SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Numerical Heat Transfer

Journal homepage:
https://semarakilmu.com.my/journals/index.php/arnht/index
ISSN: 2735-0142

Modelling and Analysis of Evacuated Tube Solar Collector Working with Hybrid Nanofluid

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ARTICLE INFO

Article history:
Received 15 May 2024
Received in revised form 19 June 2024
Accepted 21 July 2024
Available online 30 August 2024

Keywords:
Evacuated Tube; Solar Collector; Hybrid Nanofluid

ABSTRACT

This research study is concerned with developing a mathematical model for an Evacuated Tube Solar Collector (ETSC) that utilizes a Hybrid Nanofluid flow in a manifold. The model consists of a set of the partial differential equations that, using the dimensional analysis approach, are reduced to a dimensionless system. The exact solution method, assisted by the Mathematica program, is used to solve the system. The study examines the impact of certain factors on flow and heat transmission, including horizontal velocity, temperature variation, heat source, magnetic field, Prandtl Number, and Eckert Number, and provides a detailed analysis of the results. The key findings of the analysis revealed that an increase in hybrid nanoparticle volume effects in a reduce in velocity and heat transfer coefficient. Additionally, elevated heat source and Prandtl number correspond to an increased heat transfer coefficient.

1. Introduction

Renewable energy is widely considered as the ideal solution for securing humanity's future, particularly as technological advancements continue to demand increasing amounts of energy. Among the many sources of clean energy available, solar energy stands out for its environmentally friendly features. Solar thermal collectors are devices that take solar radiation and transform it into thermal energy, which is then transferred to a working fluid. Evacuated tube solar collectors (ETSCs) exhibit exceptional thermal performance evaluated to other standing collectors, such as flat plate solar collectors (FPC), because they lose less heat and are simpler to transport and install. Additionally, Evacuated tube solar collectors are well-suited for use in unfavourable environments [1-3]. In evacuated tube solar collectors, the vacuum created between the glass tubes decreases both conduction and convection loss, giving the collector the ability to function at great temperatures [4-

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https://doi.org/10.37934/arnht.23.1.8896

6]. However, the traditional fluids utilized as the heat transfer instrument within solar collectors have subpar thermal and assimilation abilities. It was discovered the addition of nanoparticles to these conventional fluids, creates what are known as nanofluids, and can improve their thermal properties [7,8]. Therefore, nanofluids have the potential to take the place of traditional fluids in solar collectors, as many studies have already demonstrated their efficiency in improving the execution of evacuated tube solar collectors [9,10].

Several researchers prepared different types of nanofluids using various nanoparticles and base fluids and studied their properties. Experimental studies conducted by [11-13] on confined geometries have demonstrated that increasing nanoparticle concentrations leads to higher Nusselt numbers and significant improvements in heat transfer performance. Additionally, Determining and modelling the practical physical characteristics of different nanofluids has been the focus of numerous studies. For example, investigations into effective thermal conductivity by [14-17]. In numerical studies study the heat transfer features of nanofluids [18-21]. The two main strategies used to model the flow of nanofluids are the single-phase and two-phase models. While the Single-Phase Model (SPM) has predominantly been utilized to research the heat transfer properties of nanofluids, the two-phase model provides a better understanding of the function of both the fluid stage and solid elements in heat transfer mechanisms.

In this study, we present a mathematical model for the movement of fluid which involves water and three different types of nanoparticles inside a manifold of evacuated tube solar collectors exposed to a source of heat and a magnetic field (see Figure 1) [22]. A system of partial differential equations assists to describe the model, which is converted into a dimensionless equation using the method of dimensional analysis and solved using the exact solution method with the aid of the Mathematica program. The effects of horizontal velocity, temperature variation, heat source, magnetic field, Prandtl Number, and Eckert Number are presented and reviewed in detail.

Fig. 1. Solar water heaters [22]

2. Modelling of the problem

Consider an unsteady, laminar, incompressible flow containing of water with three types of nanoparticles, namely Copper (Cu), Silver (Ag), and Aluminum oxide (Al_2O_3), moving in a horizontal manifold of an evacuated tube solar collector at a low Reynolds number. Due to the close proximity of heat pipes to each other, they can be considered as a homogeneous heat source Q, and a magnetic field B_0 can be applied (see Figure 2). As a result of these assumptions, the problem is defined by a group of partial differential equations, which include the continuity, momentum, and heat equations [23-28].

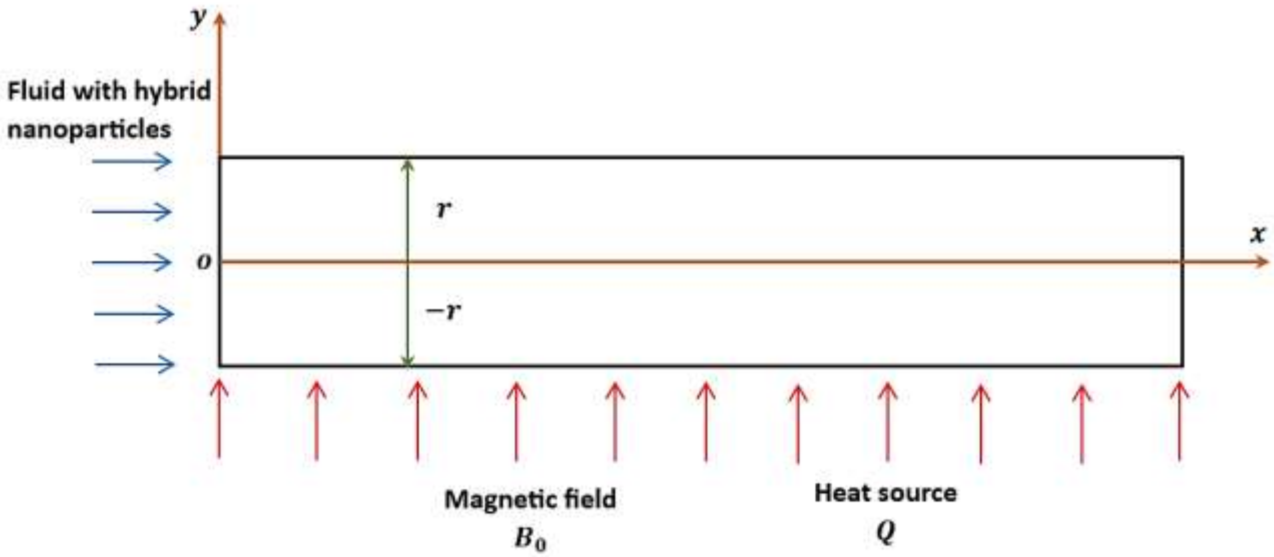

Fig. 2. Physical model and coordinate system

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{1}$$

$$\rho_{thnf}\left(\frac{\partial U}{\partial \bar{t}}+U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}\right)=-\frac{\partial P}{\partial X}+\mu_{thnf}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right)-\sigma_{thnf}B_0^2U \tag{2}$$

$$\rho_{thnf}\left(\frac{\partial V}{\partial \bar{t}}+U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}\right)=-\frac{\partial P}{\partial Y}+\mu_{thnf}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \tag{3}$$

$$\left(\rho c_p\right)_{thnf}\left(\frac{\partial T}{\partial \bar{t}}+U\frac{\partial T}{\partial X}+V\frac{\partial T}{\partial Y}\right)=k_{thnf}\left(\frac{\partial^2 T}{\partial X^2}+\frac{\partial^2 T}{\partial Y^2}\right)+\sigma_{thnf}B_0^2U^2+Q \tag{4}$$

where $\mathrm{U}=\mathrm{U}(\mathrm{X},\mathrm{Y},\bar{t})$ denotes axial velocity, $\mathrm{V}=\mathrm{V}(\mathrm{X},\mathrm{Y},\bar{t})$ denotes transverse velocity, the flow temperature $\mathrm{T}=\mathrm{T}(\mathrm{X},\mathrm{Y},\bar{t})$, the pressure $\mathrm{P}=\mathrm{P}(\mathrm{X})$, ρ_{thnf} is the hybrid nanoparticles density, k_{thnf} is the hybrid nanoparticles thermal conductivity of the fluid, $\left(\rho c_p\right)_{thnf}$ is the hybrid nanoparticles heat capacitance, μ_{thnf} is the hybrid nanoparticles Dynamic viscosity, and σ_{thnf} is the hybrid nanoparticles Electrical Conductivity. Also, the properties of thermophysical properties between water as a base fluid and nanoparticles can be clarified as in Table 1.

Table 1
Thermophysical properties between water as a base fluid and nanoparticles

Physical Properties	H_2O	Cu	Ag	Al_2O_3
$\rho(Kg/m^3)$	997.1	8933	1500	3971
$c_p(J/kgK)$	4179	385	235	765
$k(W/mK)$	0.613	401	249	40
$\sigma(s/m)$	0.05	5.96×10^7	3.6×10^7	1×10^{-5}

Appling the following dimensionless variable on the Eqs. (1)-(4):

$$x=\frac{X}{\lambda},\ y=\frac{Y}{d_0},t=\frac{c\,\bar{t}}{\lambda},\eta=\frac{d_0}{\lambda},U=c\,u\,,V=c\,\eta\,v\,,P=-\frac{\mu_f\,c\,\lambda}{d_0^2},\theta=\frac{T-T_0}{T_0} \tag{5}$$

where η is the wave number, we get

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{6}$$

$$\left(\frac{\rho_{thnf}}{\rho_f}\right)\eta\,Re\,\left(\frac{\partial u}{\partial t}+u\,\frac{\partial u}{\partial x}+v\,\frac{\partial u}{\partial y}\right)=\frac{\partial p}{\partial x}+\frac{\mu_{thnf}}{\mu_f}\left(\eta^2\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\left(\frac{\sigma_{thnf}}{\sigma_f}\right)M^2\,u \tag{7}$$

$$\left(\frac{\rho_{thnf}}{\rho_f}\right)\eta^3\,Re\,\left(\frac{\partial v}{\partial t}+u\,\frac{\partial v}{\partial x}+v\,\frac{\partial v}{\partial y}\right)=\frac{\partial p}{\partial y}+\frac{\mu_{thnf}}{\mu_f}\left(\eta^4\frac{\partial^2 v}{\partial x^2}+\eta^2\,\frac{\partial^2 v}{\partial y^2}\right) \tag{8}$$

$$\frac{(\rho c_p)_{thnf}}{(\rho c_p)_f}\left(\frac{k_f}{k_{thnf}}\right)\eta\,Pr\,Re\left(\frac{\partial\theta}{\partial t}+u\frac{\partial\theta}{\partial x}+v\frac{\partial\theta}{\partial y}\right)$$
$$=\left(\eta^2\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}\right)+\left(\frac{\sigma_{thnf}}{\sigma_f}\right)\left(\frac{k_f}{k_{thnf}}\right)Pr\,Ec\,M^2\,u^2+\left(\frac{k_f}{k_{thnf}}\right)Q \tag{9}$$

where M^2 denotes magnetic parameter, Re denotes Reynolds number, Pr denotes Prandtl number, and Ec denotes Eckert number.

$$M^2=\frac{B_0^2\,d_0^2\,\sigma_f}{\mu_f},\;Re=\frac{\rho_f\,c\,d_0}{\mu_f},Pr=\frac{(c_p)_f\,\mu_f}{k_f},Ec=\frac{c^2}{T_0\,(c_p)_f} \tag{10}$$

Due to the horizontal manifold, the wave number η equals zero, so Eqs. (7)-(10) become:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{11}$$

$$\frac{\partial p}{\partial x}+\frac{\mu_{thnf}}{\mu_f}\left(\frac{\partial^2 u}{\partial y^2}\right)-\left(\frac{\sigma_{thnf}}{\sigma_f}\right)M^2\,u=0 \tag{12}$$

$$\frac{\partial p}{\partial y}=0 \tag{13}$$

$$\frac{\partial^2\theta}{\partial y^2}+\left(\frac{\sigma_{thnf}}{\sigma_f}\right)\left(\frac{k_f}{k_{thnf}}\right)Pr\,Ec\,M^2\,u^2+\left(\frac{k_f}{k_{thnf}}\right)Q=0 \tag{14}$$

subjected to the following boundary conditions:

$$at\ y=\pm r,\quad u(x,y,t)=0,\quad \theta(x,y,t)=0$$
$$at\ y=0,\quad v(x,y,t)=0,\quad \text{and}\quad at\ y=r,\quad v(x,y,t)=\left(\frac{\partial r}{\partial t}\right) \tag{15}$$

3. Methodology of Analysis

The mathematical solutions for Eqs. (12) and (14) were obtained by using Mathematica software version (13.2). The solutions can be found by using the command DSolve and it can be presented in the following forms:

$$u(x,y,t)=\frac{\left(\frac{\partial p}{\partial x}\right)-\left(\frac{\partial p}{\partial x}\right) Cosh\left(\frac{\sqrt{H_2}\,M\,y}{\sqrt{H_1}}\right)Sech\left(\frac{\sqrt{H_2}\,M\,r}{\sqrt{H_1}}\right)}{(H_2\,M^2)} \tag{16}$$

$$\theta(x,y,t)=\frac{1}{8\,H_2^2\,H_3\,M^4}\left\{\begin{array}{c}\left(\begin{array}{c}\left(-8\,H_1\,Ec\,Pr\left(\frac{\partial p}{\partial x}\right)^2+2\,H_2M^2\left(\left(2\,Ec\,Pr\left(\frac{\partial p}{\partial x}\right)^2+H_2\,M^2\,Q\right)\right)(r-y)(r+y)\right)\\ +\left(-7\,H_1 Ec\,Pr\left(\frac{\partial p}{\partial x}\right)^2+2\,H_2M^2\left(Ec\,Pr\left(\frac{\partial p}{\partial x}\right)^2+H_2M^2\,Q\right)(r-y)(r+y)\right)Cosh\left(\frac{2\sqrt{H_2}\,M\,r}{\sqrt{H_1}}\right)\\ +\left(H_1\,Ec\,Pr\left(\frac{\partial p}{\partial x}\right)^2\right)\left(8\,Cosh\left(\frac{\sqrt{H_2}M(r-y)}{\sqrt{H_1}}\right)-Cosh\left(\frac{2\sqrt{H_2}M\,y}{\sqrt{H_1}}\right)+8\,Cosh\left(\frac{\sqrt{H_2}\,M(r+y)}{\sqrt{H_1}}\right)\right)\end{array}\right)\\ \times Sech\left(\frac{\sqrt{H_2}\,M\,r}{\sqrt{H_1}}\right)^2\end{array}\right\} \tag{17}$$

where

$$H_1=\left(\frac{\mu_{thnf}}{\mu_f}\right),\quad H_2=\left(\frac{\sigma_{thnf}}{\sigma_f}\right),\quad H_3=\left(\frac{k_{thnf}}{k_f}\right) \tag{18}$$

4. Results

In this section, we will discuss the effect of the embedded characteristics on fluid flow and thermal properties, while considering the hybrid nanofluid. The focus will be on examining how these parameters affect the properties of fluid stream and thermic behaviour.

The velocity and heat transfer coefficient graphs in Figures 3 and 4 depict the impact of the volume percentage of hybrid nanoparticles in the deliquescent. The study concludes that a raise in the volume proportion of hybrid nanoparticles results in a reduction of velocity and transfer of heat measurements. The heat coefficient of transfer is governed by the proportion of $\left(\frac{k_f}{k_{thnf}}\right)$, and the use of hybrid nanoparticles decreases this ratio, leading to a decrease in temperature. Similarly, the velocity profile is regulated by the ratio of $\left(\frac{\mu_{thnf}}{\mu_f}\right)$, and the use of hybrid nanoparticles increases this ratio, leading to a decrease in velocity.

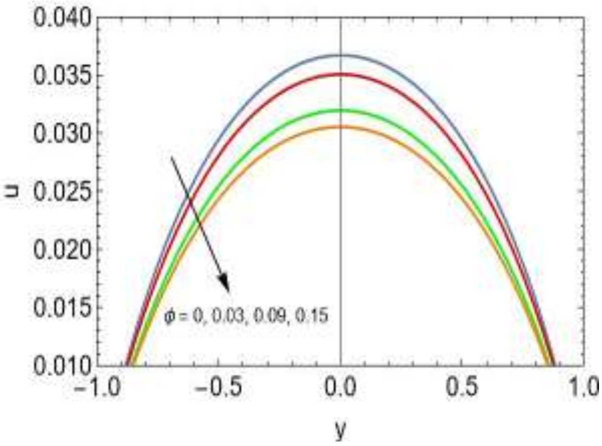

Fig. 3. Variation amounts of hybrid nanoparticles ϕ for velocity profile

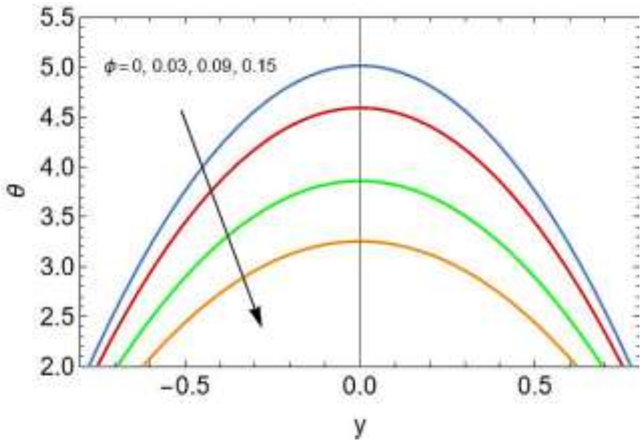

Fig. 4. Variation amounts of hybrid nanoparticles ϕ for heat transfer coefficient

Figures 5 and 6 consider the effect of the magnetic factor on velocity and the transfer of heat coefficient concerning $Pr = 7$ and $\phi = 0.03$. The findings indicate that, as depicted in Figure 5, the velocity decreases for a given value of M. Similarly, as illustrated in Figure 6, the transfer of heat coefficient increases for a particular amount of M.

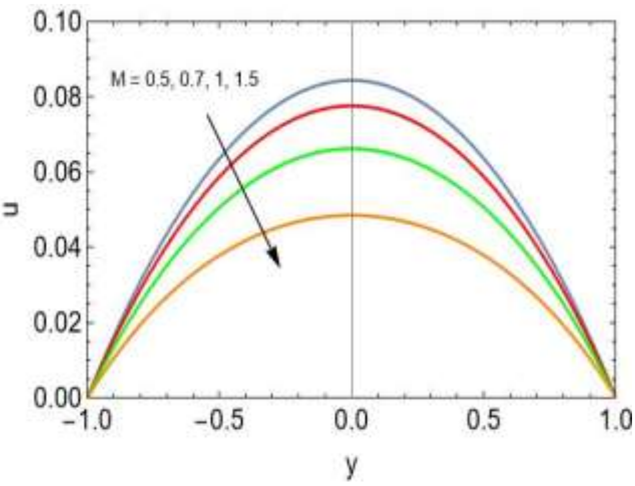

Fig. 5. Variation amounts for the magnetic parameter M for the velocity profile

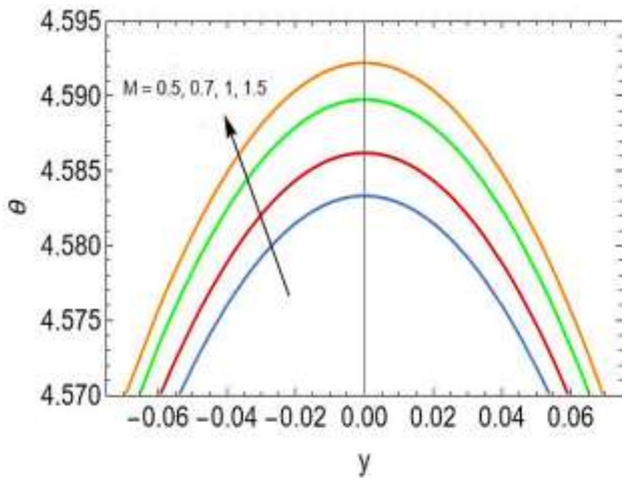

Fig. 6. Variation amounts for the magnetic parameter M for heat transfer coefficient

Figures 7, 8, and 9 examine the effect of the heat source, Prandtl number, and Eckert number at the transfer of heat coefficient. The results indicate that, so shown in Figure 7, the transfer of heat coefficient increases for a given value for Q. Similarly, Figure 8 demonstrates that the transfer of heat coefficient increases for a given value for Pr. Moreover, Figure 9 illustrates that the transfer of heat coefficient increases for a given amount of Ec.

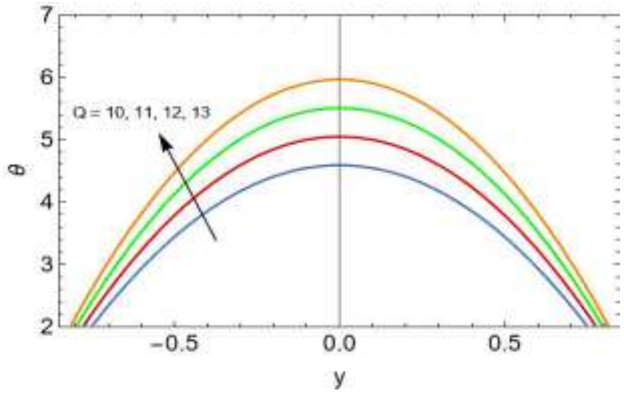

Fig. 7. Variation amounts of heat source Q for heat transfer coefficient

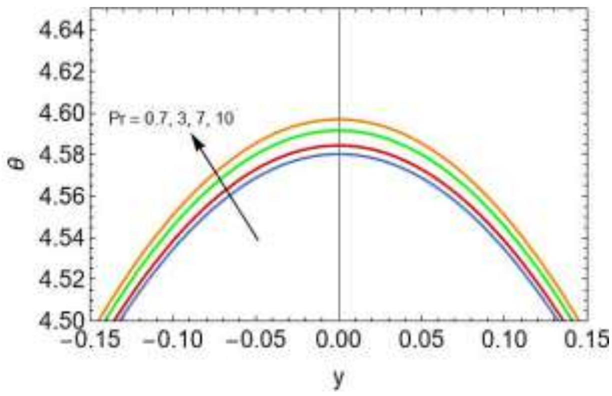

Fig. 8. Variation amounts of Prandtl number Pr for heat transfer coefficient

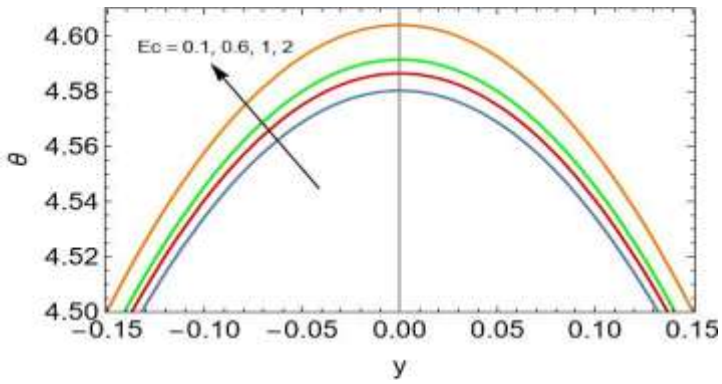

Fig. 9. Variation amounts of Eckert number Ec for heat transfer coefficient

5. Conclusions

According to recent research, the following inferences can be made A rise in hybrid nanoparticle volume indicates to in a reduce in velocity and the transfer of heat coefficient. Additionally, the magnetic factor leads to a reduction in velocity and a raise in the transfer of heat coefficient. Furthermore, a rise in the heat source, Prandtl number, and Eckert number also indicate to in a growth in the transfer of heat coefficient. Ultimately, our future research aims to utilize numerical methods to examine how the transfer of heat coefficient is affected by different nanoparticles in relation to the heat source, Prandtl number, and Eckert number.

Acknowledgement

The authors are very thankful to the anonymous referees and the editors for their worthy suggestions and comment. This research was not funded by any grant.

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