}), one obtains the following well known equation for the enthalpy $h = u + pV/m$,

$$h = (c_v + R)T + A. \qquad (3)$$

The substitution of (2,3) into (1) results finally in

$$mc_v dT = -pdV + RT dm. \qquad (4)$$

This is the correct form used in [2, 3]. Yuan et al. [1] derive the erroneous equation (see their eqs. 7,8) that can be rewritten in the present notation as

$$mc_v dT = -pdV + (h_{fg} - c_v T)dm, \qquad (5)$$

where h_{fg} is the latent heat. Such an equation originates from usage of h_{fg} instead of h in eq. (1). The mistake becomes obvious after the substitution of (2) into (1) with h replaced by h_{fg}: the arbitrary energy A enters the resulting equation, which is wrong.

Yuan et al. argue that the evaporation at the gas-liquid interface brings to the vapor the energy $h_{fg} = h - h_L$ per unit mass, where h_L is the liquid enthalpy. This statement is incorrect. It would be true if their control volume consisted of both liquid and vapor. Indeed, during evaporation of the unit mass, the liquid loses the enthalpy h_L while the vapor gains the enthalpy h so that the total enthalpy increase is h_{fg}.

Note that the numerical error introduced by the replacement of the coefficient RT in (4) by $h_{fg} - c_v T$ might be considerable. Indeed, for water at atmospheric pressure the second of these quantities is about 10 times larger. It means that the effect of the mass exchange (which is the moving force of the oscillations in the PHP) is probably considerably exaggerated in [1].

[1] D. Yuan, W. Qu, T. Ma, Flow and heat transfer of liquid plug and neighboring vapor slugs in a pulsating heat pipe, Int. J. Heat Mass Transfer 53 (7-8) (2010) 1260 – 1268. doi:10.1016/j.ijheatmasstransfer.2009.12.042.

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