Numerical Study Of Natural Convection Through A Photovoltaic-Thermal (PV/T) Building Solar Chimney Suitable For Natural Cooling

A. Ndiho, K. N'wuitcha, H.A. Samah, M. Banna

Abstract: Transient mixed convective airflow in a novel Building Solar Chimney, designed in connecting together, as a single device, a Photovoltaic/Thermal (PV/T) collector with transparent PV cells as active wall and a solar thermal flat-plate collector, has been analyzed numerically using a stream function, vorticity formulation and employing a finite difference scheme. The Photovoltaic-Thermal Building Solar Chimney could not only generate electricity but also achieve potential energy saving by the reduction of the air conditioning cooling loads when it is applied in tropical climate conditions. The results are presented in the form of streamlines, isotherm contours, local Nusselt number, mass air flow characteristics and the dimensionless temperature. The effects of Grashof and Reynolds numbers and the geometrical parameters on the performances of the Building Solar Chimney are presented and analyzed. Based on the resulting numerical prediction, it is found that the Photovoltaic/Thermal Building Solar Chimney (PV/T-BSC) model offers a good electrical efficiency while Photovoltaic/Thermal Reverse Building Solar Chimney (PV/T-RBSC) collector offers a good thermal efficiency. Finally, the results showed that no Building Solar Chimney studied can simultaneously provide good electrical and thermal efficiency.

Index Terms: Fluid flow, convective heat transfer, transparent photovoltaic (PV), building solar chimney, simulation

1 INTRODUCTION

IN hot tropical areas, thermal loads into building exceed the thermal comfort level of the occupants and cooling is desirable. In most of these situations and for the purpose of improving natural ventilation performance and achieving better indoor thermal comfort, two passive predominant methods and techniques are used:

- Thermal insulation materials as molded polystyrene plates, false ceiling, vegetable covers, etc... for the reduction of the heat gains into the building.
- Night ventilation, wind towers, Trombe walls and solar chimneys for improving natural ventilation performance.

In low energy building design, the Photovoltaic (PV) modules are nowadays integrated in building's fabric, functioning as Hybrid Photovoltaic/Thermal systems (Wall Solar Collector or Trombe Walls) to provide natural ventilation and generate better more the electricity energy. It is an attractive concept leading to minimize the temperature effect by integrating the PV cells in titled open channel; in which the air gap beneath PV cells provides natural cooling of the PV cells and reduces its operational temperature.

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According to Rakesh Kumar and Marc A. Rosen [1], natural cooling using free convection is a simple method with lower cost to remove heat from the back of the PV modules and to keep the electrical efficiency at an acceptable level. Their works and analysis have shown that solar chimney is an excellent passive ventilation strategy to use in buildings for enhancing natural ventilation and to provide thermal comfort for the occupants. Indeed, Hybrid Photovoltaic/Thermal (PV/T) collectors provide electricity and necessary ventilation cheaply. It is a thermal unit, employing low temperature circulating fluid, used to extract, by natural ventilation, the absorbed sunlight that is not converted into electricity and could be harmful to the PV cells. This heat input can increase the cells temperatures thus decreasing the conversion efficiency of solar cells. In fact, only about 16% of the solar energy absorbed by photovoltaic (PV) device is converted into electricity [2]. For crystalline silicon solar cells the associated elevation of PV temperature reduces solar energy conversion efficiency by 0.4–0.5% K^{-1}[3, 4]. Independent testing of the ''BP Saturn'' PV cell showed a reduction in conversion efficiency from 15.8% at 25°C to 12% at 80°C, yielding a temperature coefficient relating conversion efficiency to module temperature of – 0.44% K^{-1}[5]. Many experimental and theoretical studies were carried out to investigate the effect of higher PV module temperature on its output power and electrical efficiency. K. Sopian et al [6], in their theoretical and experimental study showed that the mean photovoltaic panel temperature is high at higher solar radiation and the photovoltaic panel efficiency decreases. The PV cells efficiency is strongly dependent on solar cells temperature, and if Solar cells temperature increases, solar cells efficiency decreases [7,18,19]. The literature review also showed that the studies on heat and fluid flow in the cavities and classic collector have proved the effect of wall boundary conditions, inclination, aspect ratio, and cavity or collector geometry. Also, the solar collectors have gained substantial attentions and been developed rapidly over the past few years especially in the natural ventilation applied in buildings [8,9,20]. Otherwise, extensive studies of water and air cooled PV/T collectors in the literature are commonly available [10-12, 21]. These studies reveal that most of the PV/T models used are based an electrical analogy where temperatures, flows, flow sources and imposed temperatures are respectively assimilated to potentials, currents, current generators and voltage generators [13-15]. Nowadays, there is a growing interest in studying heat and mass transfers in air gap behind PV cells. In order to optimize the utilization of the solar energy in the PV system and to deepen the understanding of heat transfer mechanisms by natural convection and to visualize the flow in this system, some studies have been undertaken to examine natural convection heat transfer in cavities and classic collectors due to its wide application areas [6, 7, 10, 11, 16, 22, 23].The flow pattern is always an important feature in such problems. Navier-Stokes and energy equations for unsteady laminar natural convection flow, resulting from thermal buoyancy effect and laminar vertical jet from below, are used for the airflow visualization. Particularly, numerical simulations have been conducted to determine the heat transfer and the flow rate characteristics of PV cells cooling [8-9]. In some of these previous studies, constant temperature, symmetric boundary conditions and asymmetric boundary conditions with adiabatic walls are commonly used. These boundary conditions are very common when the double PV skins are formed by opaque PV panels at the outer and an opaque wall at the inner side. Using these conditions, Nougblega Y. et al [13] and X.Q. Zhai et al [14] summarized the main configurations and the integrated renewable energy systems based on solar chimneys. A careful review of literature reveals that the nodal discretizations are most used in studying heat transfer models without taking into account the fluid flow. In the Computational Fluid Dynamics (CFD) models found, non-realist imposed temperature condition on the PV cells active walls is often used, without taking into account the climatic and the atmospheric conditions (ambient air temperature, solar radiation, inlet wind velocity) [13]. Although the cooling process is observed in the air PV/T collectors and really improve the electricity production, the air flow rate in the natural convection is very weak so that a simple PV/T collector cannot be directly applied in Building and improve indoor air ventilation for cooling inside the Building effectively; thus, the air flow has to be improved in these devices. The objective of the present study is to develop a heat transfer model and to design an innovated hybrid Photovoltaic/Thermal (PV/T) collector as Building Solar Chimney for improving more cooling and saving solar electricity. In such case, the hybrid Photovoltaic/Thermal Building Solar Chimney (PV/T-BSC) is designed by connecting together, a simple PV/T collector (using transparent PV cells flat-plate as active wall) and a solar thermal flat-plate collector (where a classic black absorber is the active plate as shown in the Fig. 1) to obtain a single device. Navier-Stokes and energy equations for unsteady two-dimensional laminar and mixed convection flow, resulting from thermal buoyancy effect and natural vertical jet from below, are proposed. Constant and imposed uniform solar radiation flux on transparent PV cells, and/or adiabatic walls are considered as boundary conditions on tilted solar chimney. Particularly, numerical simulations have been conducted to determine the heat transfer, the flow rate characteristics and the hybrid Photovoltaic/Thermal Building Solar Chimney (PV/T-BSC) performances.

2 Physical and Mathematical Model

A two-dimensional (2D) air heating flat-plate innovated Building Solar Chimney, of height L, of thickness (air gap) e and inclined angle φ is considered. Fig. 1 shows the hybrid Photovoltaic/Thermal Building Solar Chimney (PV/T-BSC) scheme, designed as a single device. The device is composed by the juxtaposition, of a hybrid PV/T collector and a flat-plate thermal solar collector. The heat transfer fluid enters from the bottom and discharge at the top of the chimney. In order to find the optimal positions of PV cells inserting in the channel, a Reverse Building Solar Chimney (PV/T-RBSC), model designed by inverting hybrid PV/T collector and flat-plate collector, has been proposed and studied (Fig.1.b). A constant heat flux corresponding to average solar radiation is imposed on the top wall which is formed in part of transparent PV cells active wall and other part of classic transparent glass. The bottom wall of the chimney is also composed by adiabatic plate behind PV cells and a classic black absorber for the classic thermal collector zone behind the transparent glass.

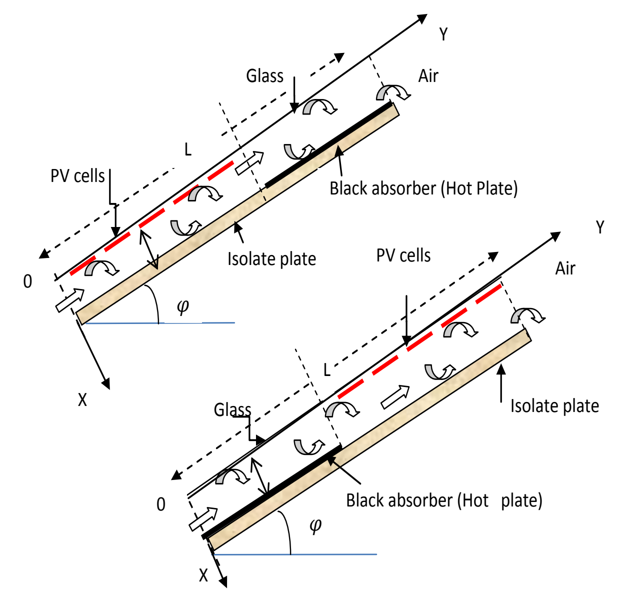


Fig.1.*Geometry and coordinate system of hybrid Photovoltaic/Thermal Building Solar Chimney*

Navier–Stokes and energy equations for unsteady laminar mixed convection flow in the channel are considered. In this study, a mathematical model and computer code are developed to analyze the heat transfer in the channel. The following assumptions are made in this analysis:

- Transfers are laminar, two-dimensional, and asymmetric boundary
- The air is supposed to be incompressible
- The constant fluid properties are considered
- The Boussinesq approximation is considered to estimate the effect of the density variation according to the temperature
- Viscous heat dissipation in the fluid is neglected

3 Normalized Transfer Equations

By elimination of pressure between two momentum equations, the vorticity transport equation, energy equation and stream function equation are obtained. Using the dimensionless variables reported in the nomenclature and the assumptions mentioned above, the dimensionless equations are expressed as follows:

$$\partial\Omega/\partial\tau + U\partial\Omega/\partial X + V\partial\Omega/\partial Y = (1/Re)(\partial^2\Omega/\partial X^2 + \partial^2\Omega/\partial Y^2) + (Gr/Re^2)[(\partial\,\theta/\partial Y)\cos\varphi + (\partial\,\theta/\partial X)\sin\varphi] \quad (1)$$

$$\partial\theta/\partial\tau + U\partial\theta/\partial X + V\partial\theta/\partial Y = [1/(Re.Pr)](\partial^2\theta/\partial X^2 + \partial^2\theta/\partial Y^2) \quad (2)$$

$$-\Omega = (\partial^2\psi/\partial X^2 + \partial^2\psi/\partial Y^2) \quad (3)$$

where the stream function, ψ, and the vorticity, Ω, are defined by:

$$U = \partial\psi/\partial Y\,; \quad V = -\partial\psi/\partial X \quad (4)$$

$$\Omega = \partial V/\partial X - \partial U/\partial Y \quad (5)$$

In these equations, U and V are dimensionless velocity components, X and Y are the dimensionless cartesian coordinates, τ is dimensionless time, θ is dimensionless temperature, φ is slope of channel, Re is Reynolds number, Gr is Grashof number and Pr is Prandtl number. The initial and boundary conditions in terms of dimensionless variables of PV/T-BSC are written as follows:

Initial conditions: at τ=0:

$$\theta(X,Y) = 0\,; \psi(X,Y) = 0\,; \quad \Omega(X,Y) = 0; U(X,Y) = V(X,Y) = 0 \quad (6)$$

Boundary conditions:

- Inlet of the channel: at $Y = 0\,;\ 0 < X < 1$

$$\Omega(X,0) = 0\,; \psi(X,0) = 1 - X; \quad V(X,0) = 1\,; U(X,0) = 0\,; \theta(X,0) = 0 \quad (7)$$

- Outlet of the channel : at $Y = A\,;\ 0 < X < 1$

$$(\partial\theta/\partial X)_{Y=A} \ ;\ (\partial\psi/\partial X)_{Y=A} \ ;\ (\partial\Omega/\partial X)_{Y=A} \quad (8)$$

- Conditions on the Walls:
  - On PV collector: at $X = 0\,;\ 0 \le Y \le A/2$

$$U(0,Y) = V(0,Y) = 0 \ ;\ \psi(0,Y) = 0 \quad -(\partial\theta/\partial X)_{X=0} = \tau_{gl}\alpha_{PV} - \eta_e \quad (9)$$

  - On the glass: at $X = 0\,;\ A/2 < Y \le A$

$$U(0,Y) = V(0,Y) = 0 \ ;\ \psi(0,Y) = 0 \quad -(\partial\theta/\partial X)_{X=0} = \alpha_{gl} \quad (10)$$

  - On the isolate plate at : $X = 1\,;\ 0 \le Y \le A/2$

$$U(1,Y) = V(1,Y) = 0 \ ;\ \psi(1,Y) = 0 \quad (\partial\theta/\partial X)_{X=1} = \tau_{gl}\tau_{PV}\alpha_{is} \quad (11)$$

  - On the hot plate at: $X = 1\,;\ A/2 < Y \le A$

$$U(1,Y) = V(1,Y) = 0 \ ;\ \psi(1,Y) = 0 \quad (\partial\theta/\partial X)_{X=1} = \tau_{gl}\alpha_{hp} \quad (12)$$

where:
A is aspect ratio;
α_{PV}, α_{gl}, α_{is} and α_{hp} are respectively, PV (Photovoltaic) cells, glass, insulation and hot plate (black absorber) absorptivity coefficients; η_e is PV cells efficiency at standard temperature; τ_{gl} and τ_{PV} are respectively glass and PV transmittance .Thom's vorticity computational formula for approximating the wall vorticity was used:

$$\Omega_n = -2(\psi_{n+1} - \psi_n)/\Delta n \quad (13)$$

where ψ_n and ψ_{n+1} are stream function values at the points adjacent to the boundary wall; n the normal abscise on the boundary wall.

4 Evaluation of the Model Characteristic numbers

The physical quantities of interest in this problem are the local Nusselt numbers and the flow rate through the chimney. The local Nusselt number (Nu) and average Nusselt number (Nu_m) for heated walls are given by:

- On PV cells plate at $X = 0\,; 0 \le Y \le A/2$:

$$Nu_{PV}(Y) = 1/\theta\ (X=0,Y) \quad (14)$$

$$Nu_{mPV} = \frac{2}{A}\int_0^{A/2} Nu_{PV}(Y)dY \quad (15)$$

- On black absorber plate at $X = 1; A/2 << Y \le A$

$$Nu_{hP}(Y) = 1/\theta\ (X=1,Y) \quad (16)$$

$$Nu_{m,hp} = \frac{2}{A}\int_{A/2}^{A} Nu_{hp}(Y)dY \quad (17)$$

The dimensionless mass flow rate through the solar chimney Q is determined at the outlet of the channel and expressed as follows:

$$Q = D_m/(\rho v_0) = \int_0^1 V(X,A)dX \quad (18)$$

where D_m is mass flow rate, ρ is fluid density and v_0 average jet velocity of the entrance.

5 Numeric Method

The present investigation deals with numerical prediction of air flow and temperature distribution in two-dimensional air channel of the Photovoltaic/Thermal Building Solar Chimney (PV/T-BSC) which is heated from PV cells plate at the bottom, and from black absorber on the other side near the outlet of the collector. The Navier-Stokes equations in terms of stream function and vorticity and energy equation formulation are solved numerically by Gauss-Seidel iteration using the finite difference technique. The governing equations, substituted by a set of algebraic equations used in all grid points in the calculation domain, are considered. For

Table 1

Numerical model input parameters

Parameters	Value
Transmittance-absorptance product of PV surface, $(\tau\alpha)_{PV}$	0.74
Absorptivity of the glass, α_{gl}	0.05
Absorptivity of hot plate, α_{hp}	0.90
Absorptivity of isolate wall, α_{is}	0.05
Transmittance of glass, τ_{gl}	0.95
Transmittance of PV surface, τ_{pv}	0.25
PV cell efficiency at standard temperature, η_e	0.15
Slope of channel, φ	45°

the computing, the input parameters are listed in Table 1 and include the surface properties, PV cells electrical efficiency and slope of Hybrid PV/T-BSC collector.

5.1 Grid independence test

To obtain a grid-independent solution, various grid dimensions were employed. The grid independence is tested in two stages: M is fixed N varied, and N is fixed M varied. As shown in table 2, it was found that a 100 x150 grid size ensure the independence of the solution on the grid with reasonable computing time. The refinement produces insignificant change in θmax and in the average Nusselt number. The set of resulting algebraic equations were solved iteratively by Tridiagonal Matrix Algorithm (TDMA) and were performed by successive under-relaxation to avoid divergence in the iterative solution of algebraic equations and to accelerate the convergence (0.6 for u and v; 0.8 for the other parameters). Convergence of iteration for the solution is obtained until the values of the variables cease to change from the previous iteration to the next by less than the prescribed value. The following criterion is employed to confirm whether the solution has converged.

$$\left|\left(\phi^{m+1}-\phi^{m}\right)/\phi^{m+1}\right| \leq \varepsilon$$

where ϕ stands for Ω, ψ, θ and m stands for the number of iterations. The value of ε chosen is 10^{-4}.

TABLE 2

GRID INDEPENDENCE TEST TO FIX M AND N

Stage	Gridsize	θ_{max}	Change (%)	$Nu_m PV$	Change (%)
M=100 N varied	100X100	0.20034	-	6.75854	-
	100X125	0.19817	0.217	6.75960	0.106
	100X150	0.20015	0.198	6.76051	0.091
N=150 M varied	75X150	0.19751	-	6.95764	-
	100X150	0.19714	0.037	6.95969	0.205
	125X150	0.19685	0.029	6.95856	0.113

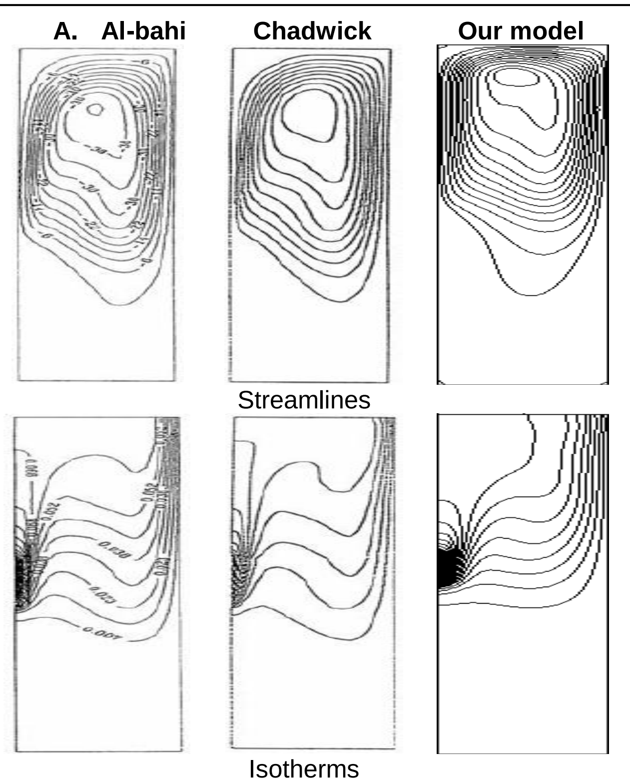


Fig. 2. *Comparison of streamlines and isotherms variations*

5.2 Validation of the model

The present numerical results are evaluated for accuracy against numerical results published in previous works reported by various authors. The comparison of the streamlines and isotherms for laminar pure free convection flow (Re=1) in a rectangular enclosure (A=L/e=5) of the results from the present numerical code and the published results of Chadwick and A. Al- Bahi [17] are shown in Fig. 2. A stretched 51x51 grid was used with Pr=1 and Gr=5.16x10^5. Significant agreement, which demonstrates the validity of the formulation and the numerical code, is observed. The present numerical result patterns inside the channel of the solar chimney are in a good qualitative agreement with the previous published results (Fig.2).

6. RESULTS AND DISCUSSIONS

6.1 Airflow and heat transfer characteristics

The temperature distribution and flow fields of the inlet jet and buoyancy force which induced the natural convective and

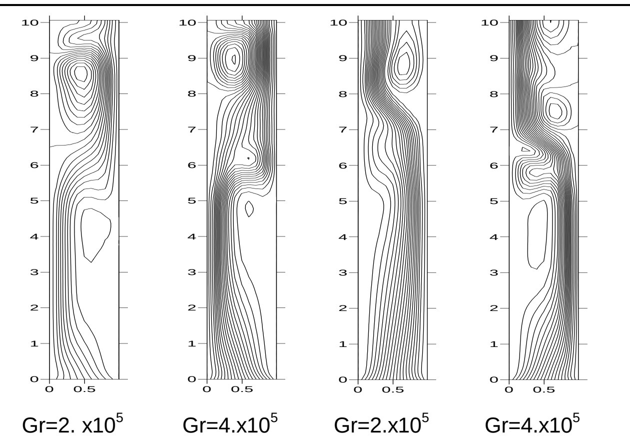


Fig. 3. *Streamlines for Re=50, A=10 and for different values of Gr*

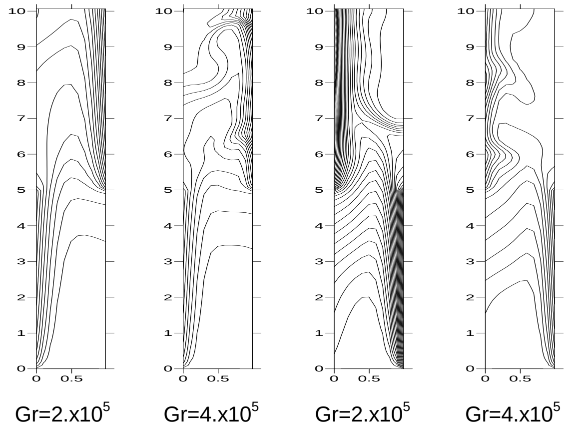


Fig. 4. *Isotherms for Re=50, A=10 and for different values of Gr*

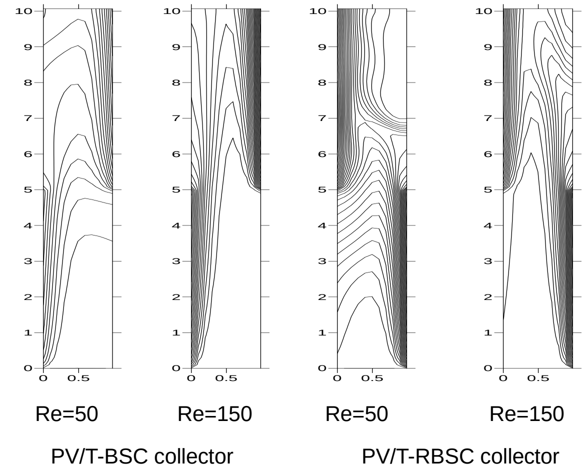


Fig. 6. *Isotherms for Gr=2x105, A=10, q=100 W.m2 and for different values of Re*

airflow in the channel of the solar chimney have been analyzed numerically for different Grashof and Reynolds numbers. The flow patterns inside the channel and thermal fields are presented in terms of streamlines and isotherms contours. As shown in Fig.3 and 5, the streamline contours exhibit circulation patterns as the fluid motion which is affected by PV cells sources, black absorber plate heated and cooled adiabatic wall. The direction of the flow, due to the thermal buoyancy force, is clockwise in this geometry as it is observed in the channels. The plot shows that from the bottom of the channel, the inlet flow air converges especially towards the active PV cells which are heated by uniform flux. And then, the buoyancy forces drive the heated air towards the hot plate before the outlet. Streamlines and the corresponding isotherm contours for Pr= 0.71 and aspect ratio A=10, presented in Fig. 3 and Fig.4 show the effect of various Grashof numbers on buoyancy force that induced natural convective flow in the channels of the two Solar Chimney collectors (Hybrid PV/T-BSC and PV/T-RBSC). As shown in Fig. 3, air circulation inside the channel is very weak at low Grashof number and a further increase of Grashof number increases the air circulation inside the channel. As shown in Fig.4, if Grashof number increases the isotherms become more distorted. The stack of isotherms near the active walls, namely PV cells collector and hot plate, indicates that most of the heat transfer takes place at the vicinity of active walls. The isotherms near active walls are almost parallel, denoting pure conduction heat transfer through theses walls. At the low values of Reynolds number (Re), it can be observed the recirculation air movement in the channel and backflow at the outlet which represent the natural convection phenomena. And at large Re numbers, the recirculation and backflows disappear, the streamlines show a parallel flow composed by the open lines which represent the forced convective mode (Fig.5). Fig.6 shows that if Re number increases, the isotherms become more tightened at the vicinity of the active walls, testifying a noticeable increase in convective heat transfer.

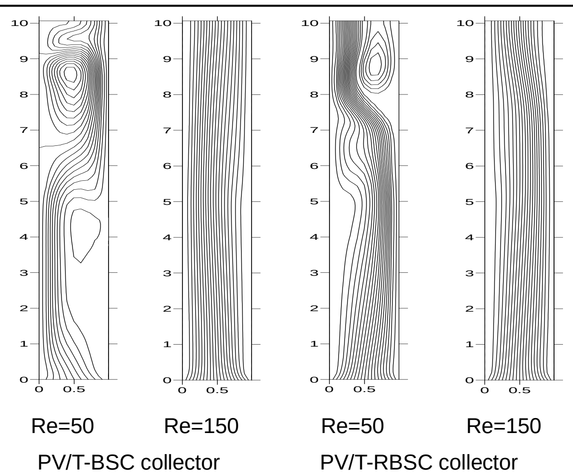


Fig. 5. *Streamlines for Gr=2x10^5, A=10, q=100 W.m^2 and for different values of Re*

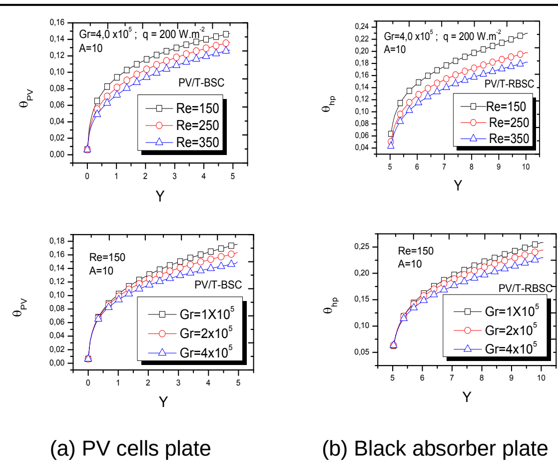


Fig. 7. *Dimensionless temperature variations along the active walls*

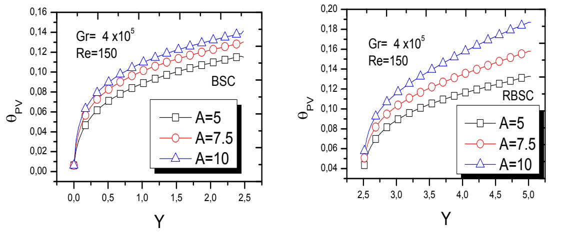


Fig. 8. *Effect of aspect ratio (air gap) on dimensionless temperature variations along the PV cells active wall*

Nevertheless, the contour isotherms are normal to the adiabatic walls, indicate that there is no heat transfer through this boundary. According to the results of the Fig. 3-6, the convective heat transfer is more noticeably in Hybrid PV/T-BSC model than the reversed model (PV/T-RBSC). Fig. 7 shows the dimensionless temperature distributions on the active walls, namely PV cells and hot plate, for PV/T-BSC and PV/T-RBSC Hybrid collectors. It can be observed that when Reynolds number increases, the dimensionless temperature decreases on the active walls because more the speed of the inlet air increases, more heat is evacuated from the active walls towards outside. It can be observed that when Grashof number increases, the dimensionless temperature decreases on the active walls θ because the dimensionless temperature is inversely proportional to the solar radiative heat flux by definition. In fact, O. Manca and S. Nardini [15] in their experimental investigation on the natural convection in the horizontal channels with the upper wall at uniform heat flux showed that when Rayleigh number increases, the dimensionless temperature inside the cavity decreases. The dimensionless temperature is relatively low near the channel entrance where the thermal boundary layer is thin and the dimensionless temperature increases quickly as the boundary layer thickness increases.

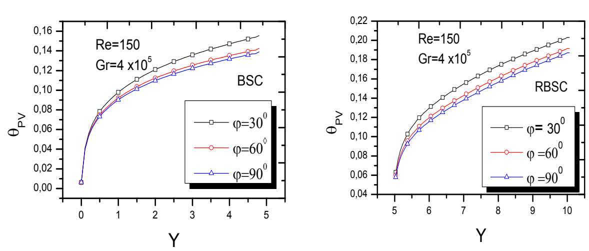
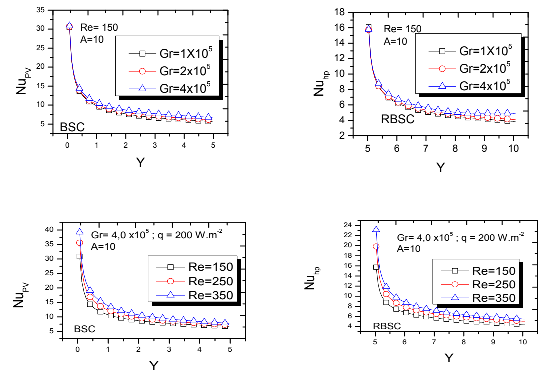


***Fig. 9**. Effect of title φ on dimensionless temperature variations along the PV cells active walls*



(a) PV cellsplate (b) Black absorberplate

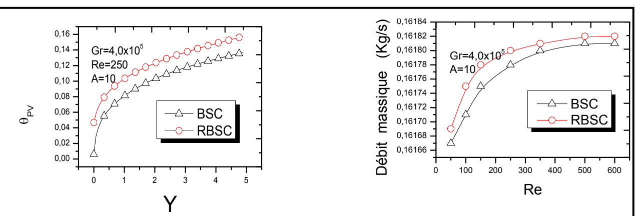
Fig. 10. *Nusselt number variations along the active walls*

Fig.8 and Fig.9 show the effect of the geometrical parameters such as aspect ratio (A) and slop of channel (φ) on dimensionless temperature variations along the PV cells active wall. As shown by K.S. Ong and C.C. Chow [9], the results of the Fig.8 show that for PV/T-BSC and PV/T-RBSC hybrid collectors, the PV cells dimensionless temperatures increase with the aspect ratio according to the dimensionless temperatures defined as inversely proportional to the air gap depth. The performances particularly show that the air mass flow rate through the chimney (tab. 3) and PV cells temperatures depend of the slope of the chimney [8]. As shown in Fig.9, the PV cells dimensionless temperatures increase with the collector's inclination angle.

TABLE 3

AIR MASS FLOW RATE IN FUNCTION OF CHIMNEY SLOP

φ	Dimensionless mass air Flow rate, Q	
	PV/T-BSC	PV/T-RBSC
30^0	0.16177	0.16179
60^0	0.16173	0.16175
90^0	0.16172	0.16174



(a)Variation of PV cells temperature (b) Outlet air mass flow rate

***Fig. 11**. Photovoltaic cells temperature variations and mass flow rates for PV/T-BSC and PV/T-RBSC Hybrid collectors.*

The Nusselt number is another characteristic parameter in the convective heat transfer problems. Its variation along the active walls is plotted in Fig.10 as function of Reynolds and Grashof numbers. The Fig.10 shows that Nu increases with Re number, this result is awaited because more the speed of the air at the inlet of the channel increases, more the heat is evacuated from the cavity towards outside. The local Nusselt number profiles versus Grashof number is shown in Fig. 10. The transfer rate of the heat from the active walls to the fluid increases with the Grashof number. It can be concluded that the increase in Grashof number leads to an increase in the local Nusselt number. In general, the Nusselt number at the PV collector and hot plate starts with high value at a point close to the bottom and decreases monotonically to a small value at the top. Local Nusselt number is higher near the channel entrance where the boundary layer thickness is very small and temperature difference between surface and inlet air temperature is very small. If boundary layer thickness increases, temperature difference increases, that make local Nusselt number decreases. The increase of Reynolds number or Grashof number leads to the increase of, Nusselt number indicating an augmentation of heat transfer rate. In fact, E. Bilgen and T. Yamane, [16] in their study on enclosure equipped with a chimney found that heat transfer and Nusselt number are an increasing function of Rayleigh number.

6.2 Solar Chimney performance: electrical and thermal efficiencies

Fig.11 plots the dimensionless temperature variations along the PV active cells plate and the outlet mass flow rate for PV/T-BSC and PV/T-RBSC Hybrid collectors for fixed aspect ratio A= L/e=10; Re =250 ; $q=200W/m^2$ and $Gr=4x10^5$. As shown in Fig.11.a, the Photovoltaic cells temperature is lower for PV/T-BSC than PV/T-RBSC Hybrid collectors. According to K. Sopian et al [6], and H.P. Garg and R.S. Adhkari [7] works, the present results of the Fig.11.a prove that the electrical efficiency decreases with increasing of the photovoltaic cells temperature, so that, the PV/T-BSC Hybrid collector offers a good electrical efficiency than PV/T-RBSC. Otherwise, as shown in Fig.11.b, the mass flow rate is further high for PV/T-RBSC than PV/T-BSC Hybrid collector; hence the PV/T-RBSC Hybrid collector has a good thermal efficiency. In fact, H.P. Garg and R.S. Adhkari, [7], proved that the increase of mass flow rate results in the increase of thermal efficiency.

7 CONCLUSION

A numerical study has been carried out to investigate the natural convection in channel PV/T connected to thermal solar collector. In order to find a good integration on channel, two models were studied, PV/T-BSC and PV/T-RBSC Hybrid collectors. Transfer equations were discretized using an implicit scheme based on finite difference, and the algebraic equations obtained are solved by Gauss Seidel iterative method. The flow patterns inside the channel and thermal fields are presented in terms of streamlines, isotherms contours, local Nusselt numbers and dimensionless temperature variations along the active walls. The main results can be summarized as follows:

- Air circulation inside the channel is very weak at low Grashof number and a further increase of Grashof number increases the air circulation inside the channel.
- At the low value of Reynolds number, it is observed the recirculation air flow in the channel and backflow at the outlet which represent the natural convection phenomena. With large Reynolds numbers, the recirculation and backflows disappear, the streamlines show a parallel flow composed by the open lines which represent the forced convective mode.
- When Reynolds number increases, the dimensionless temperature decreases on the active walls because the inlet flow rate increases the heat evacuated from the active walls towards outside.
- When Grashof number increases, the dimensionless temperature decreases on the active walls.
- The local Nusselt number increases with Reynolds number.
- The increase in Grashof number leads to an increase in the local Nusselt number.
- The PV/T-BSC collector integrated in buildings offers a good electrical efficiency than PV/T-RBSC, while PV/T-RBSC Hybrid collector offers a good thermal efficiency than the first one. According the present study, it seems not possible to obtain simultaneously a good electrical efficiency and a good thermal efficiency from one of these collectors. By considering PV/T-BSC collector that gives a good electrical efficiency, it is possible in feature to shape the air jet by a nozzle classic collector.

NOMENCLATURE

A	Aspect ratio, L/e (-)
Cp	Specific heat capacity, $(J.K^{-1}.kg^{-1})$
Dm	Mass flow rate, $(kg.s^{-1}.m^{-2})$
e	Air gap thickness, (m)
g	Gravitational acceleration, $(m.s^{-2})$
Gr	Grashof number, $g\beta\, qe^4/\lambda\nu^2$ (-)
L	Length of cavity, (m)
Nu	Nusselt number (-)
Pr	Prandtl number, $\mu\, ccp/\lambda$ (-)
q	Uniform solar radiative heat flux $(W.m^{-2})$
Q	Dimensionless mass flow rate through the channel, $(Q = Dm/\rho v_0)$
Re	Reynolds number, $\rho(2e)v_0/\ \mu$(-)
t	Time, (s)
T	Temperature, (K)
U,V	Dimensionless velocity components $U=u/v_0$; $V=v/v_0$ (-)
V_0	Average jet velocity of the entrance (m.s-1)
x,y	Cartesian coordinates (m)
X,Y	Dimensionless Cartesian coordinates, X=x/e, Y=y/e (-)

Greek symbols

α	Wall's absorptivity coefficients (-)
β	Thermal expansion coefficient of fluid, (K^{-1})
θ	Dimensionless temperature, λ(T-T0)/(qe) (-)
λ	Thermal conductivity of fluid, $(W.m^{-1}K^{-1})$
ϕ	Stream function, (m^2s^{-1})
φ	Slope of channel (°)
ρ	Fluid density, $(kg.m^{-3})$
μ	Absolute viscosity of fluid $(Kg.m^{-1}.s^{-1})$
ψ	Dimensionless stream function, φ/eV_0 (-)
ω	Vorticity, (s^{-1})
Ω	Dimensionless Vorticity, $e\omega/v_0$ (-)
ν	Kinematic viscosity of air, $(m^2\ s^{-1})$
τ	Timeless, $(\tau = tv_0/e)$ (-)
ηe	PV cells efficiency at standard temperature (-)

Subcripts

a Air
gl glass
hp hot plate (black absorber)
in into cavity
loc local
m mean
ma x maximum
out out of cavity
gl glass
pv photovoltaic
is insulation
0 ambient condition

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