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FLOW OF TAYLOR BUBBLE IN MICROCHANNEL HAVING AN OBSTACLE

Sudhakar Thippavathini
Graduate Student
Department of Mechanical Engineering
National Institute of Technology Rourkela
Rourkela, Odisha, India

Manoj Kumar Moharana
Assistant Professor
Department of Mechanical Engineering
National Institute of Technology Rourkela
Rourkela, Odisha, India
moharanam@nitrkl.ac.in

ABSTRACT

A novel concept of mixing based on 2-D numerical study is proposed where Taylor bubble flows past an obstacle inside a horizontal microchannel. A square shaped obstacle of size 0.02 × 0.02 mm^2 is considered inside a microchannel of diameter 0.2 mm. Water and air enters at the two inlet ends of a T-junction and creates Taylor bubble flow at the junction. The obstacle is placed in the downstream at a sufficient distance from the junction where air and water meet. This ensures stability of the Taylor bubble by the time it touches the obstacle. The position of the obstacle is varied along the perpendicular to the flow direction. First, the obstacle is placed exactly at the centre, thus providing equal space of 0.09 mm each on its either side. When Taylor bubble touches this obstacle, it splits and moves through both sides of the obstacle with perfect symmetric flow. The bubbles again join to form the original bubble as it moves past the obstacle. This is inline with the prior expectation. Next, the obstacle is moved by 0.02 mm away from the centre line towards one side, thus providing gap of 0.11 mm and 0.07 mm respectively on the two sides of the obstacle. Now it is found that when the bubble touches the obstacle it do not split in to two, rather the whole bubble moves through the bigger opening of 0.11 mm and only water flows through the smaller opening of 0.07 mm. Similar phenomena is observed when the bubble is further moved away from the centre line towards one side. The liquid-gas interface is found to be continuously changing its shape due to disturbance created by the presence of an obstacle. This causes turbulence inside the liquid plug between two consecutive bubbles, which is confirmed from velocity vector fields. This raises a hope to enhance heat and mass transfer in microchannels by placing multiple obstacles.

Keywords: Taylor bubble flow, microchannel, T-joint, obstacle, two-phase flow.

INTRODUCTION

When two immiscible fluids e.g. Liquid-gas flow inside a small channel with certain volume flow ratio, it results in taylor bubble flow. Taylor bubble flow is a liquid-gas flow pattern consisting of elongated bubbles separated by liquid slugs [1]. The bubbles normally completely or nearly completely fill the channel cross-section where as a very thin liquid film separates the gas bubble from the channel wall. Normally, taylor bubble flow is created by using a t-junction [2], y-junction [3], or a concentric passage [4] where gas and liquid flow through two inlet passages and meet inside the channel. Two phase flow in microchannels has wide range of applications in microscale heat transfer enhancement, biomedicine, microfiltration, and controlled drug delivery etc. To name a few.

Bubbles are formed and flow when gas at very low flow rate enters into a liquid flowing channel. On further increase in the gas flow rates such that diameter of the bubble exceeds the channel diameter, it results in elongated gas bubbles separated by liquid slugs, called Taylor bubble flow. The most commonly used microchannel geometry for creating Taylor bubble flow is a T-junction. Garstecki et al. [2] described the process of formation of bubbles in microfluidic T-junction geometries.

LITERATURE REVIEW

The earliest study of Taylor bubbles dates back to a century ago when Gibson [5] studied motion of air bubbles rising up in a vertical tube. Other historically significant works in this field include Fair brothers and Stubbs [6], Bretherton [7], Taylor [8] to name a few. Later on many researchers focused on understanding the hydrodynamics of Taylor bubble flow. With the emergence of micromanufacturing technology, many applications dealing with Taylor bubble flow emerged with time. This motivated researchers to relook at Taylor bubble flow in microchannel systems. Taylor bubble flow is predominantly found in small diameter channels where surface tension forces dominant the gravitational force.

Qian and Lawal [9] numerically studied Taylor flow in a microchannel, particularly on gas and liquid slugs using a T-junction empty microchannel with varying cross-sectional width (0.25, 0.5, 0.75, 1, 2 and 3 mm). The gas and liquid slug lengths at different operating and fluid conditions were obtained and found to be in line with existing literature. Several correlations in the T-junction microchannel were also developed based on the numerical simulation.

Santos and Kawaji [10] both numerically and experimentally studied gas-liquid two-phase flow in a microfluidic T-junction with nearly square microchannels of 113 μm hydraulic diameter. The prediction of slug flow through numerical simulation demonstrated that CFD codes can also accurately predict taylor flow in microchannels.

Pham et al. [11] numerically simulated gas-liquid flows in a T-junction microchannel using Volume-of-Fluid (VOF) model and predicted the distribution of velocity, pressure, and phase of fluid in the microchannel. They also analyzed the pressure distribution along the channel walls in order to understand the formation of microbubbles in the T-junction microchannel.

Majumder et al. [12] experimentally studied local thermal performance of square mini-channel during gas-liquid Taylor bubble flow with an objective to study the heat transfer enhancement due to Taylor bubble train flow, as compared to single phase thermally developing flows. They found that presence of bubble drastically changes the local temperature profiles and the Taylor bubble train regime increases the transport of heat up to 1.2-1.6 times compared to single-phase laminar flow. Secondly, it is found that the length of adjacent gas bubble and water plug also influence the local heat transfer enhancement.

The flow in microchannel systems is mostly laminar in nature due to very small hydraulic diameter and lower flow rate. Conventionally, turbulent flow causes mixing of fluids, and hence higher heat transfer. Wakes are formed as fluid flows past any structure, and creates turbulence. In recent times, pin fins are used as micro structures over plane microchannel wall to increase heat transfer surface area, and create mixing and turbulence; hence enhance heat transfer compared to plane rectangular microchannels. Kishimoto and Sasaki [13] used this concept to enhance heat transfer in microchannels where they used diamond shaped micro pin fins with staggered arrangement. Recently, Rubio-Jimenez et al. [14] proposed micro pin fin heat sink with variable fin density in order to gradually increase the heat transfer coefficient while maintaining uniform surface temperature.

Taylor flow enhances heat and/or mass transfer due to internal circulation inside the liquid plugs [15]. But once the Taylor bubble is formed, it hardly changes its shape when it flows through a straight horizontal microchannel. The work by Manjumder et al. [12], Kishimoto and Sasaki [13], and Rubio-Jimenez et al. [14], and Thulasidas et al. [15] motivated to consider combining the concept of pin-fin with Taylor bubble flow and verify the thermal performance characteristics of microchannels under such condition. Under this background a numerical study is undertaken to study hydrodynamics of Taylor bubble as it flows past an obstacle placed inside a microchannel. In this work an obstacle (square in shape) is placed inside the microchannel with an expectation to create disturbance to the gas-fluid interface of Taylor bubble and thus affect the flow pattern. The effect of the obstacle positions (along the cross sectional area of the microchannel) on the flow pattern has been studied.

SUMMARY AND CONCLUSION

A novel concept of mixing and turbulence in microchannel is proposed where Taylor bubble (due to air-water flow) flows past an obstacle inside a horizontal microchannel. A numerical study has been carried out to understand the effect of an obstacle, at different positions along the cross section, on the Taylor bubble flow in micro channel. The flow is laminar, water velocity and gas velocity at inlet is 0.251m/s and 0.073m/s respectively. The result shows that the bubble always try to move to the maximum cross sectional area and doesn’t split unless the cross sectional areas are same.

A two-dimensional numerical study has been carried out to understand the hydrodynamics of a Taylor bubble as it flows past an obstacle positioned inside a horizontal microchannel. An obstacle square in shape, of each side 0.02 mm is used while the microchannel diameter is 0.2 mm. Water and air enters through the main channel and the transverse channel inlet which are horizontal and vertical respectively. The T-joint creates Taylor bubble at the junction and it flows through the downward channel. The obstacle is placed sufficiently away from the junction to ensure stability of the Taylor bubble by the time it touches the obstacle. The position of the obstacle is varied at right angles to the flow direction by considering its centre’s distance y from the right wall. First, the obstacle is placed exactly at the centre, where equal space (0.09 mm) is provided on both left and the right side of the obstacle. Taylor bubble touches the obstacle at the tip of the front meniscus and splits in to two, and moves through both sides of the obstacle with perfect symmetric flow. The bubbles again join to form the original bubble as it moves past the obstacle. Next, the obstacle is moved by 0.02 mm away from the centre line towards the right, thus providing a gap of 0.11 mm and 0.07 mm respectively on the left and the right sides of the obstacle. Now it is found that when the bubble touches the obstacle it moves through the bigger opening of 0.11 mm only and water flows through the smaller opening of 0.07 mm only. Unlike previous case, in this case no split in the bubble is observed. Similar phenomena are observed when the obstacle is further moved away from the centre line towards one side. The water-air interface is found to be continuously changing its shape due to disturbance created by the presence of an obstacle. This creates turbulence inside the liquid plug. This increases anticipation to enhance heat and mass transfer in microchannel systems by placing multiple obstacles.

NOMENCLATURE

C	Courant number, (-)
Ca	Capillary number, (-)

$\vec{F}$	Surface tension force of the fluid, N/m^2
p	Pressure force, N/m^2
R	Channel radius, m
t	Time, sec

Greek symbol

δ	Liquid film thickness between wall and bubble, m
μ	Dynamic viscosity, N·s/m^2
ρ	Density, kg/m^3
σ	Coefficient of surface tension, N/m
$\vec{v}$	Velocity vector, m/s
Ω	Volume fraction, (-)
Δt	Time step size , sec
Δx	Length interval, m

Subscript

L	liquid
G	Gas

Superscript

T	Transpose

REFERENCES

1. Angeli, P., and Gavriilidis, A., 2008, “Taylor flow in microchannels,” In: Li, D., (ed.) Encyclopedia of Microfluidics and Nanofluidics. (1971 - 1976). Springer: New York.
2. Garstecki, P., Fuerstman, M. J., Stone, H. A., and Whitesides, G. M., 2006, “Formation of droplets and bubbles in a microfluidic T – junction - scaling and mechanism of break-up,” Lab on a Chip, 6, pp. 437-446.
3. Yue, J., Luo, L., Gonthier, Y., Chen, G., and Yuan, Q., 2008, “An experimental investigation of gas-liquid two-phase flow in single microchannel contactors,” Chemical Engg. Science, 63(16), pp. 4189-4202.
4. Salman, W., Gavriilidis, A., and Angeli, P., 2006, “On the formation of Taylor bubbles in small tubes,” Chemical Engg. Science, 61, pp. 6653-6666.
5. Gibson, A. H., 1913, “On the motion of long air-bubbles in a vertical tube,” Philosophical Magazine Series 6, 26(156), pp. 952-965.
6. Fairbrother, F., and Stubbs, A. E., 1935, “Studies in electro-endosmosis. Part VI. The “bubble-tube” method of measurement,” J. Chem. Soc., 1, pp. 527–529.
7. Bretherton, F. P., 1961, “The motion of long bubbles in tubes,” J. Fluid Mech., 10, pp. 166-188.
8. Taylor, G. I., 1961, “Deposition of a viscous fluid on the wall of a tube,” J. Fluid Mech., 10, pp. 161-165.
9. Qian, D., and Lawal, A., 2006, “Numerical study on gas and liquid slugs for Taylor flow in a T-junction micro channel,” Chemical Engg. Science 61, pp. 7609-7625.
10. Santos, R. M., and Kawaji, M., 2010, “Numerical modeling and experimental investigation of gas-liquid slug formation in a microchannel T-junction,” Int. J. Multiphase Flow, 36, pp. 314-323.
11. Pham, H., Wen, L., and Zhang, H., 2012 “Numerical simulation and analysis of gas-liquid flow in a T-junction microchannel,” Adv. Mech. Engg., pp. 1-8.

12. Majumder, A., Mehta, B., and Khandekar, S., 2013, "Local Nusselt number enhancement during gas-liquid Taylor bubble flow in a square mini-channel: An experimental study," Int. J. Thermal Science, 66, pp. 8-18.
13. Kishimoto, T., and Sasaki S., 1987, "Cooling characteristics of diamond-shaped interrupted cooling fin for high-power LSI devices," Electronic Letters, 23(9), pp. 456-457.
14. Rubio-Jimenez, C. A., Kandlikar, S. G., and Hernandez-Guerrero, A., 2012, "Numerical analysis of novel micro pin fin heat sink with variable fin density," IEEE Trans. Components, Packaging Mfg. Tech., 2(5), pp. 825-833.
15. Thulasidas, T. C., Abraham, M. A., and Cerro, R. L., 1997, "Flow patterns in liquid slugs during bubble-train flow inside capillaries," Chemical Engg. Science, 52(17), pp. 2947-2962.
16. Gupta, R., Fletcher, D. F., and Haynes, B. S., 2009, "On the CFD modelling of Taylor flow in microchannels," Chemical Engg. Science, 64(12), pp. 2941-2950.
17. Bretherton, F. P., 1961, "The motion of long bubbles in tubes," J. Fluid Mechanics, 10(2), pp 166-188.
18. Zaloha, P., Kristal, J., Jiricny, V., Völkel, N., Xuereb, C., and Aubin, J., 2012, "Characteristics of liquid slugs in gas–liquid Taylor flow in microchannels," Chemical Engg. Science, 68(1), pp. 640-649.
19. Abadie, T., Xuereb, C., Legendre, D., and Aubin, J., 2013, "Mixing and recirculation characteristics of gas–liquid Taylor flow in microreactors," Chemical Engg. Research Design, 91(11), pp. 2225-2234.
20. Abiev, R. S., 2013, "Bubbles velocity, Taylor circulation rate and mass transfer model for slug flow in milli- and microchannels," Chemical Engg. J., 227, pp. 66-79.
21. Mehta, B., Khandekar, S., 2014, "Measurement of local heat transfer coefficient during gas–liquid Taylor bubble train flow by infra-red thermography," Int. J. Heat Fluid Flow, 45, pp. 41-52.