EXPERIMENTAL STUDY ON EVAPORATION OF A MOVING LIQUID PLUG INSIDE A HEATED DRY CAPILLARY TUBE

Victor Marty-Jourjon[a], Vyas Srinivasan[b,c,d], Peeyush P. Kulkarni[b,c,d], Sameer Khandekar[*,b,c,d]

[a] INSA-Lyon, F-69621, Villeurbanne, France
[b] Department of Mechanical Engineering
[c] Indian Institute of Technology Kanpur
[d] Kanpur (UP) 208016 India

[×] Corresponding author: Tel: +91 512 259 7038, Fax: +91 512 259 7408
Email: samkhan@iitk.ac.in

Abstract. The paper reports an experimental study to understand the effect of heat on an isolated liquid plug (methanol) of length L moving inside a long, dry, horizontal circular mini-channel (inside D = 1.5 mm). The plug (with specified range of L/D ratios) is pushed from rest by controlled injection of air from its one side, till a quasi-steady terminal plug velocity is achieved in the adiabatic section of the capillarity tube. It is then allowed to move through the heated section maintained at constant wall temperature. It is evident from the experiments that there is a significant increase of the plug velocity in the heated region, which can be attributed to the evaporation of liquid; this increases as the wall temperature increases. Also, it is observed that evaporation is not primarily from the bulk of liquid plug but from the thin film trailing behind it.

Keywords: Taylor liquid plug, Capillary plug flow, thin film evaporation, meniscus motion, terminal velocity, constant wall temperature

1 Introduction

The fundamental understanding of two-phase micro-/mini-channel flows (systems with Bo < 2) is one of the critical issues for the development of many emerging technologies. For example, it has been highlighted that such phase-change process in mini/micro systems are effective in passive thermal energy management in pulsating heat pipes, electronic cooling, lab-on-chip, PEM fuel cells etc. [3]. However, comprehensive understanding of such processes is limited, largely due to the simultaneous involvement of several coupled and complex transport issues such as contact line dynamics and its hysteresis, wettability, capillary instabilities, etc. In this background, this

adfa, p. 1, 2011.
© Springer-Verlag Berlin Heidelberg 2011

experimental study makes an attempt to understand the behavior of a single liquid plug of methanol (chosen due to its good volatility and moderate boiling point at atmospheric conditions) in a micro-/mini-channel when its motion is subjected to a constant wall temperature.

2 Experimental details and procedure

The experiment is conducted with a simple, horizontally placed transparent glass circular capillary tube of 1.5 mm I.D., shown in Fig. 1. As the system is very sensitive to containments, a thorough cleaning and drying procedure (with deionised water, methanol, and dry air) is carried out before each run, to have good reproducibility. A methanol liquid plug of known volume is placed inside the tube at the starting (pre-conditioning) adiabatic section (Fig. 1 (b)) and is forced to move inside the capillary tube by injecting air at known mass flow rate (25 mlph), pumped via a syringe pump, as shown in Fig. 1a. The pre-conditioning section is long enough to ensure that all methanol plugs reach the heated section with a terminal velocity (Fig. 1 (b)). A large reservoir is connected to the outlet of syringe pump, so as to make the volume of mass injection significantly larger than the volume of circular tube. This is done so that a known mass flow rate of air can be pushed quasi-statically at near constant volume and temperature. Besides, all the experiments were done at controlled ambient conditions. The set up is very sensitive to any variation of temperature. A 0-100 Pa range differential pressure transducer (Huba Control®; 699 series) is used to get pressure drop across the liquid plugs, while the high speed images (captured using Photoron® SA-3) are post-processed to estimate the change in plug length and its velocity during its passage through the capillary tube. To maintain constant wall temperature, a constant temperature water bath (Julabo® - F25) is used.

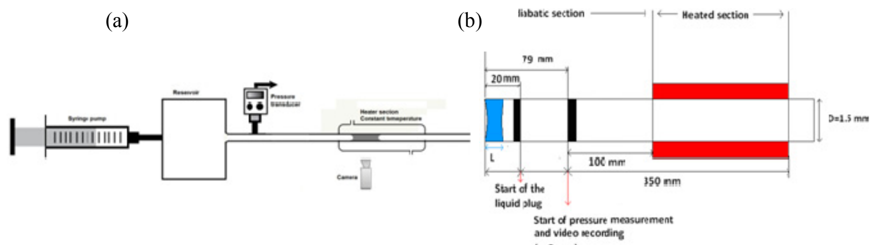

Fig. 1. (a) Schematic of the experimental setup **(b)** Zoom-in view of the capillary tube highlighting the adiabatic (pre-conditioning) and the diabatic sections.

3 Results and Discussions

The experiments are carried out for two different boundary conditions viz., fully adiabatic and diabatic. For both the cases, the variation of pressure, velocity and L/D with time are obtained.

(a) Adiabatic behaviour for different L/D

As can be seen from Fig. 2(a), the pressure seems to oscillate throughout the movement of the plug through the capillary. These oscillations can be attributed to the irregularities/contact line pinning on the inner capillary wall. Local pinning of three-phase contact line cannot be completely eliminated. It can be clearly observed that the pressure is almost independent of the liquid plug length and is due to surface forces dominance; this is in accordance with the observations made by Srinivasan et al. [4] which highlight the dominance of surface tension forces in contributing towards overall friction, as compared to viscous wall friction. There is only very minor change in the pressure with L/D. This observation is in line with the pressure variation curve where there is some amount of lag between each curve towards the end of the recording.

As the plug moves through the capillary tube its velocity intermittently varies. As noted earlier, these velocity estimates were made with the help of video recordings and their subsequent image processing. The velocity plot (Fig. 2(b)) for a good extent, is inline with the pressure variation (Fig. 2(a)). As can be seen, the velocity decreases just before an irregularity/pinning sets in due to an increase in friction, at the same time the pushing pressure increases.

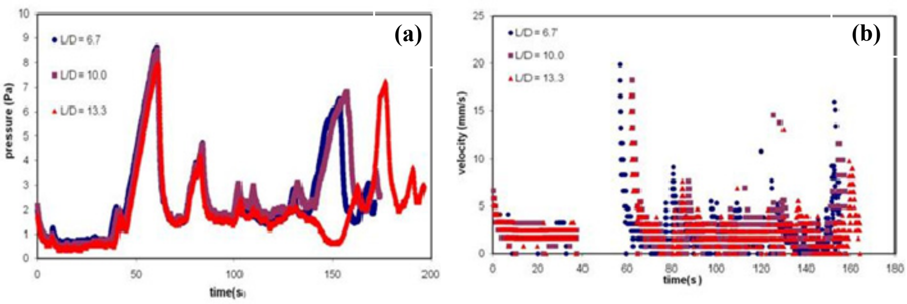

Fig. 2. (a) Pressure variation with time for different length of methanol plug at adiabatic condition. **(b)** Velocity variation under adiabatic condition. The discontinuity in the graph is due to strong influence of pinning.

Once, the plug has crossed the irregularity, there is a peak of velocity observed and correspondingly a sudden drop of pressure due to a sudden decrease in friction. The gap in the velocity plot around the 50 sec time interval is due to the non-availability of the video recordings because of gasket present at the physical joint. Incidently, in this gap region, the first major irregularity occurs which can be attributed to the roughness of the tube wall, which matches with the first significant rise in pressure (~ between 45 sec to 55 sec) on the pressure plot (Fig. 2(a)). As also seen in the pressure plot, there is an effect of increasing friction on the last peak of velocity where there is a little lag between each curve.

When liquid plugs moves through the capillary tube it can be seen that it leaves a thin layer of fluid on the surface, which leads to a decrease of length of the methanol cell (see Fig. 4). The classical papers of Taylor [5] and Bertherton [2] talk extensively on the thin film deposition. A more recent paper by Aussillous and Quere [1] provides new data on the quick deposition of fluid on the wall of a tube. Taylors formula is used by Bretherton [2] to calculate the thin film thickness (Eq. 2) depending of a dynamic Capillary number (Eq. 1), and thus, the theoretical decreasing of length shown in Fig. 3. For each L/D this decreasing of length seems to match well with the experimental data.

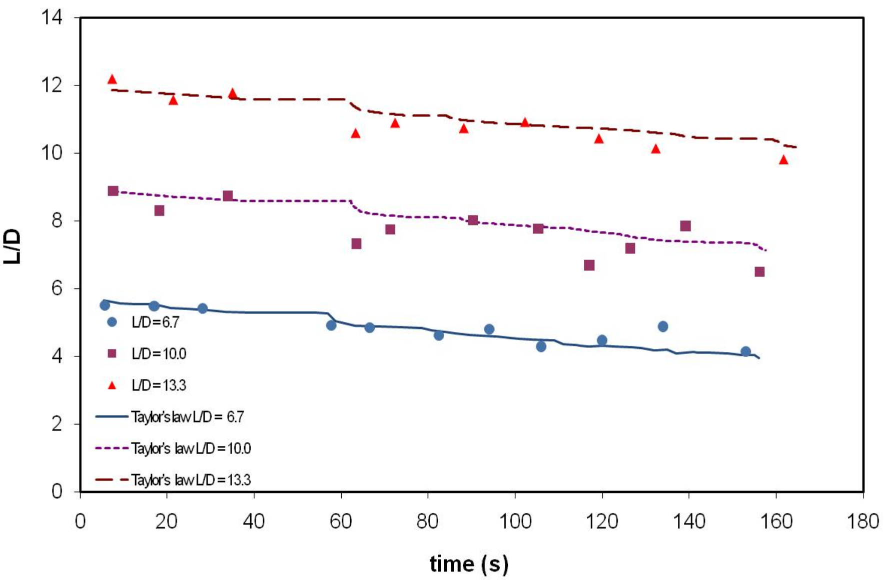

Fig. 3. Change of length with time due to drainage in form of thin film for different initial L/D ratios at adiabatic condition

Capillary number is defined as:

$$Ca = \frac{\mu \cdot v}{\sigma} \tag{1}$$

Once the Capillary number is known, the thickness of trailing thin film is calculated based on Taylor law [5] as:

$$\frac{h}{r} = \frac{1.34Ca^{2/3}}{1 + 1.34(2.5Ca)^{2/3}} \tag{2}$$

(b) Behaviour of a single liquid plug at different temperatures

The experiment was carried out with the application of constant wall temperature around the capillary tube. Under the effect of imposed boundary conditions there are interesting modifications of the pressure profile along the channel. The variation of pressure for L/D ratio = 6.7, at different wall temperature, is shown in Fig. 4(a).

The region of the curve corresponding to around 10 sec to 40 sec represents the adiabatic region, where there is no heat applied and it can be seen that the curves are almost similar. The region where the pressure starts to rise (~45 sec), corresponds to the beginning of the heated section which also matches with region of first mean irregularity. In either cases, for ΔT = 0 (adiabatic case) and T = 55°C, two main peaks can be identified. However, the time interval between the two peaks is not the same for both cases. Indeed, the time interval between the two peaks is approximately 100 sec for the adiabatic case and around 40 sec for wall temperature of 55°C.

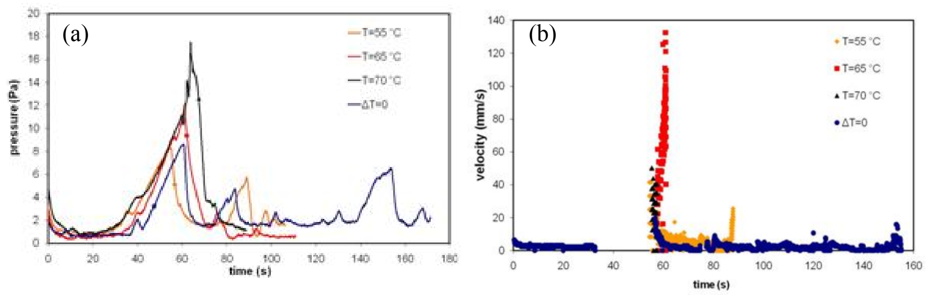

Fig. 4. (a) Gauge pressure vs. time for L/D = 6.7 at different wall temperatures **(b)** Variation of velocity with time for L/D = 6.7 at different wall temperature

An important implication of this difference is that the velocity of the methanol plug increases as it travels through the heated section. It is observed that this increase in velocity is higher, as the wall temperature is increased, which is dicernable from the reducing time intervals between the pressure peaks. However, it is difficult to identify the second peak for higher temperatures of 65°C and 70°C for which the plug attains a very large velocity and hence overcomes the irregularities in its path, thereby reducing the pinning tendency.

It is interesting to see the global evolution of velocity with time for the liquid plug corresponding to different temperatures. Fig. 4(b) shows the variation of velocity with time. At the beginning of the plug motion which corresponds to the adiabatic section, the velocity variation is same for different temperatures. But as the plug moves into the heater section, there is sudden increase in the velocity. Also, as identified in the pressure variation plot (Fig. 4(a)), the time interval between different velocity peaks for both the adiabatic and T = 55°C cases can be identified clearly. Besides, for all the readings corresponding to different temperatures, the last point on each curve corresponds to the same position in the channel. Thus, the variations of velocity lead to a delay at the end of the channel which is nearly 70 sec and 100 sec for T = 55°C and T = 70°C respectively.

For the wall temperature of 70°C, which is above the boiling point of methanol (~65°C) the video recording could not be done at the same position as at this temperature the creation of bubbles in the liquid plug is observed (Fig. 5) because of vigourous nucleate boiling.

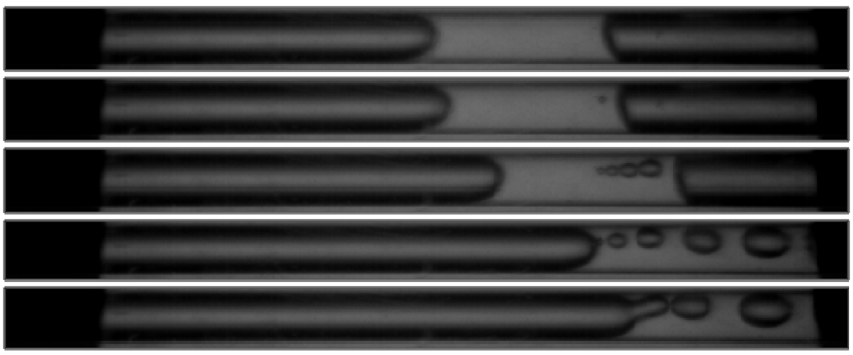

Fig. 5. Development of nucleation and bubble breakup at wall temperature of 70°C (boiling point of methanol at room conditions = 64.7°C)

The effect of increase of evaporation rate on increase of velocity can be clearly seen for higher wall temperature of T = 65°C. The velocity behaviour is totally different from lower wall temperatures. In fact the velocity does not drop after the irregularity but keeps on increasing further. For the wall temperature of 70°C, the beginning of the profile seems to be similar to the lower temperature readings, however as there is a rapid break-up of the plug so it does not allow the analysis to be carried at same location.

As the liquid plug moves through the heated section, its length decreases, the rate of decrease being higher temperatures. This change in length is plotted as function of time in Fig. 6. Except for T = 70 °C, the experimental values are compared with the values obtained by the Taylor's Law [5]. To calculate the values from Taylor's law, thermo-physical characteristics of methanol were taken at 33°C, 55°C and 65°C, assuming that the liquid plug temperature reaches these values instantly.

It can be seen that the experimental values match with the Taylor's Law values to a reasonable extent. It can be concluded that the decrease of plug length is because of evaporation via the film drainage route. In other words, evaporation rate from the bulk liquid plug is too small to affect the decrease of length of the liquid plug; the evaporation mainly occurs in the thin trailing film left behind the liquid plug. However, the wall temperature has an indirect significant effect on the reduced plug length as it affects the velocity, which in turn, affects the drainage.

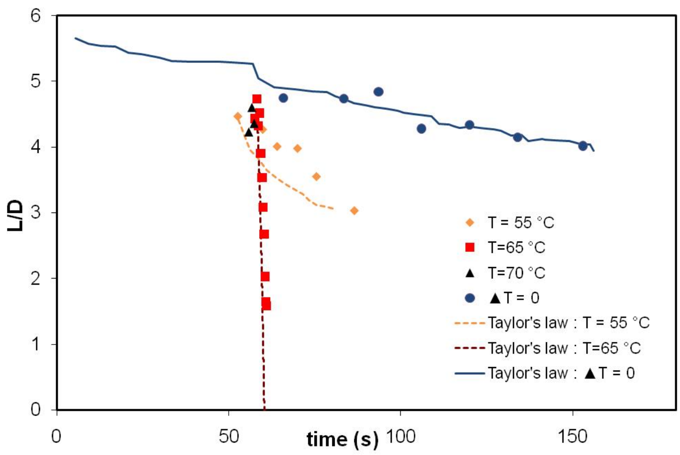

Fig. 6. Change in length of liquid plug (initial L/D = 6.7) with time for different wall temperatures.

4 SUMMARY AND CONCLUSIONS

Experiments were carried out to understand the hydrodynamics of a single liquid (methanol) plug inside a horizontal, dry, mini/micro circular tube. A single liquid plug of known L/D ratio is pushed from rest by controlled injection of air. The drainage of liquid film left behind was compared with the model of Aussillous and Quere [1]. It is demonstrated that under adiabatic conditions, the experimental data of change in length match with the theoretical predictions of Taylor. Also, it can be clearly observed that the pressure is almost independent of the liquid plug length, due to surface forces dominance which is in accordance with the observations made by Srinivasan. et al. [4].

The experiments imposing a constant wall temperature highlight that there is no significant direct effect of the evaporation rate on the decreasing of plug length. Indeed the experimental data still match with the Taylor's law which does not take into account evaporation rate. However, the velocity of the plug is markedly affected by the wall temperature, resulting in significant modification of the drainage rate visible in the Taylor's law. Finally, results show a very important indirect influence of the evaporation on the decreasing plug length. Thus, this evaporation seems to occur mainly in the drained thin film. Future, work involves scrutinizing the current finding and to study the effect of heat for different lengths of liquid plug and using different liquid.

5 References

1. Aussillous, P., and Quéré, D. (2000) Quick Deposition of a Fluid on the Wall of a Tube. Physics of Fluids 12:2367-2371.
2. Bretherton FP (1961) The Motion of Long Bubbles in Tubes. Journal of Fluid Mechanics 10:166-188.
3. Khandekar S, Panigrahi PK, Lefevre F, Bonjour J (2010) Local Hydrodynamics of Flow in a Pulsating Heat Pipe: a Review. Front. Heat Pipes 1:023003.
4. Srinivasan V. And Khandekar S. (2013) Motion of an Isolated Liquid Plug inside a Dry Circular Capillary. Proc. of 17th International Heat Pipe Conference (17th IHPC), India
5. Taylor G. (1961) Deposition of a Viscous Fluid on the Wall of a Tube. Journal of Fluid Mechanics 10:161.