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Research Paper

Rotating Cylinder Turbulator Effect on the Heat Transfer of a Nanofluid Flow in a Wavy Divergent Channel

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Abstract. In this research study, the numerical Galerkin Finite Element Method (GFEM) is used for forced laminar convection heat transfer of Cu-water nanofluid in a divergent wavy channel including a rotating cylinder turbulator. The above boundary of the channel is in low temperatures and the bottom boundary is in hot temperatures as well as the cylinder wall temperature. It is assumed that the cylinder rotates in the cavity and makes vortexes to enhance heat transfers. The dimensionless governing equations including velocity, pressure, and temperature formulation are solved by the Galerkin finite element method. The results are discussed based on the governing factors such as nanoparticle volume fraction, Reynolds number, cylinder diameter and rotating velocity. As a main result, among the all studied parameters (Re, u, ϕ and r), increasing the Re number has the most effect on heat transfer which has 4.8 and 1.6 Average Nu for the cylinder wall and wavy wall, respectively.

Keywords: Turbulator; Nusselt Number; Forced Convection; Nanofluid; GFEM.

1. Introduction

Nanofluids, which were proposed by Choi et al. [1] in 1995, has attracted many scholars' attention due to the excellent heat transfer performance. Nanofluids are two-phase suspension systems formed by adding nanoparticles in the base solution in a certain proportion, which consists of base fluids and nanoparticles. Nanoparticles can be made of metallic oxide, metals, carbon nanotubes and semiconductors, while the base fluids are water, glycol or oil. Nanofluids are widely applied in many enhanced heat transfer processes, such as electronic component cooling [2], engine cooling [3], heat pipe heat sink [4], solar collectors [5], etc.

In recent years, forced convection of nanofluids has been examined by many scientists. Liu et al. [6], numerically investigated the heat transfer in forced convection type of nanofluid in an arched square channel using the Eulerian-Lagrangian method. Their findings showed that multiple flow constructions result in temperature contour values and concentration distribution of multiple nanoparticles. Nguyen et al. [7], simulated the nanofluid forced convection increment in the wavy channel with obstacles. They showed that the heat transfer values improves greatly as the spherical nanoparticles substitute by platelet particles. Andreozzi et al. [8], presented a numerical study on turbulent forced convection for water-Al2O3 nanofluid in a symmetrically heated duct include ribbs in above and below walls. Their results revealed that the thermal performances of the trapezoidal rib were lower than that of the triangular rib, but the loss of this rib was also significantly reduced. Ho et al. [9], examined the forced convective heat transportation of Al2O3-water nanofluids in an iso-flux heated cylinder, numerically and experimentally. They found that the forced convective heat transfer between wall and fluid was enhanced by adding the Al2O3 nanoparticles in the water base fluid.

Magnetic field special effects are applied in different practical applications. An external magnetic field can be used to enhance the convective heat transfer for many thermal industrial applications [10]. Therefore, the forced convection heat transfer of nanofluids in presence of an external magnetic field is worth studying. Sheikholeslami [11], investigated the nanofluid flow in a 3D porous enclosure under the magnetic field using the lattice Boltzmann method. The results showed that temperature gradient had a straight relation with Darcy number and Reynolds number while growing Lorentz forces makes a reduction in Nusselt number. Selimefendigil et al. [12], used the finite element method for the simulation of forced convection of CuO-water nanofluid over circular cylinders in a channel in presence of uniform magnetic field. Their study reported that the magnetic field has an important effect on the wake region of the cylinder. Besanjideh et al. [13], investigated the influence of uniform magnetic field on the heat transfer of nanofluid through a forward facing step channel. The results indicated that the magnetic field could strongly influence the flow separation and reattachment phenomena.

Among many methods for solving heat transfer problem, finite element modeling is one of the most powerful numerical methods for the analysis of practical engineering, which is used to solve approximate solutions of partial differential equations. With the development of computer technology, the popularization of this method improves the efficiency of solving heat transfer problem. Uddin et al. [14], investigated the 2D incompressible natural convective flow of nanofluids using finite element method (FEM). The results revealed that the thicker annulus has the best effect on improving the heat transfer rates. Ranal et al. [15], numerically modeled a vertical slender hollow cylinder by FEM and investigated the steady laminar and mixed convection flow and heat transfer characteristics of Al2O3-water nanofluid. They found the influence of nanoparticle volume fraction, wall conduction factor and physical parameters.

Recently, most of the researchers focused on the nanofluid flow behavior in different channels and investigated the effects of turbulence, vortex, heat transfer flow, etc. Islami et al. [16] investigated the effect of micromixers in a microchannel filled by nanofluids, numerically and found that recirculation zones behind the baffles are the main mechanism of heat transfer enhancements. Hussain et al. [17] investigated the influence of a rotating cylinder in flow on the heat transfer in a simple channel filled by nanofluid. Nath et al. [18] discussed the thermo-solutal buoyancy driven fluid convection and associated heat and mass transfer in a backward facing step duct include Cu-water nanofluid. Before their study, Hussain et al. [19] in a similar channel investigated the effect of adiabatic obstacles on the heat transfer of hybrid nanofluids under the magnetic field effect. Recently, Ali et al. [20] in a different numerical study, studied the effect of the oriented magnetic field and rotating cylinder in a grooved channel and reported that average heat transfer amount improves remarkably by the Reynolds number and volume fraction increment while reduces by increasing the Hartmann number. Rahimi-Esbo et al. [21] introduced the convergent sinusoidal channel and considered the turbulent forced convection jet flow in it and reported that aspect ratio and amplitude on the average Nusselt number will be improved by growing the Reynolds number. More studies about the particles/nanoparticles and nanofluids behavior are performed by the authors by different analytical methods such as DQM [22], DTM [23], DTM-Pade [24] and Ms-DTM [25]. Ghadikolaei et al. [26] investigated the nanofluid behavior in a porous medium under the MHD effect. Hatami et al. [27-30] optimized the geometry of wavy enclosures to have the better heat transfer efficiency. Also, they [31-32] presented the optimized geometry for rectangular and microchannels to reach the maximum Nusselt numbers. Ali et al. [33] investigated the mixed convection in an annulus enclosure between two cylinders which used FEM as an efficient technique for this type of problems.

In some high-level studies, Alsabery et al. [34-35] and Dinarvand et al. [36]investigated the nanofluid flow results to analysis the magnetic, porous medium and hybrid particles effects, respectively. Another mechanism of heat transfer increment is rotating cylinder which used by Nouri-Borujerdi and Nakhchi [37]. Also, Nakhchi et al. [38-41] examined the different turbulators such as louvered strip inserts for increasing the heat transfer in heat exchangers applications. They reported that the Nusselt number increased 15.6% by using nanofluid instead of water at Re = 14000 in heat exchangers. Using the hybrid nanofluids and wavy geometries are also efficient ways to increase heat transfer with are used by Ghalambaz et al. [42], Tayebi et al. [43], Alsabery et al. [44-45] and Mehryan et al. [46]. Furthermore, divergent/convergent flows such as Jeffery-Hamel flows are used widely [47-50] as well as the parallel plates [51] and special shapes of geometries [52-53] in their numerical studies. Also, Cong Qi et al. [54-56] used the nanofluid experimentally and tested the results of heat transfer enhancement in CPU cooled heat sink as microchannels [57]. Based on reviewed literature, the present work studies the heat transfer of a rotating cylinder as a turbulator in the nanofluid flow through divergent wavy channel by finite element method to find the most parameters effect on the turbulation and heat transfer.

2. Physical Model Description and Governing Equations

As depicted in Fig. 1a and b, the geometry is a sinusoidal divergent channel including a rotating cylinder turbulator and filled by cu-water nanofluid flow. Fig. 1a shows the application of this wavy channel in microchannel. As mentioned in introduction, many studies are performed by using inserts as turbulators in micro-channels/channels. So, a rotating cylinder used here as a turbulator in the channel. The inlet region wall is insulated while the upper wavy wall is in cold and below wavy wall is in hot temperatures. The geometry is selected based on [21] with a major difference in creating more turbulence in the flow. Also, no slip velocity condition between the discontinuous phase of the Cu nanoparticles and the continuous water and the local thermal equilibrium between them are considered [16]. Furthermore viscous dissipation and thermal radiations are ignored due to low temperatures and laminar flow.   So, by defining the below non-dimensional parameters [33]:

$$X = \frac{x}{D}; Y = \frac{y}{D}; U = \frac{u}{u_b}; V = \frac{v}{u_b}; P = \frac{p}{\rho_f u_b^2}$$

$$\theta = \frac{T - T_c}{\Delta T}; \Pr = \frac{\nu_f}{\alpha_f}; \text{Re} = \frac{u_b D}{\nu_f} \tag{1}$$

The 2D mixed convection flow in the problem is written in the follow using the conservation of mass, momentum, and energy by the next dimensionless forms [16]

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{2}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{\text{Re}}\frac{\nu_{nf}}{\nu_f}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{3}$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{\text{Re}}\frac{\nu_{nf}}{\nu_f}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) \tag{4}$$

$$U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{1}{\text{Re}\Pr}\frac{\alpha_{nf}}{\alpha_f}\left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right) \tag{5}$$
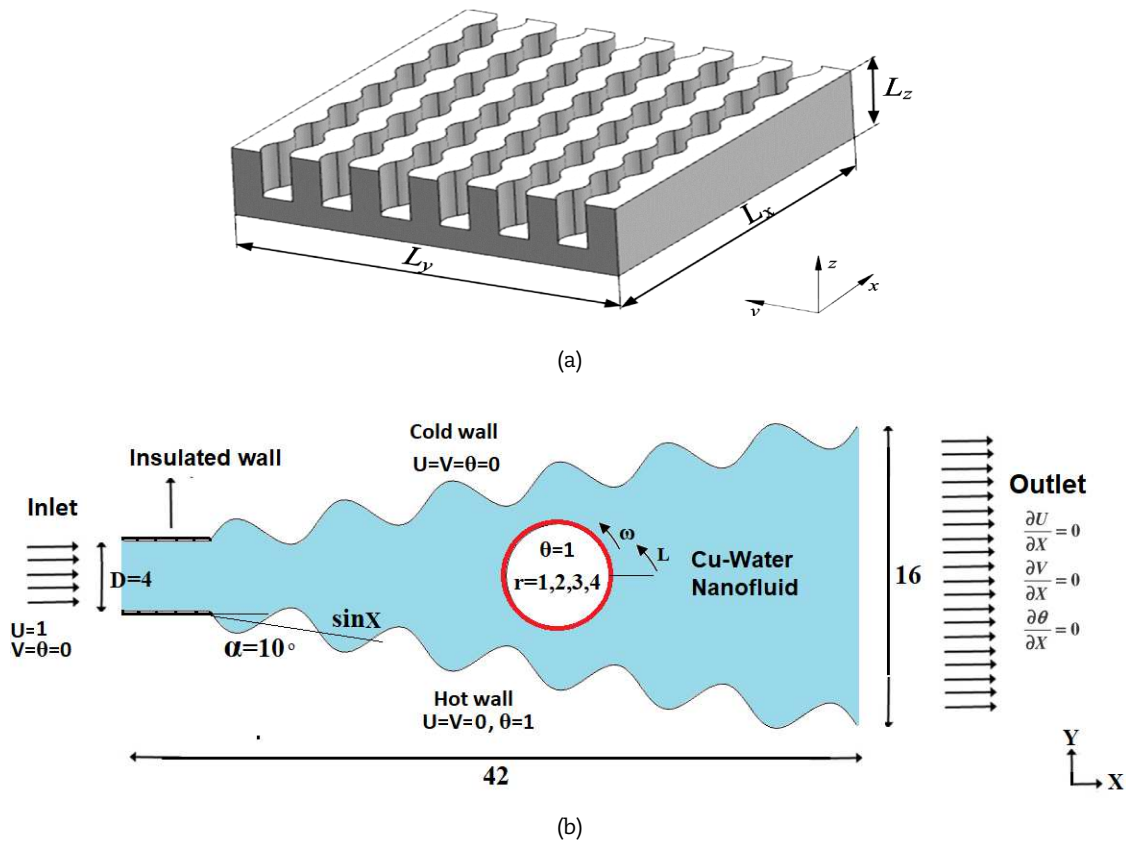
(a)

(b)

Fig. 1. a) a wavy micro-channel [57], b) Schematic of wavy divergent channel with cylinder turbulator

Based on the described problem, the boundary conditions at the inlet are

$$U = 1, \quad V = 0, \quad \theta = 0 \tag{6}$$

and at the outlet

$$\frac{\partial U}{\partial X} = \frac{\partial V}{\partial X} = \frac{\partial \theta}{\partial X} = 0, \tag{7}$$

at inlet solid boundaries (insulated)

$$U = 0, \quad V = 0, \quad \frac{\partial \theta}{\partial N} = 0 \tag{8}$$

at the bottom wavy wall

$$U = 0, \quad V = 0, \quad \theta = 1 \tag{9}$$

and for above wavy wall

$$U = 0, \quad V = 0, \quad \theta = 0 \tag{10}$$

Finally, for the rotating cylinder wall

$$u = a\omega, \quad \theta = 1 \tag{11}$$

which u is the tangential velocity and ω is the rotational velocity, a is the non-dimensional radius (=r/D). To find the nanofluids properties (based on Table 1), the common relations from the literature are excluded. The nanofluid density and its heat capacity can be calculated as following [33]:

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_{np} \tag{12}$$

$$\left(\rho C_p\right)_{nf} = (1-\varphi)\left(\rho C_p\right)_f + \varphi\left(\rho C_p\right)_{np} \tag{13}$$

The effective dynamic viscosity of nanofluid is used based on Brinkman's equation [33]

$$\mu_{nf} = \frac{\mu_f}{(1-\varphi)^{2.5}} \tag{14}$$

Table 1. Properties of base fluids and copper (Cu) nanoparticles [18]

Material/Properties	ρ (kg/m³)	Cp (J/kg-K)	k (W/m-K)	μ (kg/m-s)
Water	997.1	4179	0.613	0.000372
Cu	8933	385	400	-

Table 2. Mesh independent study for pure water ($\varphi = 0$), when Re = 20, u = 1, r = 3

Mesh type	Mesh element	Nu1	Nu2	CPU time (s)
Extremely coarse	605	0.8429	1.3233	8
Extra coarse	916	0.8826	1.3321	9
Coarser	1487	0.8283	1.7399	10
Coarse	2640	0.8536	2.1131	11
Normal	4272	0.7501	2.2720	13
Fine	5193	0.7504	2.3873	14
Finer	7548	0.6939	2.2863	14
Extra fine	23766	0.6399	2.2847	40
Extremely fine	85473	0.6267	2.2804	133

and Maxwell equation is applied to find the nanofluids thermal conductivity [33]:

$$k_{nf} = k_f \frac{\left(k_p + 2k_f\right) - 2\varphi\left(k_f - k_p\right)}{\left(k_p + 2k_f\right) + \varphi\left(k_f - k_p\right)} \tag{15}$$

The local Nusselt numbers over the lower wavy wall and cylinder wall are calculated by [53]

$$Nu = \left(\frac{k_{nf}}{k_f}\right)\frac{\partial\theta}{\partial n} \tag{16}$$

where n is the normal direction. In this study, the average Nusselt numbers on the describe surfaces are calculated as [53]:

$$\bar{N}u = \frac{1}{L}\int_0^L Nu(\theta)\ d\theta \tag{17}$$

where L is the arc length which is calculated for wavy wall and cylinder wall lengths. In this study, the fluid motion is presented by the stream function (ψ) which can be defined from the velocity components in X and Y directions (i.e. U and V). In a two dimensional study, the relationships of stream function and velocity components can be presented as [33]:

$$U = \frac{\partial\psi}{\partial Y}, \quad V = -\frac{\partial\psi}{\partial X} \tag{18}$$

In a single equation, the definition can be written as

$$\frac{\partial^2\psi}{\partial X^2} + \frac{\partial^2\psi}{\partial Y^2} = \frac{\partial U}{\partial Y} - \frac{\partial V}{\partial X} \tag{19}$$

3. Numerical methodology, Grid Test and Code Validation

Due to coupled PDE governing equations of continuity, momentum and energy equations which were presented above, the problem must be solved by an efficient numerical technique. For this purpose, the dimensionless Eqs. (2-5) and accompanying boundary conditions of Eqs. (6-11) wants to be solved numerically with assistance of the Galerkin finite element method (GFEM). P2-P1 Lagrange finite element is applied to solve the continuity and momentum equations while the Lagrange-quadratic finite element is chosen for the energy equation. The variables within the domain are divided into non-flapping zones through employing initiation functions. After replacement the variables into the dimensions governing equation, residual will produce and it must be resolved to reinforce equal to zero up the computational region. To simplify the nonlinear terms in the momentum equations, a Newton-Raphson iteration algorithm was used. The iteration of the present study is assumed to be convergence solution when the corresponding error of each variable is equal or less than 10^{-5}. Table 2 shows the mesh independence of the problem for pure water when Re=20, u=1, r=3. In this Table, Nu_1 and Nu_2 indicates the average Nusselt number over the wavy wall and cylinder wall, respectively. As seen, finer mesh type with 7548 elements is the best mesh number due to acceptable Nusselts accuracy and lower CPU time. After that, CPU time increased significantly, while Nusselt values haven't major changes. So, this type of mesh is used for all parts of modeling.

Also, the grid independency examination has been considered for investigating the effect of rotating turbulator on forced convection in a divergent wavy channel filled by a nanofluid. The parameter value set for this test is set to ϕ=0.06, u=1, r=3 and Re=20. The grid independence test is examined for both average Nusselt numbers over the bottom wavy wall and cylinder. As seen in the highlighted area of Fig. 2, two boundary layers are considered which their stretching factor is 1.2 and thickness adjustment was 5. By comparing the results of 9 different mesh types, the fine triangular meshing with 7548 domain elements and 390 boundary element was the suitable grid from both accuracy and CPU time (14s) viewpoints. So, this type of mesh is used for the whole document study.
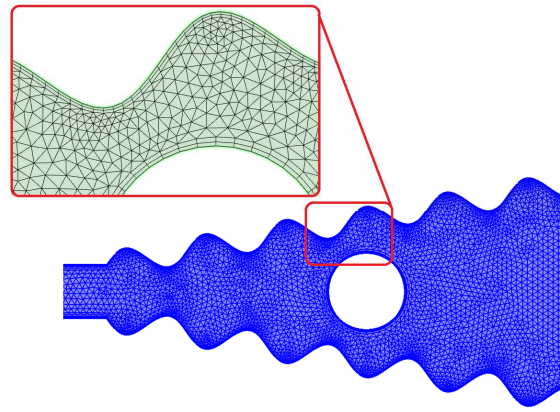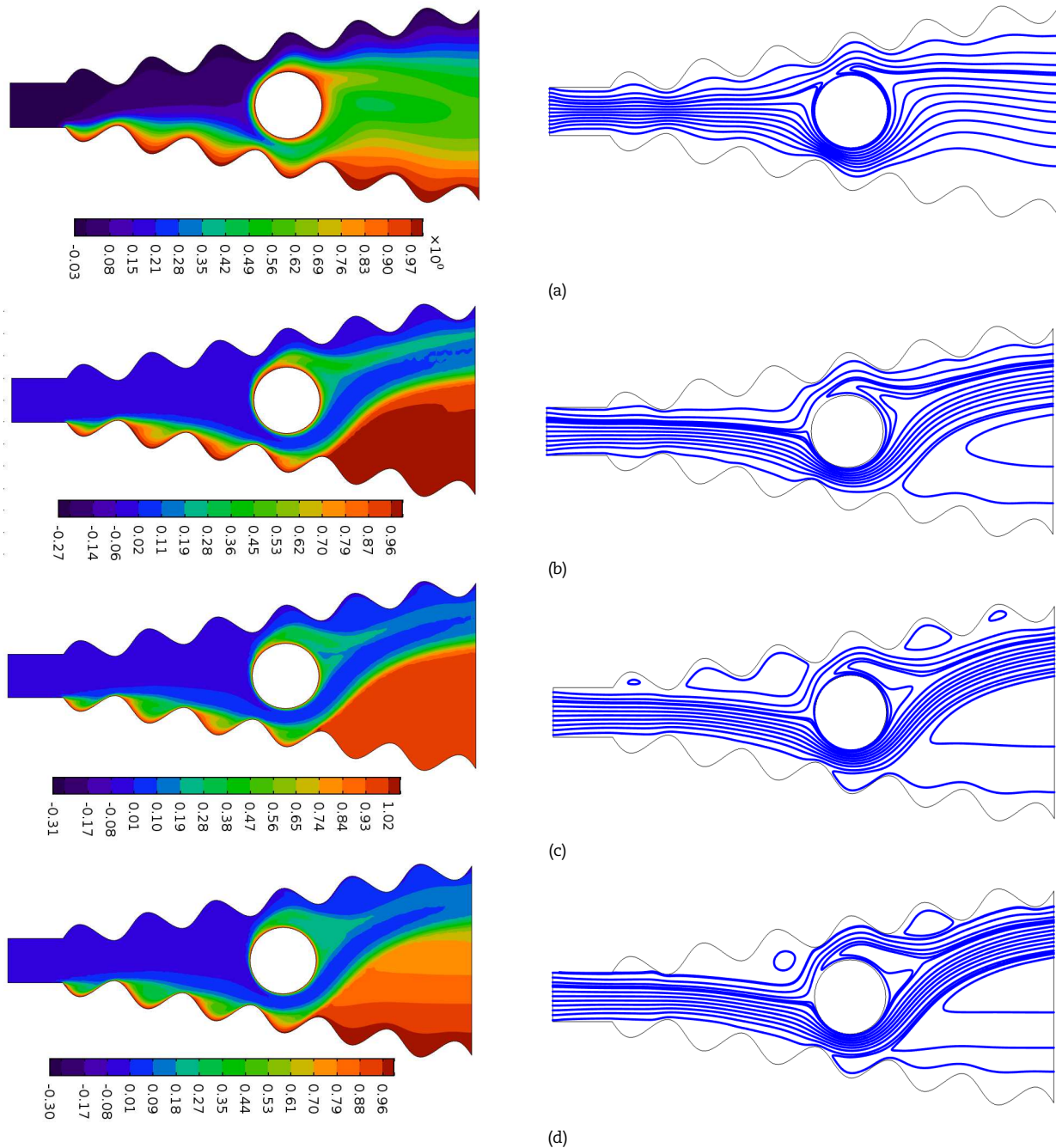
Fig. 2. Generated Mesh and boundary mesh layers

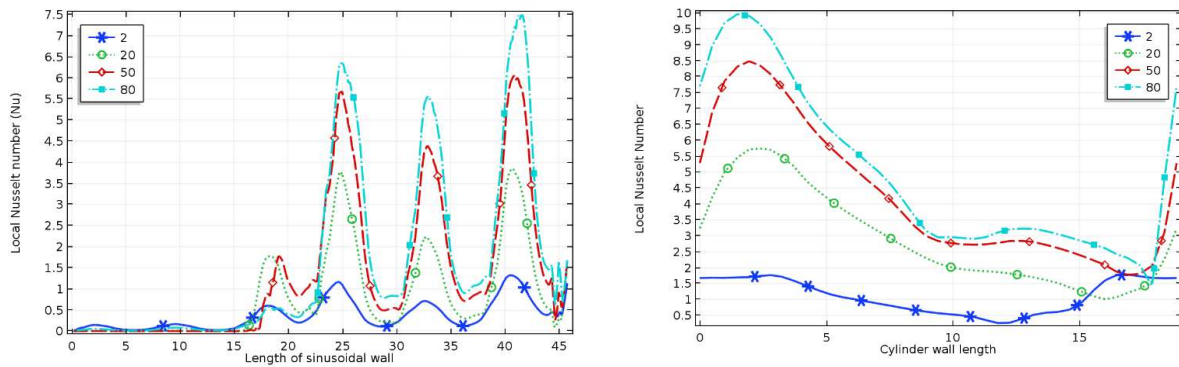**Fig. 3.** Temperatures (left) and streamlines (right) for a) Re=2, b) 20, c) 50 and d) 80 when ϕ =0.06, u=1, r=3

Fig. 4. Effect of Reynolds numbers on Local Nusselt numbers, ϕ =0.06, u=1, r=3
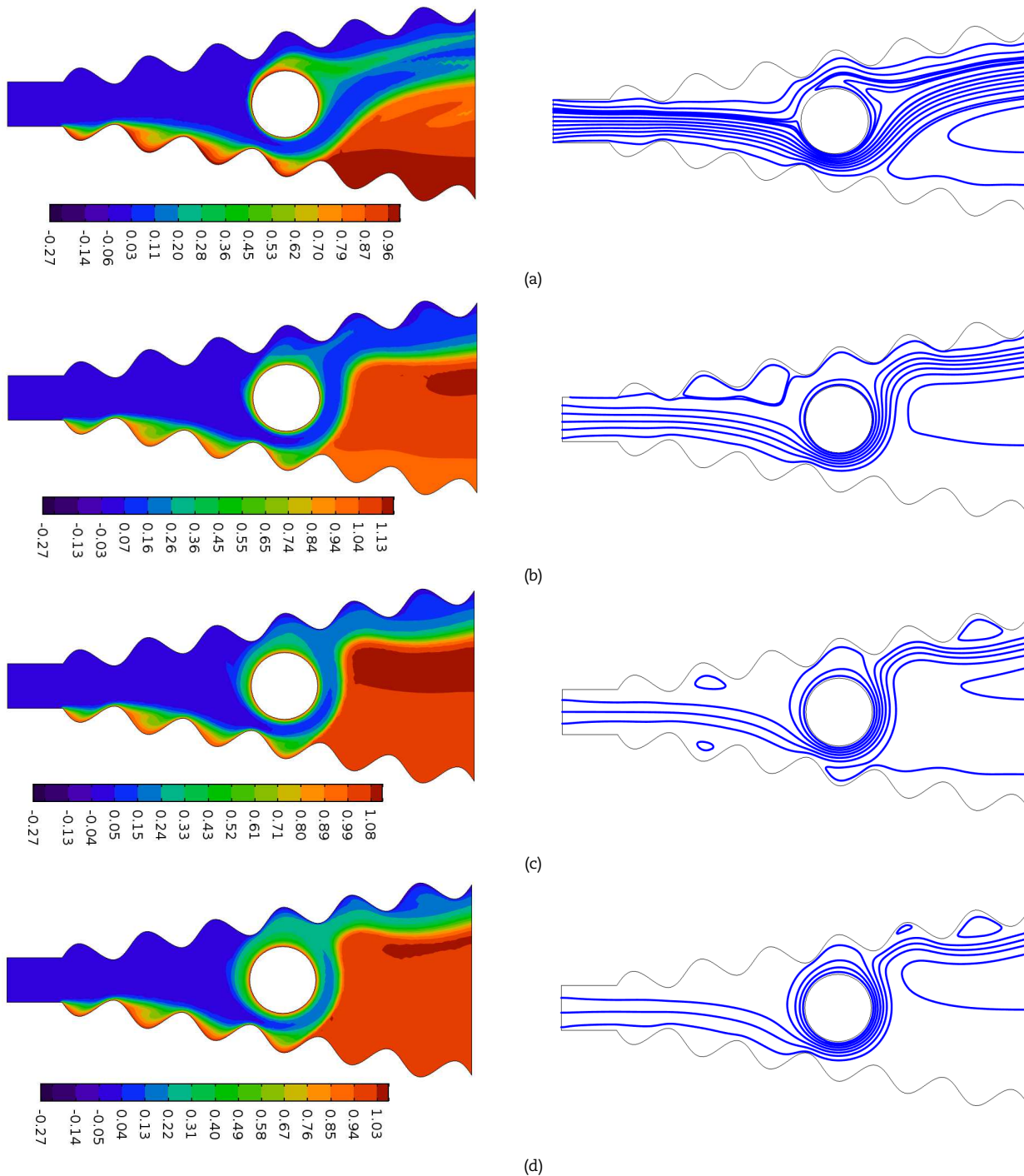

(a)

(b)

(c)

(d)

Fig. 5. Temperatures (left) and streamlines (right) for a) u=1, b) 3, c) 5 and d) 7 when ϕ =0.06, Re=20, r=3
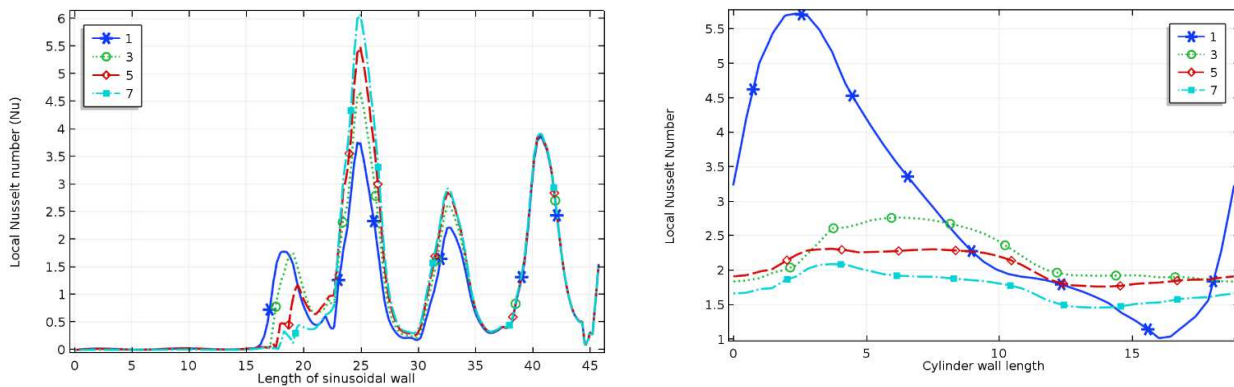
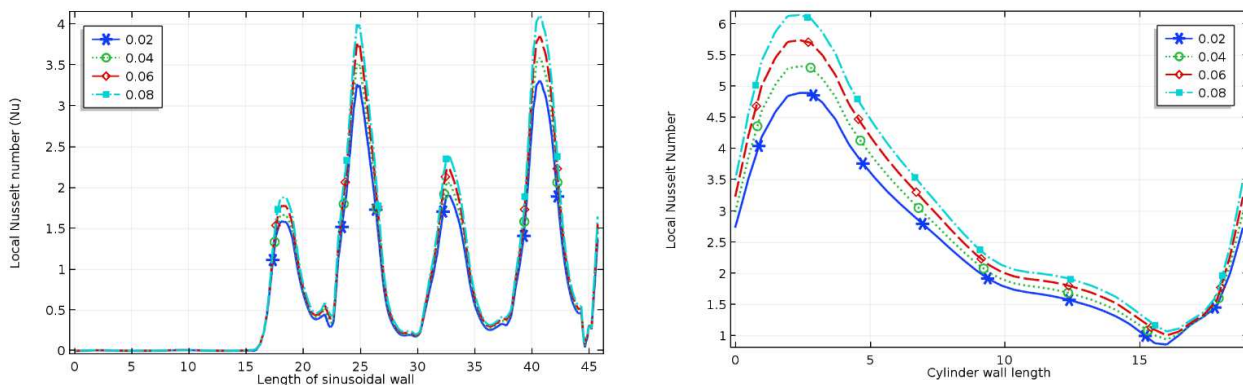**Fig. 6.** Effect of cylinder tangential velocity on Local Nusselt numbers, ϕ =0.06, Re=20, r=3

Fig. 7. Effect of nanoparticles volume fraction on Local Nusselt numbers, u=1, Re=20, r=3

4. Results and Discussion

As mentioned before, the goal of this study was modeling the laminar Cu-water nanofluid flow and heat transfer in a divergent wavy channel including a rotating circular turbulator as depicted in Fig. 1 and meshing through Fig. 2 and detailed properties are presented via Table 1. Fig 3 shows the effect of Reynolds number on temperatures and streamlines when φ=0.06, u=1, r=3.From these figures, it can be concluded that by increasing the Re numbers the vortexes or recirculation zones around the wavy walls and cylinder are increased and this is the main reason for higher temperature areas downstream. This fact is presented in Fig. 4 as local Nusselt numbers. By increasing the Reynolds number up to 80, the local Nusselt numbers on the wavy wall peaks reach 7.4 maximum and for the turbulator cylinder wall, it reaches to near 9.9. From the local Nusselt number, it is also evident that for wavelengths of more than 17 the peak values are increased significantly which is due to the presence of rotating cylinder turbulator caused by both its higher temperature and vortex generations.

To find the effect of the tangential velocity of turbulator (u), Fig. 5 and Fig. 6 are depicted. As seen, by its greater rotating velocity (3-4), the streamlines more forced to rotate around the cylinder and push the flow to upper direction, so at the entrance flow (length of wavy wall up to 23 in Fig. 6), by increasing u, more heated flow is guided to upside of the channel and the local Nusselt number decreased at the lower wavy wall. But, for the downstream of the flow, the Nusselt number is increased due to more recirculation zones caused by greater turbulator velocity. For the local Nusselt number around the cylinder, it can seem that more rotating velocities make lower heat transfer from its wall. In this paper, the effect of nanoparticles volume fraction on the results is also investigated. Due to not a great difference in the contours, their results are not presented, but Fig. 7 shows its details which confirms that increasing the ϕ is efficient of Nusselt number enhancements for both the wavy and cylinder walls. Another important parameter of the rotating cylinder turbulator is its diameter in the flow as presented in Fig. 8.

Although increasing the cylinder diameter makes a more blockage on the flow patterns, but it also make more vortexes which is easily fundable by comparing the parallel streamlines in Fig. 8-a which those of Fig. 8-d. So, these recirculation zones caused high temperatures when r=4 up to 1.4 in downstream areas. These notable increases in the local Nusselt numbers are shown in Fig. 9 which are maximum 5.6 and 7.1 for the wavy wall and cylinder wall, respectively.

Finally, to have a comparison between the studied parameters on the average Nusselt numbers, Figs. 10 are depicted in constant y-value. It can be concluded that by increasing all these parameters (except u parameter for cylinder wall), the Average Nu number is increased. But, among the all studied parameters (Re, u, ϕ and r), increasing the Re number has the most effect on heat transfer which has 4.8 and 1.6 Average Nu for the cylinder wall and wavy wall, respectively. Also, the minimum effective parameter among them is the tangential velocity of cylinder which has a maximum 2.9 and 1 average Nu for the cylinder wall and wavy wall, respectively.
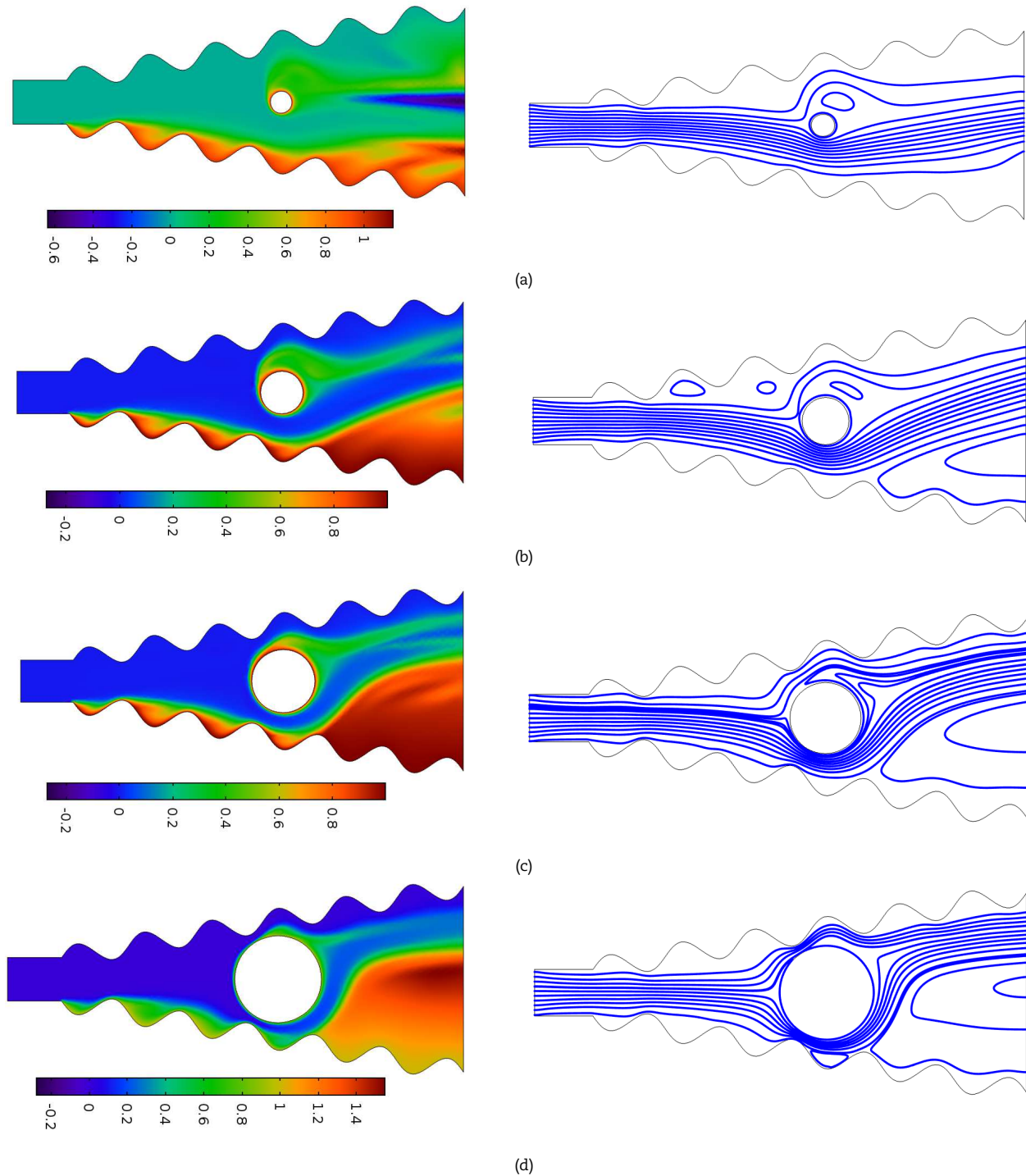
(a)

(b)

(c)

(d)

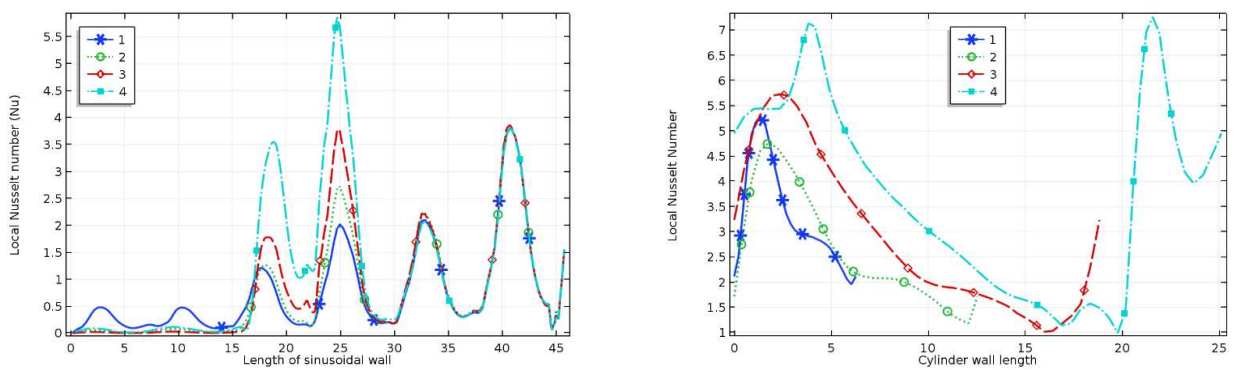**Fig. 8.** Temperatures (left) and streamlines (right) for a) r=1, b) 2, c) 3 and d) 4 when φ=0.06, Re=20, u=1

Fig. 9. Effect of cylinder radius on Local Nusselt numbers, u=1, Re=20, φ=0.06
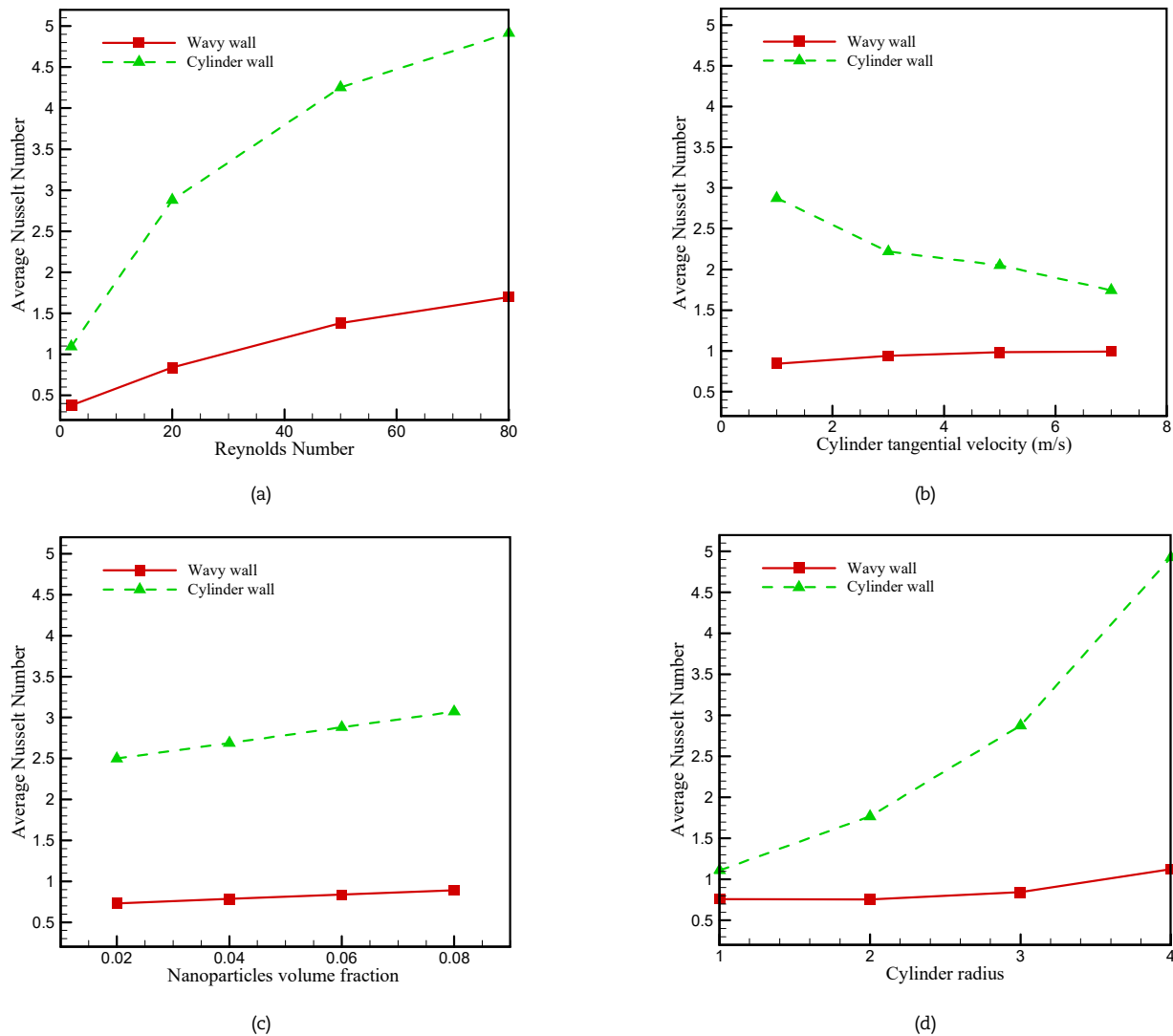
Fig. 10. Average Nusselt number effect of a) Reynolds number, b) Cylinder velocity, c) Nanoparticles volume fraction and d) Cylinder radius

5. Conclusions

In this paper, forced convection heat transfer of divergent wavy channel filled by Cu-water nanofluid in the existence of a rotating cylinder turbulator was studied numerically using the Galerkin weighted residual finite element method. The enclosure is sinusoidal divergent channel and the influence of nanoparticles volume fraction, Reynolds number, velocity and diameter of turbulator on the heat transfer mechanism is investigated and it is found that growing the Re number and diameter makes the vortexes or recirculation zones around the wavy walls and cylinder which is the main reason of heat transfer enhancements. Also, it is founded that the minimum effective parameter among them is the tangential velocity of the cylinder which had a maximum 2.9 and 1 average Nu for the cylinder wall and wavy wall, respectively.

Author Contributions

M. Hatami and L. Sun planned the scheme, initiated the project and solved the numerical code together at Xi'an Jiaotong University; D. Jing analyzed the results; developed the mathematical modeling and examined the theory validation. H. Günerhan and P.K. Kameswaran provided suitable mathematical equations. The manuscript was written through the contribution of all authors in each related section. All authors discussed the results, reviewed and approved the final version of the manuscript.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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Nomenclature

Symbol	Description	Unit
a	Non-dimensional radius	
c_p	Heat capacitance	J/ kg. °C
D	Inlet width	
g	Gravitational acceleration	m/s^2
k	Thermal conductivity of the fluid	W/m. °C
L	Length of wavy/cylinder arc	
Nu	Nusselt number	
N	Number of undulations	
P	Dimensionless pressure	
p	Pressure	N/m^2
Pr	Prandtl number	
r	Radius of the inner cylinder	m
R	Dimensionless radius of the inner cylinder	
Re	Reynolds number	
T	Temperature	°C
U	Dimensionless velocity component in x-direction	
u	Dimensional velocity component in x-direction	m/s
V	Dimensionless velocity component in y-direction	
v	Dimensional velocity component in y-direction	m/s
X	Dimensionless coordinate in horizontal direction	
x	Cartesian coordinate in horizontal direction	m
Y	Dimensionless coordinate in vertical direction	
y	Cartesian coordinate in vertical direction	m

Greek Symbols

α	Thermal diffusivity	m^2/s
θ	Dimensionless temperature distribution	
ϕ	Solid volume fraction	
Ω	Dimensionless angular rotational velocity	
ω	Angular rotational velocity	rad/s
υ	Kinematic viscosity	m$_2$/s
ρ	Density	kg/m^3
μ	Dynamic viscosity	kg./m.s
ψ	Dimensionless stream function	

Subscripts

ave	Average
fl	Base fluid
loc	Local
c	Cold
eff	Effective
h	Hot
Max	Maximum
Min	Minimum
na	Nano fluid
p	Solid particles

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