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Two-phase flow and heat transfer through wavy microchannel

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--***ABSTRACT***--

In the Present paper, numerical simulations have been carried out on two-phase fluid flow and heat transfer in plain and wavy circular microchannels of diameter 100microns and length of 30D. Microchannel is divided into two sections of cold and hot sections. Two immiscible fluids water and mineral oil are considered as primary and secondary fluids. In the plain circular microchannel, droplet shape is constant when it the flow is fully developed, whereas in wavy channels because of uneven surface, the droplet shape is continuously changes. This will increase the pressure drop in the wavy microchannel. The droplet shape, pressure distribution along axis and channel wall have been also discussed for plain and wavy circular channels. To study heat transfer characteristics a constant wall temperature of 65.15 0C is applied to heating section. Results shows that two-phase in wavy channel enhance the Nussent number up to 130% in comparison with liquid only flow and up to 6% augmentation in comparison with two-phase flow in plain circular microchannel.

KEYWORDS; -*Two-phase flow, wavy channel, pressure drop and heat transfer*

I. INTRODUCTION

Microchannels has widely used in many industrial applications like lab-on-chip, heat exchangers, micro-reactors, and micro electro mechanical systems. Earlier, single phase heat transfer used for heat removal in microchannels, but it is limited to low heat fluxes. To remove the higher heat fluxes two-phase flows are introduced. Different multiphase flow regimes are developed when two immiscible fluids are forced into a microchannel at various flow rates [1]. Generally Slug or Taylor flow regime is generates in microchannels as the surface tension forces dominate over the gravitational forces.

In the two-phase Taylor flow regime, secondary phase fluid (gas/liquid) is separated by primary phase liquid slugs and a thin liquid film separates the secondary phase from the channel wall. Internal recirculation in the primary liquid slug and higher local fluid velocity in the secondary fluid significantly improves the heat and mass transfer rates in the two-phase Taylor flow compared with single-phase flow [2]. In the gas-liquid Taylor flow heat transfer process, the role of gas phase is negligible because of its low thermo-physical properties. By replacing gas bubble with an immiscible liquid droplet helps increases the heat transfer performance in two-phase flows. Liquid-liquid slug flows are widely used various in applications, such as in micro separation [3], Nitration of benzene to toluene [4], polymerase chain reaction [5], and electronics cooling [6].

Numerous experimental and numerical studies have been reported by researchers to understand the hydrodynamics and thermal behavior of Two-phase slug flows. Internal circulations within the liquid slugs were observed using Particle Image Velocimetry (PIV) technique [7] and these internal circulations improve the Nu of liquid-liquid slug flow by four times over the liquid-only flow [6]. Local Nu of liquid-liquid Taylor flows increases with increase in slug length and it decreasing with increase in liquid film thickness between wall and secondary fluid interface [8]. Based on numerical and experimental studies a correlation was developed to predict the heat transfer in two-phase Taylor flows [9].

The flow and heat transfer rates are examined numerically in 3D wavy rectangular microchannels in a Re range of 100-800 [10]. Along the wavy walls, vortices developing and contribute to heat transfer augmentation as a penalty small pressure drop increases. The experimental study[11] explored the flow and heat transfer behaviour in a wavy microchannel both experimental and numerically at low Re range (10-100) and reveals that heat transfer improved up to 26% as compared to plain microchannels. The flow patterns and pressure drops of two-phase flows in a wavy channel experimentally investigated by varying phase shifts between the side walls of 0^0, 90^0 and 180^0 [12], but the slug flow exist only in the range of 0^0 and 90^0 phase shifts. Based on the literature, it is found that two-phase in microchannel widely studied in uniform surface channels by varying slug flow variables. Outcomes of single-phase flows inside wavy channels revealed higher heat transfer rate over uniform microchannels and only few studies found on flow patterns using two phase flow. The present work investigates the two-phase Taylor flow and thermal behavior inside plain and wavy circular microchannel.

II. NUMERICAL MODELLING

A commercial computational package, ANSYS Fluent has been used to study the liquid-liquid Taylor flow and heat transfer performance in the microchannels. In the present study, simulations are performed for two types of geometries i.e. plain and wavy circular microchannel. Two immiscible fluids, water and mineral oil are considered as working fluids and the properties of fluids are shown in Table 1. The governing equations of flow, energy, volume fraction and surface tension model [13] are solved by present numerical model are adopted from literature [14].

2.1. Computational domain and boundary conditions

A two-dimensional, axisymmetric (x-r), laminar, incompressible liquid-liquid Taylor flow is modelled in a plain circular microchannel is shown in Fig. 1. The length of microchannel is 3000microns and having the diameter of 100microns. At the inlet boundary 0.22m/s velocity and at the outlet of the channel 0 Pa pressure is considered. The microchannel length has divided into two sections with low and high temperature sections, so that only a hydro-dynamically developed liquid-liquid Taylor flow can entered into the heating region. The length of 10D (1000microns) allotted for Taylor flow to be developed with a wall temperature of 23 ^{0}C and heating region of 20D is maintained with a temperature of 63.15 ^{0}C. Wavy microchannel is modelled with same dimensions of plain microchannel, where the heating section walls having the wavy surface. Amplitude and wavelengths of wavy surface are 2microns and 200 microns, wavy surface of the channel is shown in in fig. 2. The length of slug and droplet are considered as 280 microns and 115 microns [14].

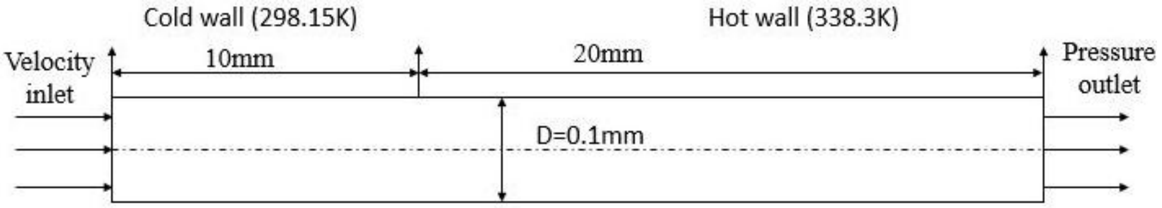


Figure 1: Schematic diagram of the computational domain

Table 1Properties of the working fluids

Material	Density [kg/m3]	Specific heat [J/kg K]	Thermal conductivity [W/m K]	Viscosity [Kg/m s]
Water	998	4182	0.6	0.001003
Mineral oil	838	1670	0.17	0.023

2.2. Differencing schemes

The governing equations were solved in ANSYS Fluent solver employing a finite volume technique. The liquid-liquid interface is captured by using VOF model. To solve the VOF equation an explicit geometric reconstruction scheme adopted with the highest courant number ($Co = \Delta t.U/\Delta x$) of 0.25. The first-order non-iterative fractional step method was used for solving the transient terms. Pressure Poisson equation solved by body force weighted scheme, and the QUICK scheme used for discretizing the momentum and energy equations.

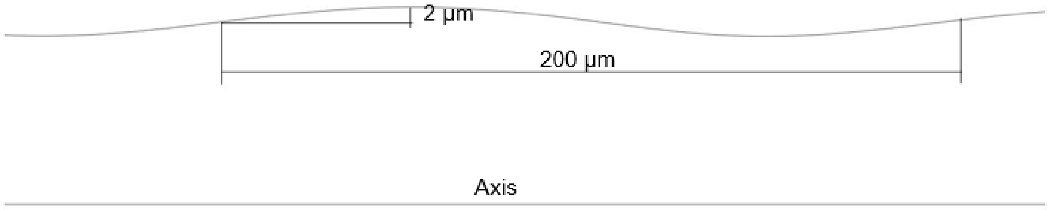


Figure 2: Design parameters of wavy surface

III. RESULTS AND DISCUSSION

3. 1. Grid independence test

Mesh has to be refined near the channel wall to capture thin film between the channel wall and the droplet interface during two-phase Taylor flows [15]. The computation domain was discretized with a uniform square elements of size 2 μm as shown in Fig 3. Droplet volume fraction and the velocity distribution (between the two droplets) along the radial direction are validated with available literature [14] are shown in fig. 4.

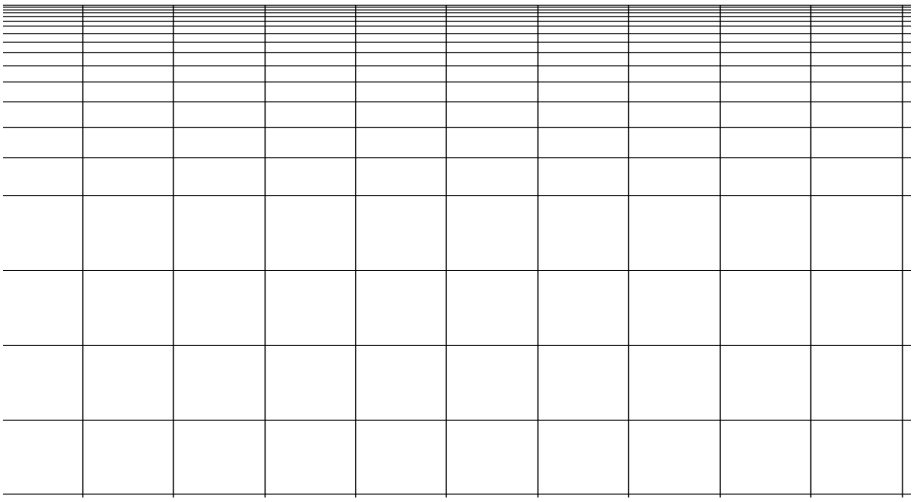
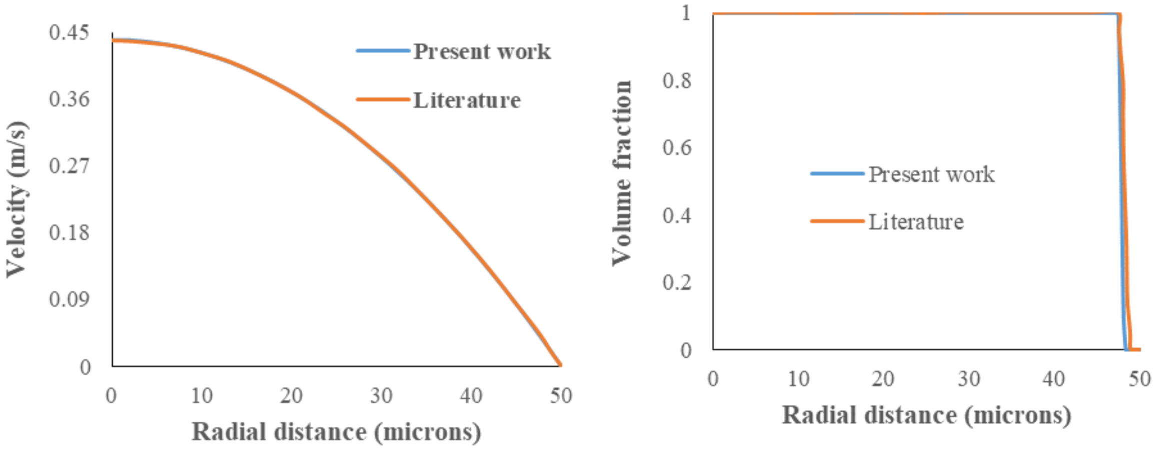


Figure 3: Computational mesh



(a) **(b)**

Figure 4: Velocity distribution and volume fraction comparison with the literature results [14]

Continuous droplet generation in the plain (a&b) and wavy (c&d) microchannels at different time steps shown in fig. 5. The dimensions of droplet and slug lengths are considered as 115microns and 280microns. In the fig. 5 red indicates the droplet and blue color indicates liquid slug. It is well known that in planar microchannels the thickness of film between the secondary fluid interface and channel wall is constant. In wavy channels the film thickness is not same as plain channel, film thickness is maximum at crest and minimum at root of wavy channel. Which affects the droplet shape and thermal behavior of the two-phase flow. The close view of droplet volume fraction in plain and wavy microchannels is shown in Fig.6. From fig. 6(a) &6(b) it's clear that droplet length in wavy microchannel slightly increased as compared to plain microchannel. Fig 6(c) and Fig 6(d) are shows the droplet volume fraction in the wavy circular microchannel at root and crest respectively. At the root the droplet length slightly increases because of reduction radial length and the droplet length slightly decreases at crest due to increasing radial length.

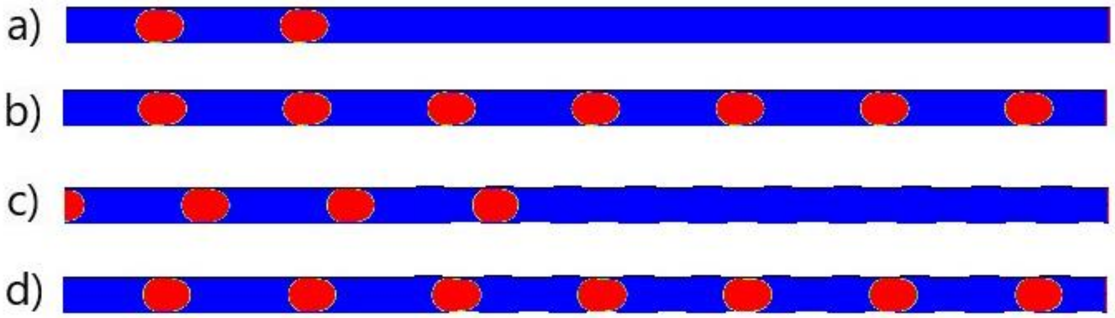
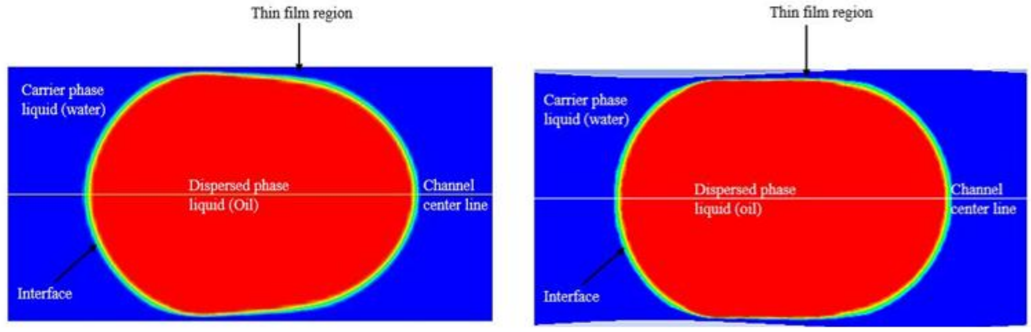
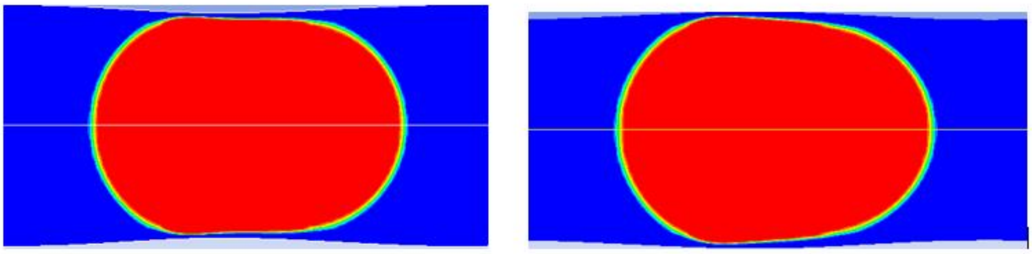


Figure 5:Droplet generation in plain and wavy microchannels at different time steps



a) Oil volume fraction contour in plain circular channel b) Oil volume fraction contour in wavy circular channel



c) Oil volume fraction contour at root d) Oil volume fraction contour at crest

Figure 6: droplet (mineral oil) volume fraction in plain and wavy microchannels

3.2. Axis and wall pressure variation

The wall pressure distribution in the plain and wavy channel wall along the axial direction in a unit cell (one slug and one droplet) is shown in fig.7. The pressure gradient is stable in the liquid slug zone i.e., pressure fluctuates linearly similar to fully-developed, single-phase flow. In the droplet zone, the wall pressure drops and reaches least at the point where the film thickness is minimum. In the constant film thickness region the pressure is sharply increases, then at the nose of the droplet, pressure decreases and follows the single phase fully developed pressure drop profile. In constant thin film region the maximum pressure is observed when droplet reaches to root of wavy microchannel, at the root film thickness is decreases so that pressure increases.

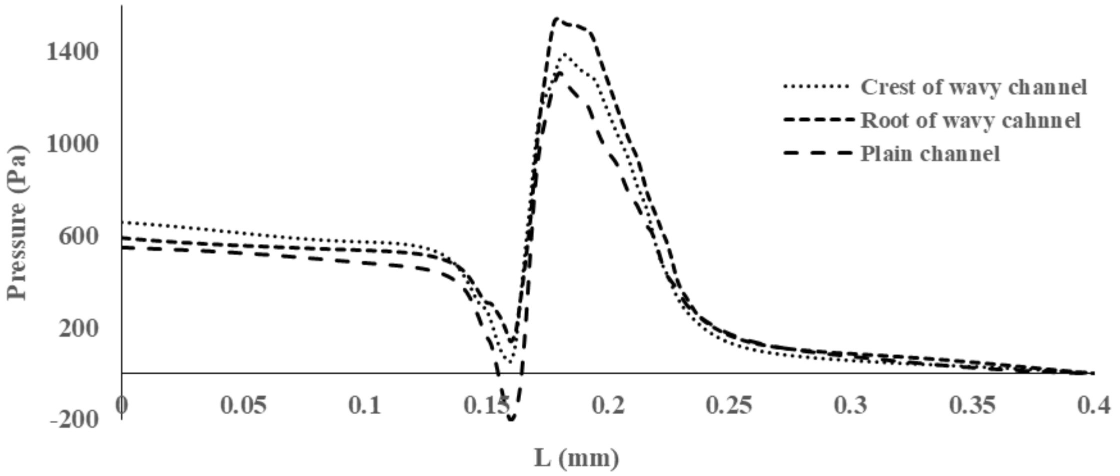


Figure 7: Wall pressure variation along the axial direction in a unit cell

The axis pressure drop in liquid-liquid Taylor phase flow is due to frictional and interfacial pressure drop. Fig. 8 shows the axis pressure distribution along the axial direction in a unit cell for plain and wavy channels. At the tail of the droplet, pressure rises on the axis as a result of the Laplace pressure distinction and at the nose of droplet, pressure deceases

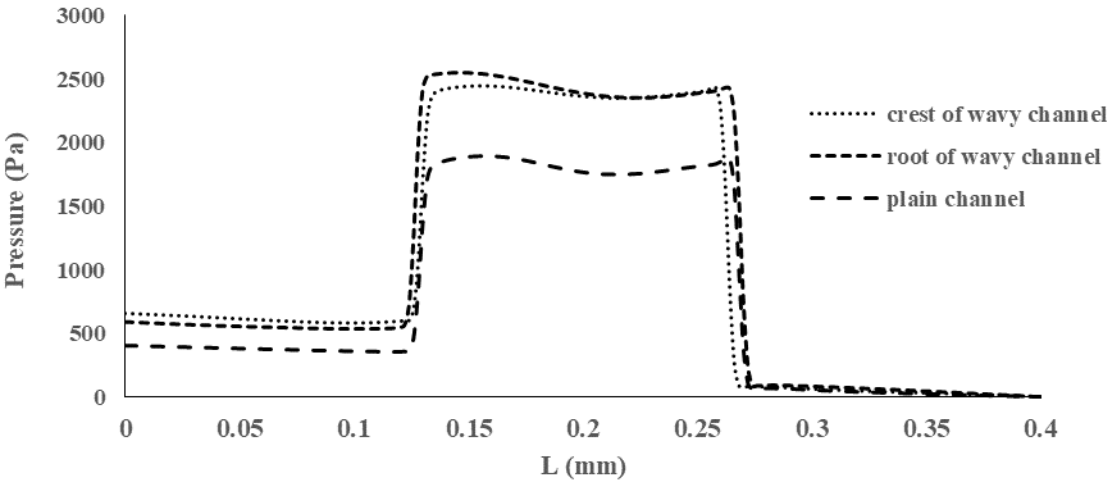


Figure 8: Axis pressure variation along the axial direction in a unit cell

3.2. Heat Transfer characteristics

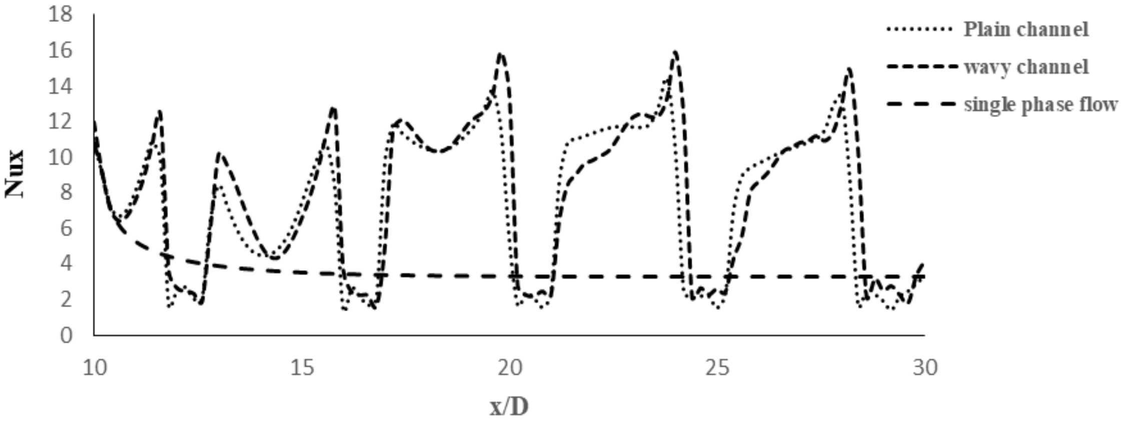
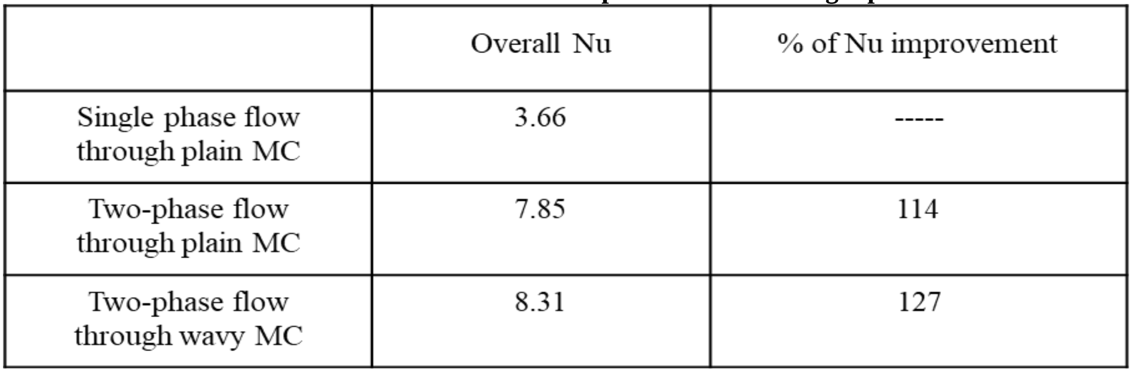


Figure 9: Local Nusselt number variation along axial direction

Constant wall temperature boundary condition has been applied to circular microchannel to investigate heat transfer through microchannel. The detailed procedure was explained in literature [6] to estimate the heat transfer characteristics in the microchannel under isothermal boundary condition. Fig. 9 shows the local Nu variation for single-phase, two phase flow inside plain microchannel and wavy microchannel. As we can see that Nusselt number of single-phase flow asymptotes towards theoretical Nusselt number value (3.66) of circular channel with isothermal boundary condition. Recirculation within the liquid slugs and droplets improves the heat transfer rate in two-phase flows. Wavy microchannels were successfully employed in single phase flow to improve the thermal performance of heat sinks, with two phase flows also heat transfer augmentation is observed. The overall two-phase flow Nusselt number with plain microchannel and wavy circular channel are found as 7.85 and 8.31.The Nusselt number of two-phase has been improved up to 130% with wavy microchannel over the single-phase flow and 6% with two phase flow through plain microchannel. The overall and % of Nusselt number of two-phase flow improvement over single-phase flow has been shown in Table 2.

Table 2: Overall and % of Nusselt number improvement over Single-phase flow



	Overall Nu	% of Nu improvement
Single phase flow through plain MC	3.66	-----
Two-phase flow through plain MC	7.85	114
Two-phase flow through wavy MC	8.31	127

IV. CONCLUSION

Numerical instigation of two dimensional liquid-liquid Taylor flow and heat transfer characteristics are carried out on plain and wavy circular microchannels using a commercial software package Ansys 15.0. VOF method is employed to capture the liquid slug and droplet interface. In the plain microchannel the film thickness is constant throughout the channel, where as in wavy channels thin film is varying because of uneven surface of the channel. The variation in the radial dimensions, slightly increases the film thickness at the crest and at the root slightly decreases as compared to plain channel, which also affects the droplet length. The wall and axis pressure distributions with a unit cell are studied, more pressure drop is observed at the root of wavy channel due to minimum film thickness. The heat transfer performance also studied in plain and wavy microchannel under isothermal boundary condition, overall Nusselt number increases up to 130% with wavy channel as compared to single phase flow and increases up to 6% compared to two-phase flow in plain circular microchannel.

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