A novel numerical simulation model for the PVT water system in the GCC region

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***Abstract*—Hybrid PV- thermal system (PV/T) is used to harvest both electrical and thermal energy from solar radiation. Using a hybrid PV/T system improves the electrical efficiency of the PV module while the thermal energy can be used for various heating applications. The aim of this work is to numerically study the performance of the PV/T system in a hot climate condition. The cooling system of PV/T consists of several channels parallel to each other. A novel three-dimensional numerical simulation of the system was performed to study the thermal efficiency. The standard k-epsilon turbulence model was used during the simulation. This novel system was based on applying different thermal boundary conditions on the sides of one channel rather than simulating the whole cooling system. Using one channel simulation allows the creation of a smaller number of meshes, hence, reduces the computational time. The thermal efficiency of the PV/T system was calculated using the superposition method for different mass flow rates. The results showed an increase in the thermal efficiency from 60% up to 68% by increasing the mass flow rates from 0.4 – 5.4 L/min. These results were in good agreement with the results in the literature.**

Keywords—PV/T system, novel numerical simulation, thermal energy

I. INTRODUCTION

The United Arab Emirates (UAE) is located in the Arabian Gulf which is recognized by the hot and sunny climate throughout the entire year [1]. This substantial exposure to solar radiation encourages the country to promote photovoltaic technology to generate electricity. Photovoltaic (PV) systems convert sunlight into electrical energy directly [2,3]. In comparison, with other renewable energy technologies, PV is environmentally friendly with no significant pollution during operation. It requires a lower operation cost and maintenance [4-6]. However, the performance of the PV systems drops considerably at elevated temperatures [7-9] and with the accumulation of dust [10 - 12]. Thus, the applications of PV systems in regions with dust and hot climate like the United Arab Emirates (UAE) are unfavorable without proper cooling and cleaning.

The electrical efficiency of commercial PV panels these days is in the range of 10-25% [13]. This means 75-90 % of the solar radiation falls on PV panels are either reflected or converted to thermal energy. The latter leads to a gradual increase in the temperature of the PV panel, a decrease in the open-circuit voltage and fill factor. This, in turn, decreases the panel electrical efficiency [14]. Nowadays, most of the PV modules used are either monocrystalline silicon (mono c-Si) or Polycrystalline Silicon (Poly c-Si) [15]. The efficiency of these types is strongly affected at elevated temperatures [14,16] with a temperature coefficient between 0.45-0.50 % [17]. On the other hand, the effect on the amorphous silicon cells is lower, with a temperature coefficient of about 0.25% [18]. Consequently, cooling is essential to maintain the PV module's electrical efficiency in a hot climate.

In this work, the PV/T system is evaluated numerically under the real condition of irradiance and temperature. A novel three-dimensional numerical simulation is performed to study the thermal behavior of the PV/T system by applying different thermal conditions on the sides of one channel of the cooling system.

II. METHODOLOGY

Three-dimensional numerical simulations to compute the thermal and hydraulic behavior of the PV/T system are carried out. The solar PV system was cooled from the backside as shown in Figure 1. Out of the eleven channels that are made of copper, one channel is considered for simulation to reduce the computational time and two different boundary conditions are applied depending on the position of the cooling channel on the backside of the PV module.

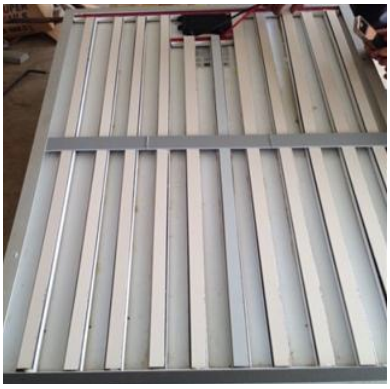

Fig. 1: Cooling channel at the backside of the PV module.

A. *Structure of the PV module*

The PV module is made up of several layers. Table 1 below shows the components of the PV module, thickness, thermal conductivity, density and specific heat capacity of each layer.

TABLE 1. DETALS OF PV STRUCTURE [18]

Layer	Thickness (m)	Thermal Conductivity (W/m.K)	Density (kg/m^3)	Specific heat capacity (J/ kK)
Glass	3×10^{-3}	1.8	3000	500
ARC	100×10^{-9}	32	2400	691
PV cells	225×10^{-6}	148	2330	677
EVA	500×10^{-6}	0.35	960	290
Rear contact	10×10^{-6}	237	2700	900
Tedlar	10×10^{-5}	0.2	1200	1250

B. *Numerical analysis*

ANSYS – Fluent program that uses the finite volume method among the CFD method is used for the analysis of the PV/T system. As discussed earlier, one channel out of the eleven channels is modeled to decrease the computational time. The standard k-ε turbulence model is used to compute the velocity and temperature field. After the assumption of the module as one homogeneous unit, the properties in table 1 are used to define the structure's layers in terms of thickness and thermophysical properties in the numerical computation.

C. *Boundary conditions*

The boundary conditions are the amount of irradiance that is received on top of the surface of the computational domain that is defined as constant heat flux providing that the solar absorptivity of the PV module is 0.9 and constant heat flux of 545, 714 and 900 W/m^2 are studied independently which corresponds to the solar irradiance in Sharjah for a typical summer day. The computational domain runs on steady-state analysis, mass inlet boundary conditions are applied on the positions of the cooling channel with two water velocity values of a mass flow rate of 0.4 kg/s and 5.4 kg/s with temperature of 307 K at the inlet as shown in Figure 2 and outflow boundary condition at the outlet.

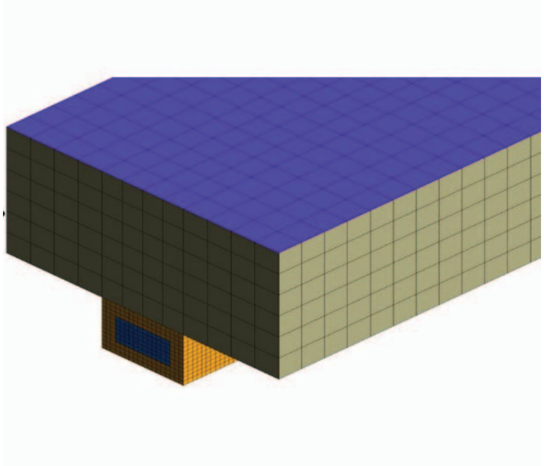

Fig. 2: Computational domain of the PV thermal system with the back-cooling method using a channel or duct.

The convective heat transfer boundary condition is applied at the bottom, lower, and the higher edge of the PV module and the heat transfer coefficient used is based on the approximation proposed by Watmuff et al. (1977) [19].

$$h = 2.8 + 3 \times V \qquad (1)$$

where V is the wind speed in m/s.

The approximation is used since the variation of wind speed is less than 4 m/s. Two different thermal boundary conditions are applied on the left and right sides of the PV module based on the position of the cooling channel. The thermal boundary conditions are symmetric boundary condition is used for the cooling channel located at the middle of the PV module, whereas both symmetric and convective heat transfer boundary conditions are used for the cooling channel located at the left and right side of the PV module and insulation thermal condition is applied on the cooling channel walls.

III. ANALYSIS RESULTS

Two-dimensional temperature distribution at the inlet, middle, and outlet of the PV/T system. The temperature has a higher value for the symmetrical boundary condition that is applied on both sides (i.e. at the middle of the PV module). However, the temperature is lower when the symmetrical and convective boundary conditions are applied on both sides of the PV/T module. In addition to that, both figures show the temperature has higher value at the top of the PV/T where constant heat flux is applied and decreases to the lowest value at the bottom of the copper pipe.

Figure 3 shows the temperature contour plot for symmetric-symmetric boundary conditions along the model length at the (a) inlet, (b) middle and (c) outlet.

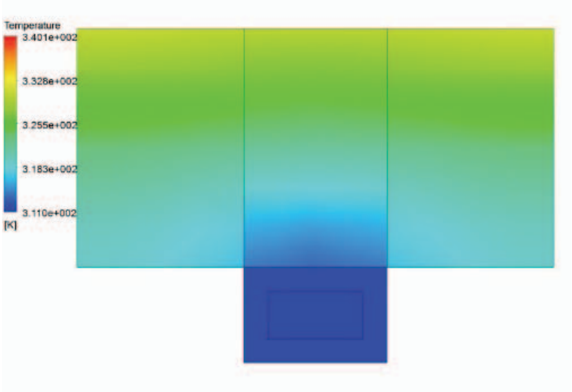

Fig. 3a: Inlet.

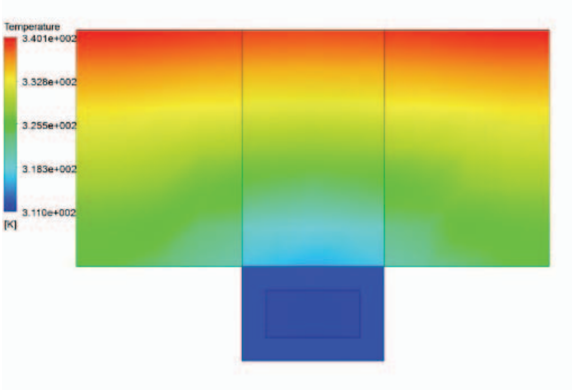

Fig. 3b: Middle

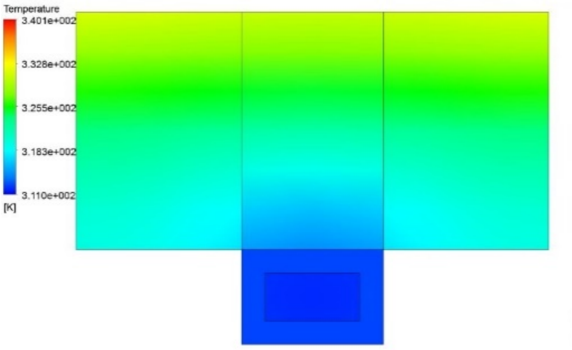

Fig. 3c: Outlet.

Figure 4 shows the temperature contour plot for symmetric- convection boundary conditions (from the right side of PV/T module) along the model length at different locations (a) inlet, (b) middle and (c) outlet.

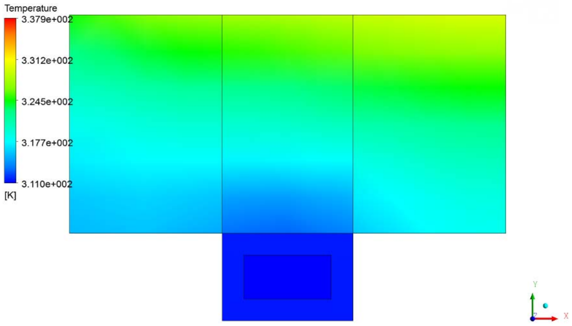

Fig. 4a: Inlet.

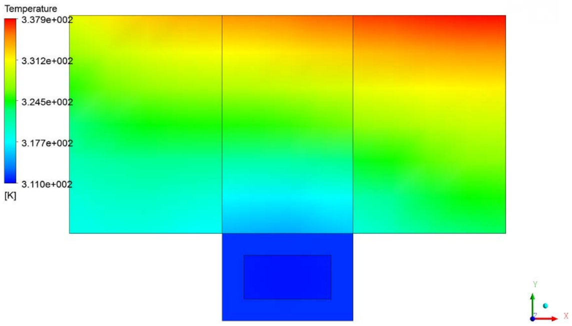

Fig. 4b: Middle.

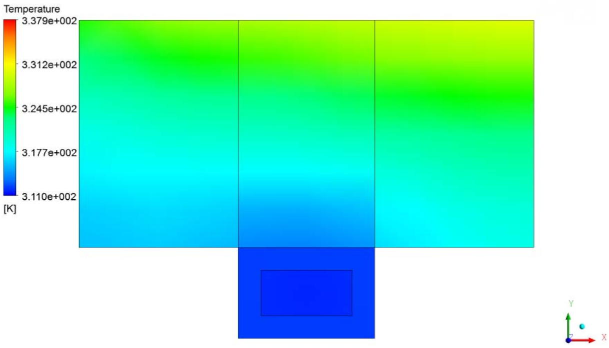

Fig. 4c: Outlet.

Figure 5 shows the temperature contour plot for symmetric- convection boundary condition (from the left side) along the model length at different locations (a) inlet, (b) middle and (c) outlet.

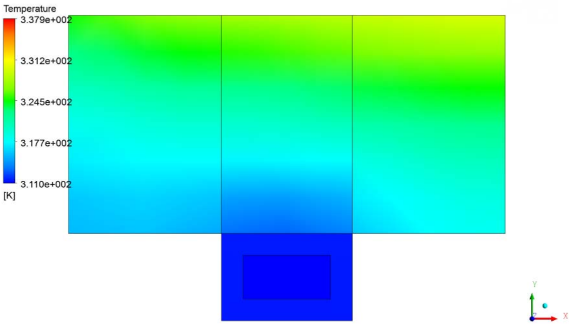

Fig. 5a: Inlet.

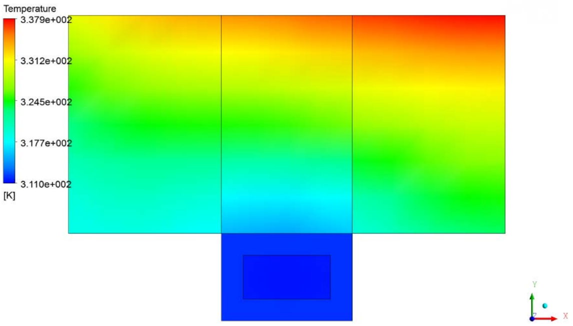

Fig. 5b: Middle.

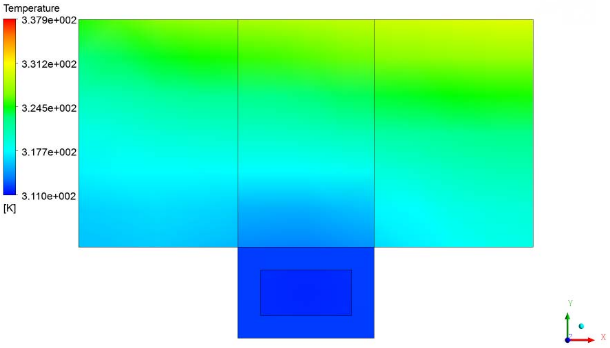

Fig. 5c: Outlet.

The thermal energy of the module absorbed by water under different values of irradiance is shown in Figure 6. This thermal energy is higher when symmetrical boundary conditions applied on both sides of the channel. This can be observed in the channels located in the middle of PV/T module where the temperature is the highest as shown in Figure 3. It is worth to mention that nine channels out of eleven have symmetrical thermal boundary conditions on both sides. While the two channels on the left and right sides of the PV/T module have symmetrical and convection thermal boundary conditions.

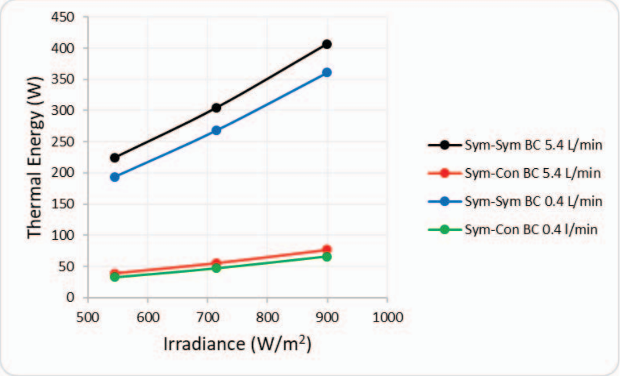

Fig. 6: Thermal energy under different mass flow rate and different thermal boundary condition.

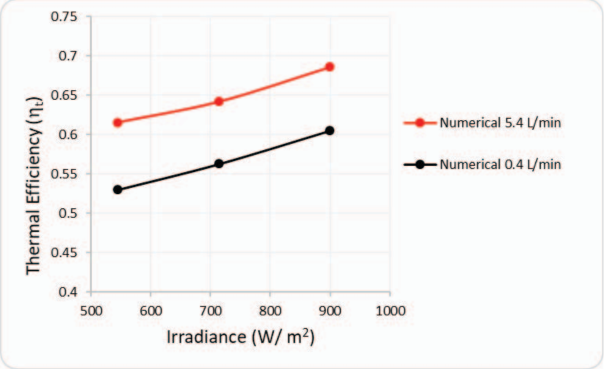

Fig. 7: Thermal efficiency of the PV/T with respect to the variation of irradiance at different flow rates.

Thermal energy and efficiency of the PV/T systems are shown in Figures 6 and 7, respectively. The efficiency increased as the values of irradiance (G) increase or ΔT/G decrease "shown in Figure 8" for both mass flow rate values. The optimum value of thermal efficiency for PV/T system as solar application is depended on many parameters such as ambient, operating conditions, spacing between the channels and the area of the PV/T module. There are many values of mass flow rate were recorded in literature where the highest thermal efficiency obtained [20 -27]. The covered or glazed PV/T has less thermal efficiency compared with the uncovered or unglazed [28].

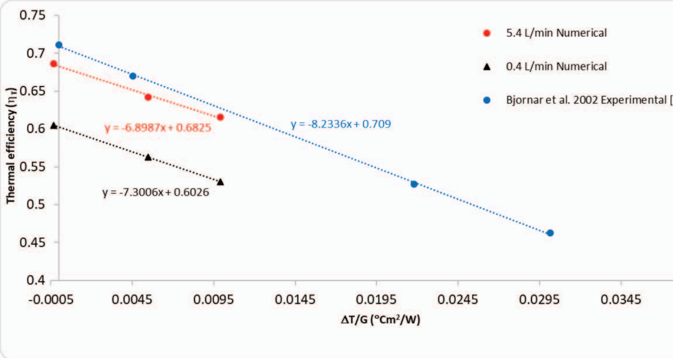

Fig. 8: Thermal efficiency versus *ΔT/G* under two mass flow rates of 5.4 L/min and 0.4 L/min

IV. CONCLUSION

Three-dimensional numerical simulations were performed for PV/T system under different irradiance and mass flow rate. The results show that the highest temperature obtained in the middle of the PV/T module were the symmetrical boundary conditions applied on both sides of cooling channel. The thermal efficiency of the PV/T system depends on the mass flow rate and ambient condition. The highest thermal efficiency obtained at higher irradiance and lower *ΔT/G* values respectively. more values of mass flow rate will simulate in the future in order to describe the thermal behaviour of PV/T system.

V. REFERENCES

[1] A. Hai Alami, K. Aokal, D. Zhang, M. Tawalbeh, A. Alhammadi and A. Taieb "Assessment of Calotropis natural dye extracts on the efficiency of dye-sensitized solar cells," Agronomy Research, vol. 16 pp. 1569–1579, 2018.

[2] J. Hu, W. Chen, D. Yang, B. Zhao, H. Song and B. Ge, "Energy performance of ETFE cushion roof-integrated photovoltaic/thermal system on hot and cold days," Appl. Energy, vol. 173, pp. 40–51, 2016.

[3] T. Salameh, C. Ghenai, A. Merabet and M. Alkasrawi, "Techno-economical optimization of an integrated stand-alone hybrid solar PV tracking and diesel generator power system in Khorfakkan, United Arab Emirates," Energy 190, 2020.

[4] Y. Wang, S. Zhou and H. Hou, "Cost and CO$_2$ reductions of solar photovoltaic power generation in China: perspectives for 2020," Renewable and Sustainable Energy Reviews, vol. 39, pp. 370–380, 2014.

[5] P. Bhubaneswari, S. Iniyan and R. Goic, "A review of solar photovoltaic technologies," Renewable and Sustainable Energy Reviews, vol. 15, pp. 1625–1636, 2011.

[6] C. Ghenai, T. Salameh, A. Merabet and A. K. Hamid, "Modeling and optimization of hybrid solar-diesel-battery power system," 7th International Conference on Modeling, Simulation, and Applied Optimization (ICMSAO), 2017.

[7] V. Perraki and G. Tsolkas, "Temperature dependence on the photovoltaic properties of selected thin-film modules," International Journal of Renewable and Sustainable Energy, vol. 2, pp. 140–146, 2013.

[8] D. Zhang, A.H. Alami, M. Tawalbeh, C. Aokal, A. Alhammadi, A. Taieb and R. Abu Rabah, "Efficiency and high-temperature response of dyesensitized solar cells using natural dyes extracted from Calotropis," 5th International Conference on Renewable Energy: Generation and Applications (ICREGA'18), United Arab Emirates, published in IEEE Xplore DOI: 10.1109/ICREGA.2018.8337593, pp. 183-187, 2018.

[9] C. Ghenai, A. Merabet, T. Salameh and E. C. Pigem, "Grid-tied and stand-alone hybrid solar power system for desalination plant," Desalination, vol. 435, pp. 172 – 180, 2018.

[10] M. Mani and R. Pillai, "Impact of dust on solar photovoltaic (PV) performance: Research status, challenges, and recommendations," Renewable and Sustainable Energy Reviews, vol. 14, pp. 3124–3131, 2010.

[11] F. Mejia, J. Kleiss, and J. L. Bosch, "The effect of dust on solar photovoltaic systems," Energy Procedia, vol. 49, pp. 2370–2376, 2014.

[12] C. Ghenai,T. Salameh, A. Merabet, "Technico-economic analysis of off grid solar PV/Fuel cell energy system for residential community in desert region," International Journal of Hydrogen Energy, 2018.

[13] M. A. Green and S. P. Bremner, "Energy conversion approaches and materials for high-efficiency photovoltaics," Nature Materials, vol. 16, pp. 23–34, 2017.

[14] E. Skoplaki and J. A. Palyvos, "On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations," Solar Energy, vol. 83, pp. 614–624, 2009.

[15] R. Kumar and M. A. Rosen, "A critical review of photovoltaic-thermal solar collectors for air heating," Applied Energy, vol. 88, pp. 3603–3614, 2011.

[16] S. Chander, A. Purohit, A. Sharma, S. P. Nehra, and M. S. Dhaka, "Impact of temperature on the performance of series and parallel connected mono-crystalline silicon solar cells," Energy Reports, vol. 1, pp. 175–180, 2015.

[17] A. K. Tossa, Y. M. Soro, L. Thiaw, Y. Azuma, L. Sicot, D. Yamegueu, C. Lishou, Y. Coulibaly and G. Razongles, "Energy

performance of different silicon photovoltaic technologies under hot and harsh climate," Energy, vol. 103, pp. 261-270, 2016.

[18] S. A. Kalogirou and Y. Tripanagnostopoulos, "Hybrid PV/T solar systems for domestic hot water and electricity production," Energy Conversion and Management, vol. 47, pp. 3368–3362, 2006.

[19] J. H. Watmuff, W. W. S. Charters and D. Proctor "Solar and wind induced external coefficients-solar collectors," Cooperation Mediterraneenne pour l'Energie Solaire, vol. 1, pp.56, 1977.

[20] S. Armstrong and W.G. Hurley, "A thermal model for photovoltaic panels under varying atmospheric conditions," Applied Thermal Engineering, vol. 30, pp. 1488 – 1495, 2010.

[21] B. Sandnes and J. Rekstad, "A photovoltaic/thermal (PV/T) collector with a polymer absorber plate. experimental study and analytical model", Solar Energy 72, 1, 63 – 73, 2002.

[22] T. T. Chow, "Performance analysis of photovoltaic-thermal collector by explicit dynamic model," Solar Energy, vol. 75, no. 2, pp.143–152, 2003.

[23] Y. Morita, T. Fujisawa and T. Tani, "Moment performance of photovoltaic/thermal hybrid panel (numerical analysis and exergetic evaluation)," Elect Eng Jpn, vol. 133, pp. 43–51, 2000.

[24] S. A. Kalogirou, "Use of TRNSYS for modeling and simulation of a hybrid PV-thermal solar system for Cyprus," Renewable Energy, vol. 23, pp. 247–260, 2001

[25] J. Gao, Y. Zhang, Y. Liu and X. Gao, "Study on the temperature variation of the water-cooled photovoltaic solar template," IEEE, vol. 2, pp. 502– 505, 2011.

[26] T. Nualboonrueng, P. Tuenpusa, Y. Ueda and A. Akisawa, "The performance of PV-t systems for residential application in Bangkok," Journal of Building Performance Simulation, vol. 21, pp. 1204 -1213, 2013.

[27] H. P. Garg and R. K. Agarwal, "Some aspects of a PV/T collector/forced circulation flat plate solar water heater with solar cells," Energy Convers. Manage, vol. 36, pp. 87–99, 1995.

[28] J. Ji, J. Han, T.-t.Chow, H. Yi, J. Lu, W. He and W. Sun, "Effect of fluid flow and packing factor on the energy performance of a wall-mounted hybrid photovoltaic/water-heating collector system," Energy Build, vol. 38, pp. 1380–1387, 2006.