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Numerical Simulation of Performance Enhancement of Solar Vortex Engine

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Abstract

The solar vortex engine (SVE) has been investigated to generate power using renewable energy. The SVE was constructed from a vortex generation engine (VGE) and solar air collector (SAC). The SVE system primarily utilizes vertical air movement. However, the airflow entering the VGE experiences an obstruction. The purpose of this paper is to propose a new design for the VGE that creates a swirling updraft capable of overcoming air obstruction and reducing energy losses. A 3D numerical model of VGE was developed to visualize vortex generation. The modeling of the VGE is carried using SOLIDWORKS software and ANSYS-FLUENT 18. The improved VGE has six vertical twisted convergence blades connected to six guide vanes to direct updraft air in an anticlockwise swirl. All blades and vanes are housed in a VGE cylinder with a diameter of 20cm and a height of 30cm. The simulation results were validated by comparing with the results obtained from the present experimental model. The simulation results match with a mean difference of less than 5% with the experimental measurements. The results of the current CFD investigation indicate that there is a gradient in air temperature and pressure within the VGE, ranging from the highest values of 314 K and 3.85 Pa to the lowest values of 308 K and 2.42 Pa, respectively. The CFD visualization shows a threefold increase in axial velocity and a fivefold increase in tangential velocity within an artificial vortex. Therefore, it can be concluded that the new VGE construction is highly efficient in generating a vortex.

Keywords: Solar Vortex Engine, Performance Enhancement, Vertical Twisted Blade, Updraft Airflow, Artificial Vortex.

محاكاة عددية لتحسين أداء المحرك الدوامي الشمسي

اياد طارق مصطفى

الخلاصة:

تمت دراسة محرك الدوامة الشمسية (SVE) لتوليد الطاقة باستخدام الطاقة المتجددة. تم بناء SVE من محرك توليد دوامي (VGE) ومجمع الهواء الشمسي (SAC) . يستخدم نظام SVE في المقام الأول حركة الهواء العمودية. ومع ذلك، فإن تدفق الهواء الذي يدخل إلى VGE يواجه عائقًا. الغرض من هذه الورقة هو اقتراح تصميم جديد لـ VGE يخلق تيارًا صاعدًا دوارًا قادرًا على التغلب على عائق الهواء وتقليل فقدان الطاقة. تم تطوير نموذج عددي ثلاثي الأبعاد لـ VGE لتصور توليد الدوامة. تم تنفيذ نمذجة VGE باستخدام برنامج SOLIDWORKS و18 ANSYS-FLUENT. يحتوي VGE المحسن على ستة شفرات تقارب ملتوية عمودية متصلة بستة دوارات توجيه لتوجيه الهواء الصاعد في دوامة عكس اتجاه عقارب الساعة. يتم وضع جميع الشفرات والدوارات في أسطوانة VGE بقطر ٢٠ سم وارتفاع ٣٠ سم. تم التحقق من صحة نتائج المحاكاة من خلال مقارنتها مع النتائج التي تم الحصول عليها من النموذج التجريبي الحالي. تتطابق نتائج المحاكاة مع متوسط فرق أقل من ٥٪ مع القياسات التجريبية. تشير نتائج تحقق CFD الحالي إلى وجود تدرج في درجة حرارة الهواء والضغط داخل VGE ، يتراوح من أعلى القيم ٣١٤ كلفن و٣,٨٥ باسكال إلى أدنى القيم ٣٠٨ كلفن و٢,٤٢ باسكال، على التوالي. يُظهر تصور CFD زيادة بمقدار ثلاثة أضعاف في السرعة المحورية وزيادة بمقدار خمسة أضعاف في السرعة العرضية داخل الدوامة الاصطناعية. لذلك، يمكن أن نستنتج أن بناء VGE الجديد ذو كفاءة عالية في توليد الدوامة.

1. Introduction

The energy from the sun that reaches the Earth can be harnessed in two ways: through the conversion of sunlight into electricity with PV panels; or by using solar thermal radiation for various purposes such as heating, air conditioning, distillation, drying, and power generation with flat and concentrating collectors. The solar updraft tower power plant, SUTPP, has developed to produce electricity, but its construction requires a significant investment. The SUTPP, also known as solar chimney technology, was designed using atmospheric air as a working fluid in conjunction with a low-temperature thermal collector. Another technique called atmospheric vortex engine, AVE, was presented to generate electricity. The AVE utilizes a sequence of heat exchangers to produce a swirling updraft of air by transferring heat to air, but unfortunately, it relies on the use of fossil fuels.

The solar vortex engine, SVE, has developed as a solution to address the limitations of using SUTPP and AVE for generating power from renewable energy sources. The SVE is a practical thermal system that shows promise as a carbon-free alternative for electricity generation. This modern method utilizes a vortex akin to a tornado that is artificially created to convert thermal energy into mechanical energy while air moves upward due to convection. Powerful airflow has generated through upward heat convection, which is achieved through the conversion of heat into work. This process involves temperature differences and heat transfer [1].

Michaud proposed two methods to calculate heat-to-work conversion for updraft swirl air (convective vortices). The first method [2] utilizes the average temperatures at which heat is received and given up. The second method [3] involves multiplying the entropy by the temperature at the position of the work dissipation. Different theories have proposed to describe the convective upward vortices; such as, the strength of convective vortices is determined by the depth of the convective layer, which is influenced by both the thermodynamic efficiency and the enthalpy perturbation present within them [4]. On the other hand, Renno et al. [5] demonstrated the strength of a vortex can be determined by the contrast in temperature and water vapor levels between the outer region and the central area of the convective vortex. Another concept shows the use of Bernoulli integral to describe the circulation of a stationary axisymmetric tornado with condensing water vapor in the air streamlines [6]. Also, "gravitational vortex column" describes the stratification of heated moist air available in the atmosphere in a gravitational field [7].

The SUTPP comprises of three main components: the solar air collector, the updraft tower, and the wind turbine. The solar air collector heats the air, which is then extracted through the updraft tower, ultimately generating power using the wind turbine. Koonsrisuk et al. [8] discretized the continuity, momentum, and energy equations mathematically for airflow under the transparent roof to obtain data on the temperature and pressure exiting the solar collector. Bernardes et al. [9] analyzed the temperature increase in a solar collector by treating it as a cavity between two parallel plates and using an iterative technique. Li et al. [10], Sangi [11], and Pasumarthi et al. [12] use the thermal equilibrium equations, along with various ambient conditions and structural dimensions, mathematically in the solar collector to estimate the power output of SUTPP.

The solar air collectors were investigated in various methods. Mustafa and Ayad [13] conducted a simulation using ANSYS-FLUENT software to study the movement of heated air under a tilted circular roof of the solar collector. The simulation revealed that as the tilt angle increased from 0° to 20°, the air velocity increased, and the airflow temperature decreased due to changes in the airflow movement. Additionally, a high decrease in airflow temperature was observed when the inlet height increased from 0.1m to 0.25m. Mohammed and Ayad [14, 15] conducted an experimental study on the thermal behavior of hot air in an inclined solar air collector. They tested the temperature distribution in the collector and designed a test rig based on a length-to-height aspect ratio of 6 and 12, with a collector height of 0.1 m and 0.2 m. The results showed that as the distance along the collector plate increases, the temperature stratification increases, and the thermal layers thickness increases with the tilt angle changes from 30˚ to 75˚. The reason dates back to the increase in the buoyancy force of the hot air over the absorber. New relationships have been established to describe the thermo-hydrodynamic characteristics of natural convection flow. These relationships consider the effect of solar radiation and the buoyancy effect on an inclined solar absorber plate [16]. A circular solar air collector has modeled mathematically and experimentally. The developed MATLAB code was used to solve the mathematical model based on the continuity, momentum, and energy equations, and was verified using data from an experimental model. The results show, when the solar radiation remains constant, an increase in airflow, canopy, and ground temperatures when the collector radius decreases; and an increase in airflow and canopy temperatures when the slope of the canopy increases. The solar air collector in the present study has been used to backing the vortex generator in the solar vortex engine system [17].

The design, measurements, and evaluation of the solar vortex engine (SVE) have been presented. The SVE consists of a solar air collector (SAC) and a vortex generation engine (VGE). Heated air is entering the VGE via curved vanes that support a rotational motion. The results demonstrated that the SVE generating a swirling air with tangent-to-axial velocity ratio of 7.5 at the VGE exit hole [18]. The techniques generation of artificial convective vortices were reviewed. The SVE is reveal a promising system, as one of the artificial vortex generator, for electrical power generation by utilizing solar energy [19, 20].

The VGE was simulated using CFD analysis to realize the artificial vortex as a 3D turbulent flow. The findings showed that a decrease in the diameter of the VGE exit hole from 0.9 m to 0.3 m increases the strength of the generated vortex [21]. Pritam and Chandramohan [22] investigated and visualized the vortex generated in the SVE using the ANSYS-FLUENT software, where their findings supported the results obtained by Al-Kayiem et al. [21]. The visualization reveals that the updraft vortex was remarkably enhanced when the exit hole diameter was increased from 0.2 m to 0.5 m. Also, the vortex generation is crucially improved by increasing the air velocity entering the VGE. The results denote that SVE can replace the solar chimney of SUTPP in electricity generation. Another experiment was tested the SVE with a PV panel to generate power. The integrated system produced a swirling air with a tangent-to-axial velocity ratio of 2.83. The results showed that the thermal efficiency of the present system decrease significantly in the presence of a PV panel. The highest thermal efficiency of 45% was obtained when the PV panel was absent [23]. Al-Kayiem et al. [24] simulated numerically the performance of the SVE compared to its basic design by adding a cone structure inside the VGE. The results showed that the basic SVE design better than the conical SVE structure. On the other, the influence of air humidity on artificial vortex generated in the SVE system is investigated. The results demonstrated high importance of humidity in the working fluid while analyzing the properties of the vortex field. When the moisture in air increases, the power produced from the SVE decreases due to a decrease in the pressure drop [25].

In conclusions, the status of SVE, AVE, and SUTPP was investigated. To address the challenges posed by the chimney in SUTPP and the fossil fuels used in AVE, SVE has been developed to generate electricity using renewable energy. The fundamental idea of hot airflow in the SVE system is to move vertically. However, the previous SVE's design had horizontal airflow inlets to the vortex generating engine. This change in airflow direction obstructs the system's air movement, causing a loss of energy from the rising air. The purpose of this paper is to improve the vortex generating engine (VGE) structure by creating a swirling updraft that allows the air to move vertically without obstruction.

2. Numerical Simulation

2.1 Configuration model and mesh generation

The modeling of the VGE is carried using SOLIDWORKS software and subsequently the mesh is imported to ANSYS-FLUENT 18 for solving and post processing. The improved configuration of the VGE has six vertical twisted convergence blades that arrange around an inverted vertical cone, as shown in figure 1(a). Each two vertical twisted convergence blades works as a nozzle for the updraft hot air passing through it. Then each vertical twisted convergence blade connected with a guide vane to direct the updraft air in an anticlockwise swirl direction, as shown in figure 1(b). The height of the vertical twisted convergence blade and the guide vane is 15 cm and 8 cm, respectively. All the blades and vanes have embraced in the VGE cylinder with a diameter of 20 cm and height of 30 cm. Also, the cylinder of the VGE has an upper hole with 12 cm in diameter, and connected with a 30 cm height test region of the generated vortex from the top.

In order to compare and evaluate the new design, the design of the previous VGE model is shown in figure 2. The previous model had eight inlet gates that allowed airflow to enter the VGE horizontally.

Numerical simulation of swirling flow requires high-quality mesh with a gradient towards the center. The grid interval selection depends on the mesh size and complexity. The global mesh size tested for the VGE model and the test region is (0.1, 0.3, 0.5, 0.8, and 1.0) cm, which represent the maximum size of any side of a triangle or tetrahedron across the whole mesh. The shell meshing parameters that used are All-Tri mesh type, and Patch Independent mesh method. Also, the volume meshing parameters are Tetra/Mixed mesh type and Delaunay mesh method. The mesh quality for the best parameters of the findings obtained is the total elements of 2147504 for the size of 0.5 cm, orthogonal quality of 0.4 – 0.95 with percentage of (0.1% - 78.8%), and aspect ratio of 1.7 - 7.1 with percentage of (82.3% - 0.2%). Then, the mesh was written out in the format used by FLUENT for solving process.

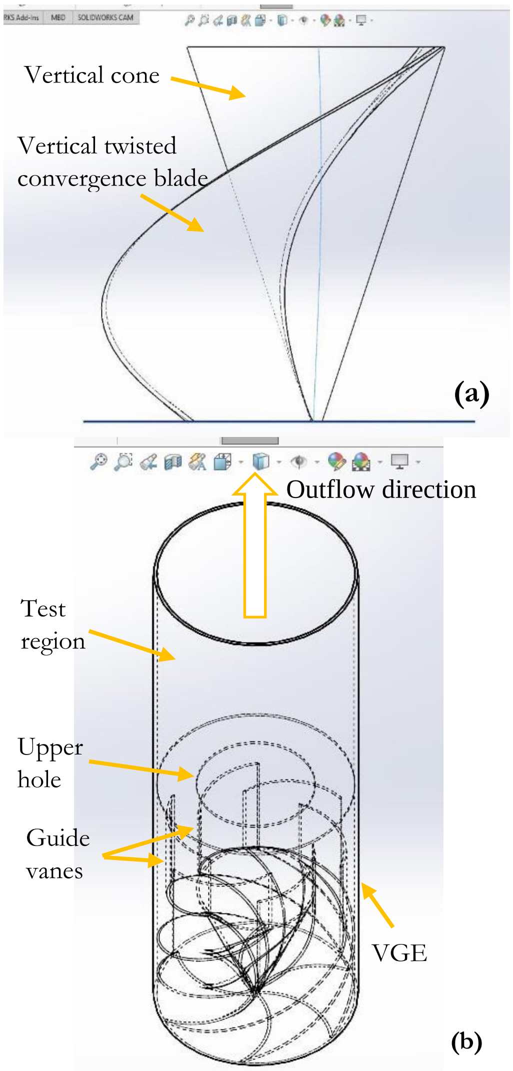

Figure (1): Design of the present VGE model

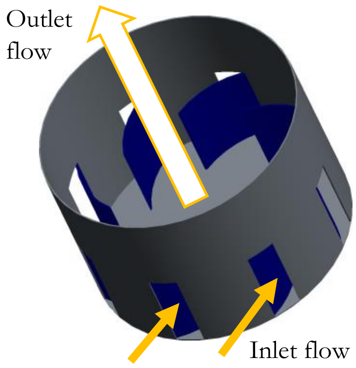

Figure (2): Design of the previous VGE model

2.2 Parameters of the CFD simulation

The parameters used in the CFD simulation are obtained from the measured data by Mustafa [1] at entry slot of the VGE. The fundamental design of the VGE was established and evaluated by Mustafa [1], which was followed by other researchers' investigations for the same design. The input parameters to the VGE in the current study are the air temperature and the flow velocity with values of 314 K and 0.5 m/s, respectively [1, 21]. Also, the ambient air temperature and density are 303 K and 1.1614 kg/m3, respectively. Numerical simulation of the VGE was carried out successfully by results compared with experimental measurements.

2.3 Numerical simulation methods

The model of the VGE with the test region was simulated in steady, compressible, turbulent and viscous flow field. Numerical method employed for CFD simulation of the VGE model consist of "pressure – based" solver applied in solution, "pressure – velocity coupling" scheme used in solving the flow problem in a segregated manner, and advanced viscous RNG k-ɛ model. RNG k-ɛ viscous model and the turbulent viscosity modification for the swirl effects are enabled to simulate the vortex field generated by the VGE. The conservation equations in cylindrical coordinates are adopted, which are continuity, Navier-Stokes, and energy. The boundary conditions used in the simulation are velocity-inlet for the down circle of the VGE, outflow for the top circle, and no-slip stationary wall for the surfaces of the VGE and the cylinder.

3. Experimental Setup

Structurally, the SVE comprises of main two parts; the SAC and the VGE. Wherefore, thermal-hydrodynamic process of air behave as a free convection flow in 1D direction in the SAC, whilst behave as a 3D convection flow in cylindrical coordinates in the VGE. The design and evaluation of the SVE model was demonstrated by Mustafa [1] and Al-Kayiem et al. [18].

The function of the VGE is to generate a 3D updraft swirl airflow, which extracts air from the base of the VGE and extends upward in the test region. Hence, the new design incorporates six vertical twisted convergence blades with air guide vanes to create a powerful vertical airflow in a swirling motion. The designed model of the VGE was manufactured using 3D printer with the material of PLA (Polylactic acid). The dimensions of the VGE cylinder are 20 cm in diameter and 30 cm in height. The height of the vertical twisted convergence blade and the air guide vane are 15 cm and 8 cm, respectively. The curvature length of the air guide vane is 10 cm, and the distance between each two opposite air guide vanes is 12 cm, which represents the circular arena of the generated vortex. An upper hole with a diameter of 12 cm was included in the VGE to allow the generated vortex to exit into the test region. A flat plate SAC was used to heat the air entering the VGE, as shown in figure 3.

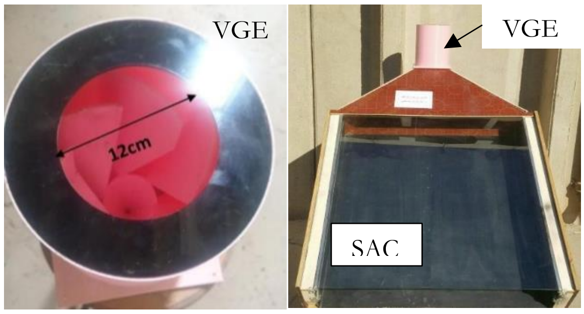

Figure (03): Small model of the VGE and the flat plate SAC

4. Results and discussions:

Results of temperature, pressure and velocity gradients of vortex generated in the VGE and test region will be presented and discussed in this section. Numerical results were computed at a temperature and velocity of air entering the VGE of 314 K and 0.5 m/s, respectively, to compare with the results obtained by Mustafa [1] and Al-Kayiem et al. [21] where appropriate.

Results of total temperature distribution are shown in figure 4(a). The simulation indicates an increase in air temperature as the VGE radius decreases from the engine wall, followed by a decrease towards the vortex center. Then, the temperature is distributed upward through the upper hole and extended vertically in the test region. The air temperature is gradient from the highest temperature of 314 K at the base of the VGE to the low temperature of 308 K at the back corner of the vertical twisted convergence blade. When comparing the results of the present study with the results shown in figure 4(b), it discloses that the temperature shown in figure 4(b) is distributed from 314 K to 308 K at the VGE center, while it is distributed from 314 K to 311 K at the VGE center shown in figure 4(a). Hot air exiting the SAC floats vertically into the VGE where it is forced by the vertical twisted convergence blades and guide vanes to twist and generate an updraft vortex. The enthalpy of the hot air has converted into kinetic energy that forces the air to form on the vanes' surfaces as the temperature decreases. The decrease in temperature difference that transformed into dynamic swirling air indicates the high efficiency of the new VGE construction compared to the VGE construction presented by Mustafa [1] and Al-Kayiem et al. [21].

Contours results of pressure gradient within the VGE are shown in figure 5(a). The results indicate an increase in air pressure as the VGE radius decreases from the engine wall, followed by a decrease towards the vortex center. Then, the pressure is distributed upward through the upper hole and extended vertically in the test region. The air pressure is gradient from the highest pressure of 3.85 Pa at the base of the VGE to the low pressure of 2.42 Pa at the central core of the vortex generated. When comparing the results of the present study with the results shown in figure 5(b), it reveals that the pressure shown in figure 5(b) is distributed from 2.81 Pa to 0.135 Pa at the VGE center, while it is distributed from 3.85 Pa to 2.42 Pa at the VGE center shown in figure 5(a). The decrease in pressure difference that transformed into dynamic swirling air indicates the high efficiency of the new VGE construction compared to the VGE construction presented by Mustafa [1].

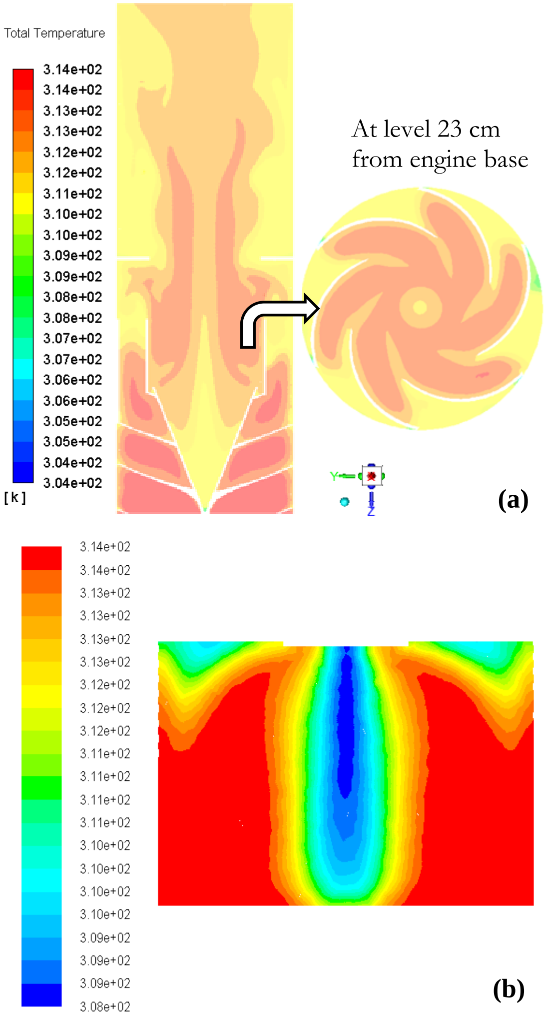

Figure (4): Contours of temperature distribution within the VGE for (a) present study, (b) Mustafa [1] and Al-Kayiem et al. [21]

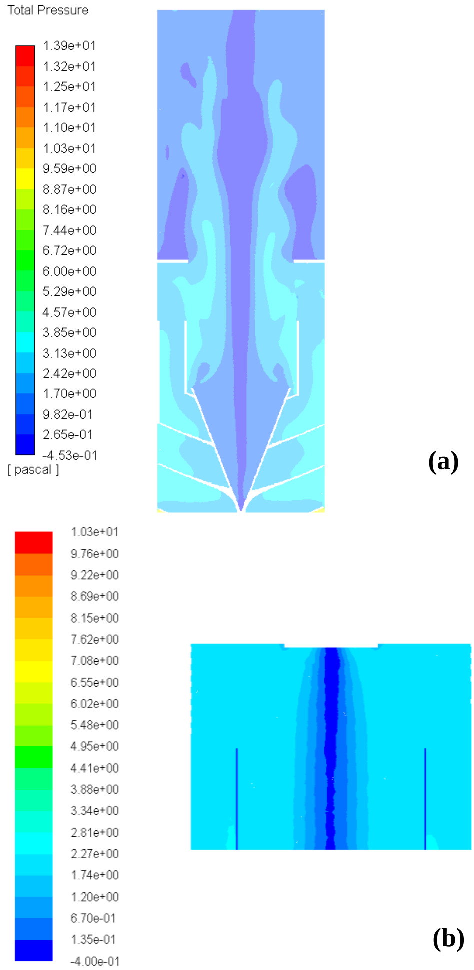

Figure (5): Contours of pressure distribution within the VGE for (a) present study, (b) Mustafa [1]

Results of tangential velocity distribution within the VGE are shown in figure 6(a). The figure clearly shows twisted air generated between the guide vanes which extended vertically through the upper hole to the test region. The tangential velocity increase from 0.254 m/s near the engine wall to the maximum value of 1.33 m/s when radius of the VGE decreases, then tangential velocity decrease toward the centerline when radius of the VGE decreases. Figure 6(a) clearly shows that the air accumulated within swirling arena between the guide vanes, which extended upward in a vortex. Also, figure 6(a) shows a weak tangential velocity occurred in the centerline of the VGE that represent the eye of the vortex generated. It was noticed from figure 6(a) that, some small tangential velocity in inverse direction motion at the back of the guide vanes which could date back to the small value of air velocity entering the VGE. When comparing the results of the present study with the results shown in figure 6(b), it reveals that the tangential velocity shown in figure 6(b) is distributed from 0.291 m/s to 1.11 m/s, while it is distributed from 0.254 m/s to 1.33 m/s as shown in figure 6(a). The difference in tangential velocity gradient indicates the high performance of the new VGE construction compared to the VGE construction presented by Mustafa [1] and Al-Kayiem et al. [21].

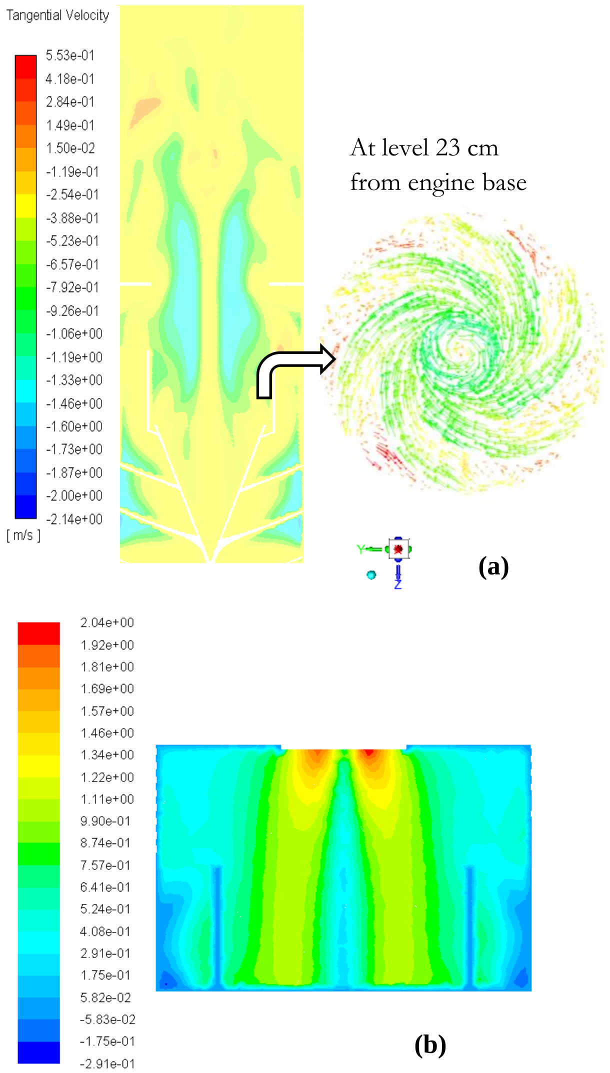

Figure (6): Contours and vectors of tangential velocity distribution within the VGE for (a) present study, (b) Mustafa [1] and Al-Kayiem et al. [21]

Results of axial velocity distribution within the VGE are shown in figure 7. The figure displays the flow velocity structure inside the VGE, which is directed upward and maximize at the upper hole and the test region. The numerical simulation demonstrates air movement from the engine base toward the upper hole, with inverse air movement at weak regions in the corners of the test region. The reason dates back to the small value of air velocity entering the VGE, which can be overcome by using high air entry velocities. The maximum axial velocity value of 1.6 m/s revealed a more than threefold magnification of the air velocity as it entered the VGE. Based on the analysis of the airflow behavior and the air velocity components, it can be concluded that the new VGE construction is highly efficient in generating a vortex. The simulation results provide a good estimate of the engine design parameters.

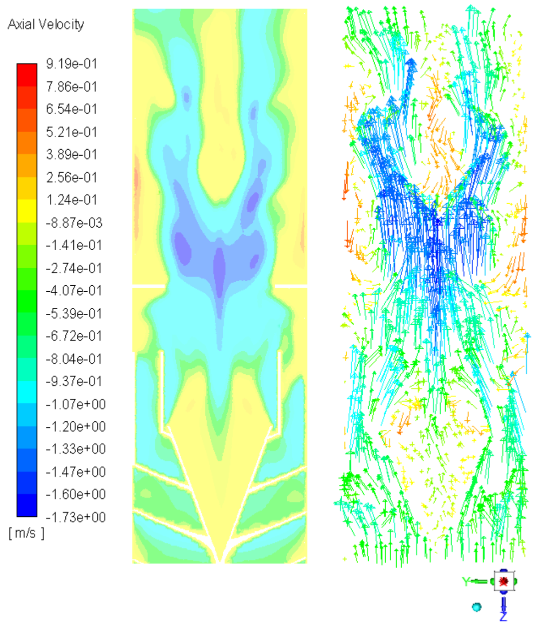

Figure (7): Contours and vectors of axial velocity distribution within the VGE and test region

4.1 Validation of CFD simulation

The air temperature results at a height of 23 cm obtained from the CFD simulation of the VGE were validated by comparing them with the experimental results obtained from the present experimental model at the inlet velocity and temperature of 0.1 m/s and 40.2 °C, respectively; and solar radiation of 605 W/m^2.

The results of simulations and experiments conducted to measure the air temperature inside the VGE at a height of 23 cm are presented in figure 8. The mean percentage difference between the simulation results and experimental measurements is less than 5%. The figure clearly shows that the air temperature increases as the VGE radius decreases. This is due to the air being accumulated within the swirling arena between the guide vanes, which extends upward in a vortex.

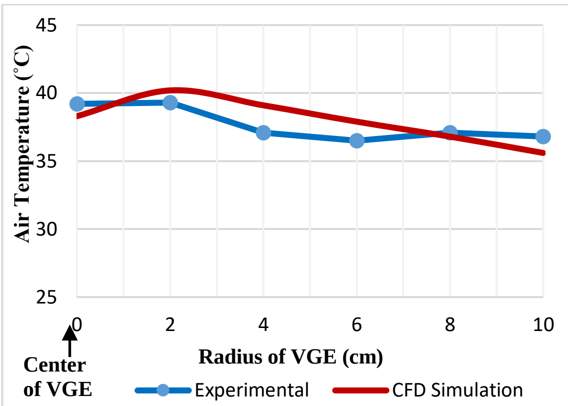

Figure (8): Validation of air temperature within the VGE

5. Conclusions

The CFD investigation of the flow field in the VGE that utilizes solar energy has conducted, and the results were validated through experimental measurements. The ANSYS-FLUENT 18 software was used to perform CFD simulation on the vortex field in the VGE. The following conclusions have drawn from the simulation investigation:

1. New design of vertical air movement inside the SVE has been presented and visualized.
2. The enthalpy of the hot air has converted into kinetic energy that forces the air to generate an updraft vortex on the vanes' surfaces as the temperature decreases.
3. The CFD visualization shows a threefold increase in axial velocity and a fivefold increase in tangential velocity within an artificial vortex.
4. The results demonstrate the high efficiency of the new VGE construction in generating a vortex, as indicated by the gradient in temperature, pressure, and tangential velocity.
5. The air temperature and pressure are gradient within the VGE from the highest values of 314 K and 3.85 Pa to the low values of 308 K and 2.42 Pa, respectively.
6. The match between the simulation results is acceptable compared with the experimental measurements. The mean percentage difference between the simulation results and experimental measurements is less than 5%.

6. References

[1] Ayad Tareq Mustafa, "Performance Evaluation of a Developed Solar Vortex Engine", Ph.D. Thesis, Mechanical Engineering Department, University Technology PETRONAS, Perak, Malaysia, 2016. http://utpedia.utp.edu.my/id/eprint/25169/

[2] L. Michaud, "Heat to work conversion during upward heat convection Part I: Carnot engine method," Atmospheric research, vol. 39, pp. 157-178, 1995. DOI:10.1016/0169-8095(95)00010-O

[3] L. Michaud, "Heat to work conversion during upward heat convection Part II: Internally generated entropy method," Atmospheric research, vol. 41, pp. 93-108, 1996. DOI:10.1016/0169-8095(95)00073-9

[4] N. O. Renno, "A thermodynamically general theory for convective vortices", Tellus A, vol. 60, pp. 688-699, 2008. https://www.tandfonline.com/doi/abs/10.1111/j.1600-0870.2007.00331.x

[5] N. O. Rennó and H. B. Bluestein, "A simple theory for waterspouts", Journal of the atmospheric sciences, vol. 58, pp. 927-932, 2001.

[6] A. M. Makarieva, V. G. Gorshkov, and A. V. Nefiodov, "Condensational theory of stationary tornadoes", Physics Letters A, vol. 375, pp. 2259-2261, 2011. DOI:10.1016/j.physleta.2011.04.023

[7] N. Ninic and S. Nizetic, "Elementary theory of stationary vortex columns for solar chimney power plants," Solar energy, vol. 83, pp. 462-476, 2009. DOI: 10.1016/j.solener.2008.09.002

[8] A. Koonsrisuk and T. Chitsomboon, "Mathematical modeling of solar chimney power plants," Energy, vol. 51, pp. 314-322, 2013. DOI: 10.1016/j.energy.2012.10.038

[9] M. d. S. Bernardes, A. Voß, and G. Weinrebe, "Thermal and technical analyses of solar chimneys," Solar Energy, vol. 75, pp. 511-524, 2003. DOI: 10.1016/j.solener.2003.09.012

[10] J.-y. Li, P.-h. Guo, and Y. Wang, "Effects of collector radius and chimney height on power output of a solar chimney power plant with turbines," Renewable Energy, vol. 47, pp. 21-28, 2012. DOI: 10.1016/j.renene.2012.03.018

[11] R. Sangi, "Performance evaluation of solar chimney power plants in Iran", Renewable and Sustainable Energy Reviews, vol. 16, pp. 704-710, 2012. DOI:10.1016/j.rser.2011.08.035

[12] N. Pasumarthi and S. Sherif, "Experimental and theoretical performance of a demonstration solar chimney model—Part I: mathematical model development," International Journal of Energy Research, vol. 22, pp. 277-288, 1998. DOI: 10.1016/S0140-6701(98)96631-0

[13] Mustafa T. Mustafa and Ayad T. Mustafa, "Numerical Simulation of Thermal-Hydrodynamic Behavior within Solar Air Collector", Journal of Engineering, Vol. 24, No. 3, 2018.

[14] Mohammed A. Neama and Ayad T. Mustafa, "Experimental Investigation and Evaluation of Inclined Solar Air Heater", Journal of Engineering and Applied Sciences, Vol.14, pp: 10291-10297, 2019. DOI: 10.36478/jeasci.2019.10291.10297

[15] Mohammed A. Neama and Ayad T. Mustafa, "Thermal behavior of natural convection flow in an inclined solar air heater", Journal of Mechanical Engineering and Sciences, Vol. 14, Issue 4, pp. 7569 – 7588, 2020. DOI: 10.15282/jmes.14.4.2020.22.0596

[16] Ayad T. Mustafa and Mohammed A. Neama, "Natural convection heat transfer on an inclined unglazed solar absorber-plate: Experimental investigation", AIP Conference Proceedings 2530, 090002, 2023. DOI:10.1063/5.0121075

[17] Ayad T. Mustafa, Hussain H. Al-Kayiem, Syed Ihtsham U. Gilani, "Investigation and Evaluation of the Solar Air Collector Model to Support the Solar Vortex Engine", ARPN Journal of Engineering and Applied Sciences, Vol. 10, No. 12, 2015.

[18] Hussain H. Al-Kayiem, Ayad T. Mustafa, Syed I. U. Gilani, "Solar vortex engine: Experimental modelling and evaluation", Renewable Energy, Vol. 121, pp. 389-399, 2018. DOI: 10.1016/j.renene.2018.01.051

[19] A. T. Mustafa, H. H. Al-Kayiem, S. I.U. Gilani, "A Review of the Vortex Engine", WIT Transactions on Ecology and the Environment, Vol. 179, pp. 911-920, 2013. DOI: 10.2495/SC130772

[20] A. T. Mustafa, H. H. Al-Kayiem, S. I.U. Gilani, "A Review of Convective and Artificial Vortices for Power Generation", International Journal of Sustainable Development and Planning, Vol. 10, No. 5, pp. 650–665, 2015. DOI:10.2495/SDP-V10-N5-650-665

[21] H. H. Al-Kayiem, A. T. Mustafa, S. I.U. Gilani, "Vortex field simulation and analysis of a solar updraft power engine", WIT Transactions on Ecology and the Environment, Vol. 205, pp. 193-202, 2016. DOI:10.2495/EQ160181

[22] Pritam Das and Chandramohan V.P., "Estimation of flow parameters and power potential of solar vortex engine (SVE) by varying its geometrical configurations: A numerical study", Energy Conversion and Management, vol. 223, 113272, 2020. DOI: 10.1016/j.enconman.2020.113272

[23] Abdullah A. Badr, Omer K. Ahmed, Omar Rafae Alomar, "Performance of solar vortex engine integrated with the PV panel: Experimental assessment", Renewable Energy, Volume 216, 119073, 2023. DOI: 10.1016/j.renene.2023.119073

[24] Hussain H. Al-Kayiem, Ali M. Tukkee, Syed I.U. Gilani, "Assessment of the design influence of the vortex generator on the performance of the solar vortex engine", Energy Conversion and Management: X, vol. 16, 100283, 2022. DOI: 10.1016/j.ecmx.2022.100283

[25] Ali M. Tukkee, Hussain H. Al-Kayiem, Syed I.U. Gilani, "Effect of density variation method and air humidity consideration on the computational simulation of solar vortex power generation systems", Thermal Science and Engineering Progress, vol. 37, 101574, 2023. DOI: 10.1016/j.tsep.2022.101574