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# OSCILLATORY CONTACT LINE MOTION INSIDE CAPILLARIES

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## ABSTRACT

Improvements in the fabrication capability have given rise to micro systems for heat and mass transfer operations. The flow of uniform/oscillating menisci or air-plug in liquid-filled tube is a hydrodynamics problem with interesting practical applications like Pulsating heat pipes, Fuel cells, Lab-on-chip devices, Electro-wetting, Microfluidics etc. Understanding the hydrodynamics of such flows will help us in manipulating the performance parameters, which will further improve the efficiency of multiphase micro-systems. Sufficient literature is available for uniform-unidirectional contact line motion for fully wetting fluids under isotropic homogeneous conditions, especially at low Capillary numbers. The present work aims to study the interfacial contact line behavior of a sinusoidally oscillating (at 0.5 Hz) (i) single meniscus (liquid-air) and, (ii) air plug formed between two different liquid slugs, in a square glass capillary having hydraulic diameter of 3.0 mm through high speed videography and subsequent image analysis. Such flows have not been reported sufficiently in the literature. To highlight important discerning physical phenomena, experiments are done with two different fluids, water and silicon oil. It was found that the contact line, in case of silicon oil, gets totally pinned whereas the contact line of deionized water shows partial pinning. The interplay of surface tension, viscous forces and inertia forces is playing important role in meniscus/air-plug shapes and thin film dynamics at different orientation of the capillary. This has profound implications on heat transfer. It was found that the sinusoidally oscillating contact line motion does not follow the classical Hoffman-Tanner Law which relates the advancing contact angle with the Capillary number.

**KEY WORDS:** Oscillating contact line motion, meniscus shape, mini-channels, pulsating heat pipe.

## 1. INTRODUCTION

The three-phase contact line, located at the intersection of a fluid-fluid interface (formed by two immiscible fluids) and a solid bounding wall, is encountered frequently in everyday experience and is of concern to many areas of science. The moving/pinning contact line problem finds application in wetting, spreading of adhesives, flowing of lubricants, the displacement of oil by water through a porous medium, etc. While the issues involved are of interest to flow boiling in narrow channels, the impact of such contact line dynamics in the specific context of the thermal performance of pulsating heat pipes cannot be over emphasized.

The existence of oscillating slug flow is now well established in the PHP parlance [2-4]. The extent of the role of latent heat transfer in the overall thermal performance of a PHP also depends on the type of flow patterns. It is also well known that the film thickness around vapor bubbles play a vital role in the heat transfer characteristics of the slug flow regime [5-6]. Hence it is necessary to understand the microscale hydrodynamics of slug flow under oscillating flow conditions.

At present, the dynamics of the fluid surrounding the contact line, and hence the contact line motion itself, is not fully understood.

## 2. CONTACT LINE MOTION

It is known that a precursor layer of the order of 100 Å usually surrounds the contact line; refer Figure 1 [1]. The difficulty in conventionally treating the contact line problem arises from the failure of continuum fluid mechanics in this precursor layer. Dussan [2] has found that when the contact line is in motion with respect to a solid surface, the usual assumptions of Newtonian fluid, no-slip boundary condition and non-deformable solid, gives rise to a non-integrable surface shear stress. The nature of the problem suggests the use of molecular mechanics in the precursor layer very close to the contact line, as mentioned by Koplik et al. [3]. Available models postulate that, when $Ca$<<1, flow in an ''inner'' region very near the contact line, cannot obey the same usual assumptions which govern the bulk flow farther from the contact line. While there have been numerous speculations, experimental identification of the unique hydrodynamics of this inner region has not been fully achieved so far. To date, most detailed experimental studies of the hydrodynamics up to, but not including, the deep inner region have focused on cases where viscous forces are small compared to capillary forces (small $Ca$) and inertia is negligible ($Re_{\varepsilon}$~0)[1].

This was perhaps due to the lack of analyses of inertia-dominated regimes in spreading, until the work of Cox [4] who found that the interface shape and the local flow field very near the moving contact line controls the macroscopic configuration and movement of the entire fluid body. Stoev [5] examined the effect of inertia on the hydrodynamics using detailed measurements of the liquid-vapor interface shape within a few microns of the contact line. Inertial effects were characterized by measuring deviation from purely viscous model (for very small Ca). The effect of inertia on the macroscopic apparent contact angle was also introduced. In qualitative agreement with Cox [4] they found that the inertia decreases this angle compared to its value at negligible $Re_{\varepsilon}$. They also found that the interface shape, and the local flow field very near the moving contact line, controls the macroscopic configuration of the entire fluid body.

Young and Davis [7] were among the first to study the oscillatory contact line motion and they simplified Dussan's model (for unidirectional creeping flow) [2]. Their analysis considered slow quasi-static oscillatory contact line motions. They found that both contact angle hysteresis increases with the contact line velocity.

## 3. EXPERIMENTAL METHODOLOGY

In this work, we examine the moving contact line in oscillatory motion inside a square capillary using high speed videography and subsequent image processing of the meniscus. In the context of a PHP, although the actual thermo-hydro dynamics in slugs-bubble system is quite complex, as first approximation, we are interested in the regime where inertia is not so large that it alone controls the process, but is large enough, along with surface tension, to produce a significant departure from the viscous controlled regime. When inertia forces become important (as for a PHP), a boundary layer develops near the solid surface when the fluid advances. This boundary layer creates a secondary flow in the inviscid region between the solid and the free surface, as seen in Figure 1, whose pressure on the free surface can be estimated. It is the normal stress from this secondary flow which causes the interface to deform (to satisfy Young-Laplace equation) thereby changing the apparent contact angle $\theta_a$.

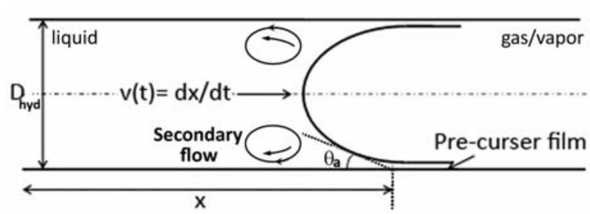

Figure 1. Schematic of a typical meniscus confined in a tube.

[1] It is to be noted that the problem has at least two length scales on which the Re can be defined; the microscopic length, ε, scales with the length scale of the precursor layer, ~$Re_{\varepsilon}$, while the macroscopic length scale corresponds to the bulk flow (tube diameter if the meniscus is confined), ~$Re_D$. There are instances when ($1<Re<\varepsilon^{-1}$), inertia is significant in the outer region but is negligible in the inner.

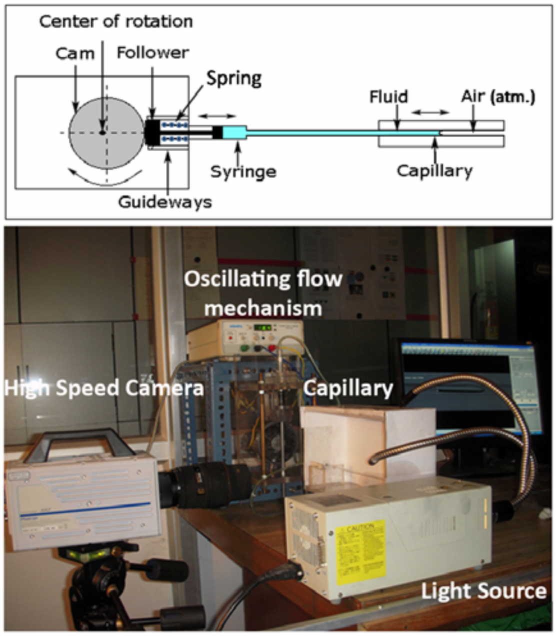

Figure 2. Details of the Experimental set-up.

Schematic diagram of the test facility is shown in Figure 2. We characterize the oscillatory motion effects by visualizing the effects of imposing a single oscillatory frequency of 0.5 Hz on (i) a single liquid meniscus and, (ii) an air bubble trapped in the liquid, inside a square capillary of $D_{hyd}$=3.0 mm. Water and silicon oil are used as working fluids. The capillary is thoroughly cleaned before usage, firstly with acetone then with the help of ethanol and deionized water. One end of the capillary is connected to the fluid to be observed and another end of the capillary is kept open to the atmosphere, as shown. To see the effect of gravity, the capillary was tested both in horizontal as well as vertical orientation.

The oscillatory flow generator set-up mainly constitutes of four parts; cam-follower oscillating flow mechanism, square capillary, high speed camera, and a diffused light source. The eccentric circular cam-follower system, made of hardened steel, rotating at a constant angular velocity is fabricated to produce sinusoidal oscillating motion to the fluid meniscus. This sinusoidal motion is transferred to the fluid in the minichannel using piston-cylinder mechanism as shown in Figure 2 (a). Eq. (1) and (2) gives the location of the meniscus from the bottom dead center and the instantaneous velocity (for more details, refer [8]):

$$x(t) = \frac{L}{2}\left(1+\sin\left(\omega\cdot t-\frac{\pi}{2}\right)\right) \qquad (1)$$

$$\dot{x}(t)=v(t)=\frac{L}{2}\omega\cdot\cos\left(\omega\cdot t-\frac{\pi}{2}\right) \qquad (2)$$

The square minichannel of cross section area 3 mm x 3 mm of length 150 mm was used for visualization. High speed camera (FASTCAM-SA3) fitted with a 105 mm F2.8 DG Macro objective lens is used for visualizing the oscillating meniscus at different locations in the minichannel. It is a fast progressive scan high speed camera, which provides maximum resolution of 1024x1024 pixels, actual least count in the acquired images is 30 microns per pixel. Moritex 150 W diffuse light source provided with an external linear intensity control is used for illuminating the capillary. Digital image processing is required to determine the various hydrodynamic features like contact angle, film thickness, operating dimensionless numbers etc. the automation of this task allows to have a lot of measurements and enables to verify their repeatability.

Table 1. Thermo physical properties and operating non-dimensional numbers

| Properties | Deionized Water | Silicon Oil |
|---|---|---|
| $\rho$ | 996.8 | 960.0 |
| $\mu$ | 0.8796 X $10^{-3}$ | 48 X $10^{-3}$ |
| $\nu$ | 0.8824 X $10^{-6}$ | 50 X $10^{-6}$ |
| $\sigma$ | 0.0728 | 0.0207 |
| $Re_{D, max}$ | 144.48 | 3.3 |
| Bo | 1.209 | 4.095 |
| $We_{max}$ | 0.0742 | 0.436 |
| $Ca_{max}$ | 5.135x$10^{-4}$ | 0.127 |

The system has periodic unsteadiness; i.e. the velocity of the meniscus is always changing sinusoidally; the inertial and viscous forces also vary continuously. Hence, all the relevant dimensionless numbers except Bond number are varying at a particular frequency. Table 1 gives the thermo physical properties and various operating non-dimensional numbers. Figure 3 shows the validation of sinusoidal motion of the meniscus, as obtained from the present experimental setup.

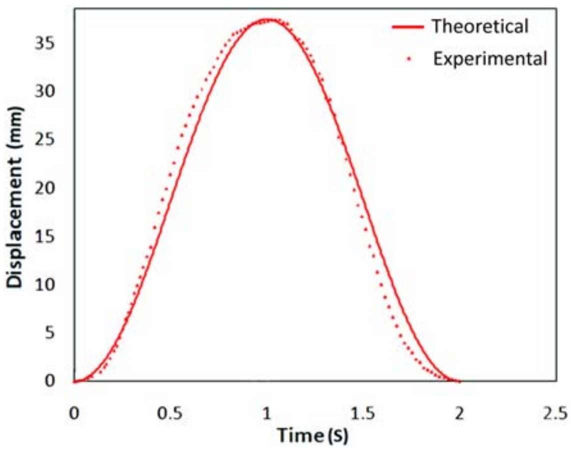


Figure 3. Validation of sinusoidal motion.

## 4. RESULTS AND DISCUSSIONS

Depending on the wettability of the fluid on the solid wall, in conjunction with the applied external surface and body forces, there can be three types of oscillatory contact line motion of the liquid-gas/vapor meniscus confined in a tube viz. (a) No pinning - the average velocity of contact line scales with the average bulk liquid velocity, (b) Partial pinning - there is a phase lag in the contact line velocity and the bulk fluid velocity, and (c) Full pinning, the contact line is motionless while the bulk liquid moves/ oscillates. Further, in cases (a) and (b), there can also be contact angle hysteresis in advancing and receding strokes. These possible cases are shown qualitatively in Figure 4 (2D axisymmetric representation); cases 4-a, b and c show three different stages during oscillating flow of single meniscus without pinning, partial pinning and full pinning respectively. Similarly, Figures 4-d, e and f show liquid slug without pinning, partial pinning and full pinning respectively.

A complete analysis of many contact-lines related fluid dynamic problems rely on an appropriate contact line model. Dussan et al. [10] did analysis for steady, unidirectional creeping flows. The complete physical picture of the physics in the immediate vicinity of the contact line is still either unclear (the validity of the constant surface tension assumption and the Newtonian constitutive relation, exactness of intermolecular force/ disjoining pressure, etc.) or difficult to measure Decker et al. [11, 12]. On the other hand, the apparent contact angle and the flow field are readily accessible by more conventional techniques of measurements where classical hydrodynamics is valid.

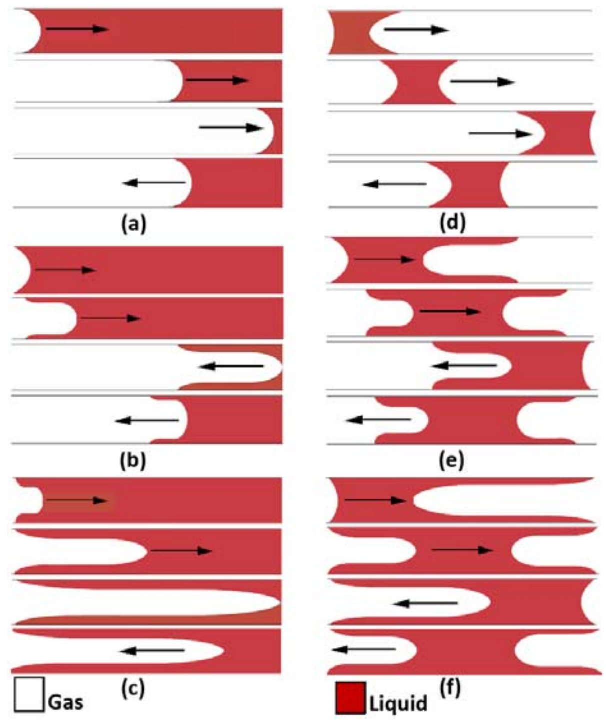


Figure 4. Possible configurations of the plugs/ meniscus under oscillatory motion.

### 4.1 Silicon oil

#### *4.1.1 Single meniscus*

During oscillations of a single meniscus of silicon oil-air interface, it is seen that the contact line of the meniscus is totally pinned at the extreme end of the stroke. This is seen in Figure 5-a, c, which shows the different stages of oscillating motion of single meniscus at 0.5 Hz, inside the capillary kept in horizontal and vertical positions respectively. The contact line is fixed relative to the glass tube and does not move at all, it literally sticks to the surface in spite of the sinusoidal motion given to the fluid alongside. Due to this pinning a liquid film is formed along the stroke length. The dominance of adhesive forces in the case of silicon oil is clearly visible. The static contact angle pf silicon oil on clean glass was found to be 14.2°. Usually, sticky motion is associated with small Reynolds number oscillations, as in this case; $Re_D$ changes from 0 to 3.3.

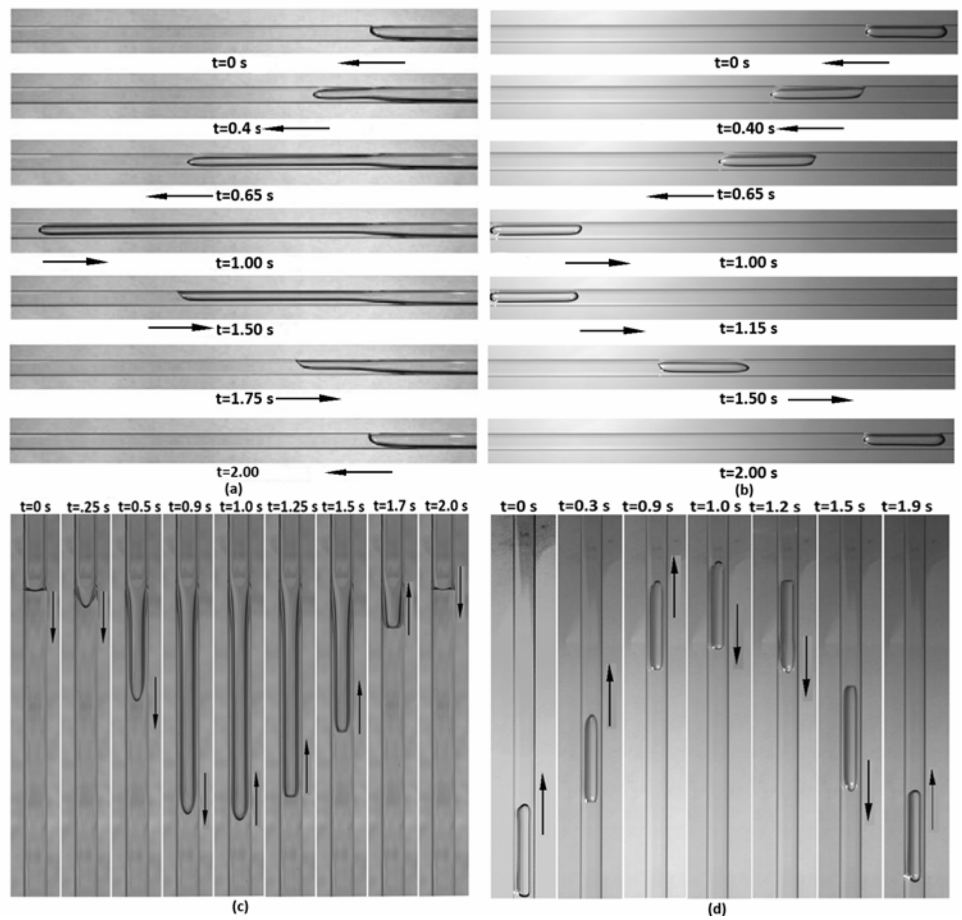


Figure 5. Fluid: Silicon oil (a) Single meniscus oscillating inside horizontal capillary (b) Air plug oscillating inside horizontal capillary (c) Single meniscus oscillating inside vertical capillary (d) Air plug oscillating inside vertical capillary.

For oscillations in horizontal tube orientation (Figure 5-a) the effect of high Bond number is clearly seen; the meniscus shape is not symmetrical, the length as well as the thickness of the bottom liquid film is always larger than the top side. Also, the contact angle hysteresis in the forward and the return stroke are clearly visible.

In vertical orientation, there is considerable change of the radius of curvature in the upward and the downward stroke. The contact line completely sticks to the glass tube inner wall. This orientation provides symmetrical body forces on the meniscus geometry.

*4.1.2 Air bubble in silicon oil*

Similar trends, as above, are seen with the oscillating trapped air bubble when it is oscillating in horizontal position (Figure 5 (c)). As clearly seen the slug is not travelling exactly at the centerline of the tube but little bit upwards; the liquid film thickness at the bottom portion of the tube is more compared to the top. In contrast, in vertical position the bubble is quite symmetric (Figure 5 (d)). Also the contact angle hysteresis is clearly seen in both the orientations when the shape of the bubble is compared in the forward and the return stroke. Although a small slip velocity was observed (relative velocity between the bubble and the liquid), it is not quantitatively reported here.

**4.2 Deionized water**

*4.2.1 Single meniscus*

As can be seen in Table 1, there is large difference in the properties of water and silicon oil and due to these differences the fluids behave completely differently.

The main parameters used to enumerate the dynamics of deionized water inside the capillary are the relative velocity at which the liquid moves across the solid, i.e. the wetting-line velocity $U$, and the dynamic contact angle $\theta_D$, From experiments it was observed that the dynamic angle generally differs from its static value $\theta_S$ and may refer to either an advancing (wetting) or a receding (dewetting) interface. On engineering surfaces, wetting lines tend to attach, and when they ultimately move they do so in an unsteady way. Such factors cause difficulties in both the measurement and interpretation of contact angle.

Experiments with water were also carried out at oscillating frequency of 0.5 Hz. In this case, the contact line is moving along with the bulk fluid/meniscus albeit with some phase shift as clearly seen in Figure 6-a, d. So this is a type of slip motion, the contact line moves freely along the tube with a varying dynamic contact angle $\theta_{D.}$

Figure 6 (a) shows the oscillations of single water meniscus inside horizontal capillary. When it is in receding stroke (t=0 to t=1 s), the effect of gravity, even at a small Bond number of 1.2, is quite visible; the meniscus shape is not quite symmetrical. The meniscus shows a relatively small radius of curvature in receding stroke. During its advancing stroke (t=1 to t=2 s) the meniscus shape became flattened.

*4.2.2 Air bubble in water*

During the oscillations of single air plug trapped in water, either in horizontal or in vertical position, its shape is not dramatically different as surface tension is predominant. Both ends of the air bubble have similar shape at all times during the oscillating period. In vertical orientation buoyancy does play a role as the bubble rise/ slip upwards can be noticed.

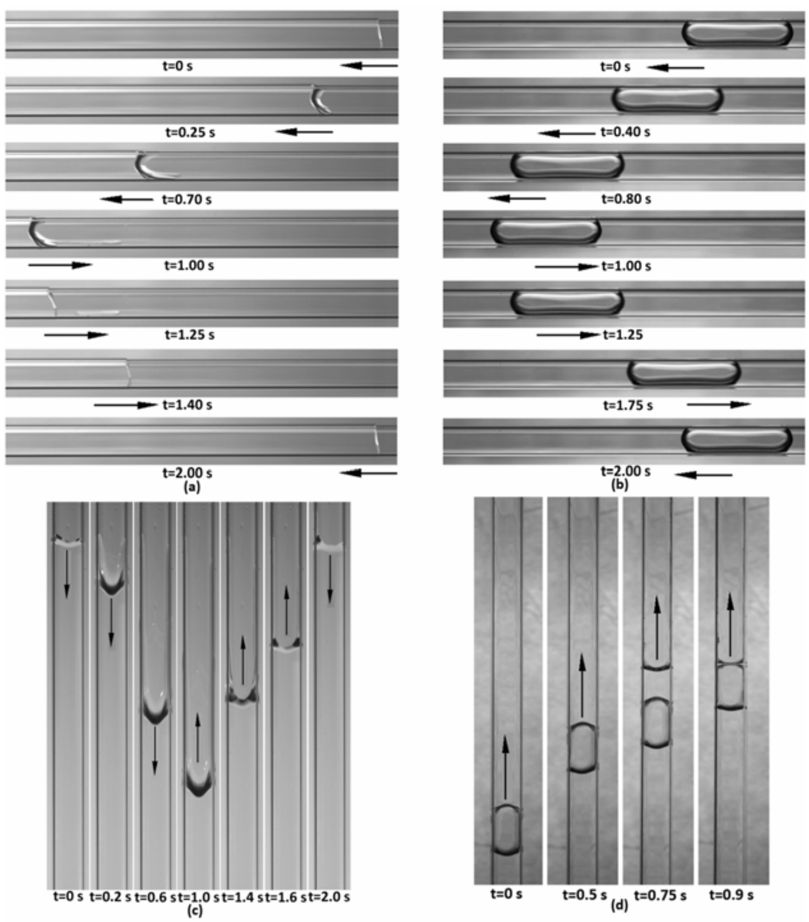


Figure 6. Fluid: Water (a) Single meniscus oscillating inside horizontal capillary (b) Air plug oscillating inside horizontal (c) Single meniscus oscillating inside vertical capillary (d) Air plug oscillating inside vertical capillary.

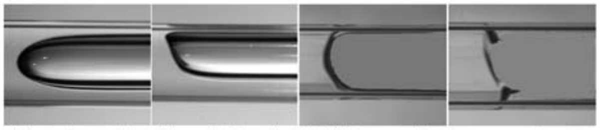

Figure 7. Close view of the meniscus.

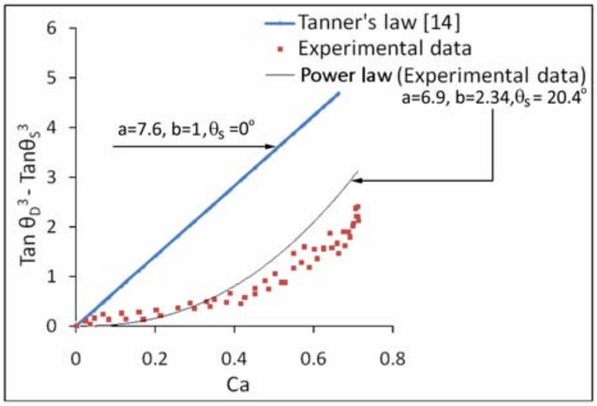

Figure 8. Variation of dynamic contact angle of oscillating water meniscus with Ca.

Figure 7 shows the close view of silicon-oil and water menisci, for both advancing and receding interfaces highlighting clear differences in the two fluids.

Figure 8 shows the variation of dynamic contact angle for advancing interface with Capillary number for the case of single meniscus of water. It is compared with the Hoffmann-Tanner's law i.e. $tan(\theta_D^3) \propto \mathrm{Ca}$ [14], which is valid for unidirectional constant velocity creeping motion (Re~0) of the interface for fluids having a zero static contact angle ($\theta_S = 0^\circ$). For higher meniscus velocity the applicable law is:

$$\tan\theta_D = a(Ca)^b \quad (3)$$

Where the parameters *a* and *b* depend on operational conditions like fluid property, capillary geometry and flow conditions [15]. The figure clearly shows that the inertia dominated oscillating meniscus motion of water does not follow the classical Hoffmann-Tanner Law. It is clear that the variation of dynamic contact angle with respect to oscillatory flows needs detailed further investigations. For the case of water meniscus the data fits reasonably well with modified Tanners Law as:

$$\tan\theta_D{}^3 - \tan\theta_S{}^3 = 6.9\cdot\left(Ca\right)^{2.34} \quad (4)$$

### 4.3 Implication on heat transfer:

It is well known that during phase change heat transfer across menisci, an important contribution comes from thin liquid films forming part of the meniscus that may cover the interior of the capillary [16]. The heat transfer is composed of liquid film conduction and evaporation at vapor-liquid interface. In the context of PHPs, the effect of the film evaporation has been clearly highlighted by models proposed by Zhang and Faghri [17 and more recent comprehensive extension by Das et al. [18 ]. These models now need further refining by taking into account the exact shape/ dynamics of the interface for different working fluids of PHPs, as has been highlighted in this paper.

## 4. SUMMARY AND CONCLUSIONS

A square mini-channel, 3mm x 3mm having oscillatory flow of single meniscus and air bubbles trapped in liquid slugs has been experimentally investigated. The profound effect of thermo physical properties of fluid and gravity on the meniscus motion and shape and gravity has been demonstrated. The following main conclusions can be drawn from the study.

- Gravity certainly affects the hydrodynamics of oscillatory contact lines of slugs inside the capillary.
- Thermophysical properties of the fluids will decide the flow configuration near menisci.
- Oscillatory contact line motion needs further detailed investigation to generate relevant scaling laws.
- Film thickness and slug/meniscus shape are important parameters in two-phase oscillating flow devices like pulsating heat pipe for modeling the heat transfer.

## ACKNOWLEDGEMENTS

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## REFERENCES


1. Berthier J., Microdrops and Digital Microfluidics, ISBN: 978-0-8155-1544-9, William Andrew Inc., 2008.
2. Dussan, V. E. B., The moving contact line: the slip boundary condition. J. Fluid Mech. Vol. 77, 1976, pp. 665-684.
3. Koplik, J., Banavar, J. F. and Willemsen, J. F., Molecular dynamics of fluid flow at solid surfaces. Physical Review Letters. Vol. 60, 1989, pp. 1282-1286.
4. Cox, R. G., Inertial and viscous effects on dynamic contact angles. J. Fluid Mech. Vol. 357, 1998, pp. 249-278.
5. Stoev, K., Thin film and inertial effects on the hydrodynamics near moving contact lines, Doctoral thesis, Dept. of Physics, Carnegie Mellon University, Pittsburgh, Pennsylvania, USA 1999.
6. Charoensawan, P., Khandekar, S., Groll, M. and Terdtoon, P., Closed Loop Pulsating Heat Pipes: Part A: Parametric Experimental Investigations, App. Thermal Engg., Vol. 23, 2003, pp. 2009-2020.
7. Young, G. W. and Davis, S. H., A plate oscillating across a liquid interface: effect of contact angle hysteresis. J. Fluid Mech. Vol. 174, 1987, pp. 327-356.
8. Shekhavat Y. S., Khandekar S., and Panigrahi P. K., Hydrodynamic Study of an Oscillating Meniscus in a Square Mini-Channel. Proc. Micro/Nanoscale Heat and Mass Transfer Int. Conf., Shanghai, China, December, 2009.
9. Groll, M. and Khandekar, S., Pulsating heat pipes: A challenge and still unsolved problem in heat pipe science, Archives of Thermodynamics. Vol. 23/4, 2002, pp. 17-28
10. Dussan, V. E. B., Ramé, E. and Garoff, S., on identifying the appropriate boundary conditions at a moving contact line: an experimental investigation. J. Fluid Mech. Vol. 230, 1991, pp. 97-116.
11. Graham, D. R. and Higdon, J. J. L., Oscillatory flow of droplets in capillary tubes. Part1. Straight tubes, J. Fluid Mech. Vol. 425, 2000, pp. 31-53.
12. Decker, E. L., Frank, B., Suo, Y. and Garoff, S., Physics of contact angle measurement. J. Colloids and Surface A. Vol. 156, 1999, pp. 177-189.
13. Ting, C. L., and Perlin, M., Boundary conditions in the vicinity of the contact line at a vertically oscillating upright plate: an experimental investigation. J. Fluid Mech. Vol. 295, 1995, pp. 263-300.
14. Chebbi, R., Deformation of advancing gas-liquid interfaces in capillary tubes. J. Colloid and Interface Science Vol. 265, 2003, pp. 166-174.
15. Schwartz, A. M. and Tejada, S. B., Studies of dynamic contact angles on solids. J. Colloid and Interface Science. Vol. 38/2, 1972, pp. 359-374.
16. Carey, Van P., Liquid-Vapor Phase Change Phenomena, Hemisphere, 1992.
17. Zhang, Y., and Faghri, A., Heat transfer in a pulsating heat pipe with open end, Int. J. of Heat and Mass Transfer. Vol. 45/4, 2002, pp. 755-764.
18. Das, S. P., Nikolayev, V. S., Lefèvre, F., Pottier, B., Khandekar, S. and Bonjour, J., Thermally induced two-phase oscillating flow inside a capillary tube, Int. J. Heat Mass Trans., 2010 (accepted with minor revisions).


## NOMENCLATURE

| | |
|---|---|
| D | : diameter (m) |
| x | : distance (m) |
| L | : characteristic length scale (m) |
| $v$ | : velocity (m/s) |
| Re | : Reynolds number, $\left(\rho\lvert v\rvert D\right)/\mu$ |
| Bo | : Bond number, $\rho g D^2/\sigma$ |
| Ca | : Capillary number, $\left(\mu\lvert v\rvert\right)/\sigma$ |
| We | : Weber number, $\left(\rho\lvert v\rvert^2 D\right)/\sigma$ |
| $\mu$ | : Dynamic viscosity (Pa-s) |
| $\sigma$ | : surface tension (N/m) |
| $\theta_D$ | : dynamic contact angle |
| $\theta_s$ | : static contact angle |
| $\rho$ | : density (kg/m$^3$) |

## ABBRIVATIONS

| | |
|---|---|
| hyd | : hydraulic |
| max | : maximum |