A COMPARATIVE STUDY ON THERMAL AND FLOW FIELDS IN GLAZED WAVY AND FLAT PLATE SOLAR COLLECTORS UTILIZING NANOFLUID

دراسة مقارنة لمدى توزيع الحرارة والجريان في حيز زجاجي مموج ومجمع شمسي مسطح باستخدام مائع النانو

Asst. Prof. Dr.
Karima E. Amori

Maher Mahmood Husain

Univ. of Baghdad/ Mech. Eng. Dept. , Baghdad-Iraq

ABSTRACT:

A numerical investigation of steady two dimensional laminar natural convection heat transfer in plain and wavy solar collector is presented in this work. The parameters adopted are Rayleigh number range (10^3 to 10^6), aspect ratios (2, and 4) for wavy enclosure with number of undulation(1 to 4), and nanofluid volume fraction range (0 to 10%). The continuity, Navier-Stokes and the energy equations are solved by utilizing (FLUENT 6.3) software which is based on the finite volume method. SIMPLE algorithm with upwind scheme is adopted to compute the velocity components, temperature, pressure and Nusselt number (local and average). This study considers the effect of different boundary conditions on the heat transfer within the air space above the absorber and base fluid or nanofluid below the absorber. It is found that, the heat transfer rate increases with increasing Rayleigh number. The Nusselt number increases with increasing volume fraction in plain enclosure. Nu No. increases with increasing volume fraction. It is found that the heat transfer in plain enclosure decreases as aspect ratio increasing, while it increases in wavy enclosure. The maximum heat transfer occurs when the wavy is designed with two undulations for pure fluid and one undulations for nanofluid. The results show that the Nusselt number in wavy collector is higher than that of flat collector.

1. INTRODUCTION

Free convection in enclosures is widely studied in the literature for square, rectangular or inclined walled geometries. In the literature are a limited number of studies with wavy walled enclosures due to the complexity of flow inside the enclosure and difficulty of obtaining boundaries of the enclosure. This kind of model can be used to enhance heat transfer in such applications as heat exchangers, solar collectors and so on. Mahmud et al. [1] made a numerical solution to investigate free convection inside an enclosure bounded by two isothermal wavy walls and two adiabatic straight walls. They observed that aspect ratio is the most important parameter or heat and fluid flows and higher heat transfer is obtained at a lower aspect ratio for a certain value of Grashof number. Mahmud and Islam [2] solved the laminar free convection and entropy generation inside an inclined wavy enclosure using SIP (Strongly Implicit Procedure) solver on a non-staggered grid arrangement. They obtained that the inclination angle of cavity affects the entropy generation due to the heat transfer and fluid friction. Kumar and Shalini[3] investigated the effects of surface undulations on natural convection in porous enclosure with global cumulative heat flux boundary conditions for different undulation numbers and thermal stratification level. They indicated that the local Nusselt numbers are very sensitive to thermal stratification. In another study, Kumar [4] made a numerical work for the natural convection in a porous enclosure which their vertical wavy surfaces under constant heat flux. Murthy et al. [5] analyzed the effect of the surface undulations on the natural convection heat transfer from an isothermal surface in a Darcian fluid-saturated porous enclosure by using the finite element method on a graded non-uniform mesh system. They found that the flow-driving Rayleigh number (Ra) together with the geometrical parameters of wave amplitude, wave phase, and the number of waves considered in the horizontal dimensions of the cavity influenced the flow and heat transfer process in the enclosure. Rees and Pop [6] performed an analytical study solving boundary layer equations for the wavy surface in a porous medium. Gao et al. [7] solved the natural convection inside the wavy and inclined solar collector but they did not interest in flow behavior. Adjlout et al. [8] performed and solved a similar problem with Gao and others, but in their case, the left vertical wall is flat and cold, whereas the right wall is wavy and hot. They indicated that the mean Nusselt number is decreased when it is compared with the square cavity. Das and Mahmud [9] analyzed the free convection inside both the bottom and the ceiling wavy and the isothermal enclosure. They indicated that, only at the lower Grashof number, the heat transfer rate rises when the amplitude wave length ratio changes from zero to other values. Recently, Dalal and Das [10] made a numerical solution to investigate the inclined right wall wavy enclosure with spatially variable temperature boundary conditions. Oztop[11] applied the elliptic grid generation to obtained sinusoidal duct geometry to enhance the forced convection heat transfer. Varol and Oztop[12, 13] investigated the effects of inclination angle on the laminar natural convection heat transfer and fluid flow in a wavy solar collector in steady state regime. They observed that the inclination angle is the most important and effective parameter on heat transfer which can be used to control the heat transfer inside the collector. The main purpose of the present paper is to provide natural convection heat transfer inside a shallow and horizontal wavy enclosure. To the best of the authors' knowledge, free convection in the shallow wavy enclosure has not yet been investigated. The Rayleigh number and the aspect ratio are the main parameters which are effective on thermal and flow fields. The results are presented in terms of streamlines, isotherms and Nusselt numbers.

2. PHYSICAL MODEL

Schematic configurations of the considered model are depicted in Fig. 1 and Fig.2. In this figure, a solution domain is chosen as the upper part of the model. Boundary conditions are also plotted on the figure showing that vertical walls are adiabatic with height, H. A and λ refers to the amplitude and wave length, respectively. The length of enclosure is fixed as 1.4 m.

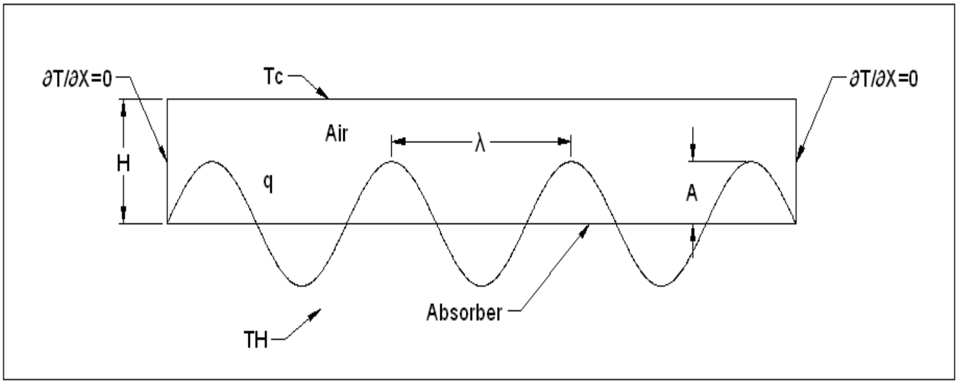


Fig.1: Schematic Configuration for a Horizontal Wavy Enclosure

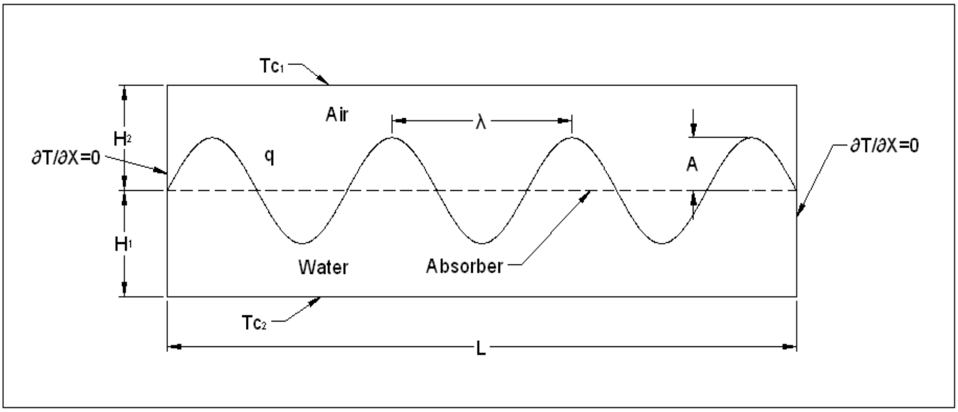


Fig.2: Schematic Configuration of Flat Solar Collector with Wavy Absorber

3. MATHEMATICAL MODEL

The continuity, momentum and energy equations can be written for a two dimensional laminar flow of an incompressible Newtonian fluid. For these equations it is assumed that there is no viscous dissipation, the gravity acts in vertical direction, and fluid properties are constant. However, the Boussinesq approximation is accepted. Thus, governing equations are obtained as

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (1)$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\nu_{nf}(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}) \quad (2)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\nu_{nf}(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2})-\beta g(T-T_c) \quad (3)$$

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

where

$$\alpha_{nf}=\frac{k_{nf}}{(\rho c_p)_{nf}} \quad (5)$$

$$\rho_{nf}=(1-\varphi)\rho_f+\varphi\rho_s \quad (6)$$

$$(\rho c_p)_{nf}=(1-\varphi)(\rho c_p)_f+\varphi(\rho c_p)_s \quad (7)$$

$$\frac{k_{nf}}{k_f}=\frac{k_s+2k_f-2\varphi(k_f-k_s)}{k_s+2k_f+2\varphi(k_f-k_s)} \quad (8)$$

$$\mu_{nf}=\frac{\mu_f}{(1-\varphi)^{2.5}} \quad (9)$$

$$\Pr=\frac{\nu_{nf}}{\alpha_{nf}} \quad (10)$$

$$Ra=\frac{\Pr g\beta(T_h-T_c)w^3}{\nu^2} \quad (11)$$

3.1 Boundary Conditions

The boundary conditions of the considered system are shown in fig. 1 for both configurations.

3.1.1 Wavy Collector

The upper wall (y=H, at any x), u=v=0, T=Tc (12)

The lower wall (y=0, at any x),u=v=0, T=T_h (13)

Vertical boundaries u, v=0, $\frac{\partial T}{\partial x}$ =0 (14)

3.1.2 Flat Solar Collector with Wavy Absorber

The upper glass wall (y=H_1+H_2, x),u=v=0, T=T_{c1} (15)

The lower wall (y=0, x),u=v=0, T=T_{c2} (16)

The absorber (y=H_1+A (sin $2\pi\frac{x}{s}$n)),u=v=0, $\frac{\partial T}{\partial y}$ =q_S (17)

$$\text{Side walls} \quad \left\{ \begin{array}{l} (x=0,\ y),\ u=v=0,\ \frac{\partial T}{\partial x}=0 \\ (x=L,\ y),\ u=v=0,\ \frac{\partial T}{\partial x}=0 \end{array} \right\} \quad (18)$$

Table 1 : Thermo-physical properties of pure fluid and nanoparticles

Physicalproperties	Fluid Phase(water)	Cu
Cp(J/kg k)	4179	385
ρ(kg/m3)	997.1	8933
K(W/m k)	0.613	400
α*107(m2/s)	1.47	1163.1
β*10-5(1/k)	21	1.67

4. NUMERICAL ANALYSIS

Equations of Vorticity and Energy are solved using the finite volume approach (Patanker, 1980; Versteeg and Malasekera, 1995). The diffusion and convective term in the Vorticity and energy equations is approximated by second order upwind scheme. Fluent and Gambit are using to solve governing equation.The mesh was generated in the preprocessor Gambit.

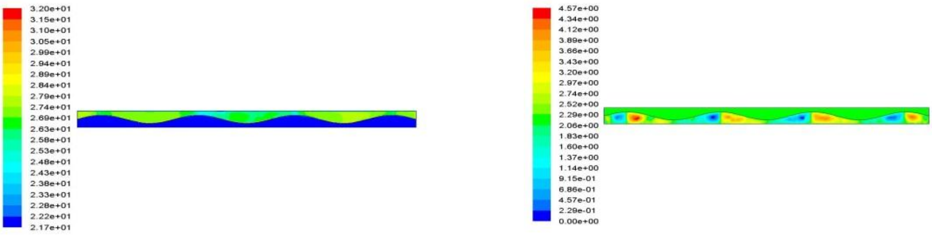
Relaxation factors are taken to be default values. Convergence criterion set for 10^{-3} for continuity, x-momentum and y-momentum and 10^{-6} for energy.

Table 2: Relaxation Factors

pressure	Density	Body force	Momentum	Energy
0.3	1	1	0.7	1

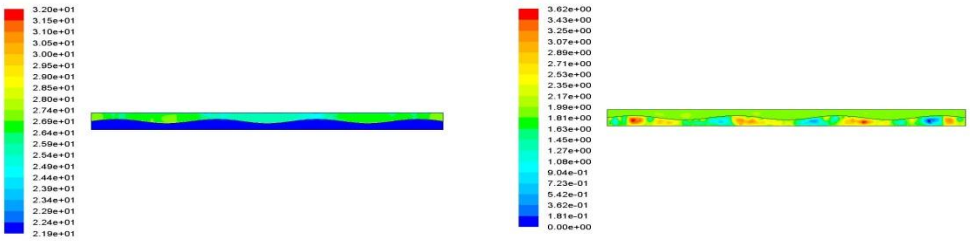
5. RESULTS AND DISCUSSION

The upper wall temperature of the solar collector is fixed to the reference temperature at 22C° whereas the hot wavy absorber temperature is set to 32C°, while the bottom and other side walls are adiabatic. The upper part of solar collector is filled air while the bottom part is filled base fluid (Water) and (nanofluid).The effect of aspect ratio in flat solar collector with sinusoidal absorber is studied by varying (AR) from 2 to 4. Isotherms and stream contours are shown in Figs. (1) And (2), for (N = 3.5), and tilt angle (γ=0˚). From the isotherms contour the temperature distribution is not clearly, in other ward solar collector is divided in two regions. Two circulation cells are formed in the crest of wavy absorber at bottom part.Local Nusselt number is presented along wavy absorber at air and water side in figures (3) and (4). In the case, the variation of local Nusselt number shows wavy variation.Figs (5) and (6) illustrate the isotherms contours, stream contours and local Nusselt number on wavy absorber. The copper particles added to water are not affecting to the general form of isotherms, stream andthe value of local Nusselt number. Figure (7) illustrates the stream contours, isotherms contours for $Ra=6*10^6$, Aspect ratio =2, number of undulation=3.5 and tilt angle =0°. Two circulation cells are formed in the bottom of wavy absorber, while other small circulation cells are seen the vertical sides. The fluid rises in the middle from the crest wavy hot absorber towards the top flat cold wall and then descends on the sides of the collector.In the case, the variation of local Nusselt number shows wavy variation.Figure (8) illustrates the stream contours, isotherms contours for $Ra=6*10^6$, Aspect ratio =8 and tilt angle =0°.The stream contours in the core region two circulation cells are stretched out toward the vertical sides of the collector.It can be observed from the isotherms contour, the heated fluid rises along the right and left side walls as a result of buoyancy forces. From the figure (9) the Nusselt number in the case of wavy collector is more than of flat collector.



Isotherms **Stream**

Fig (1)Specification of Natural Convection in Wavy collector (Water, AR=2, N=3.5, Ra (air) =1.33*105, Ra (water) =3.03*107 and γ=0˚)



Isotherms **Stream**

Fig (2)Specification of Natural Convection in Wavy collector (Water, AR=4, N=3.5, Ra (air) =1.33*105, Ra (water) =3.03*107 and γ=0˚)

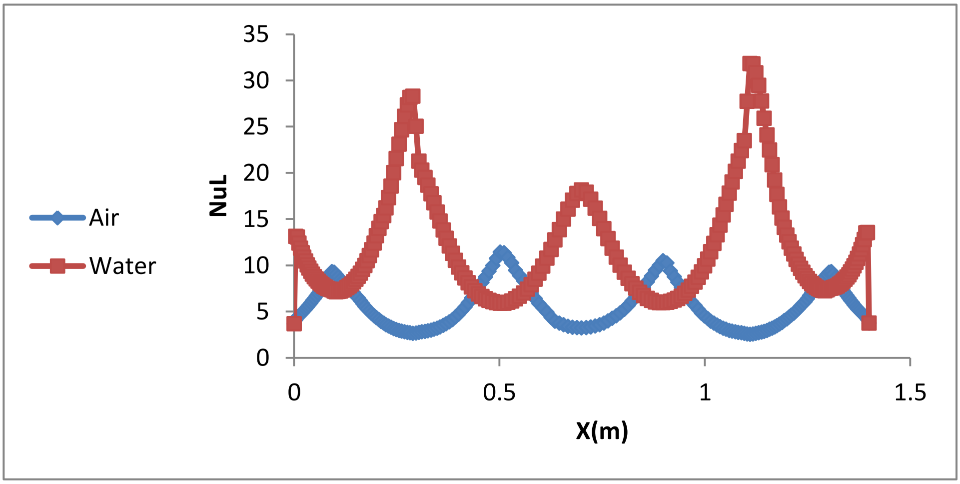


Fig (3) Variation of local Nusselt number on absorber on a-air side, b-water side for (Water, AR=2, N=3.5, Ra (air) =1.33*105, Ra (water) =3.03*107 and γ=0˚)

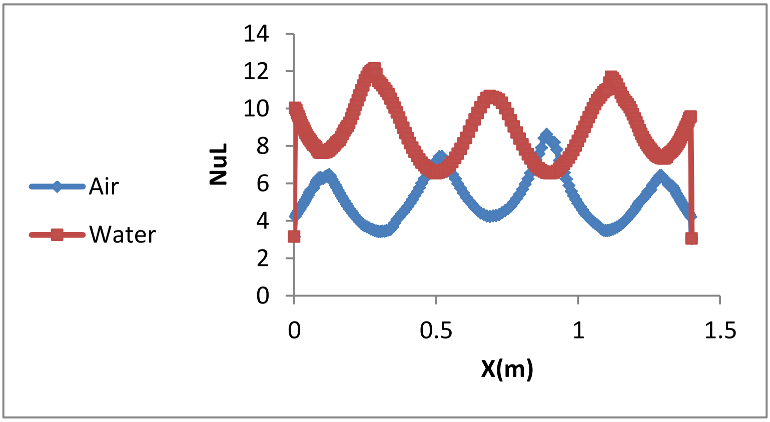
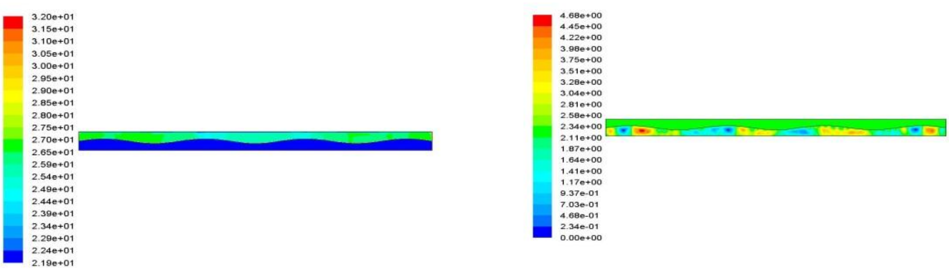


Fig (4) Variation of local Nusselt number on absorber on a-air side, b-water side for (Water, AR=4, N=3.5, Ra (air) =1.33*105, Ra (water) =3.03*107 and γ=0˚)



Isotherms **Stream**

Fig.(5): Specification of Natural Convection in Wavy collector (Cu-water, AR=4, N=3.5, φ=5%, Ra (air) =1.33*105, Ra (Nanofluid) =1.39*107 and γ=0˚)

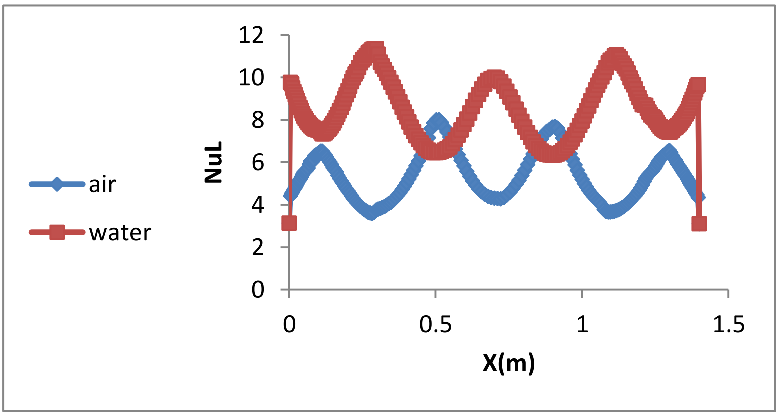
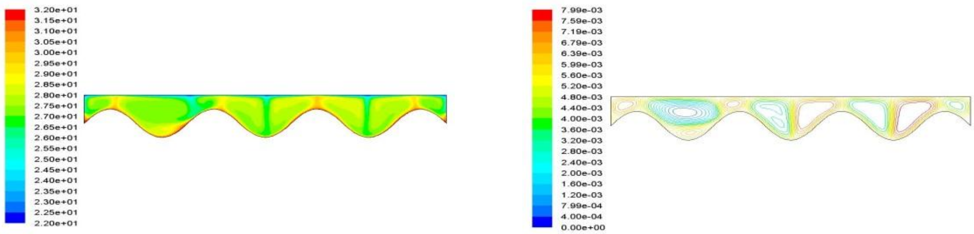


Fig (6) Variation of local Nusselt number on absorber on a-air side, b-water side for (Cu-water, AR=4, N=3.5, φ=5% Ra (air) =1.33*105, Ra (Nanofluid) =3.03*107 and γ=0˚)



Isotherms Stream

Fig (7)Specification of Natural Convection in Wavy collector Heated from Below (Air, AR=2, N=3.5, Ra =6*106 and γ=0˚)

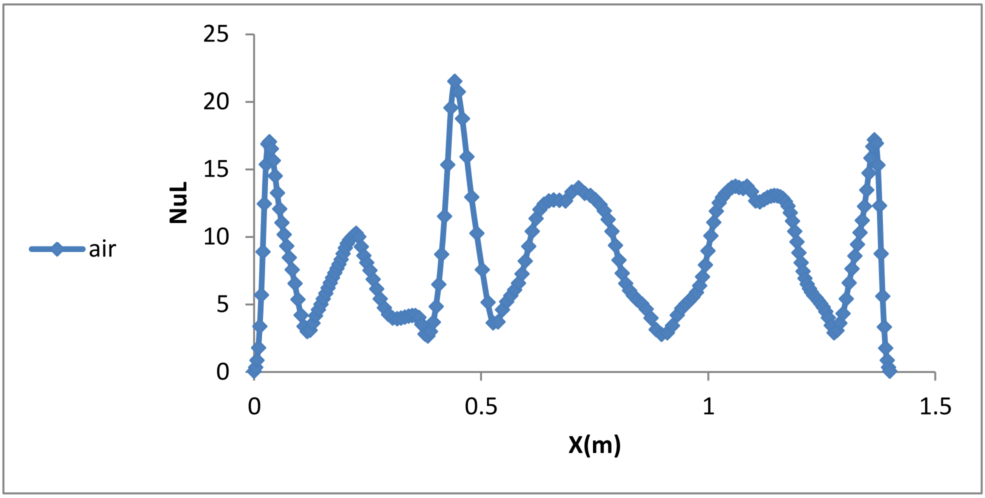
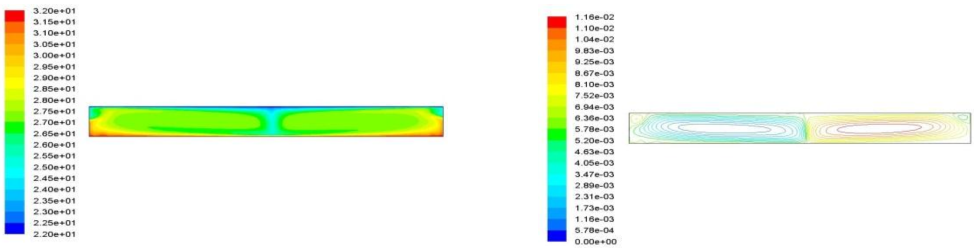


Fig (8) Variation of local Nusselt number on Wavy heated absorber on for (Air, AR=2, N=3.5, Ra =6*106, and γ=0˚)



Isotherms Stream

Fig (9)Specification of Natural Convection in Plain collector Heated from Below (Air, AR=2, N=3.5, Ra =6*106 and γ=0˚)

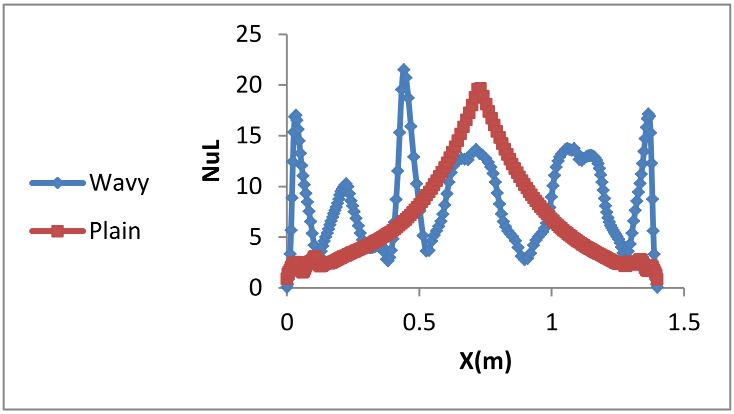


Fig (10) Variation of local Nusselt number on Wavy heated absorber on for (AR (wavy) =2, AR=8 (plain), N=3.5, Ra =6*106, and γ=0˚)

6 CONCLUSIONS

Natural convection heat transfer in steady-state regime in shallow wavy enclosure has been studied numerically. The main conclusions that are drawn from the present study are provided below.

1. Flow and thermal fields are affected by geometrical parameters
2. Local Nusselt numbers show wavy variation
3. Heat transfer is increased with the decreasing of aspect ratio
4. The Nusselt number in the case of wavy collector is higher than for flat collector.
5. The copper nanoparticles added to water are not affecting on the value of local Nusselt number.

الخلاصة:

في العمل الحالي تم عرض دراسة نظرية لحمل طبيعي طباقي مستقر ثنائي البعد في مجمع شمسي مستوي و مموج. المتغيرات المعتمدة في هذه الدراسة هي عدد رايلي (بمدى ١٠^٣ إلى ١٠^٦)، نسبة باعية (٢ و ٤) للحيز المموج مع عدد تموجات يبلغ (١ الى ٤)، و النسبة الحجمية لمائع النانو كانت ضمن مدى يتراوح من (٠ الى ١٠٪). تم حل

معادلات الاستمرارية، نافير- ستوكس و الطاقة باستخدام برنامج FLUENT الذي يعتمد طريقة الحجوم المحددة. أتبع منهج SIMPLE بالطريقة الهجينة لحساب قيم كل من مركبات السرعة، درجة الحرارة ، الضغط وعدد نسلت (الموضعي والمتوسط). تضمنت الدراسة تأثير مختلف الشروط الحدية على انتقال الحرارة داخل حيز الهواء فوق السطح الماص وللمائع الأساسي أو مائع النانو تحت السطح الماص. تبين ان انتقال الحرارة يزداد مع زيادة عدد رايلي. ان قيمة عدد نسلت يزداد مع زيادة النسبة الحجمية لدقائق النانو في الحيز المسطح الجوانب. قلَ انتقال الحرارة في الحيز المسطح الجوانب مع زيادة النسبة الباعية له. وجد اعظم انتقال للحرارة عند تصميم حيز مموج ذو موجتين للمائع الأساسي وحيز ذو موجة واحدة لمائع النانو. بينت النتائج ان عدد نسلت للمجمع الشمسي المموج اعلى من ذلك المستحصل للمجمع المسطح.

7. REFERENCES

[1] S. Mahmud, P.K. Das, N. Hyder, A.K.M.S. Islam, Free convection heat transfer in an enclosure with vertical wavy walls, Int. J. Therm. Sci. 41(2002) 440–446.

[2] S. Mahmud, A.K.M.S. Islam, Laminar free convection and entropy generation inside an inclined wavy enclosure, Int. J. Therm. Sci. 42 (2003)1003–1012.

[3] B.V.R. Kumar, Shalini, Natural convection in a thermally stratified wavy vertical porous enclosure, Numer. Heat Transf., A Appl. 43 (2003)753–776.

[4] B.V.R. Kumar, A study of free convection induced by a vertical wavy surface with heat flux in a porous enclosure, Numer. Heat Transf., A Appl.37 (2000) 493–510.

[5] P.V.S.N. Murthy, B.V.R. Kumar, P. Singh, Natural convection heat transfer from a horizontal wavy surface in a porous enclosure, Numer. Heat Transf., A Appl. 31 (1997) 207–221.

[6] D.A.S. Rees, I. Pop, Free convection induced by a horizontal wavy surface in a porous medium, Fluid Dyn. Res. 14 (1994) 151–166.

[7] W. Gao,W. Lin, E. Lu, Numerical study on natural convection inside the channel between the flat-plate cover and sine-wave absorber of a cross corrugated solar air heater, Energy Convers. Manag.41 (2000) 145-151.

[8] L. Adjlout, O. Imine, A. Azzi, M. Belkadi, Laminar natural convection in an inclined cavity with a wavy wall, Int. J. Heat Mass Transfer 45(2002) 2141–2152.

[9] P.K. Das, S. Mahmud, Numerical investigation of natural convection inside a wavy enclosure, Int. J. Therm. Sci. 42 (2003) 397–406.

[10] A. Dalal, M.K. Das, Laminar natural convection in an inclined complicated cavity with spatially variable wall temperature, Int. J. Heat Mass Transfer 48 (2005) 3833–3854.

[11] H.F. Oztop, Numerical study of flow and heat transfer in curvilinear ducts: applications of elliptic grid generation, Appl. Math. Comput. 168 (2005) 1449–1460.

[12] Y. Varol, H.F. Oztop. , Effects of inclination angle on natural convection in wavy solar air collectors: a computational modeling, The 2nd International Green Energy Conference, UO IT, Oshawa, Canada, 25–29 June 2006 (in press).

[13] Y. Varol, H.F. Oztop, Buoyancy induced heat transfer and fluid flow inside a tilted wavy solar collector, Building Environment (in press).