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Numerical prediction of heat transfer and fluid flow characteristics in a circular microchannel with Bifurcation plate

Valaparla Ranjith Kumar[1,*], Karthik Balasubramanian[1], K Kiran Kumar[1],

[1]*National Institute of Technology, Warangal, Telangana, India-506004*

[*]*Corresponding author's email address: valaparlaranjith@gmail.com*

Abstract:

In this paper heat transfer and fluid flow characteristic in circular wavy microchannels (MCs) with bifurcation was numerically studied and compared its hydrothermal performance with sinusoidal wavy MC. The numerical investigations were carried in the Reynolds number range of 100 to 300 with constant heat flux wall boundary condition. It is observed that, as fluid flows through the circular wavy MC, continuously absorbing heat from the channel and the temperature difference between the channel and the fluid is decreased. Hence, heat dissipation along the channel length is decreased. To enhance the heat transfer along the flow direction in circular wavy MC, introduced the bifurcation plate in the middle of the channel. The parametric study on bifurcation plate length was also conducted. It is identified that in circular wavy MC with bifurcation plate length 12.5mm gives the higher Nusselt number with a smaller pressure drop penalty. Nusselt number is further increased by providing slots on bifurcation plate.

***Keywords*:** Circular wavy microchannel; bifurcation plate; single-phase liquid cooling; electronic cooling.

1. Introduction

Due to the rapid development of technology and the miniaturization of electronic devices, various traditional cooling technologies have been unable to meet the required cooling effect. Thermal management of these electronic devices plays a major role in the effective working of these devices. For the thermal management of these electronic devices, an innovative cooling technology i.e. Microchannel heat sink cooling technology was first proposed and developed by Tuckerman and Pease in 1981 [1]. Satish G. Kandlikar et al. in their review[2]studied various cooling technologies (air cooling, water cooling) that had been adapted to cool the high heat flux integrated circuit chips. They discussed its merits, demerits, fouling considerations, manufacturing technologies and cost. Their review found that air-cooling technology has low heat removal capacity and requires high input pumping power due to low specific heat and high specific volume of air. They also discussed the need for microchannels and performance enhancement techniques such as microstructures within the channels and microstructures within the microchannel walls. Karathanassis.I.K. et al.[3]numerically investigated the hydro-thermal performance of MCs with stepwise varying width. The common observations from all their work were: compared to a fixed-width microchannel configuration, variable-width design exhibit the superior overall performance. The possible reasons for this augmentation are (i) the rate of heat transfer is enhanced due to the increase of heat transfer areas in second heat sink section and also due to the formation of longitudinal vortices (ii) the pressure drop is minimal due to the presence of wider channels in the first sink section and fewer friction surfaces.

Gongnan Xie et al.[4] numerically investigated the heat transfer and fluid flow characteristics of straight microchannels with integrated internal vertical Y-shaped bifurcation plates having different lengths (10mm,15mm and 25mm) and different angles (60^0, 90^0,120^0,150^0 and 180^0) of the arms. They concluded that 25 mm internally Y-shaped bifurcation microchannel has higher heat transfer performance with the same pumping power than other geometries. The thermal resistance of 25 mm internal Y-shaped bifurcation microchannel was found to decrease by 41.02% compared with straight microchannels. It is due to the re-initialization of the boundary layer in internal Y-shaped bifurcation microchannel. In their study, they observed that microchannels with integrated internal vertical Y-shaped bifurcation plates with an arm angle of 180^0 gives 10% lower thermal resistance than other geometries considered, with the same pumping power. Y. Sui et al.[5]numerically investigated the heat transfer performance and fluid flow behaviour in a wavy microchannel by changing the relative waviness. They reported that heat transfer performances of wavy microchannels were better than that of straight microchannels with a smaller increase in pressure drop penalty. Z.L.Chiam et al.[6]numerically studied the heat transfer and fluid flow characteristics of wavy microchannels by introducing secondary branched channels, at every crest and trough, which are at 45^o to the channel axis. They also studied the overall performance factor at full amplitude (0.45mm) and half amplitude (0.225mm). They concluded that wavy microchannel with 45^o branched secondary channel results in higher heat transfer and lower pressure drop at lower Reynolds number(<100) and higher pressure drop at higher Reynolds number(>100). They also concluded that wavy microchannel with 45^o branched secondary channel with half amplitude results higher has higher overall performance factor than full amplitude in all Reynolds number in their study. W.R. Dean[7] first made a theoretical prediction of secondary flow caused by centrifugal force while the fluid flows through curved passages. Fluid at the outer the wall experiences higher centrifugal force than the fluid at inner wall. As a result, the pressure becomes maximum at the outer wall and minimum at the inner wall. To balance such centrifugal force, a pressure gradient is required across the channel. This pressure gradient leads to a secondary flow in the form of counter-rotating roll cells pair known as Dean's Vortices.

By conducting, the above literature survey of various numerical and experimental studies, it is observed that in wavy microchannel Dean's Vortices strength varying from crest to trough. As the fluid flows from the inlet to outlet through the microchannel, the temperature difference between the fluid and channel was decreased. To addresses, these issues, in this work introduced circular wavy MC, circular wavy MC with bifurcation plate (BFP) and circular wavy MC with BFP with slots in BFP are proposed and compared their hydrothermal characteristics with sinusoidal wavy MC.

2. Microchannel model and mathematical formulation:

Fig.1 shows the circular wavy MC with a sectional view and circular wavy MC with bifurcation plate was used for this present investigation. The geometrical models were created in SOLID WORKS modelling software by using the equation $y = Acos\,(2\pi x/L)$ and in circular wavy MC fluid domain was created by the circular profile for the total length of the heat sink. The created model is imported into ANSYS fluent and meshing of the simulation domains is done in ANSYS Mesh. Channel substrate height and width are 1.2mm and 0.6mm and channel passage dimensions are half of its value. In circular wavy MC with bifurcation plate (BFP), a thin fin with a thickness and height of 0.1mm and 0.6mm was introduced in the middle of the channel. Bifurcation plate length varying from the outlet in the range of 7.5mm to 12.5mm in the steps of 2.5mm.

The Navier-Stokes and energy equations are solved to analyze the hydrothermal performance of wavy MC by considering the following assumptions: (I) Fluid flow is laminar in nature. (ii) Heat transfer and fluid flow are in steady state. (iii) Fluid is incompressible and without phase change (iv) Thermophysical properties of water and MC material are temperature independent. (v) The fin tip of the MC heatsink is perfectly adiabatic and uniform heat flux is applied in the bottom heat flux wall.

Taking into account the temperature rise of the fluid along the channel length, the dynamic viscosity was considered to vary based on the following equation[8].

$$\mu(\mathrm{T}) = 2.414 \times 10^{-5} \times 10^{(247.8/(T-140))}$$

where μ is the dynamic viscosity of fluid and T is the temperature of the fluid in Kelvin (K). The variation in all other properties was seen to be insignificant for the temperature variation of the fluid along the channel length. Hence they were assumed to be constant.

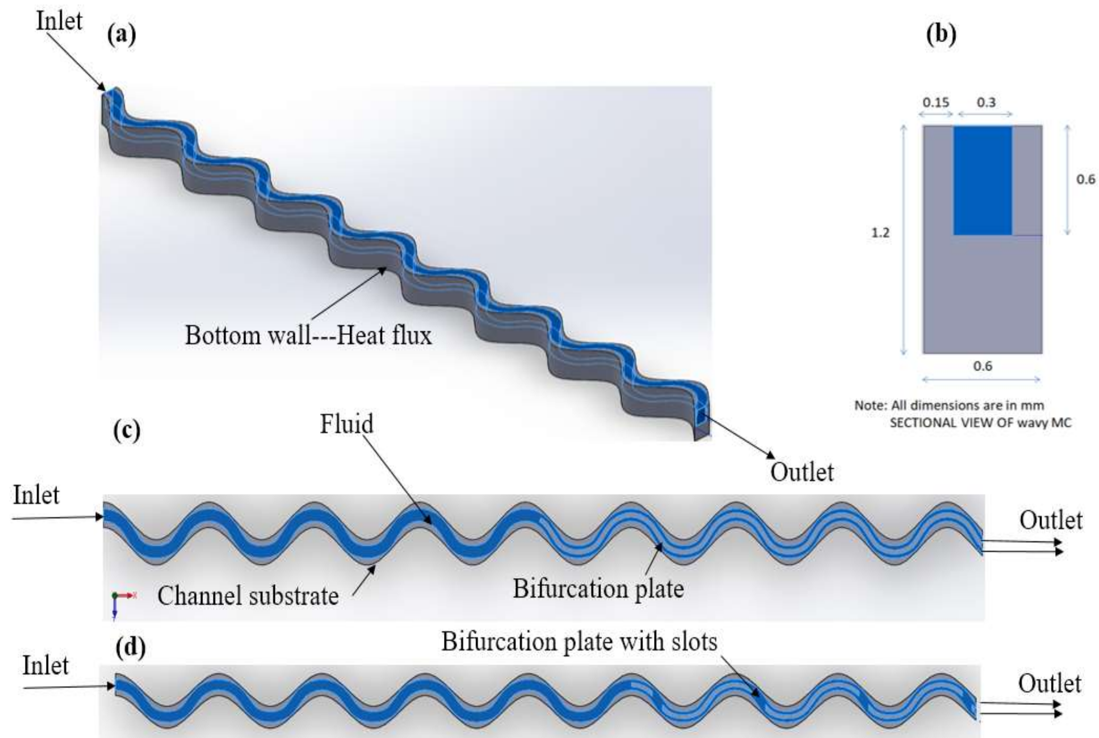

Fig.1. (a) Circular wavy MC for computational domain (b) sectional view of circular wavy MC(c) Circular wavy MC with Bifurcation plate (d) Circular wavy MC Bifurcation plate with slots

The final grid size is chosen in this study by conducting the grid independence test. The grid independence test is performed at various edge sizes such as coarse (0.0375mm), medium(0.025mm) and fine(0.01875mm).The Nusselt number and friction factor are calculated and compared. The refinement in both Nusselt number and friction factor is very small as the grid is refined from medium to fine. Hence, to minimize the computational time medium edge size is chosen. Numerical results obtained at various Reynolds number for regular wavy MC are in reasonably good agreement with the experiments studies carried by Chiam [6].

The continity ,momentum and energy equations for the present study can be written as given in [9]:

Continitity equation : $\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}+\frac{\partial W}{\partial Z}=0$ (1)

x--Momentum equation : $U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}+W\frac{\partial U}{\partial Z}=-\frac{dp}{dX}+\frac{1}{Re}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}+\frac{\partial^2 U}{\partial Z^2}\right)$ (2a)

Y-- Momentum equation : $U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}+W\frac{\partial V}{\partial Z}=-\frac{dp}{dY}+\frac{1}{Re}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}+\frac{\partial^2 V}{\partial Z^2}\right)$ (2b)

Z-- Momentum equation : $U\frac{\partial W}{\partial X}+V\frac{\partial W}{\partial Y}+W\frac{\partial W}{\partial Z}=-\frac{dp}{dZ}+\frac{1}{Re}\left(\frac{\partial^2 W}{\partial X^2}+\frac{\partial^2 W}{\partial Y^2}+\frac{\partial^2 W}{\partial Z^2}\right)$ (2C)

Energy equation : $U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}+W\frac{\partial \theta}{\partial Z}=\frac{1}{Re.P_r}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}+\frac{\partial^2 \theta}{\partial Z^2}\right)$ (3)

Where, U, V W are velocity components in X, Y Z direction, θ is dimenssionless Temperature , $\frac{dp}{dX}$ is the pressure gradient and Re, P_r are Reynolds and Prantals number. In numerical simulation, fluid (water) domain is surrounded by channel substrate material (copper) with half thicknesses is considered. The periodic boundary conditions were applied on both sides of the channel. At the inlet, water temperature is assumed to be 300ºK and inlet velocity of water is calculated from Reynolds number and hydraulic diameter. The numerical investigation is carried in the Reynolds number range of 100 to 300 with constant heat flux wall boundary condition.

3. Results and discussion:

3.1. Span-wise velocity vector profiles and stream-wise velocity contours:

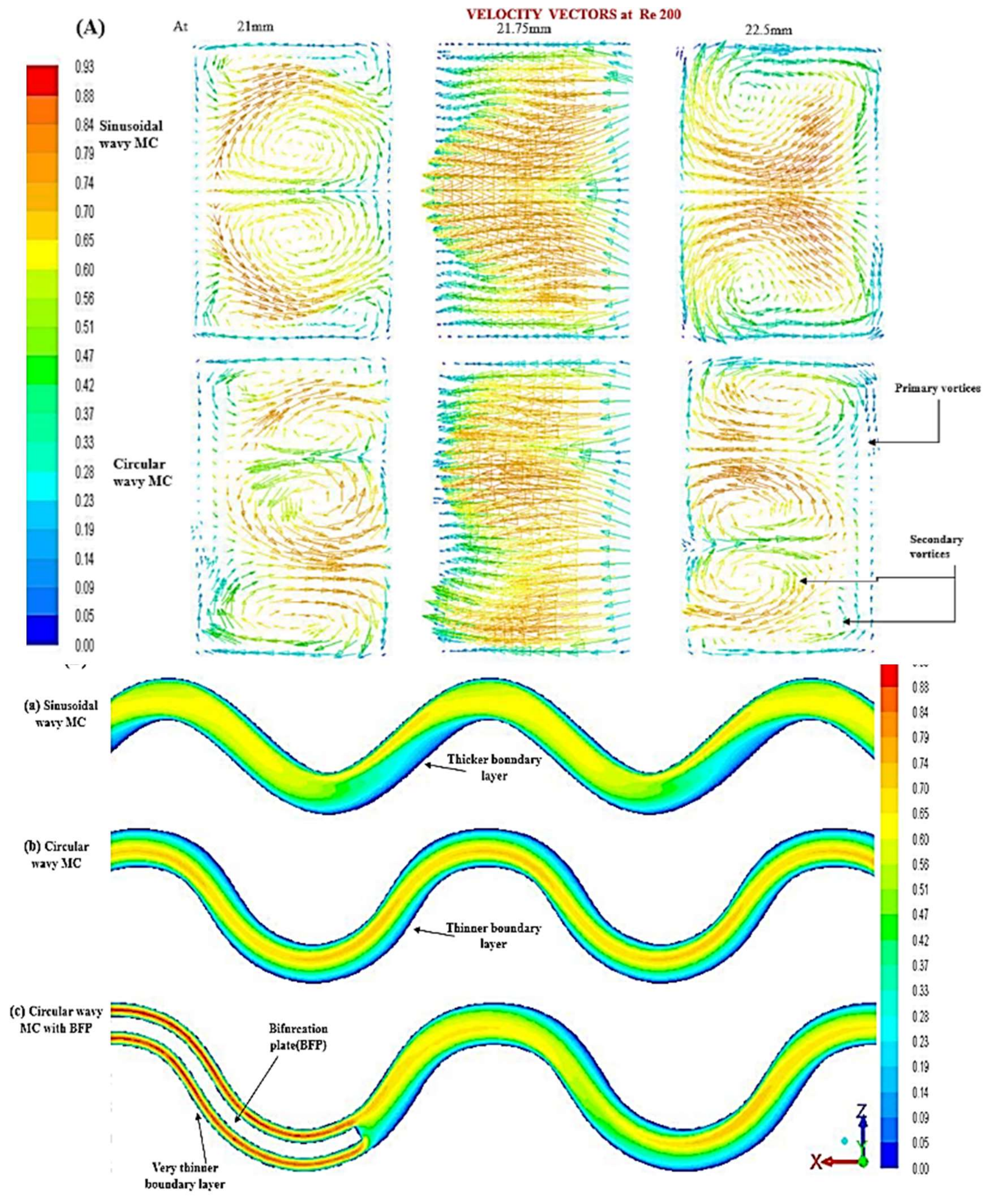

Fig.2. (A) span-wise velocity vector profiles, **(B)** stream-wise velocity contours at Re 200

Fig.2 shows the span-wise velocity vector profiles and stream-wise velocity contours at Re 200. From fig. 2 (A), it is observed that circular wavy MC has more Dean's vortices than the sinusoidal wavy MC. These Dean's vortices motion takes away the high temperature fluid from channel base to top level and brings the low temperature fluid from the top level to channel base. In the circular wavy MC formation of secondary vortices (counter-rotating pairs of Dean’s vortices) are also higher. These are leads to an effective fluid mixing and subsequently enhance the heat transfer. From fig.2 (B), it is observed, thicker boundary layer in sinusoidal wavy MC, thinner boundary layer in circular wavy MC and boundary layer thickness further reduces in circular wavy MC with BFP. As boundary layer thickness reduces, higher temperature differences between the channel substrate and fluid. It leads to augments convective heat transfer and subsequently the Nusselt number. As the Reynolds number increases, the boundary layer thicknesses reduce further and consequently increases the Nusselt number. As bifurcation plate (BFP) is introduced in the middle of the channel, it leads to farther thinner the boundary layer thicknesses. This leads to increases the heat transfer area and formation of longitudinal vortices in addition to the Dean's vortices. These are favourable to enhance the heat transfer. In circular MC with BFP, as slots are introduced in BFP it leads to further thinning and re-initialization of boundary layer.

3.2.Heat transfer enhancement :

Fig.3 shows the numerical plot of Nusselt number variation with Reynolds number of various designs used in the current study. From fig.3, it is observed that Nusselt number enhancement has a positive relation with Reynolds number. Circular wavy MC has higher Nusselt number than the sinusoidal wavy MC with smaller pressure drop penalty in the Reynolds number range of 100 to 300. This is due to the formation of more Dean's vortices in circular wavy MC than the sinusoidal wavy MC. In sinusoidal wavy MC radius of curvature of channel passage changes from crest to trough, smaller at crest and trough and larger in between these two. Hence stronger Dean's vortices at crest and trough and weaker Dean's vortices in between these two. In circular wavy MC radius of curvature of channel passage is constant. Hence, uniform Dean's vortices strength. Dean's vortices strength can be observed from fig.2(A). In circular wavy MC with BFP and slots in BFP has higher heat transfer than the sinusoidal wavy MC and circular wavy MC, reasons are explained in an earlier section. From the numerical investigation it is observed that the heat transfer enhancement in circular wavy MC is 12.7 %, in circular wavy MC with BFP(7.5mm,10mm and12.5mm) are (64.8%,85.4% and 90%) respectively and in circular wavy MC with BFP=10mm with slots is 109.2% higher than the sinusoidal wavy MC with pressure drop penalty at Reynolds number 200.

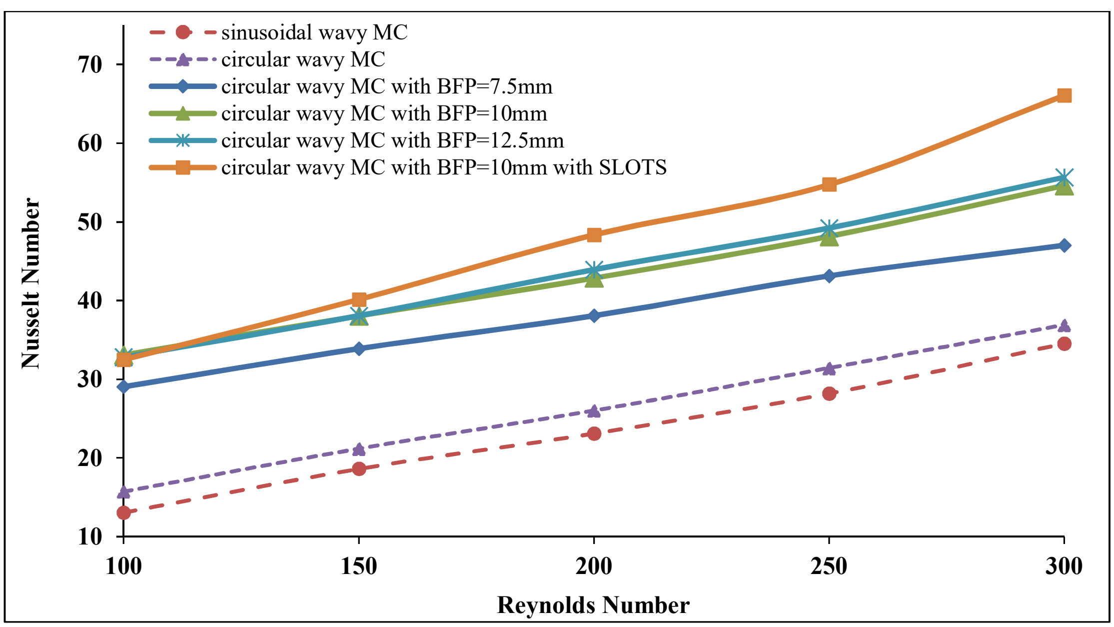

Fig.3. Numerical plot of Nusselt number vs Reynolds number

3.2. Channel inner surface and fluid temperature difference in the stream-wise direction:

Fig.4 shows the numerical Plot of channel inner surface and fluid temperature difference in a stream-wise direction at Re 200. From fig.4, it is observed that temperature difference(temperature difference between the channel inner surface and fluid) variation in sinusoidal wavy MC is in cyclic variation and in circular wavy MC it is in linear variation. It is also observed that in circular wavy MC temperature difference is lower than the sinusoidal wavy MC. This is due to more Dean's vortices formation in circular wavy MC and reasons are explained in earlier sections(3.1 &3.2). Due to this fluid absorbing more heat from the channel substrate material and subsequently enhance the heat transfer. In circular wavy MC with BFP, the temperature difference is lower than sinusoidal wavy MC and circular wavy MC. Temperature difference is further lower as BFP length increases and circular wavy MC (BFP=10mm with slots) gives lowest temperature difference. Reasons are explained in earlier (section 3.1).

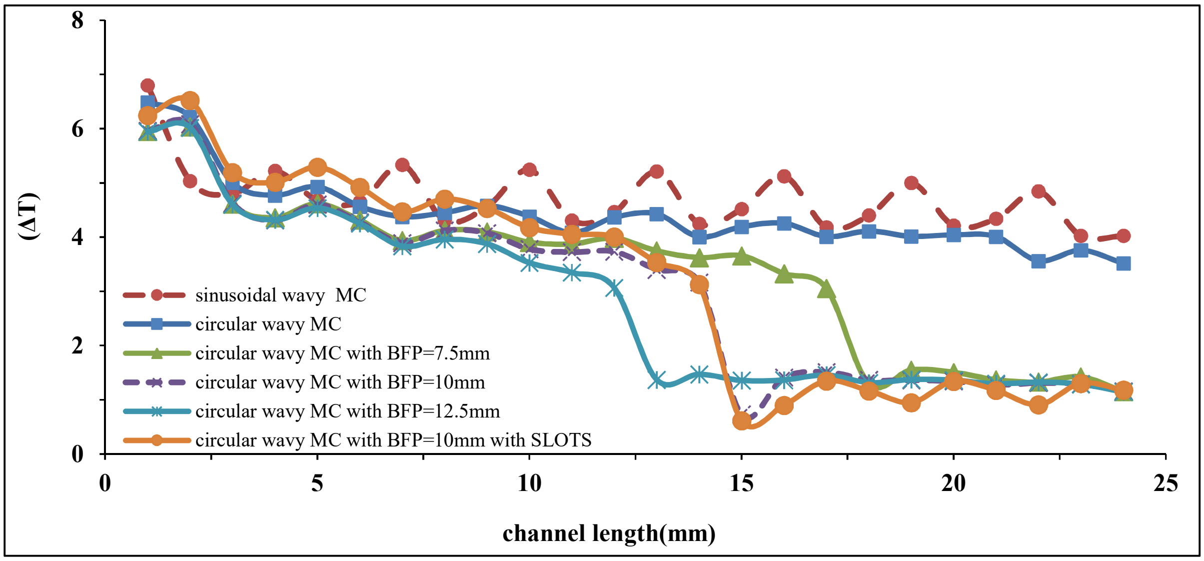

Fig.4. Numerical Plot of channel inner surface and fluid temperature difference in a stream-wise direction at Re 200

3.3.Pressure drop penalty:

Fig.5. shows the numerical plot of pressure drop vs Reynolds number of various designs used in the current study. In circular wavy MC pressure drop penalty is higher than the sinusoidal wavy MC in all Reynolds number range. This is due to fluid has to make a 180^{o} turn while flowing through circular channel passage. This causes to momentum losses and leads to higher pressure drop than the sinusoidal wavy MC. As bifurcation plate introduced in the middle of circular wavy MC channel passage, it restricts the fluid flow. Hence pressure drop penalty increases than the sinusoidal wavy MC and circular wavy MC. As bifurcation plate length increases pressure drop penalty increases further. In circular wavy MC with BFP=10mm (with slots on BFP) have lower pressure drop than the circular wavy MC with BFP=10mm. This is due to BFP with slots, allow the fluid flow with smaller frictional resistance. From the numerical investigation it is observed that pressure drop penalty in circular wavy MC is 16.5 %, in circular wavy MC with BFP(7.5mm,10mm and12.5mm) are 161.8%, 216.3% and 272.5% respectively and in circular wavy MC with BFP=10mm with slots is 202.6% higher than the sinusoidal wavy MC at Reynolds number 200.

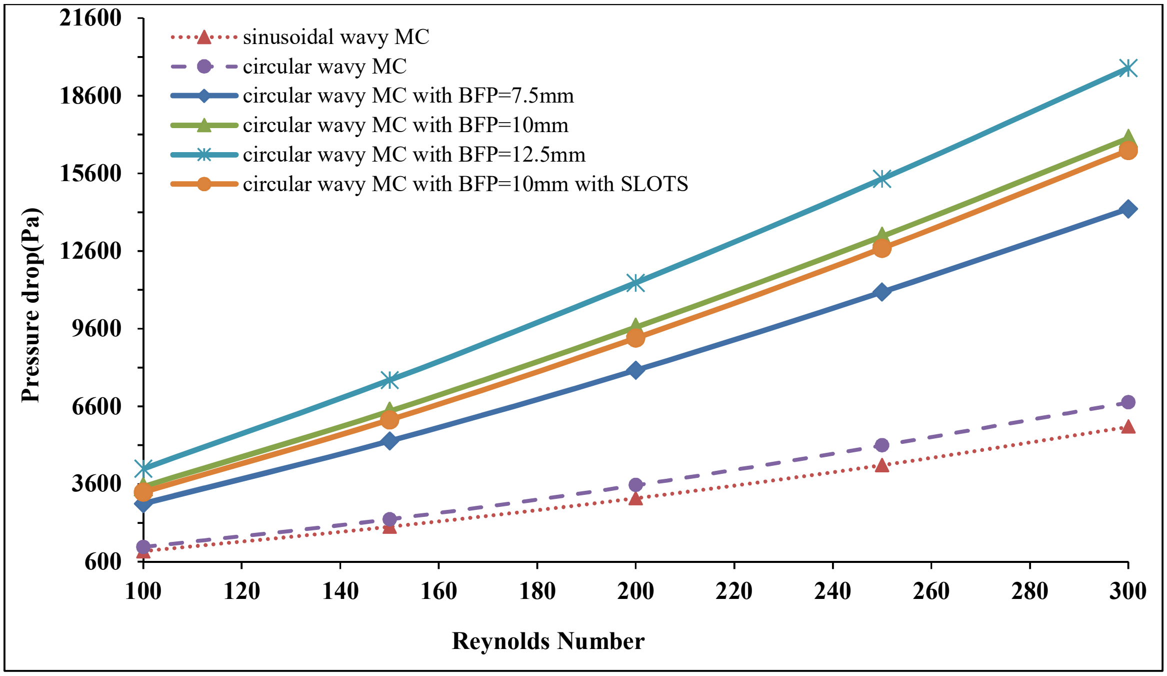

Fig.5. Numerical plot of pressure drop vs Reynolds number

3.4. Performance factor (P_f):

Fig.6 shows the numerical plot of Performance factor Vs Reynolds number of various designs used in the current study. It is the ratio of heat transfer performance to the pressure drop penalty.

The performance factor of design (B) may be defined as $P_{fB} = \frac{\frac{Nu_B}{f_B}}{\frac{Nu_A}{f_A}}$ ---------- [6]

Where 'A' refers to reference design(sinusoidal wavy MC) and 'B' refers to design present design. It is observed that in all design performance factor decreases gradually as Reynolds number increases. It is due to pressure drop penalty is predominant than the heat transfer enhancement. In present study is observed that circular wavy MC has the higher P_f, circular wavy MC with BFP=12.5mm has lower 'P_f' and circular wavy MC with BFP=10mm with slots has moderate P_f .

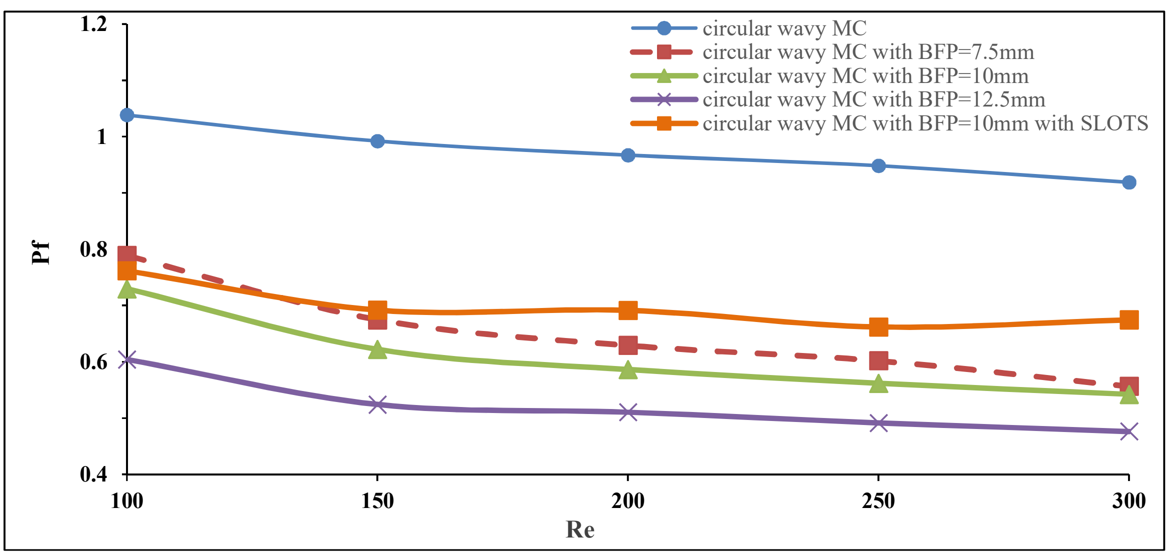

Fig.6: Numerical plot of Performance factor Vs Reynolds number

4. Conclusion:

Numerical simulation was conducted on circular wavy MC and circular wavy MC with BFP(with slots) and compared their results with sinusoidal wavy MC. The following are the concluding remarks are made from this numerical study.

- Circular wavy MC has higher Nusselt number than sinusoidal wavy MC with pressure drop penalty at all Reynolds number range.
- As is bifurcation plate is introduced in circular wavy MC, temperature difference between fluid and channel inner surface is decreased.
- Circular wavy MC with bifurcation plate provides higher Nusselt number with an expense of pressure drop penalty. Circular wavy MC with bifurcation plate length 10mm with slots provides moderate performance factor.

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