Pumping effect of bubble growth and collapse in microchannels: Thermo-hydraulic modeling

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Abstract In the past two decades, microfluidic systems have become more appealing due to their wide applications in many areas, such as electronics, biotechnology, medicine, etc. Recently, the advantages of using the bubble growth phenomenon as a robust actuator in microfluidic devices have directed research interests towards the investigation of various applications. In this research, a new transient thermo-hydraulic model has been developed for bubble growth in confined volumes. The present model has been used to describe the pumping effect produced by the bubble growth and collapse phenomenon in microchannels. The results show relatively good agreement with experimental data. This study is useful in getting a better understanding of the bubble growth mechanism in confined volumes, and its application as a reliable micro actuator.

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1. Introduction

The development of microfluidic devices for use in electronic cooling systems, biological and chemical analyzers and other applications requires simple, reliable and robust components, such as valves, pumps, actuators, etc. [1]. In recent years, the potential for utilizing the bubble growth phenomenon as a reliable actuator in microfluidic systems has motivated many researchers towards the investigation of various applications, such as actuating [2], pumping [3,4], mixing [5] and switching [6]. In designing such devices, it is important to predict bubble behavior in confined volumes.

Although there is widespread knowledge about bubble dynamics in unconfined spaces, little work has been done on the bubble growth process in confined volumes whose dimensions are comparable with bubble size. Although a limited number of research deals with boiling heat transfer in capillary tubes [7], microchannel heat sinks [8] and heat pipes [9], in all of them heat transfer occurs continuously from the entire surface rather than localized pulse heating, which is important in our case.

For the reliability of micro devices, bubble generation must be precisely repeatable. So, the usual non homogenous nucleation process, which is mainly affected by heating surface conditions, is not quite suitable for this purpose. On the other hand, the boiling phenomenon, under an extremely high heat flux, is different from the usual boiling mechanism in many aspects [10]. Due to the very high heat flux, the liquid temperature rises rapidly near the heating surface, whilst the remaining liquid remains at the initial temperature. In such a situation, the liquid becomes metastable, and spontaneous nucleation occurs before the gas or vapor nuclei, trapped in the surface cavity, grow. As a result of the very high initial pressure of the bubble, this boiling phenomenon is also known as explosive evaporation. As the bubble grows, the initial temperature and pressure of the bubble falls rapidly in several microseconds, mainly due to the bubble expansion work.

The spontaneous boiling process is mainly governed by liquid properties instead of surface conditions, which are important in the non homogenous nucleation. So, the explosive boiling is more reproducible and reliable, and it is more convenient to work as a robust actuator in microfluidic systems. It must be noted that explosive evaporation is not only a theoretical or purely experimental phenomenon, but rather has been used successfully as a commercial actuator in thermal ink-jet printer heads [11]. This mechanism was used as an
actuator in micropumps by Tsai and Lin [5], who designed and tested a valve-less nozzle-diffuser micropump. Valve-less nozzle-diffuser micropumps, introduced by Olsson et al. [12], use the difference in pressure resistance between the nozzle and the diffuser ports to direct the flow in a favorable direction. They may facilitate various mechanisms as an actuator, e.g. a boiling bubble. Recently, a new peristaltic bubble micropump with a simple structure has been reported, based on the bubble growth mechanism [13], which is completely different from previous valve-less micropumps. Bubbly-actuated peristaltic micropumps have no nozzle-diffuser ports, and are simpler than nozzle-diffuser micropumps accordingly. Although bubble-actuated nozzle-diffuser micropumps have been investigated, both experimentally [14] and numerically [15], during recent years, there are no comprehensive studies on peristaltic ones. Yuan and Prosperetti [16] showed that the growth and collapse of a single bubble in the microchannels can produce the pumping effect, provided that it is not located at the middle of the microchannel. However, their model is based only on a hydrodynamic analysis of the phenomena, which leads to some lack of knowledge about its heat transfer mechanism. Saidi and Sajadi [17] developed a non-dimensional solution for bubble growth dynamics in confined volumes, and studied the effect of various parameters on the process. Koizumi and Ohtake [18] investigated the pumping effect in a micropump using a single boiling bubble as an actuator. They concluded that the generation of the flow is mainly attributed to the difference in the velocity of the bubble interface at its two sides. Most recently, Lemmens and Meng [19] conducted experimental research on bubble-driven micropumps, although they used an electrolysis mechanism to generate the bubbles. Based on the results, they suggested that micropump geometry may have a considerable effect on its performance.

In this research, a bubble growth process has been modeled as a set of ODEs, including all thermo-hydraulic aspects of the phenomenon, to describe bubble growth behavior in confined volumes. After verification, the present model is used to investigate the pumping effect of bubble growth and collapse in microchannels. The results give a better understanding of the bubble growth process in microchannels, and are useful in the analysis and design of various microfluidic actuators.

2. Analytical modeling

A sketch of the geometry considered in the model is shown in Figure 1. A microchannel connects two reservoirs, which are assumed to be large enough for their pressures to be almost constant. A micro heater situated on the microchannel substrate warms up the liquid locally. As a result, the liquid temperature rises rapidly and, if the heat flux is large enough, an explosive evaporation can occur. As mentioned previously, the bubble internal pressure falls down rapidly, and collapses after reaching its maximum volume. It is convenient to investigate the boiling process at separate stages including:

1. Pre-heating,
2. Vapor film growth,
3. Bubble growth,
4. Bubble collapse,
5. Final net flow.

At the first stage, named the pre-heating stage, the liquid near the micro heater surface warms up to the homogeneous nucleation temperature, after which explosive evaporation occurs. At this time, many tiny vapor bubbles nucleate and coalesce with each other to cover the entire heater surface, like a film. The vapor film grows rapidly until it occupies the whole microchannel cross section, named the vapor film growth stage. Afterwards, the bubble grows longitudinally, named the bubble growth stage. When the bubble reaches its maximum volume, it will collapse rapidly, named the bubble collapse stage. As the bubble collapses longitudinally, the governing equations of bubble collapse stage are similar to the bubble growth stage, and are modeled with it as a single stage. Finally, due to bubble collapse, the net flow can be produced under specific conditions.

2.1. Pre-heating

As shown by Sajadi [20], if the heating time is small enough, the liquid and the substrate can be modeled as a semi infinite
medium without significant error. So, the wall temperature becomes:

\[ T_{\text{wall}}^* = \frac{2 \dot{Q}}{F_c \pi} \]

(1)

where:

\[ F_0 = \frac{\alpha \cdot t^+}{D^2}, \]

\[ \dot{Q} = \frac{\dot{q}^c D}{k \cdot (T_{\text{sp}} - T_{\text{amb}})} \]

(2)

The correction factor, \( F_c \), describes the heat transfer to the microchannel substrate, which is defined as:

\[ F_c = 1 + \frac{k_s}{k} \frac{\alpha}{\alpha_s} \]

(3)

As the heat flux is extremely large in this study, the nucleation time is very small, and can be predicted from Eq. (1). The spinodal temperature, at which the liquid becomes metastable, is nearly 0.9 of the critical temperature, and in the absence of experimental data, can be estimated by Lienhard's equation [21]:

\[ T_{r,sp}^* = 0.905 + 0.095T_{r,\text{sat}}^* \]

(4)

2.2. Momentum equation

As already noted, when nucleation occurs, initial bubble pressure is extremely high, but after a few micro seconds, it rapidly falls. Previous investigations in both unconfined [22] and confined [23] volumes show that bubble pressure falls to vapor pressure at the ambient temperature, with an almost exponential behavior. Asai [11] suggested the following equation for bubble pressure:

\[ p_b = [p_{sp} - p_{\text{sat}}] \cdot \exp \left[ -\left( \frac{t}{t_e} \right)^3 \right] + p_{\text{sat}}. \]

(5)

where the bubble growth time constant, \( t_e \), strongly depends on heating conditions, and the free parameter, \( \lambda \), is expected to be between 0.5 and 1 [11].

As the initial slope of Eq. (5) is very large, it is common to approximate it by an ideal impulse:

\[ p_b = p_{sp} - p_{\text{sat}}. \]

where:

\[ P = \frac{p_{sp} \tau_e}{\lambda}. \]

(7)

Based on our previous studies [17,24], the normalized governing momentum equations for the various stages are:

Vapor film growth stage:

\[ \frac{d^2 V^*_i}{dt^2} + \frac{f}{\text{Re} \cdot \text{St}} \frac{dV^*_i}{dt} = -\Delta p^*_i, \]

(8)

Bubble growth and collapse stages:

\[ \left( V^*_i - V^*_0 \right) \frac{d^2 V^*_i}{dt^2} + \frac{f}{\text{Re} \cdot \text{St}} \left( V^*_i - V^*_0 \right) \frac{dV^*_i}{dt} = \Delta p^*_i, \]

(9)

Final net flow:

\[ \frac{d^2 V^*}{dt^2} + \frac{f}{\text{Re} \cdot \text{St}} \frac{dV^*}{dt} = -\Delta p^*, \]

\[ V^*(0) = V^*_r \] and \[ \frac{dV^*}{dt} (0) = \left. \frac{dV^*}{dt} \right|_{f}. \]

(10)

where \( i \) stands for \( r \) (right reservoir) and \( l \) (left reservoir), and \( f \) and \( c \) are abbreviations for filling time, end of film growth stage, collapse time and end of bubble collapse stage, respectively. In addition:

\[ L^* = \frac{L}{L_{mc}}, \quad V^* = \frac{V}{V_{mc}}, \quad \tau = \frac{t}{t_e}, \quad p^* = \frac{p}{p_{mc}}, \quad \text{Re} = \frac{D^2 t^+}{D_{mc}}, \quad \Delta p^* = p_{\text{sat}}^* - p^*. \]

(11)

2.3. Energy equation

As mentioned previously, the time constant, \( t_e \), depends on heating conditions. So, the energy equation must be solved to close the governing equations. To estimate the time constant, the bubble growth process at initial times is studied in detail. At these times, the bubble volume can be neglected, but it must be noted that the volume change is large, and must be taken into account. It is also assumed that the heat flux has been turned off just after the bubble was generated. In other words, the bubble does not gain any heat flux from the heater during its growth process. When the heat flux is high, turning off of the heat flux is recommended to prevent damage of the heater [11].
which is a completely reasonable assumption. According to Asai's approach, it can be shown that:

\[ S_q \delta c \approx \rho_s h \frac{dV_b}{dt}. \]  

(12)

At initial times, by assuming \( p_b \approx p_{ap} \), it can be shown that [24]:

\[ \frac{dV_b}{dt} = \frac{\rho_p A}{\rho_f} \left( \frac{1}{L_{t,0}} + \frac{1}{L_{r,0}} \right) t. \]  

(13)

Combining Eqs. (12) and (13):

\[ \delta q'_c = \frac{\rho_p h A \rho_c}{S_h \rho_f} \left( \frac{1}{L_{t,0}} + \frac{1}{L_{r,0}} \right) t. \]  

(14)

As the bubble grows, its pressure falls rapidly. By a semi-infinite model, the bubble pressure is [11]:

\[ p_b = p_{ap} \exp \left[ -\left( 1 + \frac{1}{t_1} \right) \left( \frac{t}{t_2} \right)^{0.5} \right], \]  

(15)

where:

\[ t_1 = \frac{3 S_h \rho_f}{2 A \rho_c \rho_p h} q_h \left( \frac{1}{L_{t,0}} + \frac{1}{L_{r,0}} \right)^{-1}, \]
\[ t_2 = \pi \left( \frac{\rho_p k \beta \gamma^2}{4 \alpha} \right), \quad \beta = 1 - \frac{\rho_s}{\rho_f}, \]
\[ \gamma = \frac{\rho_s}{\rho_f}. \]  

(16)

Using Eq. (15) instead of \( p_b \approx p_{ap} \), the more exact solution for \( \delta q_c \) can be extracted in a similar way to how Eq. (14) was obtained:

\[ \delta q'_c = \frac{\rho_p h A \rho_c}{S_h \rho_f} \left( \frac{1}{L_{t,0}} + \frac{1}{L_{r,0}} \right) \times \left[ 1 - \left( \delta + \delta' \frac{t}{t_1} \right) \left( \frac{t}{t_2} \right)^{0.5} \right] t, \]  

(17)

where:

\[ \delta = \frac{5}{4} \left( 1 - \beta \gamma + \frac{8}{15} \right) - \frac{\gamma}{4}, \]
\[ \delta' = \frac{7}{4} \left( 1 - \beta \gamma + \frac{8}{35} \right) - \frac{3 \gamma}{4}. \]  

(18)

As supposed by Asai [11], we assume that Eq. (15) is valid until time \( t_3 \) reaches its maximum value. This time, \( t_3 \), can be calculated as:

\[ t_3 = \frac{3 \delta}{\delta'} \frac{t_f}{f} \left[ \frac{2}{3 \delta} \left( \frac{5 \delta'}{3 \delta} \frac{t_2}{t_1} \right)^{0.5} \right]. \]  

(19)

where \( f \) is the following transcendental function:

\[ (1 + f) \sqrt{f} = \kappa. \]  

(20)

Equalizing Eqs. (5) and (15) at \( t_3 \), with a reasonable assumption that \( p_b \gg p_{sat} \), leads to:

\[ t_c = t_3 \left( 1 + \frac{t_3}{t_1} \right)^{-1/\kappa} \left( \frac{t_3}{t_2} \right)^{-0.5/\kappa}. \]  

(21)
located in the left half of the microchannel. In Figure 3, the initial pressure impulse is too low for the maximum bubble volume to occupy the entire microchannel cross section. As a result, only the vapor film growth occurs, and the bubble does not enter the longitudinally growth stage. As the inertia of the left liquid column is less than that of the right, its liquid is pushed out of the channel faster, due to the initial pressure impulse. But, as the bubble does not grow longitudinally, bubble conditions are similar during its growth and collapse stages. Consequently, the bubble collapses in the same manner as it grows, and finally there is no net flow production, as depicted in Figure 3. As shown in Figure 4, where there is a condition in which the bubble grows longitudinally, i.e. where the bubble growth stage occurs, variation in bubble volume is completely different.

In addition to Figures 4 and 5 can help in getting a better understanding of the bubble growth and collapse process in this situation. As depicted in Figure 5(a), the initial length and inertia of the left liquid column is less than that of the right. During the vapor film growth stage (hatched area in Figure 4), the left liquid column exits out more rapidly than the other, due to its lower initial inertia (Figure 5(a)). This trend continues at initial times of the bubble growth stage, where momentum nonlinear effects are not considerable (Figure 5(b)). As the bubble grows, the length of the left liquid column, which gains a greater velocity from the previous stage, reduces more rapidly than does the right one. Consequently, its momentum falls down rapidly and the flow direction reverses before the right one, due to the lack of momentum and pressure of the left reservoir (Figure 5(c)). This occurs in a normalized time,
about 0.022, in Figure 4. Finally, the right column also loses its momentum and begins to reverse (Figure 5(d)). Because of this asymmetry in the motion of liquid columns, the bubble collapses at a position which shifts over to the right. This indicates the production of net flow (Figure 5(e)). The net flow can be clearly recognized in Figure 4(a), where the final volume is positive.

Regarding the above discussions, it can be concluded that the main reason for the pumping effect of the bubble growth and collapse process in confined volumes is the asymmetric initial length of the liquid columns, which leads to the asymmetric momentum variation of the liquid columns during bubble growth and collapse stages. So, if the bubble is generated at the middle of the channel, no net flow can be predicted. This result is confirmed by previous experimental work [13]. Applying the present model, the bubble growth process in confined volumes and its pumping effect are modeled in a simple robust manner. The results can be used to study the effect of various parameters on the operation of bubble microactuators.

4. Concluding remarks

The bubble growth process in microchannels was modeled theoretically. Based on the extracted set of thermo-hydraulic equations, the pumping effect of this phenomenon was investigated. The results showed that the present model can predict generated flow with an acceptable accuracy. Consequently, the model was used to physically describe the pumping effect, due to the bubble growth-collapse sequence, in microchannels. The results are quite useful in obtaining a physical discernment of the bubble growth process in confined volumes. The present model can be used to study the effect of various parameters on the produced net flow and to optimize construction of a bubble microactuator, including its operating conditions.

References

[1] Judy, J.W. "Microelectromechanical systems (MEMS): fabrication, design and applications", Smart Materials and Structures, 10, pp. 1115–1134 (2001).
[2] Bergstrom, P.L., Ji, J., Liu, Y.N., Kaviann, M. and Wise, KD. "Thermally driven phase-change microactuation", Journal of Electrochemical Systems, 4, pp. 10–17 (1995).
[3] Jun, T.K. and Kim, C.J. “Valveless pumping using traversing vapor bubble in microchannels”, Journal of Applied Physics, 83, pp. 5638–5644 (1998).
[4] Saidi, M.H., Saidi, B., Safaei, H. and Pirouzpanah, S. “Experimental and analytical modeling of phase change micropump”, 8th Biennial ASME Conference Engineering Systems Design and Analysis, ESDA2006, Torino, Italy (2006).
[5] Tsai, J.H. and Lin, L. “Active microfluidic mixer and gas bubble filter driven by thermal bubble micropump”, Sensors and Actuators A, 97–98, pp. 665–671 (2002).
[6] Cheng, C.M. and Liu, C.H. "A capillary system with 1 x 4 microflow switches via a micro nozzle-diffuser pump and hydrophobic-patch design for continuous liquid handling", Sensors and Actuators A, 130–131, pp. 430–437 (2006).
[7] Peles, Y.P., Yarin, L.P. and Hestrini, G. “Steady and unsteady flow in a heated capillary”, International Journal of Multi-phase Flow, 27, pp. 577–598 (2001).
[8] Qu, W. and Mudawar, I. “Flow boiling heat transfer in two-phase micro-channel heat sink-II: annular two-phase flow model”, International Journal of Heat and Mass Transfer, 46, pp. 2773–2784 (2003).
[9] Khristafov, D. and Faghri, A. “Heat transfer during evaporation on capillary-grooved structures of heat pipes”, Journal of Heat Transfer, 117, pp. 740–747 (1995).
[10] Skripov, V.P. Metastable Liquids, John Wiley & Sons, New York, USA (1974).
[11] Asai, A. “Bubble dynamics in boiling under high heat flux pulse heating”, Journal of Heat Transfer, 113, pp. 973–979 (1991).
[12] Olsson, A., Stemme, E. and Stemme, G. “A valve-less planar fluid pump with two pump chambers”, Sensors and Actuators A, 46–47, pp. 549–556 (1995).
[13] Zhizhong, Y. and Prosperetti, A. “Blinking bubble micropump with microfabricated heaters”, Journal of Micromechanics and Microengineering, 15, pp. 1683–1691 (2005).
[14] Jung, J.Y. and Kwak, H.Y. “Fabrication and testing of bubble powered micropumps using embedded microheater”, Microfluidics and Nanofluidics, 3, pp. 161–169 (2007).
[15] Pan, L.M., Deng, J.W., Yuan, D.W., Chen, D.Q. and Zhang, J.Q. “Numerical investigation of a periodic heating thermal-bubble actuated diffuser-nozzle valveless pump”, Microgravity Science and Technology, 21, pp. S345–S350 (2009).
[16] Yuan, H. and Prosperetti, A. “The pumping effect of growing and collapsing bubbles in a tube”, Journal of Micromechanics and Microengineering, 9, pp. 402–413 (1999).
[17] Saidi, M.H. and Sadjadi, B. “Analytical modeling of bubble growth in microchannels”, ASME International Mechanical Engineering Congress and Exposition, IMECE2006, Chicago, USA (2006).
[18] Koizumi, Y. and Ohmke, H. “Study on micropump using boiling bubbles”, Journal of Heat Transfer, 130, 022403 (8 pages) (2008).
[19] Lemmens, R.J. and Meng, D.D. “A comparative study on bubble-driven micropump in microchannels with square and circular cross sections”, Sensors and Actuators A, 169, pp. 154–170 (2011).
[20] Saidi, B. “Thermo-hydraulic modeling of phase change micropumps”, M.S. Thesis, Sharif University of Technology, Tehran, Iran (2006).
[21] Cöller, J.G. and John, R.T., Convection Boiling and Condensation, Oxford University Press, London, UK (1996).
[22] Asai, A., Hara, T. and Endo, I. “One-dimensional model of bubble growth and liquid flow in bubble jet printers”, Japanese Journal of Applied Physics, 26, pp. 1794–1801 (1987).
[23] Yuan, H., Oguz, H.N. and Prosperetti, A. “Growth and collapse of a vapor bubble in a small tube”, International Journal of Heat and Mass Transfer, 42, pp. 3641–3657 (1999).
[24] Saidi, M.H. and Sadjadi, B. “Pumping effect of bubble growth and collapse in microchannels: thermo-hydraulic modeling”, 15th Annual International, Conference on Mechanical Engineering, ISME2007, Tehran, Iran (2007).
[25] Lindemann, T., Sassano, D., Bellone, A., Zengerle, R. and Kolty, F., “Three-dimensional CFD-simulation of a thermal bubble jet printhead”, NSTI Nanotechnology Conference and Trade Show, Boston, USA (2004).