International Journal of Mechanics and Energy (IJME)
Vol. 9, Issue 1, 2022, ISSN: 2286-5845

MHD's impact on entropy production and natural convection in a particular shape of a cavity filled with a nanofluid Al_2O_3 - water

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Abstract: An analysis of the impact of the magnetic field on the flow of the Al_2O_3-water nanofluid which results from the natural convection that occurs inside a cavity having a non-regular shape was investigated. For this study the monophasic model is applied. Analytical solution of the transport equations is difficult; therefore, the use of Ansys-Fluent software appears essential.
An analysis of the impacts of Rayleigh numbers ($7.68.10^4$, $1.5.10^5$ and $3.072.10^5$) and Hartmann (0 to 75) as well as the concentration of nanoparticles expressed as a percentage (0 to 5%) on heat transmission and entropy production was exposed. Numerical results are expressed in form of streamlines, isotherms and Nusselt number. Mean Nusselt number and entropy production vary proportionally with the Rayleigh number and the volume fractions of the particles and they are inversely proportional to the Hartmann number.
For volume fractions of the chosen Al_2O_3 nanoparticles, heat transfer is improved.
After analysis of obtained results, correlations for Nusselt number expressed as an expression of two variables which are Hartmann and volumes fractions of nanoparticles have been proposed to predict the rate of heat transmission inside the enclosure. These laws are rarely presented in this kind of study.

Key words: Magneto-hydrodynamic, free convection, nanofluid, enclosure, entropy production.

1. Introduction

In recent years, study of natural convection associated with magneto-hydrodynamics (MHD) in confined or ventilated cavities having different shapes in the presence of a nanofluid become important because it is involved in conception and design of several thermal systems where the objective is to increase the rate of heat transfer. Several applications arise, among which we find energy storage systems, nuclear reactors, electronic accessories.

Natural convection of a fluid having improved thermal properties compared to that of the base fluid and in particular its thermal conductivity, is a means of increasing heat transfer.

Study of natural convection resulting from the movement of a nanofluid associated with a magnetic field receives great interest because it has a considerable influence on heat transfer, this has prompted several researchers to focus on this research theme where the main objective is to find new fluids which give better thermal efficiency.

Several theoretical and experimental investigations have been developed in this research field, among which we find that of [1]. These authors tried to analyze the effect of magnetic field on natural convection in an enclosure filled with a nanofluid. It was found that the heat transfer rate became better by increasing the volume fraction of the chosen nanoparticles and that the Rayleigh and Hartmann numbers significantly influence the fluid circulation inside the cavity.

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An analysis of entropy production in a natural convection flow of the nanofluid Al_2O_3 associated with Magneto-hydrodynamics in a sinusoidal enclosure filled with nanofluid Al_2O_3-water was investigated [2]. It was concluded that heat transfer becomes better with increasing Rayleigh number and conduction becomes dominant with increasing Hartmann number.

The entropy production which is obtained from natural convection flow of Cu-water nanofluid inside a cavity in the presence of a hot obstacle has been carried out [3]. These authors found that increasing Rayleigh number makes fluid motion and heat transmission more intense, and increasing Rayleigh number reduces the Bejan number, this is due to high fluid friction.

A study of mixed convection coupled to a magnetic field has been developed and the production of entropy has been determined in an unclosed cavity. Inside this cavity is introduced a pipe containing an obstacle considered to be adiabatic. The fluid used is the hybrid Al_2O_3-Cu/water nanofluid. It has been found that heat transfer improves and entropy production increases with increasing Richardson number [4].

Production of entropy and natural convection which occur simultaneously under the action of the Lorentz force in a porous corrugated cavity containing a heating block and filled with a nanofluid has been investigated [5]. It has been found that in the laminar regime, Nusselt number and entropy production increase with increasing Rayleigh and Darcy numbers and decrease with increasing the Hartmann. For turbulent flow, the average Nusselt number decreases as the Darcy number increases.

In this study, an investigation of the laminar natural convection of the nanofluid Al_2O_3-water under action of the Lorentz force produced from a magnetic field has been developed in a square cavity having a particular shape. Following the bibliographic research that we conducted, this study has not been conducted before in geometries having this form.

In this work, we are interested to the study of effect of Rayleigh and Hartmann numbers and volume fraction of the chosen nanoparticles on heat transfer, fluid movement and the average Nusselt number. This study is completed by correlations expressed as a law which gives the variation of the Nusselt number as a function of the Hartmann number and of the volume fraction for different Rayleigh numbers. Few studies in this area where we find this type of correlation.

2. Physical Model

In figure 1, we represent the studied configuration, it consists of a square cavity having a hollow inside which is supposed to be hot. In this work, we want to determine the entropy production and to see the nanofluid flow in natural convection under the effect of an external magnetic field oriented in the horizontal direction. The cavity has a height and a width of 10 mm and a hollow with a diameter of 4 mm. Vertical walls are maintained at a cold temperature Tc while the horizontal ones are assumed to be at zero heat flux and the hollow is assumed to be at hot temperature. Studied cavity is filled with Al_2O_3-water nanofluid assumed to be incompressible and Newtonian. This study is two-dimensional, stationary and laminar. All the physical properties that describe this flow are assumed to be constant and independent of temperature with the exception of density, which varies with temperature and this variation is expressed by Boussinesq's law, which takes into account of the buoyancy effects. Viscous dissipation and thermal radiation are assumed to be negligible. For the chosen volume fractions, the fluid resulting from the mixture of the nanoparticles and the water is assumed to be homogeneous under a thermal equilibrium.

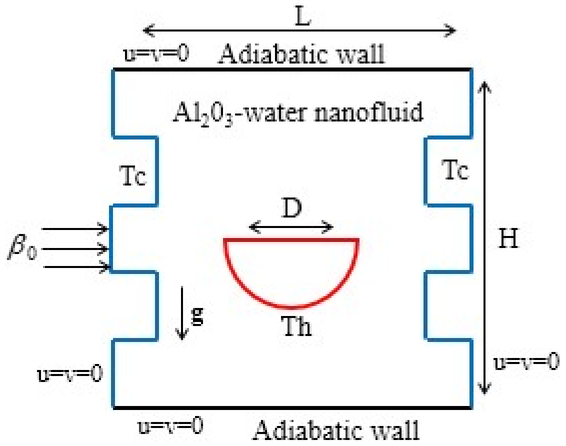

Fig. 1 Studied geometry

The equations that govern the flow of the nanofluid in laminar natural convection are:

Continuity equation:

Taking into account the assumptions written before, this equation is written:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

Momentum equation:

According to the two directions x and y, the momentum equation has the expression:

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial P}{\partial x}+\upsilon_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial P}{\partial y}+\upsilon_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\beta_{nf}g(T-T_C)-\frac{\sigma_{nf}}{\rho_{nf}}\beta_0^2 v \tag{3}$$

Energy equation:

The energy equation is written:

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

Entropy production is given by the expression [6]:

$$S_l=\frac{K_{nf}}{T_0^2}\left[\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial y}\right)^2\right]+\frac{\mu_{nf}}{T_0}\left[2\left(\frac{\partial u}{\partial x}\right)^2+2\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2\right]+\frac{\sigma_{nf}\beta_{nf}^2 v^2}{T_0} \tag{5}$$

$$S_l=S_{HT}+S_v+S_m \tag{6}$$

The temperature T_0 is chosen as:

$$T_0=0.5\left(T_c+T_f\right) \tag{7}$$

Expressions of thermal conductivity, viscosity, density, thermal expansion coefficient and nanofluid specific heat can be determined using conventional formulas developed for solid-liquid mixtures [7].

The following equation is used to calculate the electrical conductivity [8].

$$\sigma_{nf}=\left[1+\frac{3\varphi(\gamma-1)}{(\gamma+2)-(\gamma-1)\varphi}\right]\sigma_f \tag{8}$$

Where: $\gamma=\frac{\sigma_s}{\sigma_f}$

The dimensionless numbers included in this study are given by:

$$Ra=\frac{g\beta_{nf}(T_h-T_c)H^3}{v_{nf}\alpha_{nf}}\ ,\quad Nu_{nf}=\frac{h_{nf}H}{K_f}\ ,\quad Ha=\beta_0 H\sqrt{\frac{\sigma_{nf}}{\mu_{nf}}}$$

Ra, Nu and Ha are the numbers of Rayleigh, Nusselt and Hartmann. Hartmann number can be considered as a control parameter in magnetohydrodynamics coupled to natural convection. It expresses the relationship between the electromagnetic force and the viscous force and it intervenes in the movement of conductive fluids in the presence of a magnetic field.

3. Numerical model

The transport equations which govern the study of natural convection in the cavity represented above are nonlinear and coupled and they are expressed in the form of partial derivatives. Their analytical solution is difficult, so the use of the numerical method based on finite volume approach appears to be very useful. To overcome this difficulty, Fluent-CFD software was used. In this numerical method, pressure-velocity coupling is ensured by the coupled algorithm for the case of a single phase. Discretization of convective and diffusive terms of transport equations is carried out by a second-order upwind method.

As the various transport equations represented before are non-linear, the use of the under-relaxation coefficients ensures the stability of the chosen iterative scheme, while the residuals and monitoring of their evolution provide an idea on the convergence.

For convergence of the different equations of the study of natural convection associated with the magneto-hydrodynamic, the residuals are fixed at 10^{-6}.

In application of the finite volume method, use of an intensified mesh close to walls and wide going towards the center of the cavity appears as a technique which allows to capture the different gradients which develop (boundary layers) and limits computation time.

4. Results and discussion

The results obtained from the study of natural convection of Al_2O_3-water nanofuide in the cavity shown above are treated taking into account of the effect of uniform external magnetic field applied in the horizontal direction by introducing the adimensional number of Hartmann.

Volume fractions of the nanoparticles range from 0% to 5%, selected values of the Rayleigh number are $7{,}68.10^4$; $1{,}5.10^5$ and $3{,}072.10^5$ respectively and the number of Hartmann takes values that vary between 0 and 75. In first part of this study, the results obtained are represented as streamlines, isotherms, entropy production and average Nusselt number. These results are shown in figures 2, 3, 4 and 5.

From obtained results, we note that the number of Hartmann influences heat transfer that occurs inside the considered cavity. When this number becomes high, convection intensity decreases and heat transfer by conduction becomes dominant. Figure 2 shows the impact of Hartmann number on streamlines for three values of Rayleigh numbers at $\varphi = 0.05$.

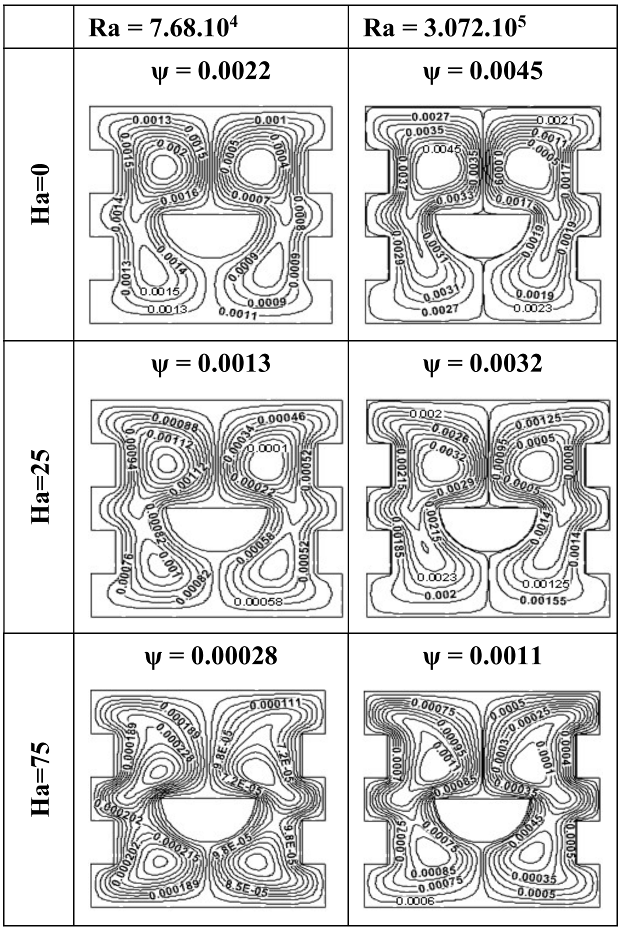

Fig. 2 Impact of Hartmann numbers on streamlines for three Rayleigh numbers at $\varphi = 0.05$

For different values of Rayleigh number, four cells take place inside the cavity. When Rayleigh number becomes high, the fluid moves advantage in the annular space. However, we find that maximum values of streamlines decrease when the Hartmann increases. So in the presence of a magnetic field, fluid becomes decelerated and therefore it can access to different areas located near vertical walls. This is given by the orientation of streamlines that occur inside the cavity.

Figure 3 shows the impact of Hartmann (Ha) and Rayleigh (Ra) numbers on temperature variation at nanoparticle volume fraction $\varphi = 0.05$. For values of the Hartmann number lower than 25, isotherms located under the trough which are vertical change shape and a

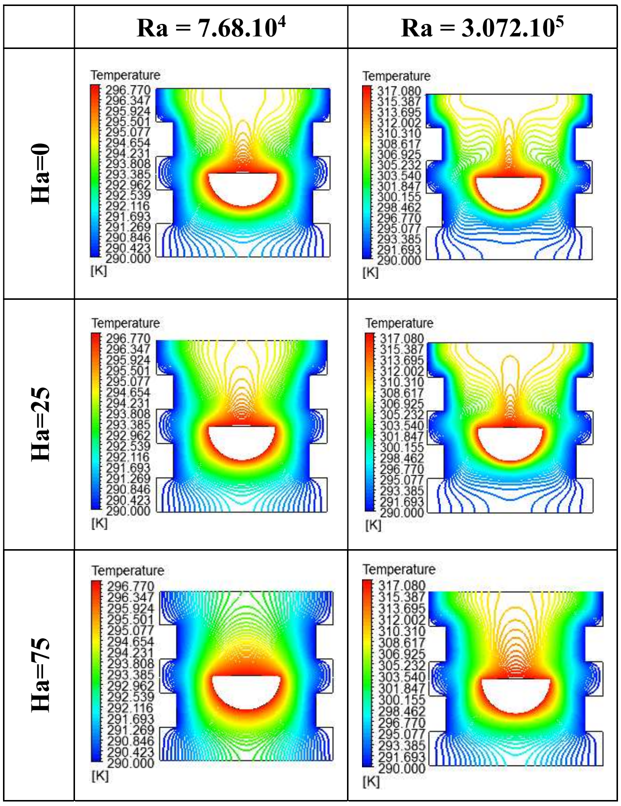

Fig. 3 Impact of Hartmann number on isotherms for two Rayleigh numbers at $\varphi = 0.05$

part becomes horizontal by increasing the Rayleigh number, but when the Hartmann number becomes significant, these isotherms do not change shape. For high values of Rayleigh, they remain vertical. For a fixed Rayleigh number and increasing Hartmann, temperature gradients become significant so the effect of convection decreases and conduction tends to become dominant. If we fix the Hartmann and increasing Rayleigh, the thickness of the thermal boundary layer decreases and the convection becomes important. Increase in the volume fraction of the nanoparticles and Rayleigh number makes the fluid accelerated and consequently heat transfer by convection becomes considerable and conduction becomes less intense. On the other hand, increase of Hartmann reduces natural convection. So, the presence of magnetic field can limit or suppress convective heat transfer.

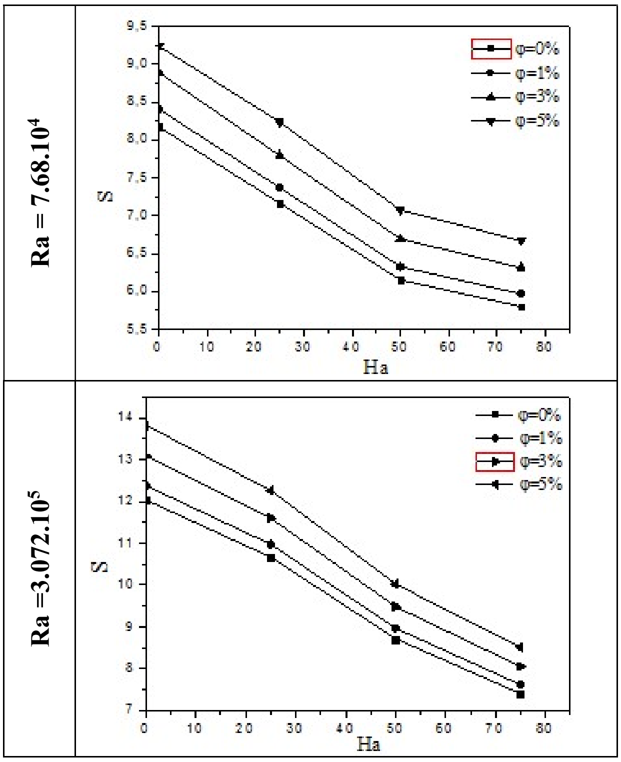

Fig.4 Entropy generation for various Hartmann numbers and nanoparticles volume fractions

4.1 Entropy generation

Figure 4 represents variation of the generation of local entropy according to the Hartmann.

An increase in volume fraction of the nanoparticles generates an increase in thermal energy and the nanofluid flow accelerates. As a result, a significant increase in local entropy with increasing volume fraction and Rayleigh numbers is observed.

Lorentz force produced by magnetic field and which opposes the convective transfer is proportional to Hartmann number, so if this number is increased, the acceleration of the fluid becomes weak. Decrease in convection gives a decrease in temperature variation and therefore a decrease in generation of local entropy.

In case where Hartmann number is low and Rayleigh is high, natural convection becomes

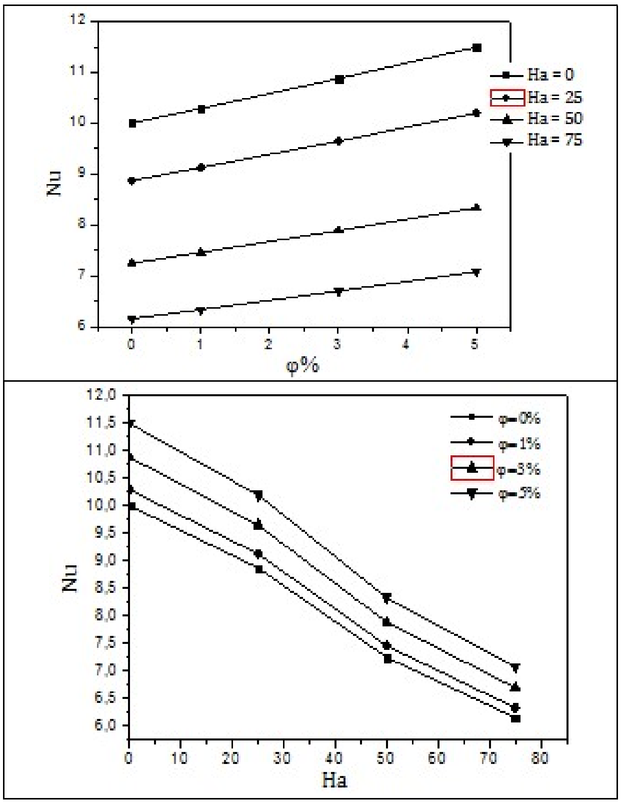

Fig. 5 Average Nusselt number for Ra =3.072.10^5 at various Hartmann numbers and nanoparticles volume fractions

important and therefore the generation of entropy is very significant.

4.2 Nusselt number variation

In figure 5, we represent variation of the average Nusselt number for a fixed Rayleigh value (Ra = 3,072.10^5) as a function of Hartmann number and volume fraction of the solid nanoparticles.

According to the results obtained, this dimensionless number increases with volume fraction and decreases with Hartmann. Addition of nanoparticles to the base fluid improves thermal conductivity of nanofluid obtained and consequently Nusselt number increases. For numbers of Hartmann high, Lorentz force becomes important and it opposes convection heat transfer, so buoyancy effect decreases and therefore Nusselt number decreases. For significant Rayleigh numbers, convection becomes dominant and hence mean Nusselt increases.

Table 1 Correlations for Nusselt number

Ra = 7.68.10^4			
Correlation	$Nu = 14.386.(Ha)^{-0.191}(\varphi)^{0.0509}$		
Solid volume fraction	$\varphi = 0.01$	$\varphi = 0.03$	$\varphi = 0.05$
Maximum error	2.24%	2.24%	2.6%
Ra = 1.5.10^5			
Correlation	$Nu = 23.199.(Ha)^{-0.283}(\varphi)^{0.0508}$		
Solid volume fraction	$\varphi = 0.01$	$\varphi = 0.03$	$\varphi = 0.05$
Maximum error	1.13%	1.1%	2.7%
Ra = 3.072.10^5			
Correlation	$Nu = 36.603.(Ha)^{-0.332}(\varphi)^{0.0688}$		
Solid volume fraction	$\varphi = 0.01$	$\varphi = 0.03$	$\varphi = 0.05$
Maximum error	2.58%	2.27%	2.6%

Hartmann number has a significant influence on Nusselt and therefore on modes of heat transfer considered.

After analyzing of results obtained, a correlation for Nusselt number as a function of Hartmann and volume fractions of nanoparticles was proposed. For each fixed value of Rayleigh number, this correlation has the expression:

$$Nu = B.(Ha)^m(\varphi)^n \qquad (9)$$

For each case studied, constants B, m and n are represented in table above. Maximum error is around 2.7%, which justifies the reliability of these correlations.

5. Conclusions

In this investigation, natural convection and entropy generation in a cavity having a particular shape and filled with Al_2O_3-water nanofluid under action of a magnetic field was carried out. Results obtained are analyzed taking into account of the impact of Rayleigh and Hartmann numbers and volume fraction of the nanoparticles. The main conclusions are:

-Magnetic field influences significantly fluid movement inside the cavity and heat transfer that occurs

- Heat transfer by convection becomes intense for a high Rayleigh number and for a low Hartmann

- Fluid becomes accelerated and heat transfer becomes enhanced for high values of chosen volume fractions and Rayleigh numbers

-Entropy generation and average Nusselt number rise with Rayleigh and volume fractions of Al_2O_3, but they decrease with Hartmann.

- For high values of Hartmann, magnetic field can maximally reduce convective heat transfer and conduction heat transfer intensifies.

References

[1] B. Ghasemi, S.M. Aminossadati, A. Raisi, Magnetic field effect on natural convection in a nanofluid-filled square enclosure, Int. J. Therm Scie, 50 (2011) 1748-1756.

[2] I. Mejri, A. Mahmoudi, M. A. Abbassi, A.Omri, Magnetic field effect on entropy generation in a nanofluid-filled enclosure with sinusoidal heating on both side wall , Powder Technology, 266 (2014) 340-353.

[3] A.SH. Mikhail, H.F. Oztop, I. Pop, N. Abu-Hamdeh, Analysis of Entropy Generation in Natural Convection of Nanofluid inside a Square Cavity Having Hot Solid Block: Tiwari and Das' Model, MDPI.J. entropy, 18 (2015).

[4] S. Hussain, S. E. Ahmed, T. Akbar, Entropy generation analysis in MHD mixed convection of hybrid nanofluid in an open cavity with a horizontal channel containing an adiabatic obstacle, Int. J. Heat Mass Transf,114 (2017)1054-1066.

[5] M.H. Tilehnoee, A.S.Dogonchi , S.M. Seyyedi ,A.J. Chamkha , D.D. Ganji ,Magnetohydrodynamic natural convection and entropy generation analyses inside a nanofluid‑filled incinerator‑shaped porous cavity with wavy heater block, J.Therm Anal and Calo, 141 (2020) 2033–2045.

[6] A. Bejan, A study of entropy generation in fundamental convective heat transfer, J. Heat Transf, 101 (1979) 718-725.

[7] M.M. Rahman, S. Saha, S. Mojumder, S. Mekhilef, R. Saidur, Numerical Simulation of Unsteady Heat Transfer in a Half-Moon Shape Enclosure with Variable Thermal Boundary Condition for Different Nanofluids, Num Heat Transf, Part B: Fundamentals, 65 (2014)282-301.

[8] Maxwell J. C, A Treatise on Electricity and Magnetism, 2nd ed. Oxford University Press, Cambridge, 1881.