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Numerical Study of Heat Transfer and Flow of Nanofluid Using Multi-Phase Mixture Model through Elliptical Tubes

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Abstract

This paper presents a numerical study of heat transfer of a fully developed turbulent flow inside elliptical tube with different aspect ratio of constant surface area, by using (AL_2O_3-water) nanofluid with average nanoparticles diameter (20 nm). Multi-phase mixture model has been used to calculate the Nusselt number, nanofluid velocity, and pressure drop. “The three-dimensional Navier-Stokes”, energy, and volume fraction equations are solved by ANSYS fluent with “finite volume method (FVM)”. The numerical results show reasonable acceptance with error bounds approximately to (10.34%) upon pervious experimental works. It is found that the increase in nanoparticles “volume concentration (φ)” will increase the Nusselt number with little “pressure drop” rise. The elliptical tube with 0.25 aspect ratio gives best enhancement in heat transfer compared with circular tube with maximum Nusselt number (52.9%) and nanofluid volume concentration of 1.5%, but it is less effective in the process of transporting fluids to distance due to the high pressure drops between entry and exit of fluid compared to tube with circular sections within a certain range of Reynolds number (3000-9240).

Key words: Aspect ratio, Multi-phase, Mixture model.

Nomenclature

AR “aspect ratio, (=B/A)”
A “horizontal ellipse semi-axis, (m)”
B “vertical ellipse semi-axis, (m)”
C constant
Cp “specific heat at constant pressure”, (kJ/kg · K)
dh “ hydraulic diameter”, (m)
F “friction factor “
hx “local heat transfer coefficient”, (W/m^2 K)
K “thermal conductivity”, (W/m.°C)
L tube length, (m)
ṁ “mass flow rate”, (kg/s)
Nu “Nusselt number”
p circumference, (m)
Pr “Prandtl number”
q uniform heat flux, (W/m^2)
Re “Reynolds number”
Ti inlet fluid temperature, (℃)
Tm mean bulk temperature, (K)
To outlet fluid temperature, (℃)
Ts surface temperature, (℃)
Tsi inlet surface temperature, (K)
Tso outlet surface temperature, (K)
u “fluid velocity”, (m/s)
x, y,z coordinates
Δp pressure drop, (Pa)
ρ fluid density, (kg/m^3)
η performance factor
μ viscosity, ($N.s/m^2$)
ϕ nanofluid volume consternation

1. Introduction

The growth of modern technology in data processing has led to a rise in the temperature of the systems in general and as a result of scientists and researchers for decades to find ways to improve the transfer of heat, which in turn increased the efficiency of cooling systems and also reduce the size and weight of these systems. The term of "nanofluid" technique drafted by Choi in 1995 a mixture of fluid (water, oil, ethylene glycol, and other) with nanoparticles, which have different shapes and sizes of less than (100 nm) and different types of metals, oxides and carbonates, which have different physical and thermal properties, and it’s mixed regularly and in consistent sizes and quantities[1]. Several studies have been conducted on the properties of “nanofluid”. One of the most prominent findings is that the “thermal conductivity of nanofluid (K)” is greater than the base-fluid[2][3][4]. One of the most common explanations for the increased cause of the thermal conductivity is due to “Brownian motion” for nanoparticles through base fluid[5]. There are many factors influencing the thermal conductivity of nanoparticles, such as liquid temperature, the type of nanomaterial, the size of nanoparticles, the form of nanoparticles, and the volumetric concentration[6][12].The researcher compared between experimental numerical results and created a good correlations for “thermal conductivity, (which depends on nanoparticles size), volume fraction, and temperature”. For analyzing and simulation flow convection heat transfer of nanofluid, two-phases or single-phase model are used. The feature of single-phase modeling approach is easier and needs less “computational time” to reaches the converge solution, which considered nanofluid (fluid and nanoparticles) flow with same velocity and the mixture is in thermal equilibrium. On other hand nanofluid properties are not completely specific with using single phase approach, which will effect on several factor such as friction between the fluid and solid particles and “Brownian motion” forces, the phenomena of “Brownian motion” diffusion, sedimentation, and dispersion, normally the single-phase approach are not in good promise with experimental results[7][8]. Two phase numerical approach is closer to the experimental results because it takes into consideration the slip velocity which represent movement between the fluid and solid molecular. And to completely describe envisage the flow and behavior of two flow. Many multi-phase model theories have been planned to solve such complex cases. Many published papers regarding “multi-phase flows” typically applied the mixture model theory[8]. Mixture model approach is based on the basic assumption that each phase can be mathematically distinguish as a continuum. Lotfi et al.[9] simulated nanofluids flow inside (horizontal state) in circular pipe with three different numerical model solutions, which are a single-phase model, two-phase Mixture model and two-phase “Eulerian model”. The result shown that two-phase mixture models is more exact than the other two models with experimental work. The advantage of elliptical cross section tubes that have resistance to cooling fluid less than the circular cross section tube which less pumping power requirement has become a focus of attention by a number of researchers[10]. Mohammad Shariat [8] studied flow inside elliptical tube with laminar flow. The result showed increasing “aspect ratio (AR= B/A)” in elliptic tubes reduces the “local skin friction factor”. Adnan M. Hussein [11] studied the effect of elliptical tube on heat transfer enhancement numerically by using TiO_2-water nanofluid with turbulent flow, and the result was elliptical tube can enhanced heat transfer about 9% more than circular tube.

This study deals with numerical simulation of nanofluid flow through elliptical cross sections tubes. The tubes of elliptical shape stats with different aspect ratio and constant wall area. Multi-phase mixture model used to obtain the behavior of numerical approach. The research objective is to study the effect of (Al_2O_3) nanoparticle “volume fraction” and aspect ratio of cross section tubes, for the force convection turbulent flow in elliptical tubes with different hydraulic diameter and constant surface area. The behavior of present work, “velocity, contours of temperature, skin friction factor and Nusselt number profiles”, are presented and discussed.

2. Nanofluid Properties

Thermo-physical properties of nanofluid are evaluated according to the following correlation [10] [12] [14]. (density, specific heat, dynamic viscosity, and thermal conductivity So, for thermal conductivity and dynamic viscosity there is many correlations to evaluate according nanofluid condition. density (ρ), specific heat (Cp), and thermal conductivity (k) for AL_2O_3 with (20nm) and water are given in table (1). according to mixing theory the thermo-physical properties are calculated.

Table (1): Properties of AL_2O_3 nanoparticles and water at T=318 K.

Properties	Water	AL_2O_3
Density ρ (kg/$m3$)	989	3900
“Specific heat” Cp (J/kg · k)	4180.5	890
“Thermal conductivity” K (W/m.k)	0.6412	40

The density for mixture fluid is [10]:-

$$\rho_m = (1 - \varphi)\rho_f + \varphi\, \rho_p \quad (1)$$

Where: ρ_p: is the density of nanoparticles.

The specific heat for nanofluid based distilled water is [12]:

$$(\rho * cp)_{nf} = (1-\varphi)\,(\rho * cp)_f + \varphi\,(\rho * cp)_p \quad (2)$$

Nanofluid mixture with spherical nanoparticles the thermal conductivity is given by [14]:

$$\frac{k_m}{k_f} = [\frac{(k_p + 2 * k_f) + 2\,(k_p - k_f)\varphi}{(k_p + 2 * k_f) - (k_p - k_f)\varphi}] \quad (3)$$

Where k_m, k_f, and k_p is thermal conductivity of nanofluid, base fluid nanoparticles respectively.

The dynamic viscosity for mixing AL_2O_3-water nanofluid with (10-150 nm) particle size is give [14]:

$$\frac{\mu_{nf}}{\mu_f} = \frac{1}{1 - 34.8\left(\frac{d_{np}}{d_f}\right)^{-0.3} * \varphi^{1.03}} \quad (4)$$

Where: $d_{np} = 20 * 10^{-9}$ (nanoparticles), $d_f = 0.275 * 10^{-9}$(base fluid molecular dimeter)

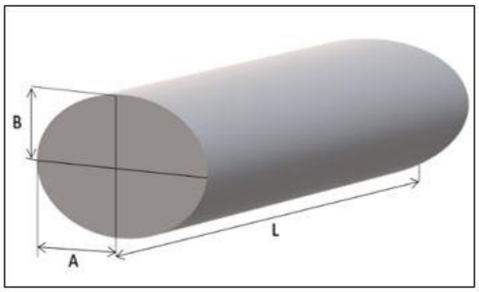
Table (2): Properties of nanofluid at T=318 K.

Properties	Water	AL_2O_3-water φ=0.5%	AL_2O_3-water φ=1.0%	AL_2O_3-water φ=1.5%
Density ρ (kg/m^3)	989	1003.55	1018.11	1032
“Specific heat” Cp (J/kg · k)	4180.5	4118.84	4054.453	3994
“Thermal conductivity” K (W/m.k)	0.6412	0.65	0.6597	0.6691
Viscosity **μ**, (kg/m·s)	0.0005666	0.00059	0.0006177	0.0006484

3. Numerical Analysis

3.1 Model description

Steady state force convection turbulent (Re =3000-9240) fully developed flow of nanofluid (Al_2O_3-water), at uniform heat flux solved numerically using program packages ANSYS FLUENT solvers which based on the finite volume method. Nanofluid flowing in a horizontal elliptical tube, with tube length L" horizontal ellipse semi-axis of A and vertical ellipse semi-axis of B" as shown in figure (1). The computational domain is composed of four tubes with different aspect ratio and same surface area as shown in figure (2). The dimensions of tubes are presented in table (3).



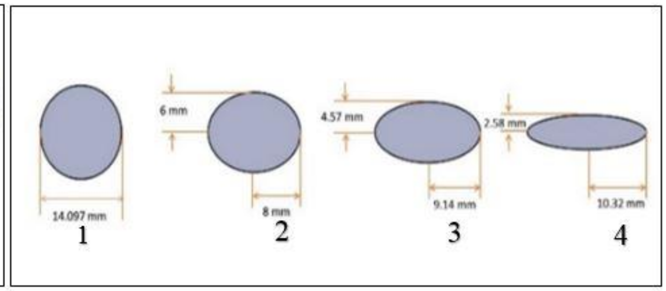


Figure (1): different tubes aspect ratio. Figure (2): Problem geometry and dimensions.

Coordinate system for an elliptic duct.

Table (3): Tubes dimensions.

	Geometry	Aspect ratio B/A	Dimensions (mm)		Hydraulic Diameter (mm)	Cross section Area (mm^2)	Surface area (mm^2)
1	**circle**	1	D =14.097		14.097	156	57573.1
2	**elliptical**	0.75	A=8	B=6	13.627	150.8	57573.1
3	**elliptical**	0.5	A=9.14	B=4.57	11.85	131.22	57573.1
4	**elliptical**	0.25	A=10.32	B=2.581	7.56	83.68	57573.1

For computational domain unistructural hexahedron mesh are used, and increase the mesh concentration near the wall to enhance the quality of the numerical prediction near the curved wall surfaces as shown in figure (3). Several mesh cell types with many different distributions in geometrical shape have been tested to safeguard that the calculated results are grid independent. Table (4) shows the number of cells used and the points of bonding, as well as the type of mesh used in computational domain.

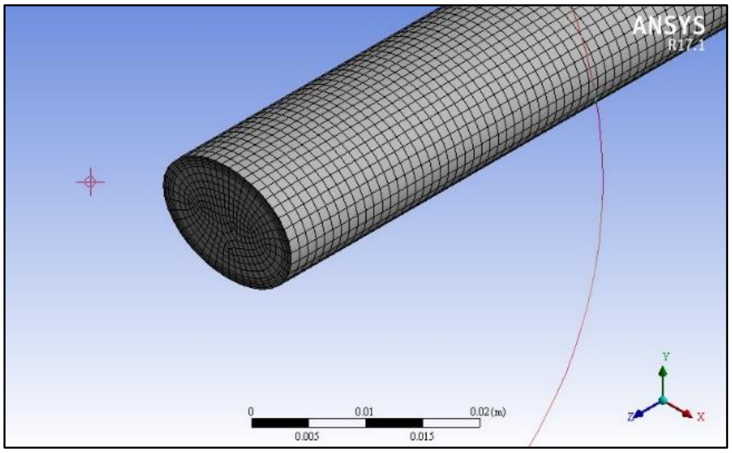


Figure (3): Unstructured used mesh for a 0.75 AR elliptic tube.

Table (4): Specifications of grid geometry.

Mesh type	Cell type	Cell size (m)	Cells no.	Nodes no.
unstructured	hexahedral	0.00085	1,078,759	1,116,576

The main assumption of current study is steady flow in three-dimensional, Newtonian fluid, incompressible fluid and turbulent flow – fully developed.

With an applied multiphase model, the nanofluid is considered to be homogenous fluid with slip velocity is equal to zero, nanofluid first phase is the “base fluid” (water) and the second-phase is (20nm) AL_2O_3 and with four nanofluid volume concentrations (φ= 0, 0.5, 1.0, and 1.5) %. For steady state mixture model governing equations describing a mixture fluid flow as shown [12]:

Continuity Equation

$$\frac{\partial}{\partial t}(\rho_m) + \nabla * (\rho_m V_m) = 0 \quad (5)$$

Where: V_m: “mass average velocity.”

$$V_m = \frac{\sum_{k=1}^{n}(\varphi_k \rho_k V_k)}{\rho_m} \quad (6)$$

Where: ρ_m: the mixture density.

φ_k: “volume fraction of phase k.”

$$\rho_m = \sum_{k=1}^{n}(\varphi_k \rho_k) \quad (7)$$

Momentum equation

$$\frac{\partial}{\partial t}(\rho_m V_m) + \nabla * (\rho_m V_m V_m) = -\nabla p + \nabla * [\mu_m (\nabla V_m + \nabla V_m^T)] + \rho_m g + F + \nabla * (\sum_{k=1}^{n} \alpha_k \rho_k V_{dr\,k} V_{dr\,k}) \quad (8)$$

Where: n: “number of phases”.

F: the body forces.

μ_m: “the viscosity of the mixture”.

$V_{dr,k}$: “the drift velocity for the secondary phase k.”

α_k : “volume fraction of phase k.”

$$\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k \quad (9)$$

$$V_{dr,k} = V_k - V_m \quad (10)$$

Where: V_k:” is velocity of phase k.”

Energy equation

$$\frac{\partial}{\partial t} \sum_{k=1}^{n} (\alpha_k \rho_k E_k) + \nabla * \sum_{k=1}^{n} (\alpha_k V_k \; (\rho_k \; E_k \; + P \;)) = \nabla * (K_{eff} \nabla T) + \; S_E \quad (11)$$

Where: K_{eff}: “the effective conductivity.”

The first term on the right-hand side of the above equation represents the energy

Transfer due to conduction.

S_E: “includes any other volumetric heat sources.”

$$E_k = h_k - \frac{p}{\rho_k} + \frac{V_k^2}{2} \quad (12)$$

h_k is sensible enthalpy of phase k and $E_k = h_k$ for incompressible phase.

K-ϵ Turbulent

The turbulent (“or eddy) viscosity”, μ_t , is computed by combining K and ϵ as follows [13]:

$$\frac{\partial}{\partial t} (\rho_m \, k) + \nabla * (\rho_m V_m k) = \nabla * (\frac{\mu_{t,m}}{\sigma_k} \nabla k) + G_{k,m} - \rho_m \epsilon \quad (13)$$

$$\frac{\partial}{\partial t} (\rho_m \, \epsilon) + \nabla * (\rho_m V_m \epsilon) = \nabla * (\frac{\mu_{t,m}}{\sigma_\epsilon} \nabla \epsilon) + \frac{\epsilon}{k} (C_{1\epsilon} G_{k,m} - C_{2\epsilon} \rho_m \epsilon) \quad (14)$$

$$\mu_{t,m} = \rho_m C_u \frac{k^2}{\epsilon} \quad (15)$$

And the production of turbulence kinetic energy, $G_{k,m}$, due to V_m means velocity gradients is expressed as:

$$G_{k,m} = \mu_t \; (\nabla V_m + (\nabla V_m)^T) \quad (16)$$

3.2 Boundary conditions

The present numerical work is performed with by uniform heat flux (q=21123 W/m^2) on the tubes wall and constant inlet fluid temperature (45℃), at nanofluid volume concentration (φ =0.5, 1.0, and 1.5) %, therefor:

- At Z=0 (inlet flow): Vi = Vm , Ti = Tm = 45℃
- At tube wall: Vm = 0, q = - k $\frac{\partial t}{\partial \eta})_{wall}$
- At outlet flow the flow rate weighting = 1

Table (5): The constant values that used in Ansys package simulation.

No.	Constant	Value	Description
1	Iterations	463	Complete Index Number
2	Convergence	10^{-6}	Convergence Absolute Criteria
3	Time	3-6 hours	Time to Reach Convergent Solution
4	Scheme	Simple	
5	Momentum	-	Second Order Upwind
6	Turbulent kinetic energy		
7	Turbulent dissipation energy		
8	Energy		

3.3 Numerical method

FVM with unstructured hexahedral mesh were employed to solve the governing equation. Momentum, volume fraction, turbulent k-ϵ, and energy was resolved by using second order upwind method to get more accurate results. The convergence criterion for all equation solution were reached with residual of 1e-6.

Nusselt number, heat transfer coefficient, and friction factor can be determined by:

$$Nu = \frac{h\,D_h}{k} \tag{17}$$

Where

$$h = \frac{q}{(T_W - T_b)} \tag{18}$$

From equations (18) and (19) the local Nusselt number will be

$$Nu = \frac{q * D_h}{k * (T_W - T_b)} \tag{19}$$

The fiction for each case is determined by Darcy equation:

$$f = \frac{2 * \Delta p * Dh}{u^2 * L * \rho} \tag{20}$$

<u>validation</u>

Figure (4) shows the average numerical “Nusselt number” versus “Reynolds number” for fully developed turbulent flow inside circular tube using water, the well-known empirical correlation of Gnielinski’s for smooth pipe is given by [15]:

$$Nu = \frac{(f/8) * (Re - 1000) * Pr}{1 + 12.7\ (f/8)^{1/2} * \left(Pr^{\frac{2}{3}} - 1\right)} \qquad (21)$$

For $1.5 \le Pr \le 2000$, $3000 \le Re \le 500000$, $f = (1.58 \ln Re - 3.82)^{-2}$

Figure (5) gives comparison of average Nusselt number of water flow with uniform heat flux inside circular tube with experimental work of A.V. Minakov[16]. It is found good agreement with maximum error bound (±9.47%).

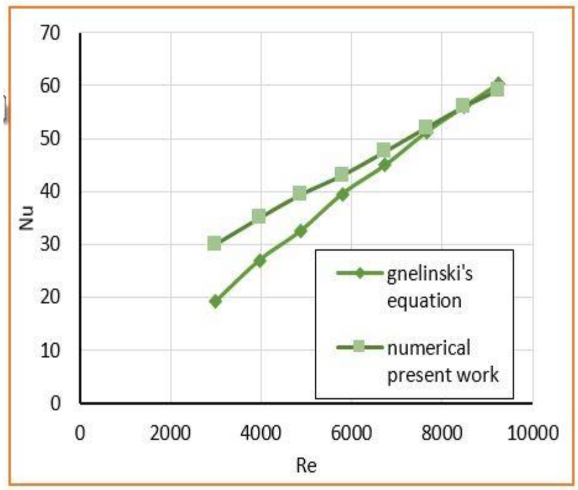


Figure (4): Compression between numerical average Nusselt numbers with Gnelinlinski correlation.

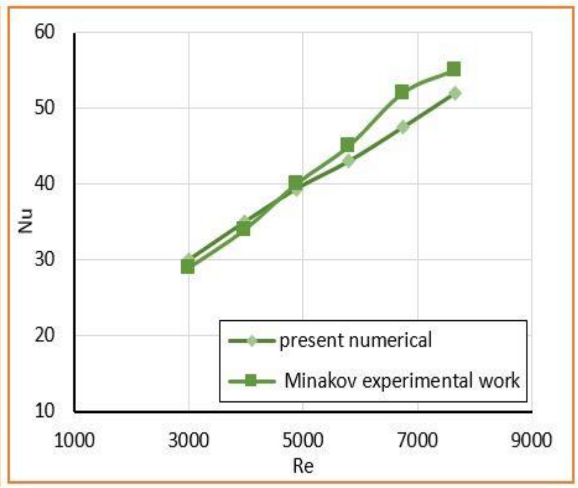


Figure (5): Compression between numerical Average Nusselt number with Minakov experimental work.

4. Result and Discussion

Steady state fully developed nanofluid (AL_2O_3-water) mixture flow with Re between (3000 to 9240) at uniform heat flux, and volume concentration (φ =0.5, 1.0, 1.5) %. The results show the effect of nanoparticles (AL_2O_3) and elliptical tube shape with different aspect ratio and constant surface area on hydrodynamics and thermal behavior.

4.1 Temperature contour

Figure (6) shows the surface temperature distribution along the elliptical wall with different tube aspect ratio with Reynolds number (6743). From temperature contour, the results show that the surface temperature increases gradually from inlet to outlet and that is due to increasing in fluid temperate and surface temperature decrease with decreasing the tube aspect ratio. The horizontal semi- axial section has a higher temperature than the vertical semi- axial section for elliptical tube and the different increase with decreasing the aspect ratio (AR). This is due to boundary layer effect which cause the different in horizontal and vertical wall temperature as shown in Figure (7).

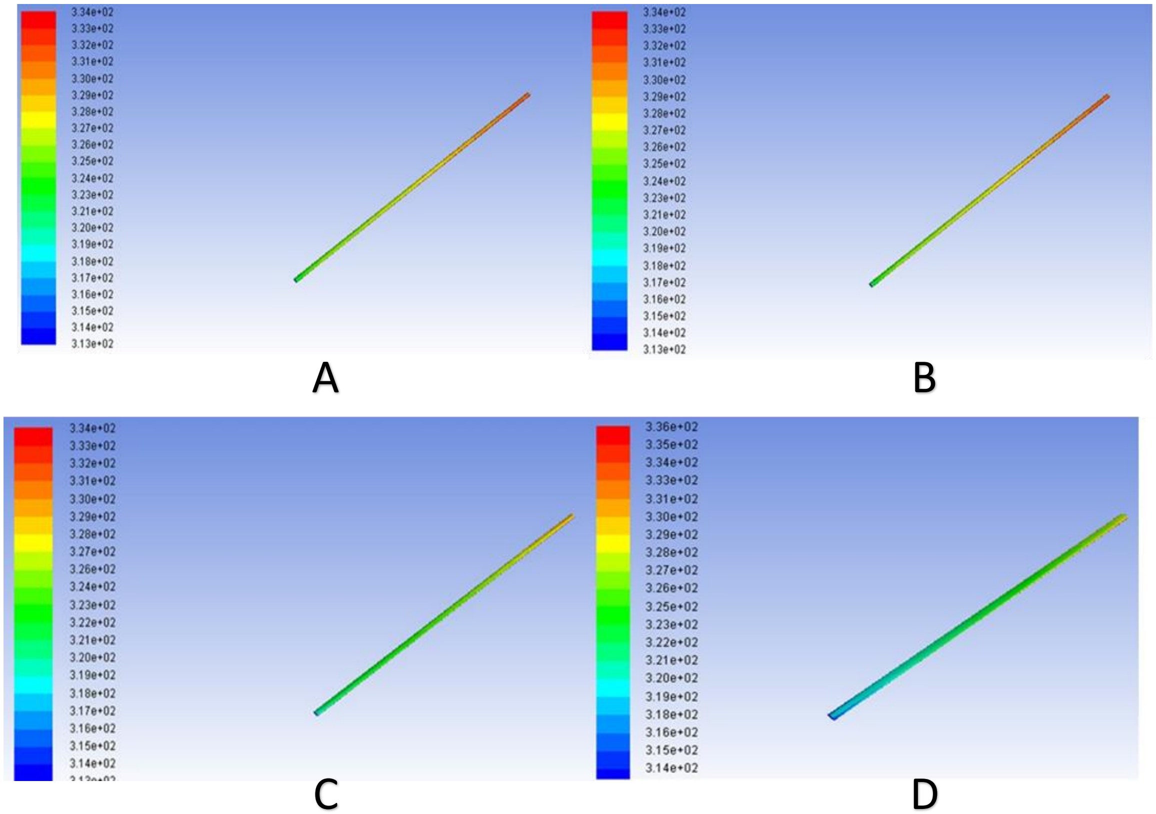


Figure (6): Surface temperature distribution of elliptical tubes with different aspect ratio at Reynolds number 6743 with uniform heat flux: A) Circular tube, B) 0.75 AR, C) 0.5 AR, D) 0.25 AR.

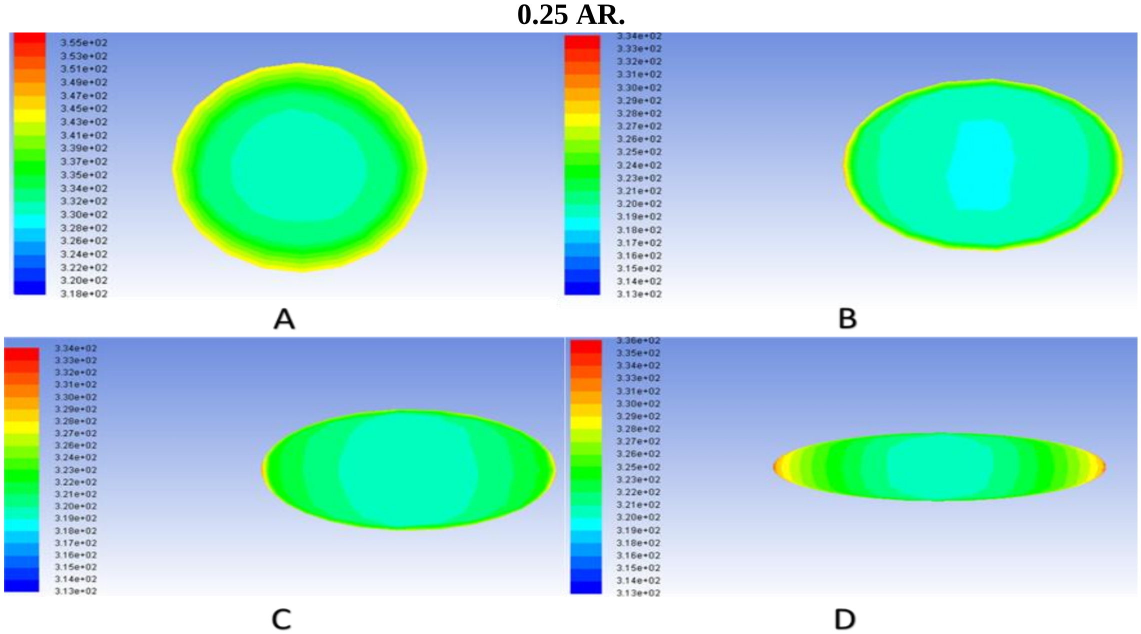


Figure (7): Cross section temperature distribution of elliptical tubes with different aspect ratio at Reynolds number 6743 with uniform heat flux. A) Circular tube, B) 0.75 AR, C) 0.5 AR, D) 0.25 AR

4.2 Velocity of flow

To obtaining specific Reynolds for comparison of circular and elliptical tubes for different aspect ratio, velocity of fluid flow inside the tubes must determine. Figure (8) shows a comparison of fluid velocity for circular and elliptic tubes for different “aspect ratio”. Figure (9) shows the fluid velocity for “aspect ratio” of 0.75 and different concentrations of nanofluid. The velocity increases with increasing of Reynolds number and increases with increased volume concentration and that because of increasing in viscosity of nanofluid, and there is difference between the elliptical and circular tubes in fluid velocity. Where we note that to obtain the same amount of Reynolds number in the elliptical and circular sections, should be increased in the velocity of the flow fluid and this shows why the improvement of heat transfer within the elliptical sections. This is due to the fact that the cross-section area of the elliptical tube is smaller than the cross-section area of the circular tube at constant surface area.

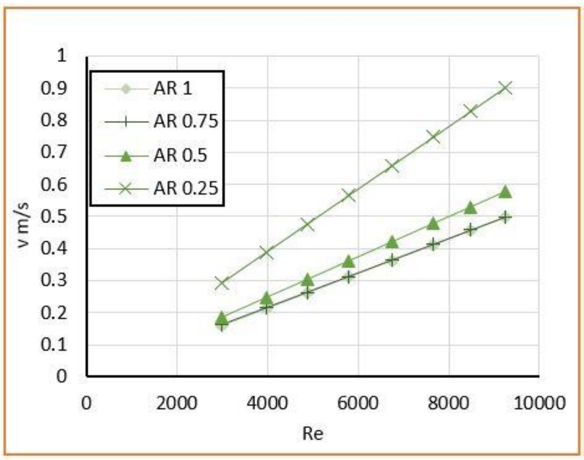


Figure (8): Fluid velocity for different tubes aspect ratio and Reynolds number.

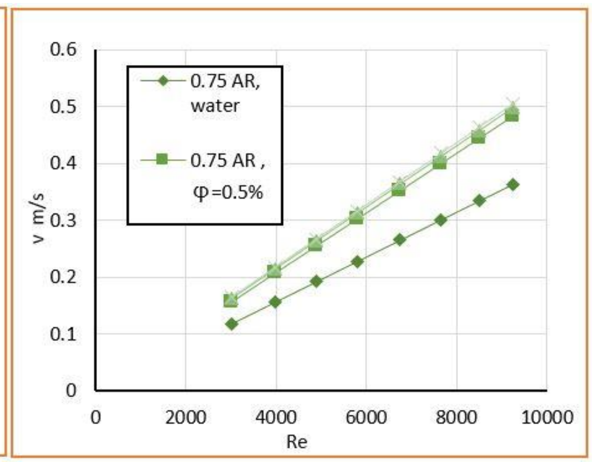
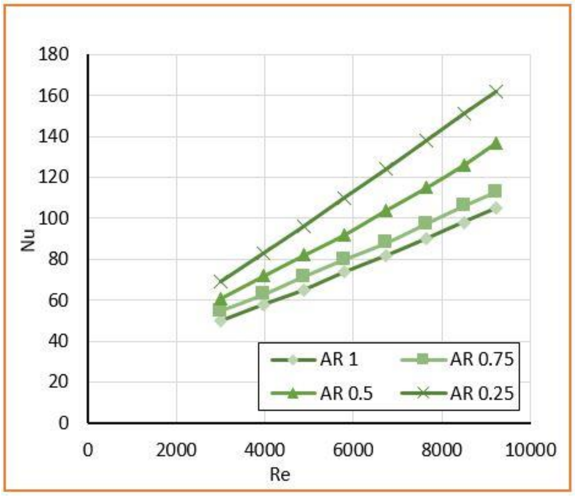


Figure (9): Fluid velocity versus Reynolds number with different nanofluid volume concentrations.

4.3 Nusselt number

Figure (10) shows the effect of tubes aspect ratio on Nusselt number. The “Nusselt number” increase with decreasing the “aspect ratio” due to velocity increase with decreasing aspect ratio. Figure (11) relates the Nusselt number with Reynolds number at different nanofluid concentration. The Nusselt number increase with increasing of nanofluid volume concentration due to effect of thermal conductivity of nanofluid with caused by Brownian Motion AL_2O_3 nanoparticles. Maximum Nusselt number at 0.25 cross section tube aspect ratio with $\varphi = 1.5$ % nanoparticles volume concentrations.



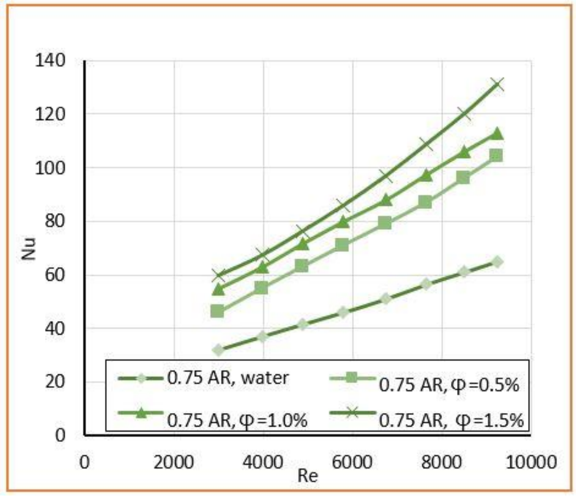


Figure (10): Nusselt number versus Reynolds number at different aspect ratio.

Figure (11): Nusselt number versus Reynolds number at different concertation volume fractions.

4.4 Pressure drop

Figure (12) shows the pressure drop for circular and elliptical tube with different aspect ratio for 1% concentration of nanofluid. It is found that pressure drop in elliptical tube is great comparing with circular tube due to larger velocity of fluid in elliptical tube for the same flow rate.

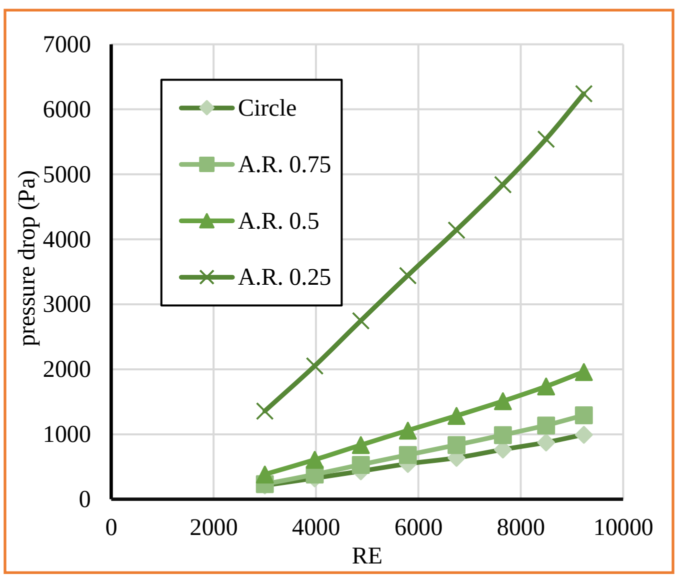


Figure (12): Pressure drop of different tubes aspect ratio with Reynolds number.

It was found that there is a clear change between the form of the tubes as the elliptic tube has a number of pressure difference greater than the circular tube as shown in figure

(12) and that is because the fluid velocity in the elliptical is larger than the circular tube when compared with the same amount of flow rate.

5. Conclusion

Numerical analysis of AL_2O_3-water nanofluid with fully developed steady state turbulent flow (RE=3000-9230) by using multi-phase mixture model inside elliptical tube with different cross section aspect ratio and with constant surface area with uniform heat flux were present. The conclusions can be summarized in the following points:

1- The average Nusselt number of elliptical tube is increase with increasing the volume concentration of nanofluid as well as increase with decreasing the cross-section tube aspect ratio various between (0.25 to 1).
2- Heat transfer enhancement of elliptical tube with (AR 0.25) aspect ratio is 1.86 higher than the circular tube at constant Reynolds number, nanofluid volume concentration and tube surface area.
3- The results show that the pressure drop increase with decrease the aspect ratio of elliptical tubes, also, the pressure drop increase with increase nanofluid volume concentration but the effect is small because the nanoparticles diameter size which (20 nm). Elliptical tube (with AR 0.25) has pressure drop greater than circular tube at same surface area with (5.27 times).
4- The elliptical tube with (AR 0.25) has higher heat convection than the circular tube and its benefit to using a heat exchanger. Any application requires heat dissipation from fluids, but to transfer the fluid from the site of feeder to the other sits prefer to use the circular tube because it has the least amount of pressure drop, therefore, much lower pumping power as demonstrated by the results.

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دراسة عددية لانتقال الحرارة وجريان المائع النانوي بأستخدام نموذج خليط متعدد الطور خلال انابيب بيضوية

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الخلاصة

دراسة عددية لنقل الحرارة وتدفق السوائل باستخدام تدفق مضطرب كامل التطور داخل أنبوب بيضاوي الشكل مع اختلاف نسبة المقطع العرضي لأنابيب وبثبات في مساحة سطح للأنبوب، وذلك باستخدام (AL_2O_3− ماء) مائع نانوي مع متوسط حجم الجسيمات النانوية (20 نانومتر). وقد تم استخدام نموذج خليط متعدد المراحل لحساب عدد نسلت، سرعة المائع النانوي، والفارق في الضغط. حيث تم حل المعادلات للأشكال الهندسية ثلاثية الأبعاد (Navier-Stokes)، والطاقة، والنسبة الحجمية باستخدام برنامج (ANSYS fluent) مع طريقة حجم محدود (FVM). النتائج المحسوبة العددية تظهر قبولية معقولة بحدود خطأ مقداره تقريباً (10.34%) مقارنةً مع النتائج العملية السابقة. وقد استنتج من النتائج العددية أن زيادة في تركيز الدقائق النانوية سيزيد من عدد نسلت وله تأثير ضئيل على الزيادة في انخفاض الضغط. أنبوب بيضوي الشكل مع نسبة الأبعاد 0.25 هو الأفضل لاستخدام في العمليات التي يتم من خلالها تبديد الحرارة أو الحصول عليها من السوائل إلى المحيط. ولكنه يكون أقل فعالية في عملية نقل الموائع لمسافات بسبب كبر فرق الضغط عبر دخول وخروج المائع بالمقارنة مع أنابيب ذات مقاطع دائرية ضمن مدى معين من معدل التدفق.

الكلمات المفتاحية: نسبة الأبعاد، متعددة المراحل، نموذج الخليط.