Int. J. Advanced Design and Manufacturing Technology, 2022, Vol. 15, No. 4, pp. 29-38

DOI: 10.30486/admt.2023.1955556.1344 *ISSN: 2252-0406* *https://admt.isfahan.iau.ir*

Heat Transfer of Wavy Microchannel Heat Sink with Microtube and Ag/Water-Ethylene Glycol Hybrid Nanofluid

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Received: 25 March 2022, Revised: 28 April 2022, Accepted: 30 April 2022

Abstract: In the present study, novel channel geometries in a wavy channel heat sink (HS) are investigated using ANSYS-FLUENT software. The Ag/water-ethylene glycol (50%) nanofluid is selected for cooling the CPU in this HS. The second-order upwind method is employed to discretize the momentum Equation and the SIMPLEC algorithm is employed for coupling velocity and pressure fields. Comparison of the two HSs with and without microtube shows that the presence of the microtube increases the uniformity of the CPU surface temperature distribution and decreases the mean surface temperature of the CPU (TCPU-Mean). However, the pumping power consumption of the system increases about 10 times. The results also demonstrate that the addition of nanoparticles results in intensification in the Performance Evaluation Criterion (PEC) of the system and up to 30%, especially at high Reynolds numbers.

Keywords: Heat Sink, Heat Transfer, Hybrid Nanofluid, Microtube, Numerical Simulation, Wavy Microchannel

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Research paper

1 INTRODUCTION

Various methods and techniques have been developed over the past few decades to improve heat transfer rate (HTR) in heat exchangers. Wavy channels have attracted a lot of attention due to that they have extremely high HTR relative to straight channels. The secondary flow formed by the wavy surfaces enhances the mixing between the fluid adjacent to the wall and the fluid in the middle of the channel, improving the thermal performance of these geometries [1]. Dean [2] was the first one who studied the effective parameters of wavy-surface flows to obtain the effects of the centrifugal force and the pressure difference between the outer and inner walls of a wavy channel. Cheng [3] investigated the influence of the aspect ratio of rectangular channels with constant wall heat flux on convective heat transfer numerically and observed that the improvement of heat transfer due to the wavy surface is higher than the intensification in flow pressure drop compared to straight channels. Kalb and Seader [4] analyzed heat transfer of fully developed flow in wavy circular tubes exposed to fixed heat flux considering the relationship between the path curvature radius and the diameter of the tube. Guo [5] performed a second law-based analysis and found that wavy channel parameters have an important influence on thermodynamic performance. Yang et al. [6] investigated the influence of alternating curvature of a channel and understood that the HTR is improved as the frequency is enhanced or the curvature wavelength decreases. Experimental studies on wavy surfaces have also shown that the thermal performance of these surfaces is better than that of straight channels [6-8]

In recent years, microchannel heat sinks (MCHS) established by Tuckerman and Pease [9] are one of the most widely used cooling techniques in microelectronic equipment. The HS microchannel, which is known as one of the cooling methods with a high heat transfer coefficient (HTC) (h), provides good conditions for rejecting high heat flux because of the small geometric dimensions and the high surface-to-volume ratio of the channel. In fact, HSs are passive heat exchangers that transfer the heat generated by mechanical or electrical devices to a fluid. For example, HSs are used for cooling the CPU of computers or used to moderate temperatures. Many studies have been done in this regard, for example, the theoretical study of Knight et al. [10] who investigated MCHS optimization. Various experimental studies have also been performed to show that the wavy walls result in the improvement of their performance [11-15]. Lin et al. [16] designed a wavy channel HS and proposed an appropriate geometry by varying the wavelength and frequency of the channels when the pumping power of the system was constant. These studies showed that MCHS performs much better than conventional energy absorbers but still needs to be studied and improved.

Nanofluid refers to a mixture of nanoparticles dispersed in a common liquid. The improvement of the base fluid (BF) thermal conductivity is because of the nanoparticle Brownian motion and the transport mechanisms inside the mixture, resulting in higher HTRs [17] Various properties of new nanofluids obtained from the composition of nanoparticles added to the BF have been reported in various experimental investigations. Esfe et al. [18] investigated the viscosity of motor oil-Al_2O_3 nanofluid at dissimilar concentrations and temperatures (5-65 °C) and presented new correlations. They showed that this nanofluid is Newtonian at dissimilar shear rates for all volume concentrations. It was also demonstrated that the nanofluid viscosity intensifies with growing the nanoparticles volume fraction (ϕ) and diminishing the temperature, which is more evident at low temperatures. Selvakumar and Suresh [19] considered the effects of water-copper oxide nanofluid on a HS with thin channels under fixed heat flux. They found that h increases with increasing the ϕ, and the pump power consumption increases by 15.11% for nanofluid with a volumetric concentration of 2%. Ermagan and Rafee [20] simulated three types of the rectangular microchannel HS with smooth, hydrophobic, and superhydrophobic wall surfaces. The results showed that microchannel HS with superhydrophobic walls has higher thermal efficiency compared to the other two types. The new HS design with rectangular and triangular two-layer channels is proposed by Ahmed et al. [21]. They used water-alumina and water-silica nanofluids. Their results revealed that the temperature of the walls of triangular channels is decreased by about 27.4% compared to that of rectangular ones. Tafarroj et al. [22] employed an artificial neural network for modeling h and the Nusselt number (Nu) of TiO_2-water in a microchannel. Their results showed that a trained network could be used as an appropriate method for costly and time-consuming nanoscale experiments in the microchannel. Esfahani and Toghraie [23] studied the thermal conductivity of silica/ethylene glycol (EG)-water nanofluid at temperatures ranging from 25 to 50 °C and ϕ = 0.1, 0.5, 1, 1.5, 2, 3 and 5%. Their results demonstrated that the thermal conductivity intensifies with growing temperature and ϕ. Their results indicated that the maximum thermal conductivity (45.5%) occurs at ϕ = 5% at 50 °C. Ghasemi and Karimipour [24] studied the effect of mass fraction of copper oxide nanoparticles and temperature on the viscosity of liquid paraffin. They prepared CuO nanoparticles by sedimentation method in which $Cu(NO_3)_2 3H_2O$ was employed as the leading material. They revealed that an increase of the nanoparticles in the BF greatly increases the viscosity. It was shown that the nanofluid viscosity falls significantly with the temperature. Karimipour et al. [25] studied the effect of CuO mass fraction and temperature on viscosity and thermal conductivity of nanofluid. In this experiment, viscous paraffin was considered as the BF. TEM and DLS tests, as well as the Zeta potential test, were implemented to obtain the morphology and stability of the nanoparticles within the BF. Afrand et al. [26] examined the effect of temperature and concentration of nanoparticles on the dynamic viscosity of silicon dioxide- carbon nanotubes/motor oil (SAE40) hybrid nanofluid at temperatures 25 and 60 °C. They found that larger nanoclusters are formed due to the van der Waals forces between the particles by increasing the concentration of nanoparticles. Adio et al. [27] inspected the viscosity of magnesium oxide-EG nanofluid with ϕ = 0-5%. They concluded that the effective viscosity of all samples is decreased exponentially with the temperature. Also, at a constant ϕ, nanofluid containing magnesium oxide with a diameter of 21 nm has a greater effective viscosity than the one containing magnesium oxide with dimensions of 105 and 125 nm. Asadi et al. [28] evaluated the viscosity of magnesium oxide (80%)/carbon nanotubes (20%)/SAE 50 oil with the ϕ = 0.25-2% at the temperatures between 25 and 50 °C. They reported that nanofluid exhibits Newtonian behavior at all temperatures and ϕ. He also reported the lowest increase (20%) in the viscosity for ϕ = 0.26%. Esfe et al. [29] provided a high-precision model for predicting the thermal conductivity of zirconium-EG nanofluid using a neural network, where ϕ = 0.0625-5%.

Zhou et al [30] used a novel response surface methodology (RSM) and revealed that the boundary layer thickness is reduced due to the creation of vortex, resulting in an increment in HTR. Hatami et al [31] also demonstrated that enhancing the Reynolds number intensifies HTR. Al-Rashed et al. [32] investigated the use of Ag/water nanofluid prepared by tea leaves synthesis method. They evaluated the effect of the addition of nanofluid on the system performance at different values of Reynolds number in a wavy channel HS and obtained the maximum efficiency.

In the present work, the optimal geometry introduced by Al-Rashed et al. [32] is used as the reference geometry and the effect of microtube mounted on the microchannel walls and the use of Ag/water-EG (50%) nanofluid are investigated. The nanofluid can be prepared through biosynthesis and thus is recognized as a bioenvironmental method.

2 NANOFLUID PROPERTIES

Sarafraz and Hormozi [33] produced Ag nanoparticles using tea leaves, which is a clean method. In the present work, water-EG (50%) is employed as the base fluid. Ag nanoparticles are suspended in the base fluid to prepare a hybrid nanofluid. The density, specific heat capacity, viscosity, and thermal conductivity of nanofluid are calculated based on volume fraction (ϕ) using the following Equations:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_p \quad (1)$$

$$\rho_{nf} C_{p,nf} = (1-\phi)\rho_{bf} C_{p,bf} + \phi\rho_p C_{p,p} \quad (2)$$

$$\mu_{nf} = \mu_{bf}(1+2.5\phi) \quad (3)$$

$$k_{nf} = k_{bf}(0.981 + 0.00114T(c^\circ) + 30.661\phi) \quad (4)$$

Where, ρ is the density, C_p is the specific heat capacity, μ is the viscosity, k is the thermal conductivity, and T shows the temperature. Subscript *bf* refers to the BF, *p* to the nanoparticles, and *nf* to the nanofluid.

3 MODEL DESCRIPTION

3.1. Geometry and Boundary Conditions

Geometry and boundary conditions: "Fig. 1" shows the schematic of the HS with two geometries: the first one has 50 wavy channels and another one has microtubes placed on the channel walls. Due to the symmetry of the problem, only a domain containing one channel and half tubes is solved. The channel walls have a surface symmetry condition and the middle plane of the two half tubes is coupled to each other. Since the plane of symmetry is located on the solid fin, the temperature gradient perpendicular to the plate is zero. For coupling the middle plane of the two half tubes, the difference of the components of velocity, temperature, and pressure on these two planes are equal to zero. "Table 1" shows the dimensions specified in "Fig. 1".

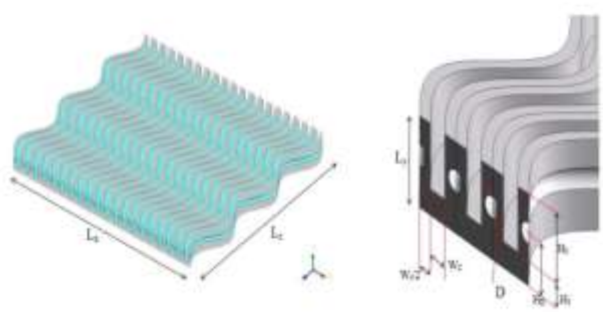


Fig. 1 Schematic of the problem.

The flow inlet temperature is assumed to be 300 K. All HS surfaces that are in contact with the surrounding are insulated.

Table 1 Dimensional parameters of the present problem

Parameter	Value
LX	10mm
LY	350μm
LZ	15mm
Wf	120 μm
WC	80 μm
D	80 μm
Hf	100 μm
HC	250 μm
HD	200 μm

Uniform inlet velocity (u) is calculated using different Reynolds numbers (300, 500, 700, 1000, and 1500) and the other velocity components (v, w) are zero. Also, the inlet pressure gradient is considered as zero.
Reynolds number is defined as follows:

$$\mathrm{Re} = \frac{\rho u D}{\mu} \tag{5}$$

Where, D is the hydraulic diameter. It is assumed that the HS is mounted on a CPU and thus the heat flux of 50 W/cm^2 is applied on its bottom. The waveform of the channel and microtube along the HS is a sinusoidal function:

$$S(z) = a_w \sin(\frac{2\pi z}{L_w}) \tag{6}$$

Where, a_W and L_W are selected according to the work of Al-Rashed et al. [33] who investigated a wavy microchannel HS. According to this study, $a_W = 138\mu m$ and $L_W = 5mm$ resulted in the highest HTR and PEC. In the present study, the same profile is used for the channel and tube along with the HS. In this study, the geometry is constant and the effect Re and ϕ is investigated. The microchannel Reynolds number is 10 times of the microtube.

3.2. Governing Equations

The present work investigates the hydraulic and thermal behavior of Ag/water-EG (50%) nanofluid with ϕ = 0.1%, 0.5%, and 1%. To do this, the conservation Equations of mass, momentum, and energy should be solved. The nanofluid is considered Newtonian and incompressible and hence the governing Equations are as follows [32], Continuity Equation:

$$\nabla.(\rho_{nf}) = 0 \tag{7}$$

Momentum Equation:

$$\nabla.(\rho_{nf}\vec{u}\vec{u}) = -\nabla p + \nabla.(\mu_{nf}\nabla\vec{u}) \tag{8}$$

Energy Equation for liquid phase:

$$\nabla.(\rho_{nf}\vec{u}C_{Pnf}T) = -\nabla.(K_{nf}\nabla T) \tag{9}$$

Energy Equation for solid phase:

$$\nabla.(K_s\nabla T) = 0 \tag{10}$$

In the above Equations, $\vec{u}$ is velocity vector and p is the pressure. Subscript *s* refers to the properties of the solid region. The uniformity of the CPU surface temperature cooled by the HS can be controlled by defining the parameter θ ("Eq. (10)"). As the value of θ reduces, the surface temperature of the HS is more uniform.

$$\theta = \frac{T_{cpu-\max} - T_{cpu-\min}}{T_{cpu-mean}} \tag{11}$$

Where, $T_{CPU,Max}$, $T_{CPU,Mean}$ and $T_{CPU,min}$ are maximum, mean, and minimum CPU surface temperature, respectively. Convective HTC is defined as follows:

$$h = \frac{q''}{T_{cpu-mean} - T_{in}} \tag{12}$$

The amount of pumping power required for the HS is calculated as follows:

$$W_{pump} = \dot{V}\nabla p \tag{13}$$

To assess the overall performance of nanofluid in the HS, the PEC is also defined:

$$PEC = \frac{h_{nf}/h_{bf}}{\Delta p_{nf}/\Delta p_{bf}} \tag{14}$$

4 NUMERICAL METHOD

ANSYS FLUENT 18.0 software is used to solve the governing Equations. The second-order upwind method is employed to discretize the momentum Equation and the SIMPLEC algorithm with the staggered grid is employed to couple pressure and velocity fields. The convergence criterion is set at 10^{-8} for the energy Equation and 10^{-6} for the other Equations based on the scaled residuals. The independence of the grid is investigated. "Table 2" shows the results for channel and tube Reynolds numbers of 700 and 70, respectively, when ϕ = 1%.

Table 2 Grid study results

W_{pump} $[W]$	ΔT $[K]$	Number of elements
0.0186	3.386	24000
0.0475	3.387	27000
0.0568	3.388	74000
0.0587	3.388	128000
0.0591	3.388	195000
0.0591	3.388	330000

Based on “Table 2”, the grid resolution of 195,000 is selected for further simulations (“Fig. 2”).

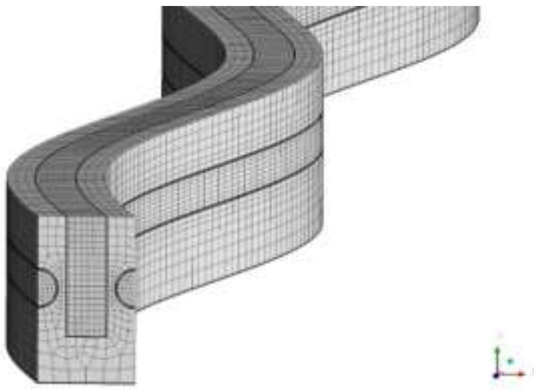


Fig. 2 An image of the grid used for current simulations.

The present work is verified with the experimental findings of Sui et al. [8]. Figure 3 illustrates a comparison between the *Nu* calculated by present numerical simulations and the one reported by Sui et al.

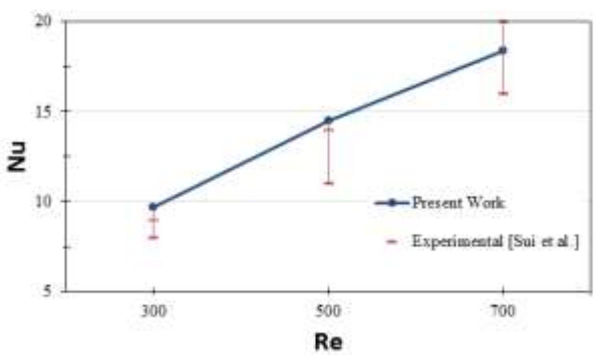


Fig. 3 Nusselt number versus values of *Re*.

According to this paper, a wavy microchannel is modeled based on the parameters presented in “Table 3”. A comparison between the amount of *Nu* calculated by numerical solution and the experimental results of Sui et al. is shown in “Fig. 3”. This figure displays that the present results are in good agreement with experimental data. The maximum error between the present study and the experimental data is 8%, which is related to the flow with *Re* = 300. For *Re* = 500, the error is 3% and for *Re* = 700, the present results are in agreement with the experimental data.

Table 3 Geometric parameters of the validation problem (Sui et al. 2011)

Value	Parameter
193 μm	W_f
207 μm	W_C
100 μm	H_f
406 μm	H_C
138 μm	a_W
25 mm	L_Z

Sivakumar et al. [34] conducted an experimental study on a serpentine microchannel in the presence of alumina/water nanofluid. Their work is used to validate the present simulations for various values of hydraulic diameter including 810, 830, 860, and 890 μm (“Table 4”).

Table 4 Dimensions of the copper microchannel considered (Sivakumar et al. 2016)

Hydraulic diameter (μm)	Height (μm)	Width (μm)	Spacing (μm)
810	830	800	13000
830	870	800	13500
860	920	800	13800
890	990	800	14000

A comparison between the amount of heat transfer coefficient calculated by numerical solution and the experimental results of Sivakumar et al. [34] is shown in “Fig. 4” for the hydraulic diameter of 810 μm. This figure displays that the present results are in good agreement with experimental data for Al_2O_3 nanofluid with ϕ = 0.01%.

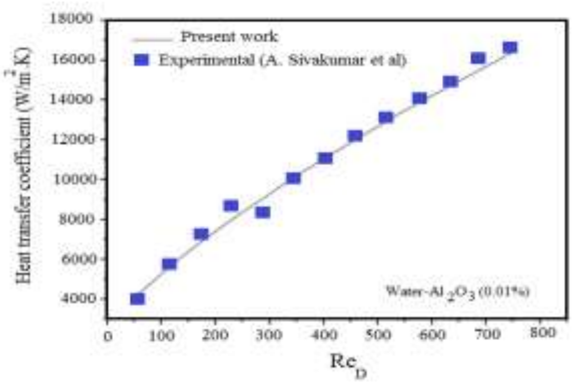


Fig. 4 The amount of heat transfer coefficient versus Reynolds number.

5 RESULTS AND DISCUSSION

The purpose of the current numerical study is to investigate the hydraulic and thermal behavior of a wavy microchannel HS with Ag/water-EG (50%) nanofluid for cooling digital processors. The influence of microtubules on HS performance is also investigated. The simulations are based on ϕ = 0%, 0.1%, 0.5%, and 1%, and *Re* = 300, 500, 700, 1000, and 1500. *h* is shown in “Fig. 5” for the HS with and without microtubes at different values of *Re* and ϕ. The dashed lines correspond to the ones without microtubes and solid lines are for that with the microtubes.

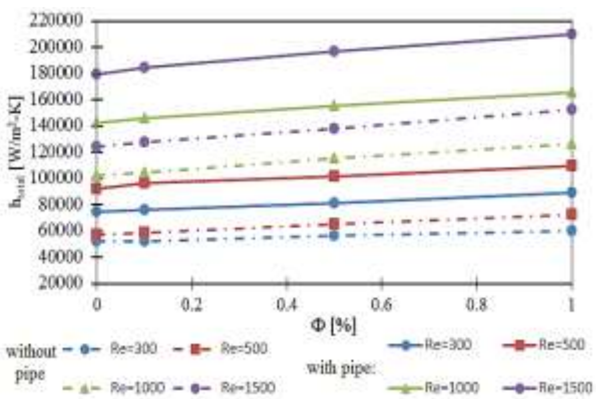


Fig. 5 Total HTC for the heat sink with and without microtubes at various values of *Re* and $\boldsymbol{\phi}$.

The figure shows that *h* increases by increasing ϕ for all the cases. On the other hand, as *Re* increases, the effect of ϕ becomes stronger. It is found that the addition of microtubes results in a substantial increase in the overall thermal coefficient of the system such that *h* for the system with microtubes at *Re* = 500 and 700 is 80% and 110% higher than that without microtubes at *Re* = 1000 and 700, respectively. This is due to that the presence of microtubes along the channel rises the heat exchange between the HS body and the fluid. On the other hand, the separation of the microchannel and tube paths and the creation of higher temperature mixing in the fluid stream cause the fluid temperature to increase along the channel wall decreases. In other words, the temperature difference between the fluid and solid does not decrease significantly, leading to an increase in the HTR. The enhancement effect of nanoparticles and microtubes can also be investigated based on $T_{CPU,Max}$ and $T_{CPU\text{-}Mean}$. As ϕ increases, the performance of the CPU is improved, leading to a reduction in the surface temperature. This is due to that a low-temperature gradient is required to transfer the heat generated by the processor (“Fig. 6”).

Figure 6 displays the decreasing trend of $T_{CPU\text{-}Mean}$ due to the addition of nanoparticles. The performance of nanoparticles at lower values of *Re* is better: the addition of nanoparticles at lower values of *Re* causes the processor surface temperature to change more. On the other hand, the addition of microtubules leads to a much stronger performance. For example, in a HS without microtubes, $T_{CPU\text{-}Mean}$ = 315 K at *Re* = 300. The addition of microtubes causes the temperature to decrease by 309 K, while the addition of 1% nanoparticles decreases the surface temperature by 313 K.

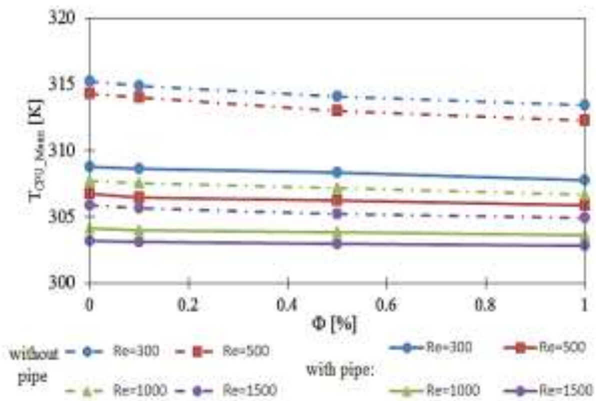


Fig. 6 $T_{CPU\text{-}Mean}$ for different values of $\boldsymbol{\phi}$.

Apart from the T_m of the CPU surface, another important parameter is $T_{CPU,Max}$ and the uniformity of the CPU temperature because very high CPU temperature and its high-temperature difference result in negative effects on the CPU performance. To evaluate this point, $T_{CPU,Max}$ is plotted in “Fig. 7” for different amounts of ϕ.

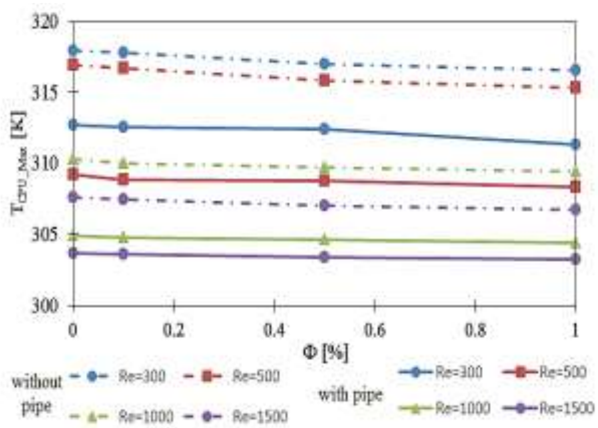


Fig. 7 $T_{CPU,Max}$ for different values of $\boldsymbol{\phi}$.

Figures 6 and 7 demonstrate that CPU surface temperature is 308 K for the case without microtubes at *Re* = 1000, while $T_{CPU,Max}$ is 310 K. This difference is due to the nonuniformity of heat transfer at the CPU surface due to different heat-transfer conditions and various thermal resistances of the points on the CPU surface, leading to the temperature difference at the surface. The nanoparticles improve cooling performance and reduce $T_{CPU,Max}$. In the same case, the presence of microtubes improves the HTR of various parts of the processor and reduces the thermal resistance of its points, resulting in a reduction in the difference between $T_{CPU\text{-}Mean}$ and $T_{CPU,Max}$. As the temperature inside the ducts becomes more uniform, the mixing of the fluid flow is improved and the thermal performance of the duct enhances. In “Fig. 8”, the nanofluid temperature contour is shown at the outlet.

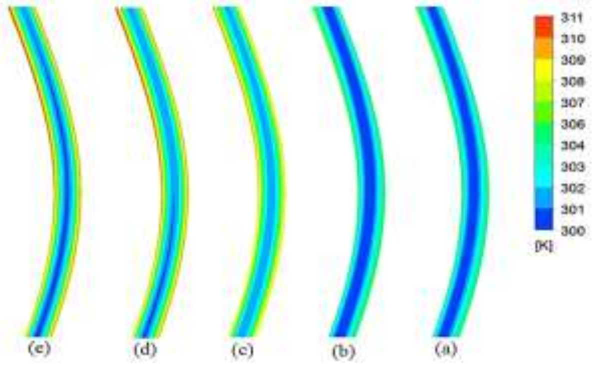


Fig. 8 Temperature distribution in the rectangular channel: (a): Re = 700, φ = 1%, (b): Re = 700, φ = 0.1%, (c): Re = 300, φ = 1%, (d): Re = 300, φ = 0.5%, and (e): Re = 300, φ = 0.1%.

In order to display the desired information properly, the image of the microtube is enlarged and is shown only in the lateral direction so that a complete arc of the microtube can be seen and also its color image and contour can be recognized. In all cases, the outer region of the fluid flow is hotter than its central part, but the central part temperature remains unchanged for cases *a* and *b*, and the influence of the addition of nanoparticles on heat diffusion from the walls to the center of the flow is not detectable.

This result is due to the high flow velocity and stronger convective HTR in the direction perpendicular to the conductive HTR. Because of the no-slip boundary condition on the walls and the establishment of the mass conservation and momentum laws, the fluid flow rate in the central part is stronger, leading to more concentration of heat capacity in the central part of the flow. As the fluid mixing enhances, the heat near the walls is transferred better and faster to the central fluid flow, which reduces the amount of temperature gradient required to transfer a certain amount of heat from the wall to the flow center. In the present work, two factors lead to the improvement of the fluid mixing: (i) the curvature in the geometry of the channel and the microwave and (ii) adding nanoparticles to the BF and the intensification in the thermal conductivity of the fluid. In the present work, the influence of the geometry of a HS is compared with the influence of adding nanoparticles, and the combined effect of the two is also investigated. In “Figs. 8c, 8d, and 8e”, which relate to *Re* = 300, thermal diffusion in the perpendicular direction is better due to the lower strength of convective heat transfer. The addition of nanoparticles accelerates this phenomenon so that the temperature changes reach the center of the flow. To reach the temperature changes to the central part of the flow, a temperature gradient perpendicular to the flow path is required, which means an increase in the outer region fluid temperature, leading to a reduction in *h* between the fluid and the solid body and intensification in the solid surface temperature for transferring heat flux. Similar to the case of the rectangular channel, this is true for the channel with microtubes, as shown in “Fig. 9”. Here, the effect of heat transfer is much higher in the vertical direction because of the smaller cross-sectional area, resulting in much higher temperature variations

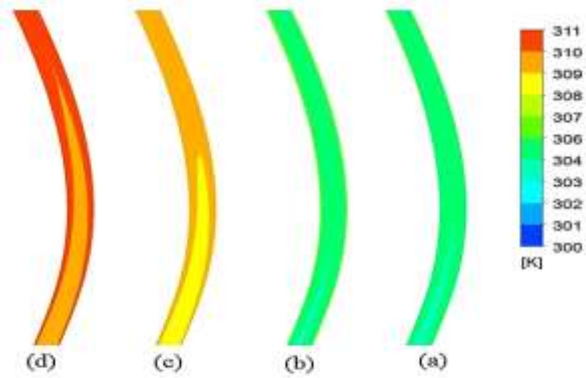


Fig. 9 Temperature distribution in microtubes: (a): Re = 700, φ = 1%, (b): Re = 700, φ = 0.1%, (c): Re = 300, φ = 1%, and (d): Re = 300, φ = 0.1%.

Figures 8 and 9 show that the effect of the addition of nanoparticles on microchannel and microtube performance is positive, but its positive effect decreases with increasing *Re*. According to the contours presented in “Fig. 8”, the temperature in the center of the flow is more variable than in the microchannel. In fact, the HTR to the center of the microchannel flow is better. This may be due to the smaller diameter of the microtube than the microchannel, which reduces the distance between the center of the flow and the walls in the microtube Another point is that the flow rate in the microtube is lower because *Re* in the microtube is 10 times less than the microchannel, which reduces its heat capacity. This makes it more effective to determine the temperature of the HS wall based on the heat capacity of the microchannel. Hence, the temperature of the walls increases, and more thermal pressure is applied to the microtube, leading to that more heat reaches the central fluid flow and the temperature enhances.

Figure 10 shows the parameter θ for different values of ϕ and *Re*. Smaller values of θ indicate more uniformity of the temperature distribution. As *h* increases because of adding nanoparticles into the BF, the thermal performance is improved. It is observed that the temperature is more uniform on the surface but there is an inverse relationship between the effect of nanofluid concentration and *Re*. As *Re* increases, the uniformity in temperature distribution is created due to the stronger convection heat transfer, and therefore the effect of nanofluid is not significant. On the other hand, the creation of microtubes results in a more uniform distribution of CPU surface temperature as a result of the increase in the HTR and reduction in thermal resistance of the furthest points of the processor. For example, the surface temperature distribution for a flow at *Re* = 700 with microtubes is more uniform than that without microtubes at *Re* = 1500.

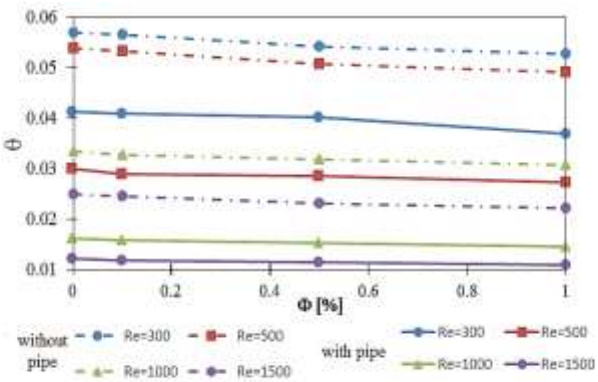
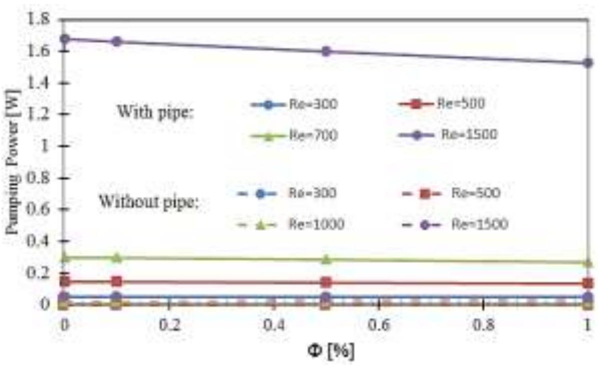
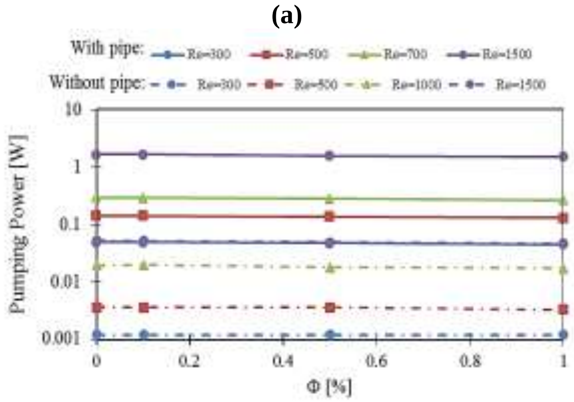


Fig. 10 Flow uniformity based on θ for different values of ϕ and *Re*.



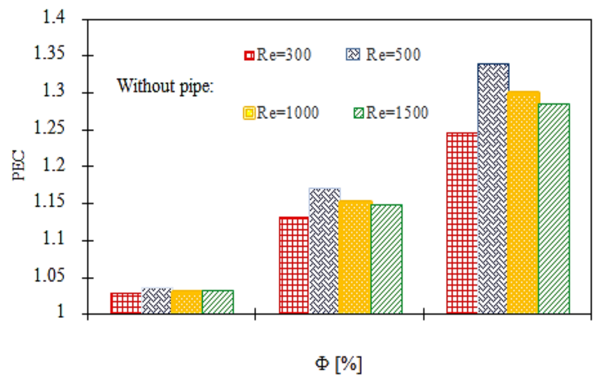
(a)



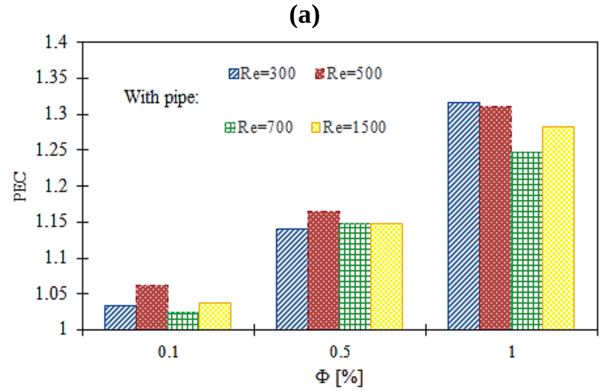
(b)

Fig. 11 The amount of pumping power required for different cases.

Thermal performance improvement requires generating a flow by the pump. In "Fig. 11a", the amount of pumping power required for different cases is presented. In "Fig. 11b", this comparison is presented as semi-logarithmic. It is observed that the addition of microtubes to the system increases the need for pumping power so that the pumping capacity of a HS without microtubes at *Re* = 1500 is equal to that with microtubes at *Re* = 300. At *Re* = 700, the power about 6 times is required compared to the case without microtubes for *Re* = 1500. On the other hand, this figure displays that the addition of nanoparticles reduces the pumping power required. This phenomenon occurs due to the decrease in the flow velocity due to an increase in the fluid density when *Re* is kept constant.



(a)



(b)

Fig. 12 PEC values for dissimilar values of ϕ and *Re* :(a): without microtubes, and (b): with microtubes.

The PEC of the system is calculated for comparison between the thermal performance improvement and the pumping power costs. This parameter considers thermal and hydraulic effects together by using a reference model. In "Fig. 12", different states are compared by defining the BF state as the reference case.

This figure displays that the addition of nanofluids does not have the same effect in different modes. While at 0.1% concentration, it has a maximum improvement of 5%, this improvement is greater for the case with microtubes. For 0.5% concentration, maximum improvement is 15% that is almost identical in both cases (with and without microtubes). The concentration of 1% leads to a 35% improvement, whereas the addition of nanoparticles improves the performance of the system without microtubes.

The reason for this is the proper performance of the BF system because adding nanoparticles improves the thermal diffusivity of the fluid. When the effective factor in improving the performance of the system depends on the fluid thermal diffusivity, the addition of nanoparticles enhances the performance of the system. In this section, the previous process is repeated and only the results are presented. The pressure drop is set to a constant value of 500 kPa, which is applied to the microtubule and microchannel when Re = 530. The power consumption of the pump is less than 60 mW.

6 CONCLUSIONS

In this work, the influence of microtubes placed on the walls of a wavy microchannel HS was examined. Furthermore, the influence of using a bio nanofluid was evaluated. This study was performed using experimental data for Ag/water-EG (50%) nanofluid prepared by tea leaves synthesis. To investigate the cooling effects under different flow conditions and concentrations of nanoparticles, the processor was considered and simulated. It was understood that the microtubes improve the thermal performance and intensify the pumping power consumption by about 10 times. The influence of nanofluid concentration on HTR was evaluated and it was demonstrated that the influence of nanofluid is more dominant at low Reynolds numbers. It was also observed that the system performance is improved with increasing *Re*. The presence of microtubes increased the uniformity of the CPU surface temperature distribution and a reduction in its TCPU-Mean. As ϕ increases, the pumping power decreases when Re is kept constant. It was revealed that an increase in ϕ results in intensification in the PEC of the system, which is higher at larger values of Re. It also seems that the idea of the same pressure drop for microtubules and microchannels is more practical and operational

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