International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395 -0056
Volume: 04 Issue: 06 | June -2017 www.irjet.net p-ISSN: 2395-0072

THERMO-HYDRODYNAMICS OF TAYLOR BUBBLE FLOW IN CONTEXT OF PULSATING HEAT PIPE: A REVIEW

Asmita M. Rahatgaonkar[1], Dr. Pramod R. Pachghare[2]

[1]PG Student, Department of Mechanical Engineering, Government College of Engineering Amravati, Maharashtra, India
[2]Assistant Professor, Department of Mechanical Engineering, Government College of Engineering Amravati, Maharashtra, India

***

Abstract - *Modeling of Pulsating Heat Pipes (PHPs) requires local, spatio-temporally coupled, flow and heat transfer information during the characteristic, self-sustained thermally driven oscillating Taylor bubble flow, under different operating conditions. Local hydrodynamic characteristics such as velocities, lengths, shapes and profiles of bubbles and slugs, their dynamic contact angles, thickness of the liquid film that surrounds the bubbles, enhanced mixing/ flow circulation within the liquid slugs and net pressure drop along the flow, etc., are needed to predict local heat transfer and thus, the global thermal performance. In this paper, we systematically review the experimental, theoretical/analytical, and modeling methodologies to predict these hydrodynamic properties in unidirectional two-phase Taylor bubble flows, in the context of Pulsating Heat Pipes. Indeed, there is little literature available for oscillating Taylor bubbles flows. In view of the state-of-the-art, we therefore recommend some directions and perspectives for furthering research on understanding and modeling PHPs.*

Key Words: Pulsating heat pipe, Two-phase flow, Taylor bubble flow, Hydrodynamics, Thin-film.

1. INTRODUCTION

Pulsating Heat Pipes (PHPs) are thermally driven two phase passive devices, which offer effective solution to the problem of overheating associated with increasing circuit density, component miniaturization and higher demands on heat flux dissipation [Akachi, 1990]. Thermo-fluidic transport phenomena occurring in the PHPs is fascinating and extremely complex and thus justifies the need for extensive research [Akachi et al., 1996; Khandekar, 2004; Vasiliev, 2005; Zhang and Faghri, 2008]. The basic structure of a typical pulsating heat pipe is shown in Figure 1. PHPs are characterized by a meandering/ serpentine tube of capillary dimensions with many turns, filled partially with a suitable working fluid. It does not contain any internal wick structure. The internal diameter of the tube is sufficiently small such that surface tension dominates and a vapor plug-liquid slug system is formed instantaneously at the time of filling of the device [Khandekar et al. 2010; Zhang and Faghri, 2008].

1.1 Two-phase Flow

In a two phase flow, due to simultaneous vaporization and condensation processes, the liquid slugs and vapor plugs move in unison inside a capillary. The morphology of the two phases can vary depending upon the fluid properties and flow conditions such as mass flow rate of the two phases involved, orientation of the system, etc. Hence during actual operation of a PHP different flow patterns such as bubbly flow, slug flow, churn flow, annular flow etc. (Figure 2) exist at different heat load which controls the transport mechanisms of heat, momentum and species, thereby affecting the performance of the device [Carey, 2007].

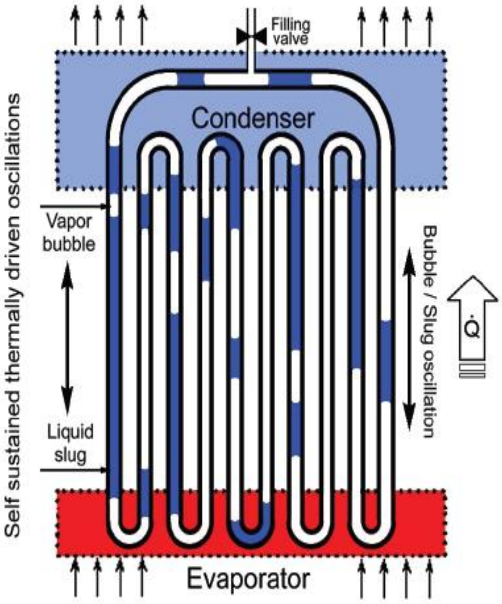

Fig-1: Schematic of a typical Pulsating Heat Pipe [Khandekar, 2010]

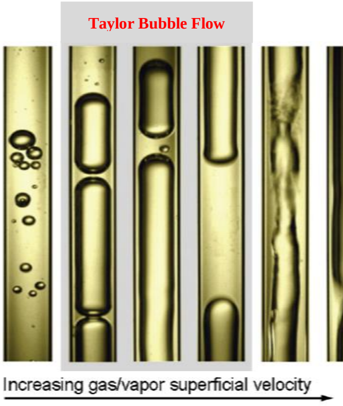

Fig-2: Different possible flow patterns in a capillary tube/micro channel based on gas superficial velocity [Khandekar, 2010]

1.2 Taylor Bubble Flow

One of the prominent flow pattern which is highly efficient in transporting heat, is the Taylor slug flow. In a slug flow, an increase in the gas flow rate leads to the coalescence of small bubbles into large bubbles called gas plugs or Taylor bubbles which occupy most of the pipe's cross-sectional area. The Taylor slug flow is characterized by a sequence of long bubbles which are trapped in between liquid plugs [Fairbrother and Stubbs, 1935; Taylor, 1961; Bretherton, 1961; Cox, 1964; Thulasidas et al., 1997]. The diametrical size of these bubbles is nearly comparable to the pipe diameter while their axial length scale can be several times the pipe diameter. A thin liquid film usually always separates the bubbles from the channel wall, as seen in the Figure 3. The thickness of this film varies depending upon the orientation of the channel, dimensions, geometry, thermo-physical properties of the fluid, flow velocity and channel used. The intermittent liquid plugs may also have small diameter bubbles (much smaller than the pipe diameter) entrapped inside them (Figure 3). Apart from PHP, Taylor bubble flow constitutes major flow pattern in many devices like micro-reactors, catalyst coating in capillaries, electronics cooling, fuel cells, MBR, nuclear reactors, oil and gas industry, PHP, refrigeration industry, porous media, flow in blood vessels and many more.

Fig-3: Taylor-bubble flow inside a capillary tube [Khandekar, 2010]

There are numerous important and unsolved issues with the current understanding of Taylor bubble flows.

(i) There is no comprehensive mathematical model to represent Taylor bubble flow for a given boundary condition.
(ii) The understanding of heat transfer and pressure drop under self-excited thermally driven oscillating two-phase flow inside capillary tubes is not convincing. The complete transport phenomena in the unit-cell need to be resolved to predict global heat transfer parameters.
(iii) Multiple unit-cells also interact with each other mutually; merger and coalescence of liquid slugs, breakage of Taylor bubbles under the impact of inertia and surface tension, nucleation inside liquid slugs, confined bubble formation, condensation on liquid films, instabilities, surface capillary waves, etc. are additional complexities for formulation of predictive tools for PHPs.

In this background, we review the present understanding and highlight the important parameters, which need consideration in our global understanding of Pulsating Heat Pipes. Primarily, the flow pattern in these systems is characterized by thermally driven pulsating/oscillating Taylor bubbles. Therefore, we focus our attention on local hydrodynamic transport behavior of Taylor bubbles. A detailed literature review is presented to highlight the present state of understanding on unidirectional as well as oscillating Taylor bubble flows, in the context of further understanding of PHPs.

2. SCALING OF FORCES

The miniaturization of fluid processes is associated with an increase in the dominance of surface forces over body forces. Thus, at micro-scale dimensions, surface tension effects are extremely important considerations in the design of microfluidic devices. For a PHP to operate effectively, the internal diameter of the tube should be sufficiently small such that surface tension forces dominate. Detailed studies have suggested that, for a liquid system to be completely dominated by surface forces over gravity or inertia, it is required that, the Bond number (Bo) of the system to be less than 2 (since, surface forces dominates the effect of gravity). Bond number is the scaling of gravity force to surface force, as:
Thus, the Bond number of the system decides whether the flow falls under the classification of mini/micro channel, exhibiting dominant interfacial characteristics. It will be a general agreement hereon, that the flow systems discussed in this chapter will all be such mini systems, where Bo<2.

Bretherton [1961] established the dominance of capillary flows in such mini channels, where the liquid velocity was low. His research highlighted that, the transport phenomena in such system is governed by capillary forces at the interface and the viscous forces at the bulk liquid. Thus, the scaling of surface forces to viscous forces, dictates the shape of the menisci and hence, the transport phenomena. Capillary number (Ca), scales this as:

Weber number (We) signifies the dominance of inertial force of the fluid to its interfacial force (surface tension). Flows with high Weber and Capillary numbers has profound implications on the meniscus shape and hence the transport characteristics. Weber number is scaled down as:

Thus Bond number and Capillary number dictates majority of the flow phenomena like the flow pattern, pressure drop, heat transfer, thin film formation, etc.

3. TAYLOR BUBBLE FLOW: HYDRODYNAMICS

3.1 Unidirectional Motion

The menisci shape of a liquid plug of a unit-cell plays vital importance on its transport behavior. In the regime of two-phase flows in micro/mini channel (categorized by Bo < 2), the predominant forces that governs menisci curvature are the capillary forces and the viscous forces. This combination is scaled by capillary number (Ca). Based on this scaling, elaborate studies have been carried out, showing the importance of capillary number on local pressure drop and heat transfer characteristic.

Capillary number is also used as a parameter in determining whether the vapor bubble will be surrounded by thin film of liquid or not. For low Ca ($<10^{-03}$), there exists no thin-film between the vapor bubble and the solid wall, due to dominating surface force. This causes direct contact of the vapor bubble, resulting in a three-phase contact line at the wall. This is known as the dry-plug regime. This regime, where a unit-cell moves without a thin film surrounding the vapor-bubble can be associated with the evaporator section of PHP or at near-dry out conditions or at very low velocities. Modeling the motion of a dry unit-cell is challenging because of the additional frictional drop due to three-phase contact line dissipation.

The recent study of Srinivasan et al. [2013], studied the hydrodynamics of such a dry unit-cell. A single liquid plug was forced to move by pushing air (at known constant mass flow rate) from one end, while the other end being open to atmosphere. Figure 4, shows the force balance on such a system. The study revealed that, initiating motion of the liquid plug required considerable amount of force, which is dispensed against the opposing capillary force in form of contact angle hysteresis. The hydrodynamics of a dry-unit cell (Figure 5) is outlined as below:

i) When a single liquid plug at rest is forced to move, it has to over-come the 'static friction', due to dominating surface forces. This friction manifests in the form of menisci deformation. As the plug is forced to move, the advancing contact angle increases, while the receding contact angle decreases from the static contact angle. This deformation behavior is found to be independent of the mass/length of the liquid plug.

ii) As the liquid plug overcomes this static friction, it accelerates due to the pushing force, which cause further increase in the pressure drop.

iii) This acceleration is then opposed by increasing wall-shear. There comes a time when the pushing force equals the opposing force (wall shear, capillary force and three-phase contact line dissipation), eventually making the liquid plug to move with 'terminal velocity' at steady state.

The highlight of this hydrodynamic study is that, both the force required to move the liquid plug and the force required to maintain the steady motion, were independent of the mass (length) of the liquid plug. This shows the dominance of surface forces, in particular, the role of contact angle hysteresis in deciding the pressure drop of a dry-unit cell.

This study provides a useful insight in understanding the dominance of surface forces in a PHP. It also suggests the need of improving the available models to accommodate contact angle hysteresis effect, as it is seen to play a much vital role than the viscous effects. A mathematical model to predict the frictional pressure drop in such case was also proposed.

Major global models described above do not include the effect of contact angle hysteresis, the negligence of which may mislead the formulation, as emphasized by the results. Since these experiments are highly dependent on surface wettability, it now becomes essential to perform such local experiments to find the effect of contact angle hysteresis on pressure drop and then use them for global modeling of PHP.

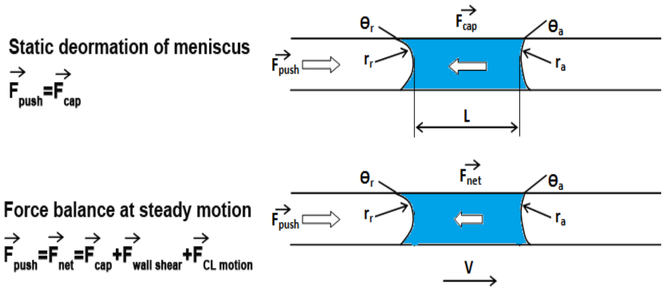

Fig-4: Force balance on a dry unit-cell at rest and steady motion [Srinivasan et al., 2013]

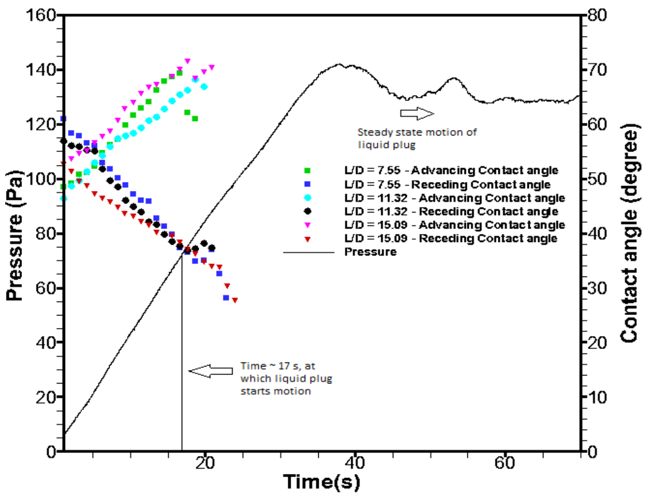

Fig-5: Hydrodynamics of a dry unit cell, pressure drop with time for different lengths of liquid [Srinivasan et al., 2013]

3.2 Oscillating Flow

Having attempted to understand the hydrodynamics of dry unit-cell in unidirectional, adiabatic conditions, an experimental study was performed on an oscillating menisci at adiabatic condition, which are typical in the adiabatic section of a PHP. The aim of the study was to understand the interfacial behavior of mechanically induced oscillating menisci. Figure 6 shows the schematic of the experimental set up. This study revealed the different flow patterns (Figure 7) that oscillating menisci can have. The results concluded that the capillary number and oscillating frequency play a major role in formation of thin film and contact angle hysteresis [Tripathi et al., 2010]. It was reported that a thin film is laid for high capillary number, due to the dominating viscous effects. Also, increasing the oscillating frequency increases the thickness of liquid film formed. Difference of dynamic contact angles during advancing and receding strokes of the oscillation was also found to be dependent on the oscillating frequency. Higher the frequency, higher was the contact angle hysteresis.

This study touches on the dependence of film thickness and contact angle hysteresis on oscillating frequency, which is very essential to model a PHP, since it is the evaporation this thin film, which plays a vital role in determining the performance of a PHP. Future direction of the study is to correlate the film thickness for oscillating menisci, which could be used for evaporation model of PHP.

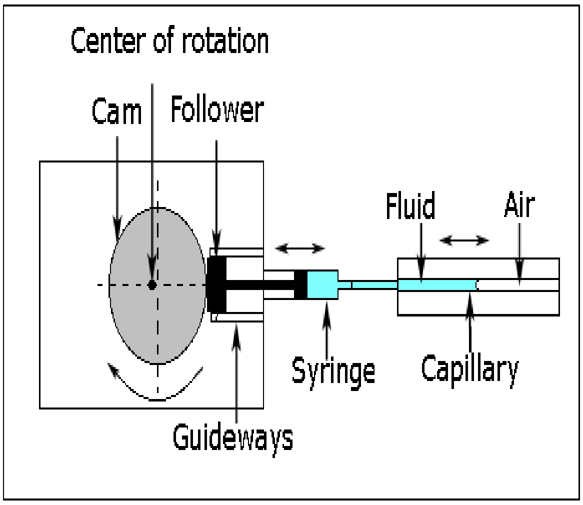

Fig-6: Schematic of experimental setup [Tripathi et al., 2010]

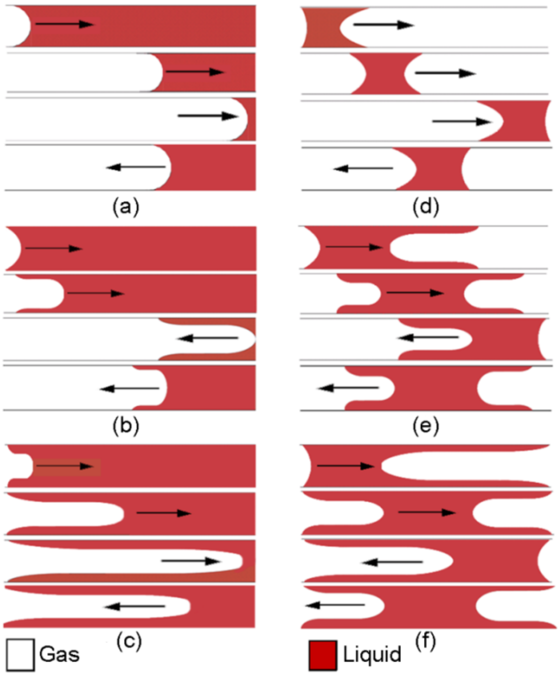

Fig-7: Possible configuration of an oscillating menisci [Tripathi et al., 2010]

4. THERMO-HYDRODYNAMIC STUDY OF UNIT CELL

4.1 Unidirectional Motion

The significance of contact angle hysteresis on local pressure drop was well established in the previous section. Also, the earlier heat transfer models have neglected to include this effect, which has led to huge scatter in the literature. Bajpai and Khandekar [2012] carried out a simulation to study the effect of including contact angle hysteresis to a dry unit-cell in its heat transfer performance. The simulation was performed at two different thermal boundary conditions namely i) constant heat flux at wall and ii) constant temperature at wall, for different lengths of liquid plug. Water and glycerol were used and the results of heat transfer co-efficient with and without contact angle hysteresis were compared. The study concluded a significant improvement in heat transfer co-efficient in the case where contact angle hysteresis was taken into account when compared with cases where it was neglected. This was attributed to formation of eddies/vortex, just behind the meniscus, which enhances mixing and creating a 3-D effect. Figure 8 shows the vortex structures behind the menisci. Figure 9 shows the development of velocity profile behind the menisci. It can be seen that, the velocity profile is disturbed behind the menisci from the expected 'parabolic' profile and gradually attains a parabolic profile towards the bulk of liquid. Effect of Prandtl number on the enhancement of thermal transport phenomena is also discussed [Bajpai and Khandekar, 2012]. The completeness of the study requires including the model of three-phase contact line dissipation of a dry unit-cell, which is not possible in a simulation as no model is available yet.

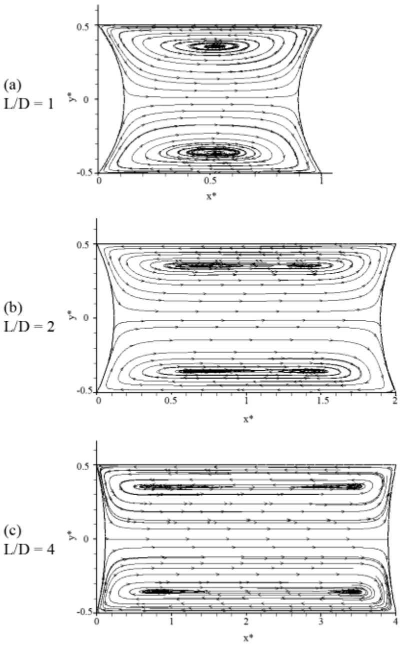

Fig-8: Steady state stream-line of a dry unit-cell (Ca = 10^{-03}) for different L/D of water [Bajpai and Khandekar, 2012]

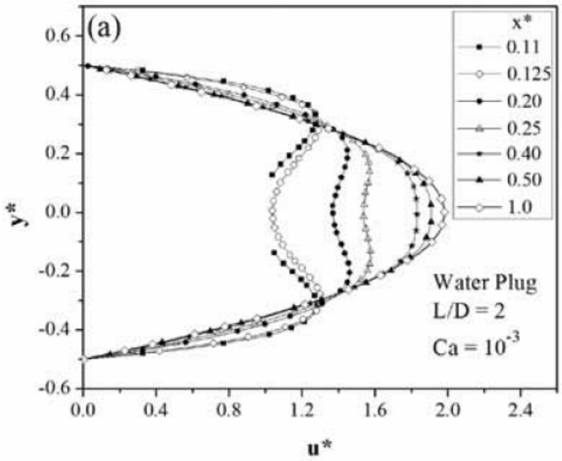

Fig-9: Development of velocity profile a dry unit-cell of water (L/D = 2) at Ca = 10^{-03} [Bajpai and Khandekar, 2012]

4.2 Thermally Induced Oscillations

This sequential exploration of local transport behavior is eventually to understand and model a thermally induced, self-sustained oscillation of a unit-cell. If such a unit-cell's performance be modeled and validated against experiment, then it provides meaningful gateway to extend the approach to design a PHP. In this spirit, recent experimental study of Rao et al. [2013] has demonstrated the transport behavior of such a unit-cell. Figure 10 depicts the schematic of their set up. Synchronization of pressure data and high-speed camera has paved way to better understanding of sequence of thermo-hydrodynamics of the system. Figure 11 shows the schematic of sequence of events that happens in a thermally induced, self-sustained unit-cell of Taylor bubble flows.

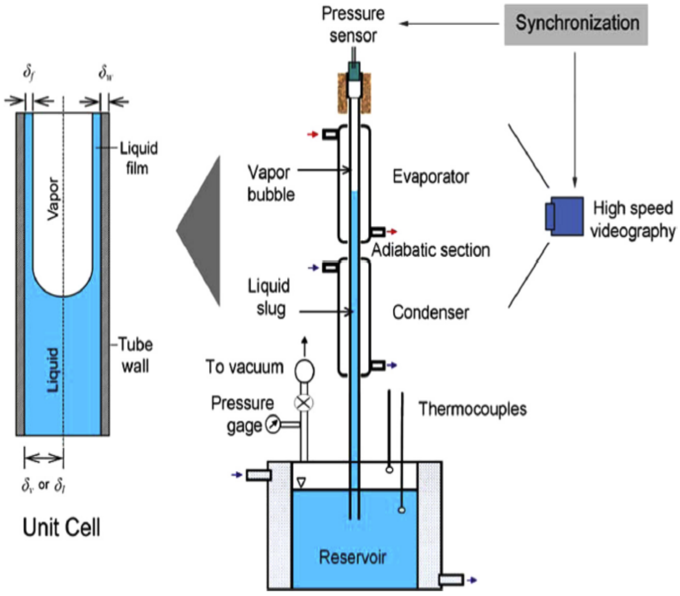

Fig-10: Schematic of experimental setup [Rao et al., 2013]

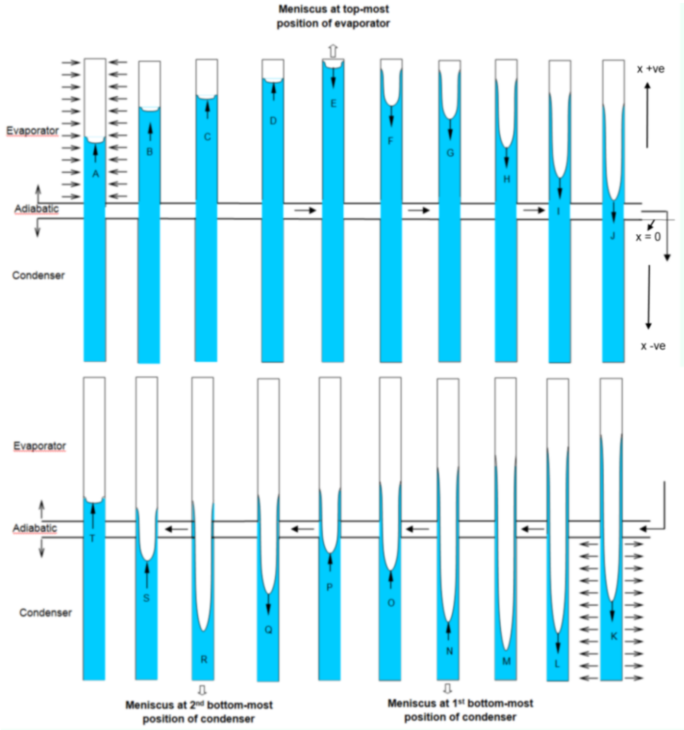

Fig-11: Temporal variation of pressure as the oscillating meniscus pass through different zone [Rao et al., 2013]

This study is exciting as it proposes a complete model, validated against the experiment, which can predict the performance of a unit-cell of PHP. This local study of thermally induced, self-sustained oscillating unit cell also reveals some intruding results on the transport behavior in a PHP, which was not thought of before. The study confirms the non-equilibrium conditions that prevail in the system. It also questions on the widely adapted way of modeling such system, which essentially treated the vapor as ideal gas. One startling observation was the fact that both evaporation and condensation can occur simultaneously and older models needs to be updated to include these effects.

5. CONCLUSION

The major reason for the failure of these global models can be attributed to the lack of understanding the local characteristic of a Taylor-bubble flow. Hence, to realize a practical global model, local thermo-hydrodynamic behavior of a unit-cell of Taylor bubble flow is essential. In this spirit, some of the recent experimental/simulation study done on a unit-cell of PHP was presented.

These recent studies on the study of local thermo-hydrodynamics of unit-cell have brought out tremendous amount of hidden physics, which were previously neglected in the global models. Some of the key observations, which need to be considered in global modeling, are:

- Effect of contact angle hysteresis on transport behavior of PHP.
- Resolving three-phase contact line motion on dry plug regimes, as these causes considerable frictional loss.
- Finding a model for thin film formation for oscillating menisci.
- Understanding the evaporation and condensation of slug-bubble system.

The power of local study of unit-cell is thus well demonstrated. This bottom-up approach has provided deep insight in understanding the physics of flow, which are not only relevant to the design of a PHP, but also to the vast area of research on mini/micro channel flows. Future direction of this local study of unit-cell is towards understanding the thermally induced instability of a unit-cell, which is very essential in context of PHP working. Also the existence of meta-stable, non-equilibrium conditions needs to be analyzed from this kind of study. A gradual buildup of this approach is to feed these local characteristic behaviors to improve on the global model.

The highlight of this unit-cell approach is that, it not only provides key updates required to the global models, but also brings out the richness of physics of multi-disciplinary aspects of two-phase flow in mini/micro channel involved. The future of this local unit-cell approach is exciting and can help resolve rich class of engineering applications, pertaining not only to those of PHP, but also those of lab-on-chips, micro-reactors, etc.

REFERENCES

[1] Akachi H., 1990, U. S. patent, Patent Number 921041.

[2] Akachi, H., Polášek, F., and Štulc, P., 1996, “Pulsating Heat Pipes,” Proceedings of 5th International Heat Pipe Symposium, Melbourne, Australia.

[3] Khandekar, S., 2004, “Thermo-Hydrodynamics of Closed Loop Pulsating Heat Pipes,” Doctoral dissertation, Universitaet Stuttgart, Germany.

[4] Vasiliev, L.L., 2005, “Heat Pipes in Modern Heat Exchangers,” Applied Thermal Engineering, 25, 1-19.

[5] Zhang, H., and Faghri, A., 2008, “Advances and Unsolved Issues in Pulsating Heat Pipes,” Heat Transfer Engineering, 29(1), 20-44.

[6] Khandekar, S., Panigrahi, P.K, Lefevre, F., Bonjour, J., 2010, “Local Hydrodynamics of Flow in a Pulsating Heat Pipe: a Review,” Frontiers in Heat Pipes, 1, 023003.

[7] Khandekar, S., Silwal, V., Bhatnagar, A., Sharma, P., 2010, “Global Effectiveness of Pulsating Heat Pipe Exchangers: Modeling and Experiments,” Frontiers in Heat Pipes, 1(3), 279-302

[8] Carey, V.P., 2007, Liquid-Vapor Phase-Change Phenomena, 2nd ed., Taylor and Francis.

[9] Fairbrother, F., and Stubbs, A.E., 1935, “The Bubble-Tube Method of Measurement,” Journal of Chemical Society, 1, 527-529.

[10] Taylor, G.I., 1961, “Deposition of a Viscous Fluid on the Wall of a Tube,” Journal of Fluid Mechanics, 10, 161-165.

[11] Bretherton, F.P., 1961, “The Motion of Long Bubbles in Tubes,” Journal of Fluid Mechanics, 10, 166-188.

[12] Thulasidas, T.C., Abraham, M.A., and Cerro, R.L., 1997, “Flow Patterns in Liquid Slugs during Bubble Train Flow inside Capillaries,” Chemical Engineering Science, 52(17), 2947-2962.

[13] Srinivasan, V., Sikarwar, B.S., Khandekar, S., 2013, “ Experimental and Simulation Study on Motion of an Isolated Liquid Plug Inside a Dry Circular Capillary,” Proceedings of 4th Micro/Nanoscale Heat and Mass Transfer Int. Conference, Hong Kong, China.

[14] Tripathi, A., Khandekar, S., and Panigrahi, P.K., 2010, “Oscillatory Contact Line Motion inside Capillaries,” Proceedings of 15th International Heat Pipe Conference, Clemson, USA.

[15] Bajpai, A.K., and Khandekar, S., 2012, “Thermal Transport Behavior of a Liquid Plug Moving Inside a Dry Capillary Tube,” Heat Pipe Science and Technology, 3(2-4), 97-124.

[16] Rao, M., Lefevre, F., Khandekar, S., Bonjour, J., 2013, “ Understanding Transport Mechanism of a Self-Sustained Thermally Driven Oscillating Two-Phase System in a Capillary Tube,” Int. J. of Heat and Mass Trasfer, 65, 451-459.