Tikrit Journal of Engineering Sciences (2022) 29 (2): 51-60
DOI: http://doi.org/10.25130/tjes.29.2.7

IRAQI Academic Scientific Journals

College of Engineering

ISSN: 1813-162X (Print); 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

An Experimental Investigation on Heat Transfer Enhancement in An Annulus with Rotating Outer Cylinder Using Nano Fluids

Samer Mahmood Khalaf *[1], **Akeel Abdullah Mohammed**[2], **Qasim Jabbar Mohammed**[3]

1 Mechanical Department, College of Engineering, Tikrit University, Tikrit, Iraq.

2 Department of Mechanical Engineering, College of Engineering, Al Nahrain University, Baghdad, Iraq.

3 Department of Chemical Engineering, College of Engineering, Al Nahrain University, Baghdad, Iraq.

Keywords:

Heat transfer; Annulus; Rotating outer cylinder; Nano fluids

ARTICLE INFO

Article history:

Received	01 Sep. 2021
Accepted	27 Dec. 2021
Available online	27 July 2022

Citation: Khalaf SM, Mohammed AA, Mohammed QJ. An Experimental Investigation on Heat Transfer Enhancement in An Annulus with Rotating Outer Cylinder Using Nano Fluids. Tikrit Journal of Engineering Sciences 2022; 29(2): 51-60. **http://doi.org/10.25130/tjes.29.2.7**

ABSTRACT

Heat transfer augmentation for Taylor-Couette flows between concentric cylinders have been investigated experimentally. Due to its importance and widespread in wide industrial applications such as heat exchangers, reactors, well dinning, packed beds, compressors and gas turbines, chemical industries, etc. Different variables are investigated in the present work as follow, Rayleigh number ($2\times10^6 \leq Ra \leq 2\times10^7$), Taylors number ($0 \leq Ta \leq 2.4\times10^{10}$), Richardson Number ($0.004 \leq Ri \leq 0.4$) and nanoparticles volume fractions(φ) of Al_2O_3 with water base ($0\ \% \leq \varphi \leq 0.225\ \%$) in which prepared in two step method. The enhancement in heat transfer was 16.5% to 24% due to rising the concentration of Nano fluids of Al_2O_3-pure water from 0% to 0.225%. Also, the Nusselt number increases with increasing Rayleigh and Richardson numbers. Finally, a correlation was deduced to describe the experimental work and linked the studied parameters with difference less than 13.5 %. The comparison between experimental work and previous works found a good agreement between them.

* Corresponding author: E-mail: samerkhalaf @tu.edu.iq, Mechanical Department, College of Engineering, Tikrit University, Tikrit, Iraq.

دراسة تجريبية لتحسين انتقال الحرارة في تجويف حلقي ذو اسطوانة خارجية دوارة باستخدام سوائل النانو

سامر محمود خلف قسم الهندسة الميكانيكية / كلية الهندسة / جامعة تكريت / العراق.
عقيل عبدالله محمد قسم الهندسة الميكانيكية / كلية الهندسة / جامعة النهرين / العراق.
قاسم جبار محمد سليمان قسم الهندسة الكيمياوية / كلية الهندسة / جامعة النهرين / العراق.

الخلاصة

تم دراسة تحسين انتقال الحرارة لجريان Taylor-Couette بين الأسطوانات متحدة المركز بشكل تجريبي. نظرًا لأهميتها وانتشارها الواسع في التطبيقات الصناعية الواسعة مثل المبادلات الحرارية والمفاعلات وحفر الابار والضواغط والتوربينات الغازية والصناعات الكيماوية وما إلى ذلك ، تم التحقق من المتغيرات المختلفة في العمل الحالي على النحو التالي ، رقم رايلي Ra ‎-2 ($2 \times 10^7 \times 10^6$) ، رقم تايلور Ta ‎(0 – 2.4×10^{10})، رقم ريتشاردسون Ri ‎(0.004 -0.4) ونسبة حجم الجسيمات النانوية φ من Al_2O_3 مع قاعدة مائية (0٪ - 0.225 ٪) التي تم تحضيرها بطريقة الخطوتين .كان التحسن في انتقال الحرارة من 16.5٪ إلى 24٪ نتيجة لزيادة تركيز سوائل النانو من 0٪ إلى 0.225٪. كما أن رقم نسلت يزداد مع زيادة أعداد رايلي وريتشاردسون. وأخيرا تم استنتاج ارتباط لوصف العمل التجريبي وربط المتغيرات المدروسة مع اختلاف أقل من 13.5٪. وجدت المقارنة بين العمل التجريبي والأعمال السابقة توافقًا جيدًا بينهما.

الكلمات الدالة: انتقال الحرارة، الحلقة، الأسطوانة الخارجية الدوارة، سوائل النانو.

1. INTRODUCTION

Many alternative methods that used by researchers to maintain the economic and environmental sustainability and to produce at low cost the maximum energy. A channel configuration and the nature of heat transfer kind are considerable to supply the biggest thermal performance. Studying thermal performance enhancement methods by an annulus configuration is among the important heat transfer investigations, because it is found in huge applications from compressors and gas turbines, heat exchangers, reactors, well dinning, chemical industries, etc. The present paper is an experimental investigation to enhance heat transfer with rotating outer cylinder in annulus configuration filled by Nano fluids. A lot of studies that directed on the impact of cylinders rotating in the annulus on heat transfer and fluid flow. Khanafer and Chamkha (2003) [1] used finite element model based on the Galerkin method of weighted residual to discretization the governing equation for mixed convection in horizontal concentric annulus with rotating outer cylinder while the heated inner cylinder was fixed and filled with a uniform fluid-saturated porous medium with internal heat generation. They observed that the Richardson number impacts on the heat transfer characterization within the annulus, as well as showed that an increasing in Reynolds number effects on the patterns of flow with respect to two-eddy, one-eddy and no-eddy flows. Zhidao (2004) [2] investigated the two-dimensional finite-difference model for mixed convection of air in a horizontal concentric and eccentric annulus with stationary inner cylinder at a higher temperature while the outer cylinder was rotating counter-clockwise. The parameters were studied such as the annulus radius ratio, the eccentricity, the Rayleigh number and Reynolds number of the rotation of the outer cylinder. In case of concentric annulus, the patterns of flow were categorized into three modes, and characteristics of heat transfer and flow patterns were elucidated. While in case of eccentric annulus, the heat transfer and flow were impacted by the eccentricity of inner cylinder. Akeel (2007) [3] examined the convection in an annulus with isothermal rotating inner cylinder and adiabatic outer cylinder in vertical annulus by using air as working fluid. A computer program in FORTRAN used to solve the governing equations in finite difference method. The ranges of investigation were as follow $0.2 \le Re^2/Ta \le 1000$, $0.2 \le \eta \le 0.9$, and $300 \le Gr/Re \le 800$. He showed that the acceleration of fluid close to the heated boundary and be slow near the opposite insulated wall and fast for opposing flow case than aiding case. The effect of Re^2/Ta on the fluid flow and heat transfer process was non-significant. The thermal boundary layer thickness increases gradually as the flow moves upstream to downstream for annulus. Ahmadbadi and Karrabi (2012) [4] examined empirically the heat transfer in a channel with non-annular configuration between rotor and stator with grooves distributed circumferentially. The results showed that by increasing rotor speed from 300 rpm to 1500 rpm, the heat transfer of the stator and rotor increased by 30% and 45% respectively, as well as they observed that the axial distribution of local Nusselt number on the rotor's surface was uniformly more than stator’s surface. El-Maghlany et al. (2012) [5] studied the characteristics of fluid flow and heat transfer in a heat exchanger with a vertical rotating inner pipe. They concluded that the heat transfer rate a increases with high speed rotation and Re number, also they obtained a correlations between computation properties of water. G. A. Sheikhzadeh et al (2013) [6] studied the mixed convection for horizontal annulus filled Alumina-water nanofluid with isothermal cylinders wall while the inner cylinder was rotating. The basic equations and boundary conditions were discretized using the finite volume model where pressure-velocity coupling is done by the SIMPLER algorithm. The study carried out for Ra from 102 to 105, Re number from 1 to 300 and nanoparticles volume fraction from 0.01 to 0.06. The results showed that the heat transfer decreases with increasing the Reynolds number. However, the heat transfer increases by increasing the Rayleigh number. Mauwafak et al. (2015) [7] studied the vibration effect on the mixed convection heat transfer in the entrance region of concentric vertical annulus with rotating inner cylinder and stationary heated outer cylinder of 0.365 as radius ratio with a heated outer cylinder of 1.2 m. The ranges of Reynold number, Taylor number, heat flux, and frequency were $514 \leq Re \leq 1991$, $10.44\times10^4 \leq Ta \leq 82.23\times10^4$, $(468 \leq q \leq 920)$ W/m², and Fr=32 & 77 Hz: respectively. They showed that the values of local Nusselt number increase as the heat flux increases at the natural frequency. The correlation equations of average Nusselt number were deduced as follows:

$$Num=1.5304\, Re^{0.5632}\, Ta^{-0.2816}\, Ra^{0.2816} \quad \textbf{(1)}$$

Without vibration

$$Num=1.7725\, Re^{0.4612}\, Ta^{-0.2308}\, Ra^{0.2308}\, Fr^{0.2308} \quad \textbf{(2)}$$

With vibration

El-Maghlany and Elazm (2016) [8] used FORTRAN language to simulate the convection heat transfer in an eccentric horizontal annulus with rotating inner cylinder and assumed isothermal walls. They used Nanofluids as working fluids in the annular gap such as TiO_2, Cu, and Al_2O_3 nanoparticles and the base fluid was the pure water. The study parameters range of Richardson number were $0.01 \leq Ri \leq 100$, solid fraction $0.01 \leq$ solid volume ≤ 0.05, and $0 \leq$ eccentricity ratio ≤ 0.9. They showed that the effect of Nanofluids on Nusselt number increases at Ri=1 and Ri>1. Nair et al. (2016) [9] used model of finite volume for two-dimensional steady state coupled with approach of pressure-velocity coupling to simulate natural, mixed convection heat transfer in an annulus with rotating inner cylinder at variable angular velocities to satisfy the natural and mixed convection. Three temperature differences 5K, 50K and 90K were represented the cases of Ra. They showed that with increasing Ra number, the heat transfer was enhanced but increasing power consumption. Through the range $1 \geq Ri \geq 0.01$, heat transfer reduces with increasing rotation velocities and increasing power consumption. For the range $Ri \leq 0.1$, Ra number increasing centrifugal force because centrifugal forces become dominant. Akeel et al (2018) [10] investigated the heat transfer characteristics in an annulus with rotating inner cylinder and outer cylinder kept stationary and uniformly heated. The parameters were studied as follow, rotational Reynolds number (Re_Ω) for inner cylinder, and Rayleigh number (Ra), annulus angle of inclination from horizontal to the vertical and eccentric ratio. They showed that Nusselt number improves as the angle of inclination deviates from horizontal to vertical position. Rajkumar et al (2019) [11] carried out an experimental and numerical work by using ANSYS CFX 14, for annulus with rotating vertical outer cylinder and the stationary inner cylinder was heated uniformly. The work studied effect some non-dimensional parameters on heat transfer in the range as follow rotation parameter ζ (0- 526), fixed radius ratio and aspect and different heat loads. The results showed that the Nusselt Number increases progressively with increasing rotational parameter, thereafter a strong decreasing in Nusselt number. They observed three modes of heat transfer convection were exist such as natural, mixed and forced convection. Table 1 is concerned with experimental literatures. Finally, Rajkumar and et al, 2021 [12] held an experimental investigation to study the convection heat transfer from a concentric vertical cylinders with fixed inner cylinder which was heated uniformly while outer cylinder was rotating and cooled by ambient. The range of study include rotation speeds from (500 to 1000) rpm. They showed through the study that a significant enhancement in Nusselt number with increasing the rotation parameter from 527 to 1190. While obtained a marginal improvement in Nusselt number with increasing the parameter of rotation from 1190 to 2860. By studying the literature studies on convective heat transfer in fixed and rotating concentric annulus, it was observed that shearing the mixture by rotating the outer drum is better than shearing the mixture by the rotating inner drum because the Taylor spiral produces the latter with a lower rotational speed. This situation is due to centripetal forces. In addition, the presence of secondary flow could be delayed by rotating the external cylinder. In addition, most of the work to date understands heat transfer in a rotating cylindrical annulus; in contrast, there are few research reports on convective manipulation in a closed cylindrical annulus. Also, in most of the above cases the inner cylinder was rotating and the outer cylinder was kept stationary. Furthermore, almost the problems were studied numerically. In this work the focus is to achieve the present study experimentally and numerically. Here the principle attention is to study the influence of induced flow originated by the rotational effect of the outer cylinder on the natural convection plume emanating from the stationary heated cylinder at different angles and also to simulate numerically the flow pattern and thermal field for a better understanding of the thermal transport phenomena by using water and nano fluids in the annular gap between two concentric cylinders. The above-mentioned factors motivate us to adapt the problem of the present work. By studying the literature studies on convective heat transfer in fixed and rotating concentric annulus, it was observed that shearing the mixture by rotating the outer drum is better than shearing the mixture by the rotating inner drum because the Taylor spiral produces the latter with a lower rotational speed. This situation is due to centripetal forces. In addition, the presence of secondary flow could be delayed by rotating the external cylinder. In addition, most of the work to date understands heat transfer in a rotating cylindrical annulus; in contrast, there are few research reports on convective manipulation in a closed cylindrical annulus. Also, in most of the above cases the inner cylinder was rotating and the outer cylinder was kept stationary. Furthermore, almost the problems were studied numerically. In this work the focus is to achieve the present study experimentally and numerically. 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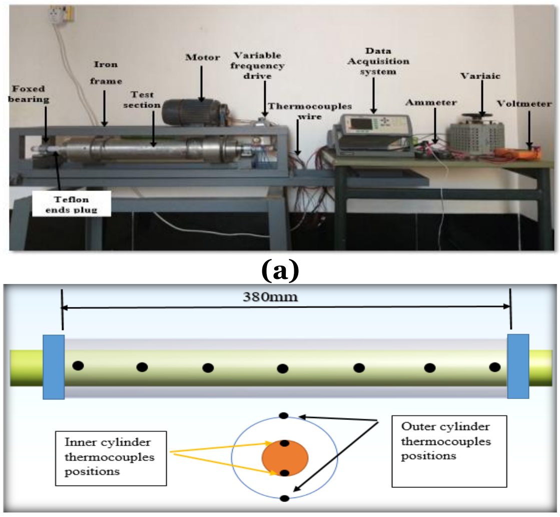
2. EXPERIMENTAL PROGRAM

The test section consists of cylindrical annulus with: rotating outer cylinder and stationary inner cylinder. The inner cylinder is made from steel, whilst the outer cylinder is made from aluminum. The dimensions of outer cylinder are 4mm wall thickness, 100 mm diameter and 400 mm length with cup thickness. The dimensions of inner cylinder are 30mm diameter and 750mm length with thickness of 4mm. The outer cylinder was cooled by air while the inner cylinder is heated at constant heat flux by an electric cartridge heater inserted inside it. The heating element (cartridge heater) is made of special stainless steel material (nickel- chrome wire) wounded as (U) shape and fixed inside a stainless steel tube (38 cm length, 2.5 cm diameter) to produce (2 kW) heating power. The heat loss excluded from heater ends inside inner cylinder by inserting a two cup of Teflon in each end of inner cylinder bored with the same inside diameter of the inner cylinder as shown in Fig. 1. While, the ends of outer cylinder were insulated using a rubber ring with a thickness of 5mm, to reduce the heat loss from ends. The temperature of inner cylinder and outer surfaces temperatures were measured by using eight and four thermocouples (type T) respectively, with the temperature range from (-200 to 1300°C) and accuracy of ±0.2%. The thermocouple arranged along the inner and outer cylinder surface and at angle (0°, 180°) around the cylinder surface. The thermocouples were fixed by drilling holes of 2 mm diameter and approximately 1.5 mm deep in along the outer cylinder wall. The measuring junctions tip dipped in thermal paste, and then were secured permanently in the holes by high temperature application epoxy steel adhesive. All the thermocouple wires and heater terminals were taken out the test section.



(b)

Fig. 1(a), Photographs of Experimental Apparatus and (b)schematic drawing shows thermocouples position along the inner and outer cylinder.

3. DATA ANALYSIS

Simplified steps have been used to analyze the mixed convection heat transfer process in annulus with rotating outer cylinder and uniformly heated stationary inner cylinder. Under steady-state conditions the energy equation for the test cylinders based on the 1st law of thermodynamics is expressed as below [13]:

$$\mathbf{Q_t = Q_{conv} + Q_{rad} + Q_{cond}} \quad \mathbf{(3)}$$

The total input power supplied to the inner cylinder can be calculated from the following equation:

$$\mathbf{Q_t = V \times I} \quad \mathbf{(4)}$$

Since two pieces of insulating material made of Teflon and rubber is placed on each end points of the cylinders, so that the conduction heat loss is were calculated to be 4%. These losses are subtracted from the electric power to obtain the net heat transfer rate. For that reason, heat transfer from the horizontal cylinder surface by convection can be calculated as:

$$\mathbf{Q_{conv} = Q_t - Q_{rad}} \quad \textbf{(5)}$$

Heat transfer from the horizontal cylinder surfaces by radiation can be represented by:

$$\mathbf{Q_{rad} = F_{1-2}\,\varepsilon\,\sigma\,A_o[(T_{so}+273)^4 - ((\overline{T_\infty})+273)^4]} \quad \textbf{(6)}$$

The radiation heat flux is very small and can be neglected. Therefore, the convection-radiation heat can be equated to the convection heat flux, $\bar{\bar{q}}$. The convection heat transfer which is the driving force of the plume can be represented by:

$$\mathbf{Q\ conv = h_i A_i (T_{si} - T_m)}\text{for inner cylinder} \quad \textbf{(7)}$$

$$\mathbf{Q\ conv = h_o A_o (T_{so} - T_\infty)}\text{for outer cylinder} \quad \textbf{(8)}$$

Nusselt number is defined as:

$$\mathbf{Nu_i = \frac{h_i\ D_i}{k}} \quad \textbf{(9)}$$

$$\mathbf{Nu_o = \frac{h_o\ D_o}{k}} \quad \textbf{(10)}$$

$$\mathbf{Nu_{av} = \frac{(Nu_o + Nu_i)}{2}} \quad \textbf{(11)}$$

The thermo-physical properties of fluid (k and ν) were evaluated at the mean film temperature. By using equations (3) to (10) may compute the heat transfer coefficient by:

$$\mathbf{\bar{h} = \frac{0.96 * Q_t}{A * (\overline{T_s} - \overline{T_f})}} \quad \textbf{(12)}$$

The non-dimensional parameter for buoyancy-driven flows is Rayleigh number, which is calculated by the following relation:

$$\mathbf{Ra_L = \frac{g\beta(T_{si}-T_{so})L_c{}^3 .\ Pr}{\nu^2}\quad or\ Ra_i = \frac{g\beta\ \bar{\bar{q}}\ D_i{}^4}{k\ \alpha\ \nu}} \quad \textbf{(13)}$$

A dimensionless parameter for free convection heat transfer is Grashof number and it is calculated by the following relation:

$$\mathbf{Grashof\ number = \frac{g\beta(T_{si}-T_{so})L_c{}^3}{\nu^2}} \quad \textbf{(14)}$$

$$\mathbf{Pr = \nu/\alpha} \quad \textbf{(15)}$$

The water thermos-physical properties (k, ν, and β) in non-dimensional parameters were evaluated at:

$$\mathbf{T_{m} = \frac{(T_{si}+T_{so})}{2}} \quad \textbf{(16)}$$

Characteristic length is the spacing between the cylinders:

$$\mathbf{L_c = \frac{(D_o - D_i)}{2}} \quad \textbf{(17)}$$

As the mixed convection invoked (ω > 0), the Richardson number became of great importance and can be defined as:

$$\mathbf{Ri = \frac{Ra}{Pr\,Re^2}} \quad \textbf{(18)}$$

For Taylor-Couette flow, a dimensionless parameter that characterizes flow type similar to the Reynolds number is called as Taylor number which is defined by:

$$\mathbf{Ta = \frac{4\omega_o{}^2 (r_o - r_i)^4}{\nu^2}}$$

4. ERROR ANALYSIS AND REPEATABILITY CHECK

It is necessary to mention that the experimental readings were taken in spring season in the period between 10 May to 30 June and at various times between the morning and afternoon along the day. There is no doubt that, the environment temperature affects slightly the final results in one form or another. A comparison was made between two reading sets taken in the morning on one day when the environmental temperature was 28 °C and in the afternoon on another day when the environment temperature was 30 °C, at the same values of heat flux (q = 88 W/m²), rotational Reynolds number (Re=3981) and angle of inclination (α=0°). Comparison results give approximately ± 1.3% & ± 0.2 % as deviation percent for temperature and Nu values along respectively. The absolute uncertainty and relative errors are given in Table 1.

Table 1. The absolute uncertainty and relative errors

Parameter	Instrument	U abs	U relative
V	Voltmeter	0.30413 volts	0.012165525
I	Ammeter	0.057039482 Amp	0.062338232
T_{si}	Inner surface temperature	0.233344821 °C	0.002047558
T_{so}	Outer surface temperature	0.084242744 °C	0.002485037
T_m	Mean temperature	0.156087536 °C	0.002111252
T_{amb}	Ambient temperature	0.078102497 °C	0.002603417
T_{si}-T_{so}	Walls temperature difference	0.16774986 °C	0.002095236
T_{si}-T_m	Inner wall to bulk temperature difference	0.094392817 °C	0.002357978
T_{so}-T_{amb}	Outer wall to bulk temperature difference	0.050604743 °C	0.012975575
Ω	Angular velocity	0.3041381 RPM	0.001013794
H	Hight of annulus	0.076164296mm	0.000200432
D_i	Inner diameter	0.00781025mm	0.000260342
D_o	Outer diameter	0.020615528mm	0.000206155
L_c	Characterstic lengh	0.008765843mm	0.000243496
A_i	Inner wall surface area	0.005000006mm	0.12698235
A_o	Outer wall surface area	0.005000059mm	0.041082961
Re	Reynolds number	27.86365422	0.006800214
Nu_i	Inner wall Nusselt number	0.626186455	0.033830388
Nu_o	Outer wall Nusselt number	5.543741175	0.03339486
Gr	Grashof number	3869.575378	0.005555727

5. RESULTS AND DISCUSSIONS

In the experimental part of the present work, a total of more than 120 test runs were carried out to cover all the possible investigated parameters. At the end running of each test, the required data were recorded and then a data analysis was performed to present the physical relationships between the considered parameters. The investigated parameters in the experimental part are Heat flux q′′ range of (93 ≤ q′′ ≤ 597) W/m² that yields internal Rayleigh number range of $1\times10^6 \le Ra \le 2\times10^7$. Wide range of rotating Reynolds number from (0 to 120,000) that yields Taylor number range from (0 to 2.42×10^{10}) and volume concentration of Nano particles from (0 to 0.225) %.

5.1. Effect of Taylors number on temperature difference

Figs. (2, 4) show the effect of changing Taylors number on outer cylinder temperature difference for annulus filled with Nano fluids of Al_2O_3-water at volume fractions of 0%, 0.125%, and 0.225%, respectively at different Rayleigh numbers. From the shown figures can be seen that by increasing Taylors number the temperature difference increases until reach critical Taylor's number (1.04×10^{10}) because the buoyancy force is higher than rotational force in this range. After the critical Taylors number occurs a decreasing in temperature difference due to increasing of rotational force.

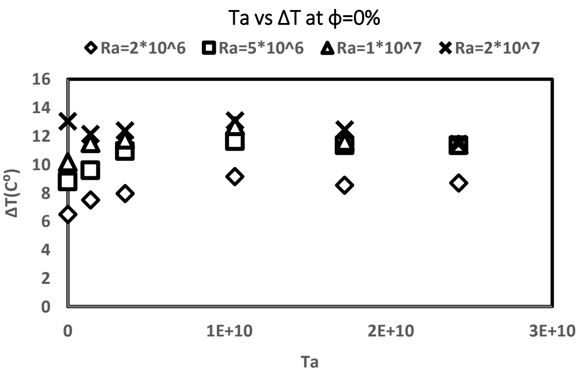


Fig. 2 Effect of experimental Taylors number on temperature difference at φ = 0%

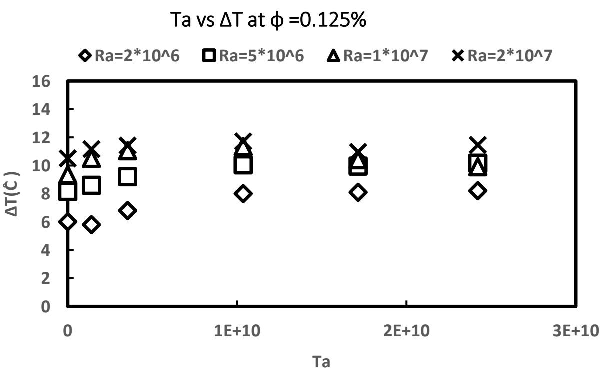


Fig. 3 Effect of experimental Taylors number on temperature difference at φ =0.125%.

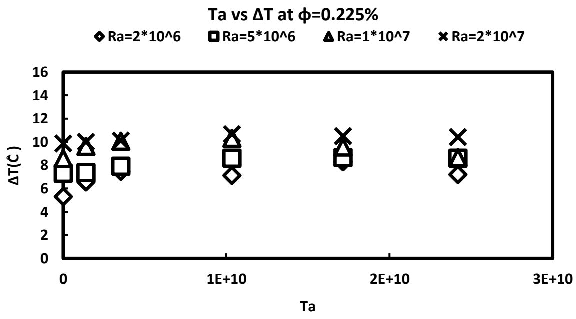


Fig. 4 Effect of experimental Taylors number on temperature difference at φ =0.225%.

5.2. Impact of nano particles percentage on temperature difference

Figs. (5, 6) explain the effect of increasing Nano particles volume fraction on temperature difference behavior at Ta=0 and Ta=2.4×10^{10} respectively, for different Rayleigh numbers. As seen from the plots that the effect of adding extra Nano particles volume fraction decreasing the temperature difference by 24.5% and 18.9% for minimum and maximum Taylors number respectively. From the basic equations of heat transfer, conclude that the heat transfer depended on two parameters, which were the temperature gradient on cylinder surface and thermal properties mainly thermal conductivity and thermal diffusivity. As shown from Figs. (5, 6), it is clear that as increasing the volume fractions of the Al_2O_3 nanoparticles, the temperature difference drops. This decreasing is due to the increasing of thermal conductivity by 1.2% and thermal diffusivity by 1.6% with respect to base-fluid at high Rayleigh number as shown in Figs. (7, 8) which are indicated the weight of thermal conductivity(k) and thermal diffusivity(α_t) parameters with volume fraction of Nano particles [14].

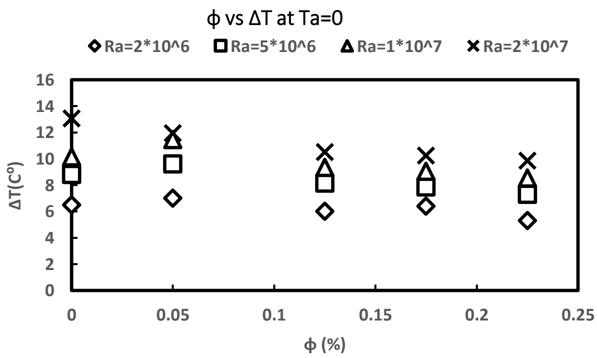


Fig. 5 Effect of variation of Nano particles volume fractions on outer cylinder temperature difference at different Rayleigh number, Ta=0

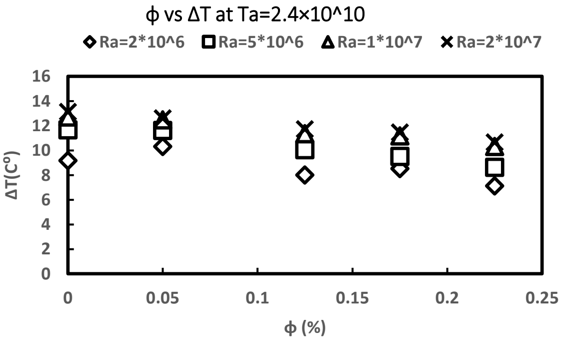


Fig. 6 Effect of variation of Nanoparticles volume fractions on outer cylinder temperature difference at different Rayleigh number, Ta=2.4×10^{10}

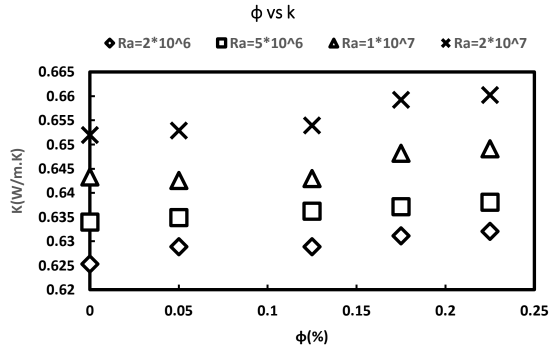


Fig. 7 Impact of Nanoparticles volume concentrations on average thermal conductivity

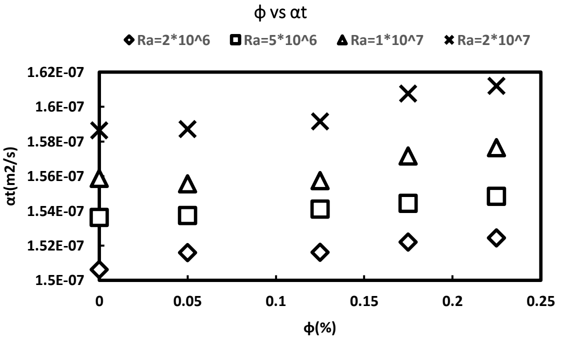


Fig. 8 Impact of Nanoparticles volume concentrations on average thermal diffusivity

5.3. *Influence of Taylors number on average Nusselt number*

Figs. (9, 10, 11) indicate the effect of variation of Taylors number on average Nusselt number for horizontal annulus filled with Al_2O_3-water fluid at Nanoparticles volume fractions of 0%, 0.125% and 0.225% respectively, and at different Rayleigh number. As observe from the figures, that the Nusselt number decreases at low Taylors number because the interactions between viscous, buoyancy and rotational forces. Since the temperature difference increases until a certain value of Taylors number then decreases. Thus the heat transfer drops then rises. In the same figures observe that with increasing Rayleigh number the Nusselt number increases.

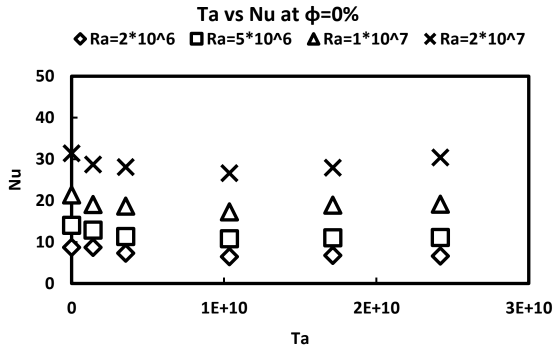


Fig. 9 Effect of variation of Taylors number on average Nusselt number at different Rayleigh numbers, φ=0%

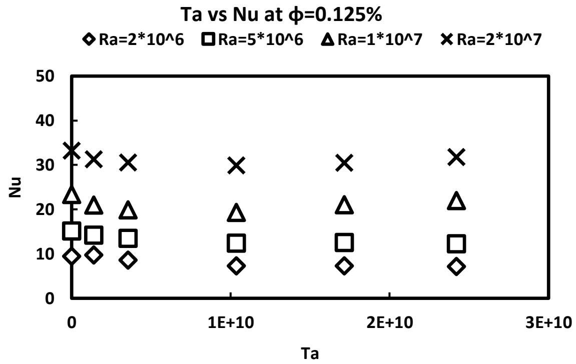


Fig. 10 Effect of variation of experimental Taylors number on average Nusselt number at different Rayleigh numbers, φ=0.125%

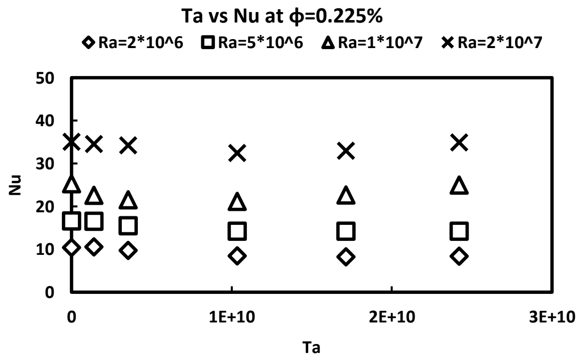


Fig. 11 Effect of variation of experimental Taylors number on average Nusselt number at different Rayleigh numbers, φ=0.225%.

5.4. *Effect of nano particles volume fractions on Nusselt number*

Figs. (12, 13) show the effect of variation of Nano particles volume fraction on average Nusselt number manner at Ta= 0 and 2.4×10^{10} respectively, and for different Rayleigh numbers. The figures show that the maximum increasing of average Nusselt number is 10.3% and 18.2% at 0.225% for Ta=0 and 2.4×10^{10} respectively. This is manner occurs due to enhance the thermal properties of base fluid as mentioned above.

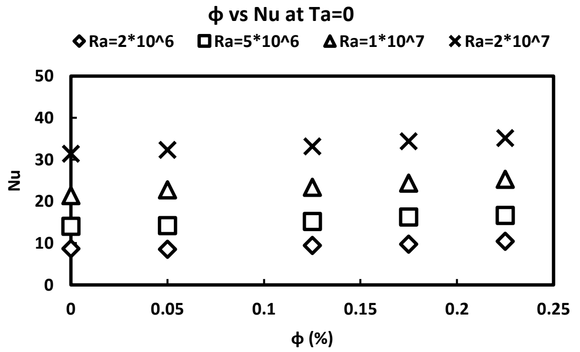


Fig. 12 Effect of variation of Nano particles volume fractions on average Nusselt number at different Rayleigh number, Ta=0

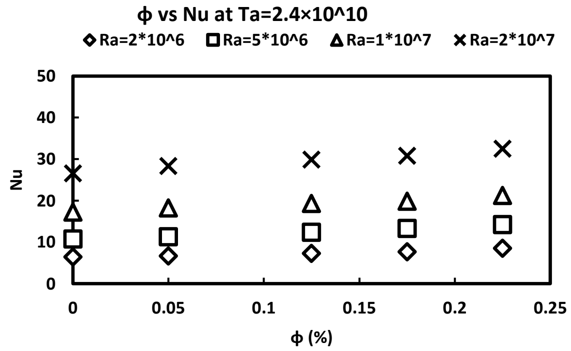


Fig. 13 Effect of variation of Nano particles volume fractions on Nusselt number at different Rayleigh number, Ta=2.4×10^{10}

5.5. Impact of Richardson number on Nusselt number

The relationship between average Nusselt number and the average values of Richardson number (Gr/Re^2) for different values of Rayleigh number for Nano particles volume fractions of 0%,0.125%, and 0.225% respectively are shown in Figs. (14, 15, 16). From all these curves, it is clear that the average value of Nusselt number decreases until reach a certain value of Ri=0.059 then proportion with Richardson number directly and this for all conditions due to competition between buoyancy and rotational forces.

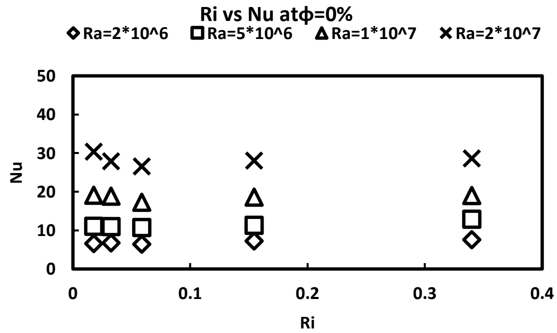


Fig. 14 Effect of variation of Richardson number on Nusselt number at φ=0%

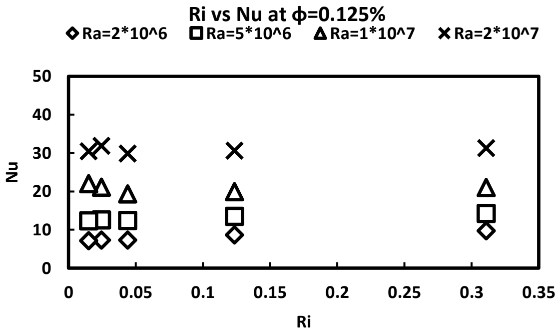


Fig. 15 Effect of variation of Richardson number on Nusselt number at φ=0.125%

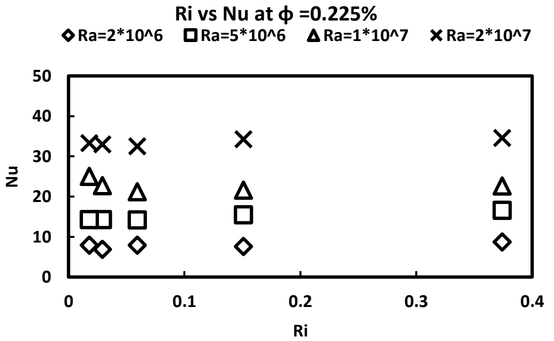


Fig. 16 Effect of variation of Richardson number on Nusselt number at φ=0.225%

5.6. Correlations of the average Nusselt number

In order to describe the relations between the dependent variable (Nu) number and the independent variables (Ra), Richardson number (Ri) and Nano particles volume fractions (φ). A correlations have been made to describe the heat transfer in rotating annulus by using the statistical analysis (STATISTICA software, release 7, by StatSoft Inc.,2005) to find these correlations as follow for rotating annulus

$$\mathbf{Nu} = [32.4(\mathbf{Ri})(\boldsymbol{\varphi} + 1)]^{0.2} \quad \mathbf{(19)}$$

At ($2\times10^6 \leq Ra \leq 2\times10^7$), and ($0 \leq \varphi \leq 0.225$) *with* $R^2 = 0.7191$

Fig. 17 give a general correlation that links all main parameters in case of annulus with rotating outer cylinder and filled by different concentration of Al_2O_3 Nano particles volume fractions and at different inclination angles. It could be seen that the average value of Nusselt number is increased with the increase of Richardson number since the flow approaches to mixed convection region.

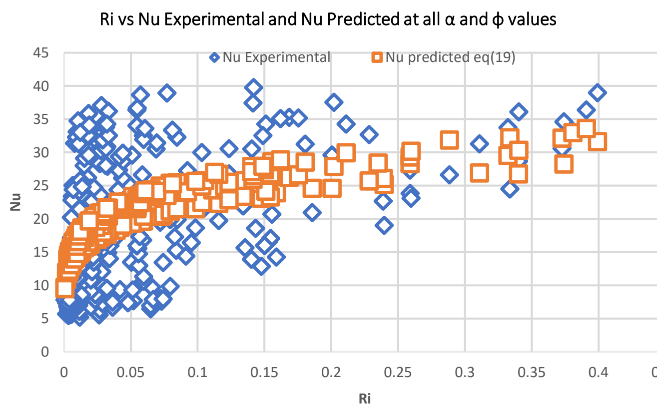


Fig. 17 Experimental and predicted values for rotating annulus from correlation Eq. (19) for different volume fractions, inclination angles and Richardson numbers

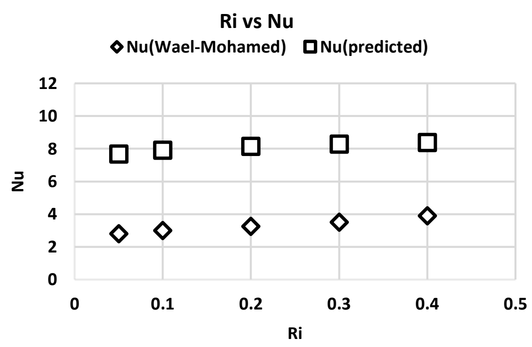


Fig. 18 Comparison between predicted present work (eq.19) and Wael and Mohamed work [8] at φ=0.05%

5.7. Comparison with previous experimental work

In fig. 18 a comparison for rotating horizontal annulus between the predicted equation (19) and Wael-Mohamed work [8], which are using Nano fluids. The comparison shows that the two works have the same trend for increasing average Nusselt number with increasing Richardson number at their boundary conditions.

6. CONCLUSIONS

Enhancement of mixed convection heat transfer in an annulus filled with nano fluid and rotating outer cylinder has been investigated numerically and experimentally. This investigating leads to a basic understanding of fluid flow and heat transfer through the gap between rotating machine parts, improving the design of such equipment and hence minimizing the possible failures that result due to thermal stresses which can shorten the useful life of the machine. Both wall and fluid temperatures increased in a manner that the wall temperatures are higher than the fluid temperatures in the tube center. The results give a good enhancement in heat transfer in an annulus. The enhancement in average Nusselt number was 7.5 % due to increasing Taylor number to 2.4×10^{10}, while the enhancement was 16 % when increasing nanoparticles volume fraction to 0.225 % for the annulus at higher Rayleigh number of 2×10^{7}.

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