A Review on Heat Transfer and Fluid Flow over Wavy Channel or Surface

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Abstract— In this article detail review in the area of heat transfer and fluid flow across wavy channel and surface has been presented. The wavy channel and surface have significant application in automotive sector, industries, and many more. The purpose of using wavy channel or surface instead of using straight channel, the wavy channel has more surface area as compared to straight channel due to which mass and momentum during heat transfer increases. Conventionally, during fluid flow turbulent flow is preferred which helps in enhancing the heat transfer rate. Several researches perform numerical-computation simulations and experimentation in order to explore the flow characteristics over wavy surfaces are presented in this paper.

Key words: Wavy channel, CFD, Heat Transfer

I. INTRODUCTION

Wavy wall flows occur under a wide variety of engineering applications and have, consequently, received considerable attention [1–2]. One of the most important applications is the heat transfer enhancement in heat exchangers. The physical process of enhancing heat transfer in such application is to introduce some geometrical modifications on the wall in question in order to break the boundary layer that forms on the exchanger wall and replace it by a fresh fluid from the free stream flow [3]. In real applications, engineers are also interested in the additional pressure drop caused by such techniques. So, the best solution is that provides the least pressure drop and the largest heat transfer rate. Other parameters such as simplicity, manufacturability, maintenance, etc., are also important parameters in the design phase [3]. Wavy wall heat transfer enhancement technique has been used extensively in the design of compact heat exchangers as can be seen from the numerous experimental and numerical investigations reported in the literature. One of the important observations in this field is that in the laminar regime, where wavy passages provide significant heat transfer enhancement when the flow is unsteady. However, for steady flow, the enhancement is insignificant. Wang and Vanka [3] conducted a numerical investigation for laminar steady and unsteady cases with wavy wall. They reported a heat transfer enhancement factor of about 2.5 for the unsteady case compared with that for a parallel-plate channel case. However, for the steady case with wavy wall the heat transfer rate is only slightly improved. The transition occurs at a Reynolds number of around 180 for the geometrical configuration studied by Wang and Vanka [3].

II. MATHEMATICAL MODELLING

For the fluid flow through pipe, duct and channel the conventional governing equations are the Navier–Stokes equations can be written in the most useful form for the development of the finite volume method:

$$\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + div(\mu gradu) + S_{Mx} \quad (1)$$

$$\rho \frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + div(\mu gradv) + S_{My} \quad (2)$$

$$\rho \frac{Dw}{Dt} = -\frac{\partial p}{\partial z} + div(\mu gradw) + S_{Mz} \quad (3)$$

Governing equations of the flow of a compressible Newtonian fluid

Continuity

$$\frac{\partial \rho}{\partial x} + div(\rho u) = 0$$

x-momentum

$$\frac{\partial(\rho u)}{\partial x} + div(\rho uu) = -\frac{\partial p}{\partial x} + div(\mu gradu) + S_{Mx} \quad (4)$$

y-momentum

$$\frac{\partial(\rho v)}{\partial y} + div(\rho vu) = -\frac{\partial p}{\partial y} + div(\mu gradv) + S_{My} \quad (5)$$

z-momentum

$$\frac{\partial(\rho w)}{\partial z} + div(\rho wu) = -\frac{\partial p}{\partial z} + div(\mu gradw) + S_{Mz} \quad (6)$$

Energy

$$\frac{\partial(\rho i)}{\partial t} + div(\rho iu) = -pdivu + div(kgradT) + \Phi + S_i \quad (7)$$

Using various correlation FEV results are been compared analytically

$$h_f = f\frac{LV^2}{D_h 2g}$$

Where,

f is the friction factor for fully developed laminar flow

L: length of the channel, duct, pipe

V: mean velocity of the flow

d: diameter of the pipe

f is the friction factor for fully developed laminar flow:

$f = \frac{64}{\mathrm{Re}}$ (For Re<2000) $\mathrm{Re} = \frac{\rho u_{avg} d}{\mu}$

C_f is the skin friction coefficient or Fanning's friction factor.

For Hagen-Poiseuille flow: $C_f = \tau_{wall} l \frac{1}{2}\rho u_{avg}^2 = \frac{16}{\mathrm{Re}}$

For turbulent flow: $\frac{1}{\sqrt{f}} = 1.74 - 2.0\log_{10}\left[\frac{\varepsilon_p}{R} + \frac{18.7}{\mathrm{Re}\sqrt{f}}\right]$

Moody's Chart

R: radius of the channel, duct, pipe

ε_p: degree of roughness (for smooth channel, duct, pipe, $\varepsilon_{p=0}$)

$\mathrm{Re} \to \infty$: Completely rough channel, duct, pipe.

III. LITERATURE REVIEW

Hamid et al. 2015 performed a 3D CFD analysis of an Printed Circuit Heat Exchanger which is applied as recuperator in International Thermonuclear Experimental

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Reactor. As a working fluid helium is used and alloy 617 as solid substrate. A parametric analysis have also been carried out for various angle of bend (θ = 0°(straight), 5°, 10° and 15°) and Reynolds number (Re = 350, 700, 1400 and 2100). Various types of flow patterns, within one wavy-section, are presented to analyze thermal-hydraulic characteristics. Thermal hydraulic performance parameters are presented for the various wavy-sections as well as within a section; and for the complete PCHE model. Heat transfer enhancement as compared to pressure penalty is higher for the wavy channel; and increases with increasing Re and θ. Wavy as compared to plane channel based PCHE is demonstrated here to give better thermal-hydraulic performance.

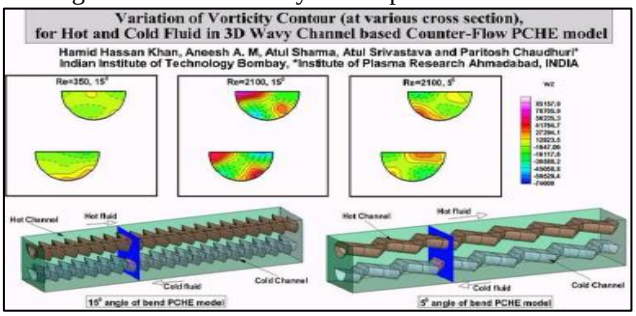


Fig. 1: Schematic of a wavy channel printed circuit heat exchanger, showing variation of vorticity

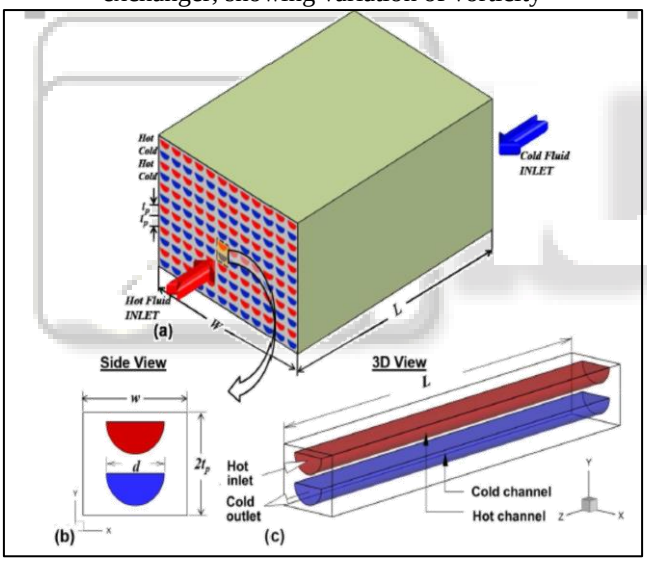
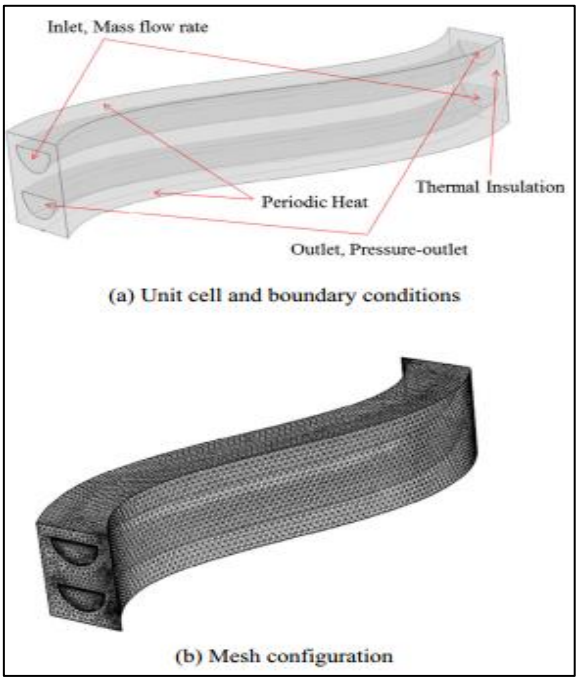


Fig. 2: Schematic of a printed circuit heat exchanger

Young-Jin et al. 2017 in their study they examined the thermal performance of wavy-channeled PCHEs, and the effects of the waviness factors: the amplitude and the period, on the thermal performance of the PCHE. The thermal performance of the wavy-channeled PCHEs is compared with that of conventional PCHEs with straight channels. Based on the numerical results, it has been shown that the wavy-channeled PCHEs can have significantly higher thermal performance than the conventional straight-channeled PCHEs due to the increased area for heat transfer. The effect of recirculating flow induced by the waviness is estimated to be negligible for the typical range of CO_2 mass flow rate of compact power generations. It has been shown that the performance enhancement can be predicted using a sole nondimensional parameter: the ratio between amplitude and period, and has linear relationship with this nondimensional parameter.



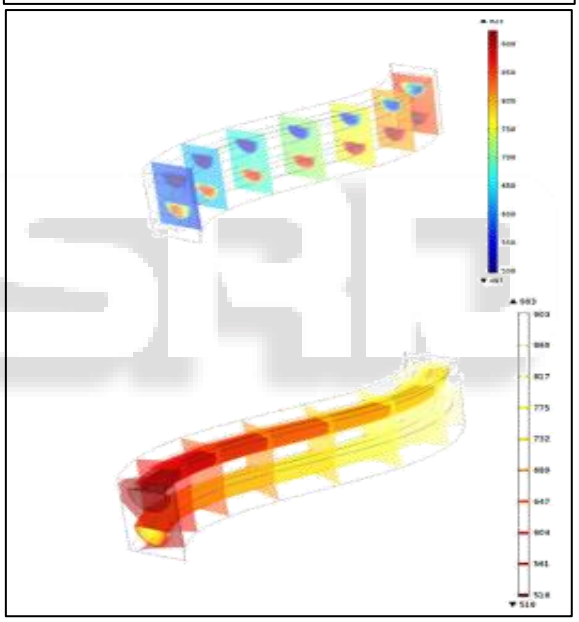


Fig. 3: Model detail (a) 2D temperature contour plot: temperature contours of selected cross-sections (left) and temperature contours of fluid/solid interfaces (right)

Sukumar et al. 2017 performed numerical experiments have been performed to investigate the thermo-fluidic transport characteristics for laminar flow through sinusoidal wavy walled channel. The heat transfer and pressure drop characteristics are assessed for two different channels, namely, raccoon and serpentine for different values of amplitude and wavelength of the wall waviness. Our results reveal that the dependence of heat transfer on the geometry of the wall is strongly influenced by the wavelength of the wall waviness. For lower values of wavelength, the rate of heat transfer is almost same for both the channel, while the heat transfer for raccoon channel is always more than that for serpentine channel for higher values of wavelength and the difference appears to be more prominent for larger values of amplitude of wall waviness and Reynolds number.

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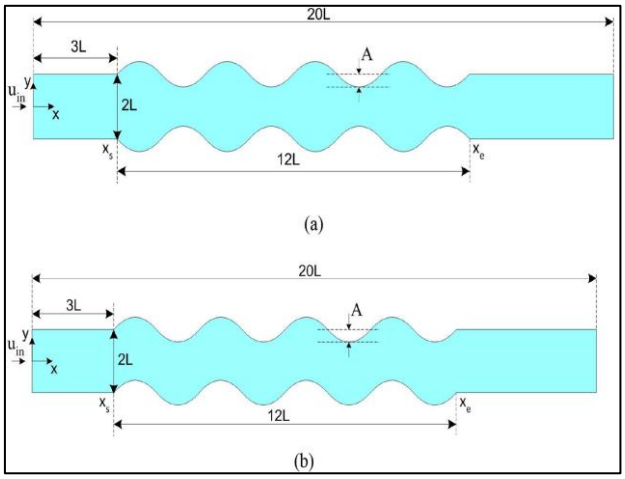

Fig. 4: Schematic diagram of the physical model (a) Raccoon channel, (b) Serpentine channel

Rush et al. 1999 experimentally examined the Local heat transfer and flow behavior underlaminar and transitional flows in sinusoidal wavy passages. The experimental geometry consists of a channel with a 10 : 1 aspect ratio bound by two wavy walls. The walls are from 12 to 14 wavelengths long, and the wave amplitude, phase angle, and wall-to-wall spacing are varied during the experiments. Using visualization methods, the flow field is characterized as steady or unsteady, with special attention directed toward detecting the onset of macroscopic mixing in the flow. The location of the onset of mixing is found to depend on the Reynolds number and channel geometry.

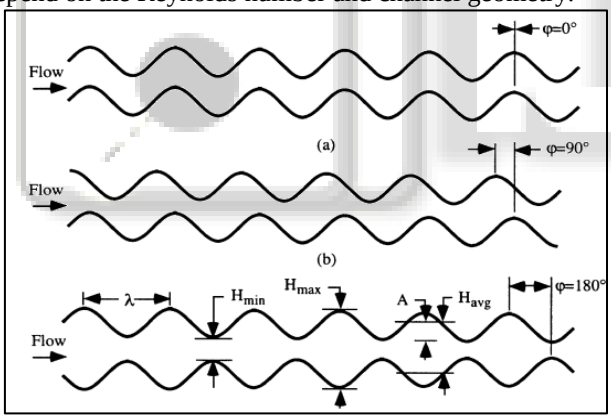

Fig. 5: Schematic of wavy passage configurations and the definition of important geometric parameters

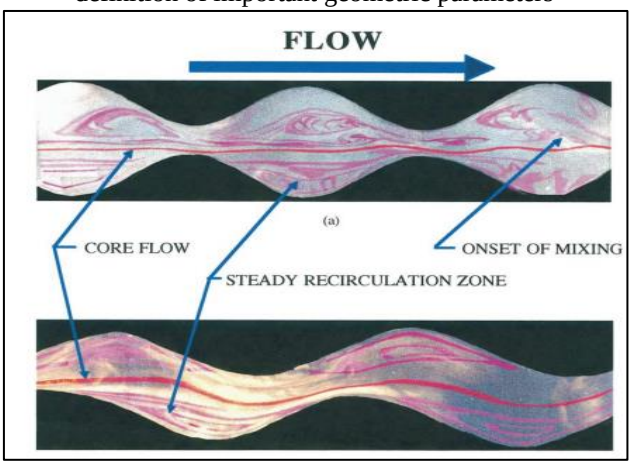

Fig. 6: Typical images from the flow visualization study

Zhou et al.2016, a sinusoidal wavy structure of microchannel heat sink intended for active cooling of compact electronic devices such as insulated-gate bipolar transistor (IGBT) has been designed. By combining with the finite volume method (FVM), the geometric parameter of the wavy wall, as the key factor to improve the heat transfer efficiency, has been optimized by a novel response surface methodology (RSM), which has found to be time-efficient and accurate. Furthermore, we use a comprehensive heat transfer index b to study whether the heat transfer enhancement outweighs the increased pressure drop. After investigating the Re, h, DP, f, b, it is concluded that the best case is occurred when wave amplitude value is 40 and wavelength is 100. For our optimized wavy channel, the heat transfer can be enhanced by a maximum of 2.8 times compared to regular straight channel. CFD simulation demonstrates that under such case, the existence and disturbance of vortex can lead to thinning of boundary layer and hence more effective heat transfer

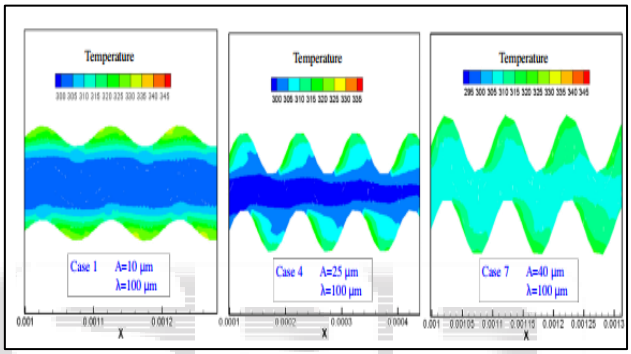

Fig. 7: Temperature contours (K) along X direction corresponding to normal (case 1), worst (case 4) and optimal (case 7) heat transfer cases, respectively

Fabbri et al.2005 the analysis of the heat transfer in the entrance region of a channel composed by a corrugated profile and a flat wall is presented. The laminar and incompressible flow of a Newtonian fluid is assumed inside the channel, and an uniform heat flux is imposed on the external surface of the corrugated wall. The governing equations are solved with the help of a finite-element method, and the results are compared with the heat transfer coefficient in the entrance region of a flat channel. In order to investigate the sensitivity of the convective heat transfer coefficient to the Reynolds number under laminar conditions, the analysis have been performed for different values of the flow rate. The effect on the flowfield of the of the corrugated profile amplitude is also discussed

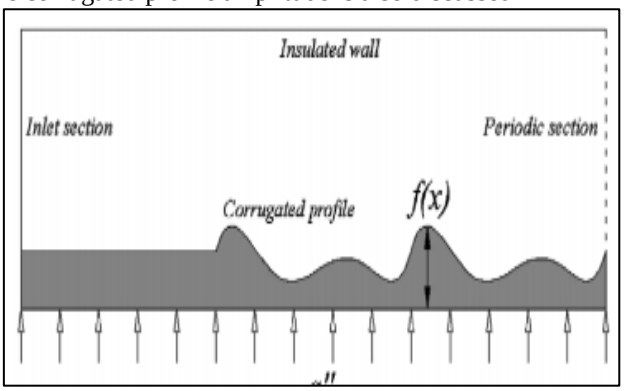

Fig. 8: Channel geometry and corrugated profile

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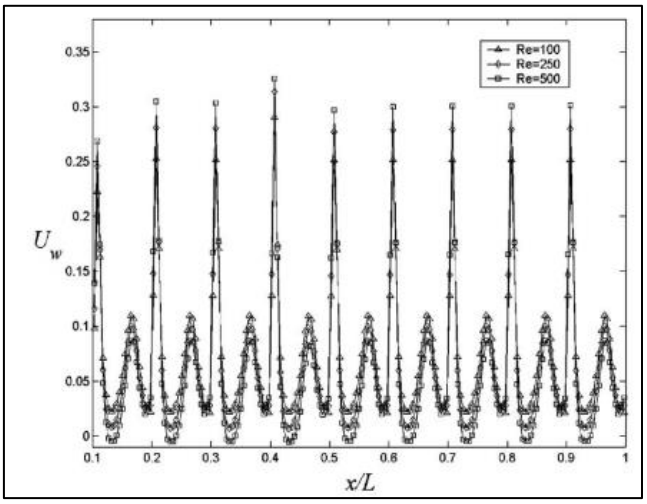

Fig. 9: Stream wise velocity component at the node adjacent to the corrugated profile for channel amplitude A= 0.2

Ahmed et al. [10] enhanced the heat transfer rate inside a wavy channel by using nanofluid. Their results indicated that the increment in heat transfer rate depends on the solid volume fraction of nanoparticle, Reynolds number and amplitude of the wavy wall rather than the wavelength.

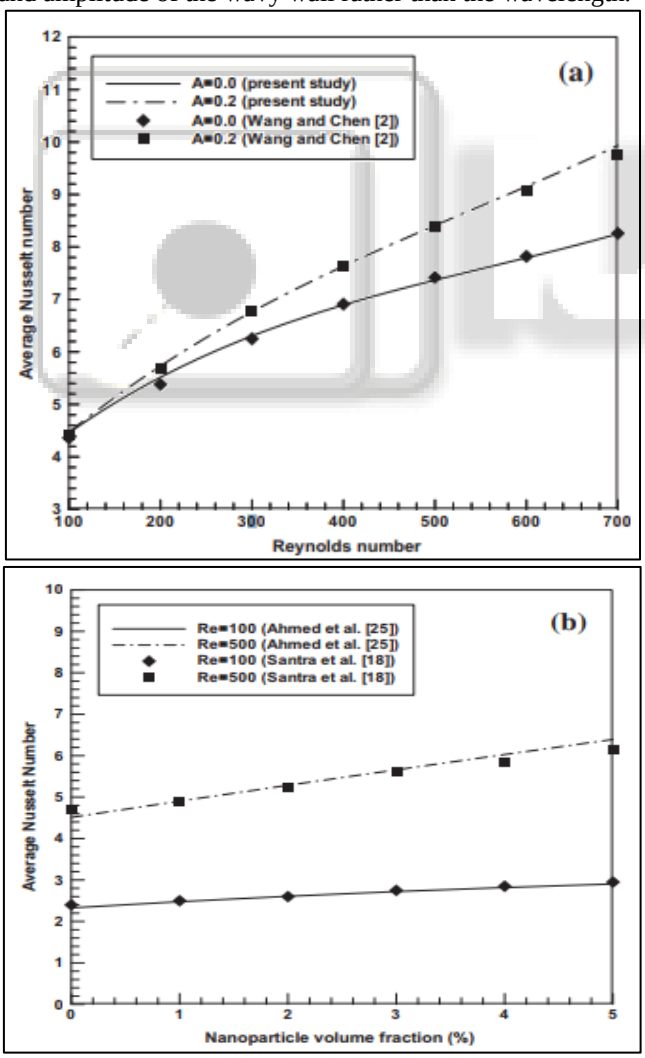

Fig. 10: Comparison of the results for (a) water flow in wavy channel, (b) nanofluid flow between two parallel plates

Yang et al. [10] studied the nanofluid flow and heat transfer characteristics in awavy channel. They showed that the local friction coefficient for the nanofluid increases by increasing the wall wave amplitudes. In their work multi-parameter constrained optimization procedure integrating the design of experiments (DOE), full factorial experimental design (FFED), genetic algorithm (GA) and computational fluid dynamics (CFD) is proposed to design two-dimensional wavy channel with nanofluids (Cu/water, Al2O3/water and CuO/water). The elliptical, coupled, steady-state, two-dimensional governing partial differential equations for laminar forced convection of nanofluids are solved numerically using the finite volume approach. Some important parameters for the influences of heat transfer enhancement such as the Reynolds number ($250 \leqq Re \leqq 1000$), the particle volume concentration ($0\% \leqq \phi \leqq 5\%$), the wavy channel amplitude ($0.1 \leqq \alpha \leqq 0.3$) and the wavy numbers ($3 \leqq \beta \leqq 12$) on the enhancement of nanofluid heat transfer have been investigated.

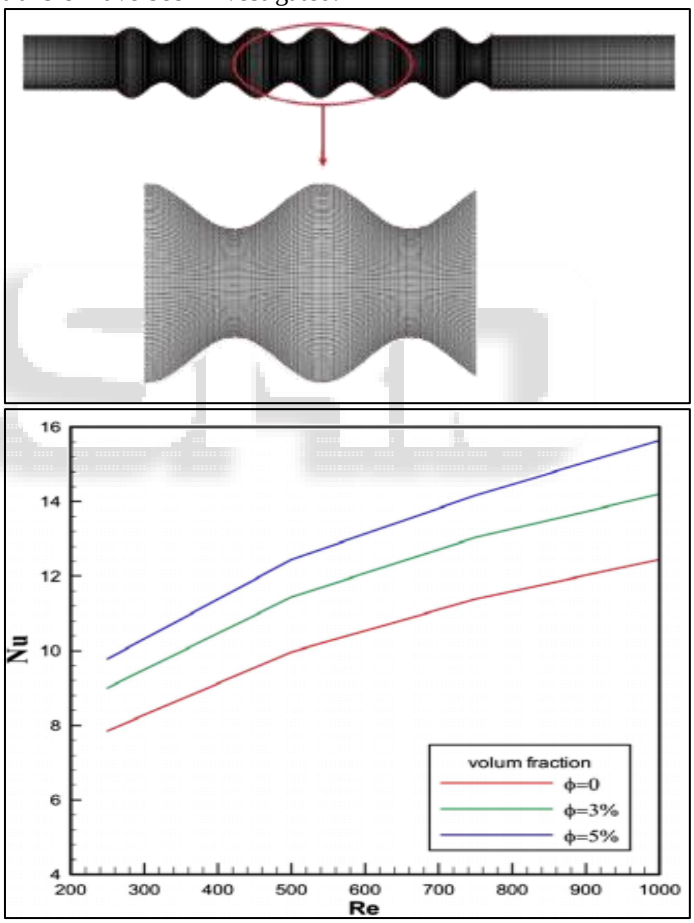

Fig. 11: Average Nu number versus Reynolds number at different values of nano-particles volume fractions at $\alpha = 0.3$ [10]

Wang and Chen [11] performed numerical experiments to explore the effects of wavy geometry, Reynolds number and Prandtl number on the rate of heat transfer for flow through a sinusoidal converging-diverging channel. They observed that local Nusselt number increases in the converging section of the channel with an increase in amplitude-wavelength ratio

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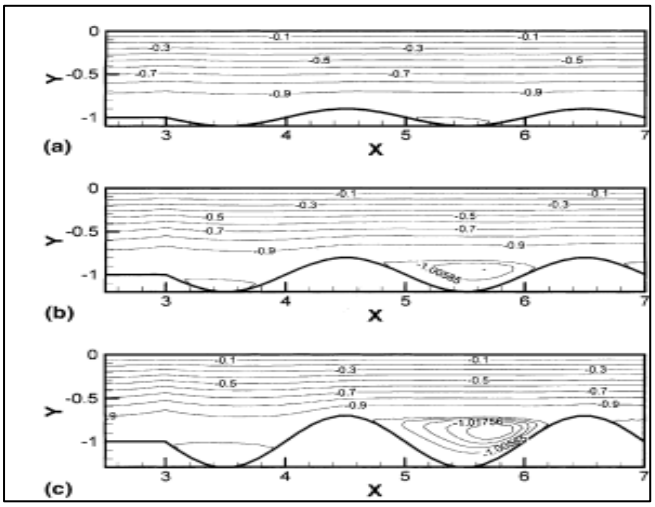

Fig. 12: Streamlines of flow for various amplitude–wavelength ratios at Re = 500 and Pr = 6:93

Xia et al. [12] studied the effects of geometric parameters on water flow and heat transfer characteristics in microchannel heat sink with triangular reentrant cavities by numerical simulation method. By comparing four different geometries of the triangular reentrant cavity, they found that the vortices in the triangular reentrant cavities could lead to chaotic advection which dramatically enhanced the convective fluid mixing

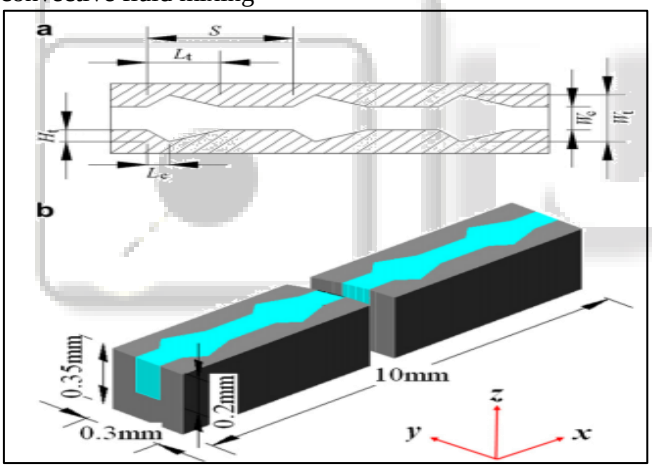

Fig. 13: The microchannel with triangular reentrant cavities. (a) Computational domain; and (b) geometric parameters[12]

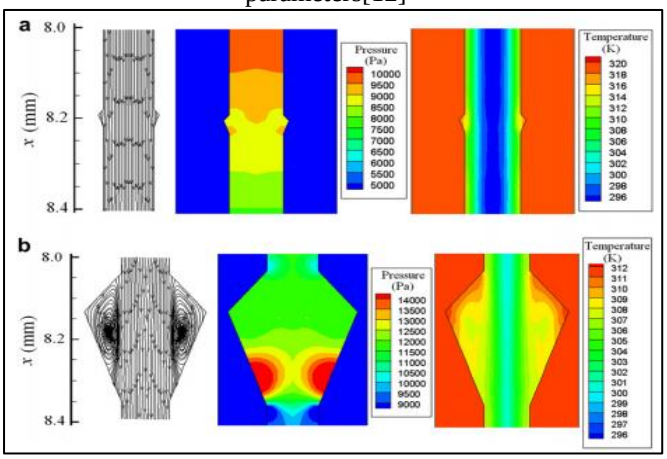

Fig. 14: Streamlines, pressure distribution and temperature distribution in Micro channel [12]

Hong and Cheng [15] presented a numerical study on laminar forced convection of water in offset strip-fin microchannels network heat sinks for microelectronic cooling. The heat transfer and fluid flow characteristics in offset strip-fin microchannel the heat transfer enhancement mechanism and the effects of geometric size of strip-fin on the heat sink performance were analyzed. It was found that therewas an optimal strip-fin size to minimize the pressure drop or pumping power on the constraint condition of maximum wall temperature, and this optimal size depended on the input heat flux and the maximum wall temperature.

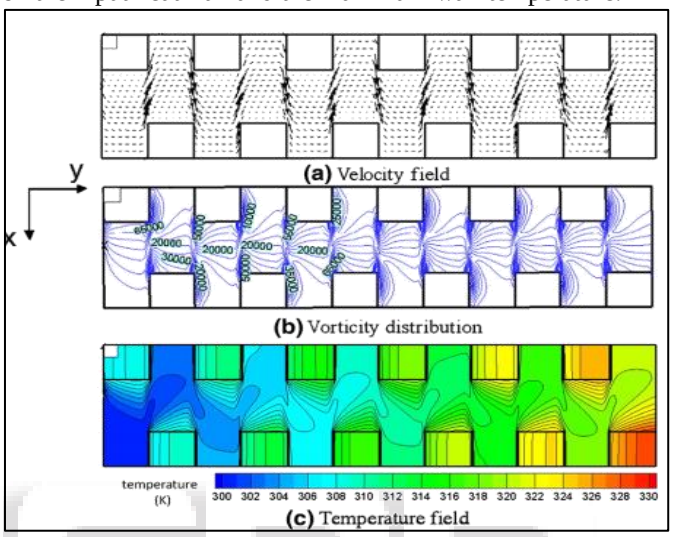

Fig. 15: Fluid flow and heat transfer characteristics at the middle plane of a strip-fin microchannel with K= 1 and M= 6: (a) The velocity, (b) vorticity and (c) temperature distribution (x:y:z= 1:30:3 and the flow direction is from the left to the right).[13]

IV. CONCLUSION

1) In comparison with straight surface wavy surface creates much turbulence at higher Reynolds number.
2) Increasing wavy amplitude the better heat transfer can be achieved.
3) The averaged Nusselt number increases until a vital value is attained where the amplitude is increased of the wave of wavy surface or channel.
4) Increasing the number of wave in the channel increases the rate of turbulence intensity.
5) The pressure drop can be reduced by implementing wavy surface instead of flat surface.
6) The separation of shear layer and the formation of vortex at near-wall stream, play an important role for the heat and momentum transfer near the wavy surface.
7) On reduce pitch distance between the two wave the rate of heat transfer can be amplified.

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