A REVIEW OF CONVECTIVE AND ARTIFICIAL VORTICES FOR POWER GENERATION

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ABSTRACT
Thermal energy transfer in the atmosphere occurs from a high temperature zone to a low one by means of convective vortices where mechanical energy is produced. There are two ways of driving vertical flow in the core of a vortex: (1) by the direct action of buoyancy acting on hot air and (2) by producing a vertical pressure gradient along the axis of a vortex because of core development involving the lateral spread of the vortex with height. In particular, it indicates that the intensity of convective vortices depends on the depth of the convective layer via thermodynamic efficiency, the enthalpy perturbation across them, and the existence of sources of vorticity. The atmospheric vortex engine (AVE) is a device for producing an artificial vortex. The operation of AVE is based on the fact that the atmosphere is heated from the bottom and cooled at the top. By artificial vortex generation, it is aimed to eliminate the physical solar updraft tower and reduce the capital cost of solar chimney power plants. This paper reviews natural convective vortices and vortex creation via physical principles of vortex generation. Vortex analysis and modelling are presented. Furthermore, a new model of a solar vortex engine (SVE) is proposed and discussed. An idea on utilizing the solar energy as the heat source for establishing the vortex and operating the SVE model is adopted. The SVE model is feasible and promising for electrical power generation.
Keywords: Artificial vortex, convective vortices, solar vortex engine, tornado, vortex analysis.

1 INTRODUCTION

In the earth's atmosphere, the elucidation of the nature of convection is greatly impeded by the strong influence of phase changes of water, which accounts for the prominence of convection in global budgets of clouds and precipitation and in the general circulation of the atmosphere. A most striking aspect of moist convection is its organization over many scales, ranging from microscale turbulence to cloud-scale arrays of convection drafts to squall lines and hurricanes, which span hundreds of miles [1].

Due to the geometry of the atmosphere of the earth, solar energy reaches its surface; solar updraft tower power plants (SUTPPs) were used for power generation, which have high investment costs of installation due to the tower height and labour costs. A development can occur to decrease the tower height, where the physical chimney (tower) is replaced by the centripetal force produced by swirly upward air flow, which is called a vortex engine.

Solar updraft towers are defined as low temperature solar thermal power plants, which use the atmospheric air as a working fluid, where only one part of the thermodynamic cycle within the plant is utilized [2]. The main features of SUTPPs are sketched in Fig. 1. Air is heated as a result of the greenhouse effect under a transparent roof (solar collector). Because the roof is open around its periphery, the buoyancy of the heated air draws a continuous flow from the roof perimeter into the chimney (updraft tower). A turbine is set in the path of the air current to convert the kinetic energy of the flowing air into electricity [2–7].

In order to understand the upward air flow process and type of energy pushing air flow, temperature difference and accompanying heat transfer improve air flow by means of heat to work conversion during upward heat convection. Michaud [8,9] proposed a method for capturing the energy produced

ISSN: 1743-7601 (paper format), ISSN: 1743-761X (online), http://www.witpress.com/journals
DOI: 10.2495/SDP-V10-N5-650-665

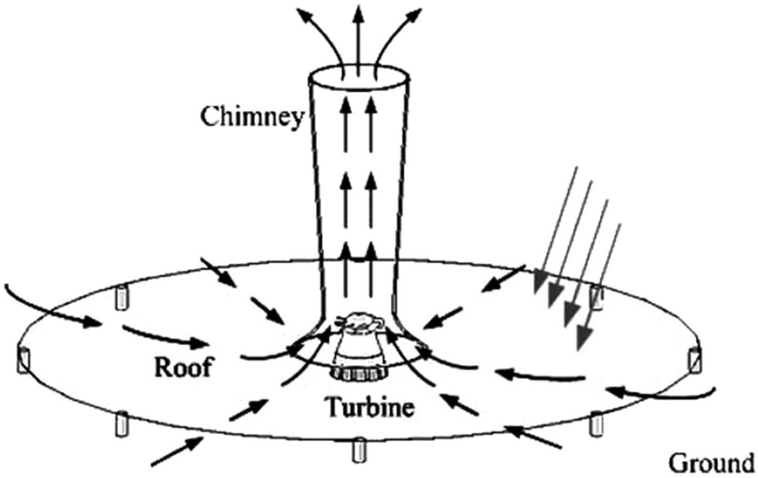

Figure 1: The main features of a solar chimney power plant: solar collector, updraft tower, and turbine [6].

through convection by using a vortex instead of a physical chimney. The method is based on the fact that when heat is carried upward by convection, it is converted to work. Michaud presented two methods for calculating this work: first [10], the work is roughly equal to the upward heat flux multiplied by Carnot efficiency calculated using the average temperatures at which heat is received and released; second [11], the work is equal to the product of the entropy produced and the temperature at which the work dissipates.

The main aim of this paper is to review the state of the art on this topic. The theory of convective vortices operation is presented; moreover, the use of vortices in producing mechanical energy is illustrated. The review reported here covers the studies on convective vortices generation using analytical and simulation modelling. Furthermore, a proposed model of solar vortex engine (SVE) could become a major source of clean energy.

2 OPERATION THEORIES ON VORTICES

2.1 Proposed previous theories

Convective vortices are common features of atmospheres that absorb lower entropy energy at higher temperatures than they reject higher entropy energy to space. These vortices range from small to large scale and play an important role in the vertical transport of heat, momentum, and tracer species. The heat engine framework is a useful tool for studying convective vortices. However, current theories assume that convective vortices are reversible heat engines. Since there are questions about how reversible real atmospheric heat engines are, their usefulness for studying real atmospheric vortices is somewhat controversial. In order to simplify this problem, a theory for convective vortices that includes irreversible processes is proposed. The main result is that the proposed theory provides an expression for the pressure drop along streamlines that includes the effects of irreversible processes. It is shown that a simplified version of this expression is a generalization of Bernoulli's equation to convective circulations. It is speculated that the proposed theory not only explains the intensity, but also sheds light on other basic features of convective vortices such as their physical appearance. In particular, it predicts that the intensity of convective vortices depends on the depth of the convective layer via thermodynamic efficiency, the enthalpy perturbation across them, and the existence of sources of vorticity. It also predicts that nonhydrostatic pressure perturbations increase with the kinetic energy of air parcels spiralling towards the vortex [12]. Makarieva *et al*. [13] used the Bernoulli integral for air streamline with condensing water vapour to describe a stationary axisymmetric tornado circulation. The obtained profiles of vertical, radial, and tangential velocities are in agreement with observations for the Mulhall tornado, for which three-dimensional (3D) velocity data are available.

Different theories of convective operation are presented. Rennó *et al*. [14] presented a simple theory for atmospheric convection that predicts the buoyancy, the vertical velocity, and the fractional area covered by convection in the state of statistical equilibrium as well as the work produced by convective available potential energy (CAPE). For the earth, a CAPE value of 1000 J/kg and its amount should increase with increases in the global surface temperature. Atmospheric convection is a natural heat engine that might operate in a system capable of doing mechanical work between the heat source and the heat sink. Rennó *et al*. [15] proposed a simple theory for dust devils and compared them to observations. This theory predicts that the potential pressure depression between the centre of a dust devil and its environment is a function of the ambient thermodynamic variables. The theory suggests that their radius must be determined by the initial angular momentum of air parcels converging towards their centre, and the ambient nature of stronger horizontal wind shears leads to larger dust devils than that of smaller wind shears. Rennó *et al*. [16] shows that the simple thermodynamic theory for dust devils also applies to waterspouts. The theory is based on the thermodynamics of heat engines and predicts the central pressure and the wind speed of convective vortices. The vortex intensity depends on the difference in temperature and water vapour content of the air at a large radius and at the centre of the convective vortex. Moreover, it provides a simple physical interpretation of their general characteristics.

The technically useful part of heated moist air availability in the atmosphere is stratified in a gravitational field. In particular, its focuses on the possibility that this availability can be concentrated at the ground level without using a solid ‘chimney’. The results reveal that this concentration can be achieved via the formation of an updraft ‘gravitational vortex column’ (GVC) situated over turbines. A numerical solution is given for a characteristic case, with a GVC process as a part of the cycle, similar to the Brayton cycle obtained in a gravitational field. Typical integration results are shown by one characteristic numerical example of a GVC in the form of a Mollier h–s diagram [17]. Ninic and Nizetic [18] obtained the Patent Cooperation Treaty (PCT) under international publication number WO 2009/060245 A1 in 14 May 2009 for the design of a solar power plant with a short solar chimney called diffuser, which utilizes the air’s ability to do work after it passes through a solar collector with special water nozzles fitted in the diffuser. Further development of a proposed elementary stationary three-layer model of GVC is provided by Nizetic [19]. Improvements that are related to the vertical velocity in the central GVC section, and also to internal friction work, are involved in this simplified model. The reduction factor of downdraft shell angular momentum is also introduced in this simplified model. A numerical solution of the improved model is approached as a characteristic case and is compared to the elementary GVC model. The results show that the introduced improvements are important parameters for further analysis of GVCs. Moreover, Nižetic [20] reviews methods of production of an artificial vortex column in the atmosphere with the purpose of identifying the state of the art. Convective vortices can be used as heat engines to convert available energy into mechanical energy and produce electricity. Furthermore, this paper analyses a few technical solutions and theoretical ideas related to energy utilization and then carbon-free electricity production. Study conclusions presented herein may form a basis for further development of this alternative carbon-free concept of energy utilization.

By integrating the radial component of the equation of motion over the radius, a generalized Boltzmann distribution is obtained for the pressure at the centre of the vortex, P(E). The Boltzmann distribution is structurally equivalent to the well-known barometric equation. Moreover, this Boltzmann distribution defines the energy of displacement as. This energy of displacement can be interpreted as the work that is necessary to generate a low pressure system. This work is also equal to the released work during the cyclolysis process [21].

2.2 Tornado theories

A tornado is a dangerous rotating column of air in contact with both the surface of the earth and the base of a cumulonimbus cloud (thundercloud) and a cumulus cloud, in rare cases. Tornadoes come in many sizes but typically form a visible condensation funnel whose narrowest end reaches the earth and is surrounded by a cloud of debris and dust [12]. Yershin and Yershina reveal a potential activating mechanism of such threatening phenomenon like twister or tornado. The understanding of this process came as a result of the discovery and study of secondary (circulating) currents within absolute liquid (gas) currents, named Taylor–Gertler's free vortices [22].

Documentary evidence is employed to present the history of tornadoes in the Czech Lands (recently Czech Republic) in AD 1119–2010. Based on contemporaneous descriptions of events, tornadoes are categorized as proven or probable. They are analysed collectively in terms of their spatial–temporal changes, annual variation, specific features, and impacts according to the Enhanced Fujita (EF) scale [23]. Goliger and Milford [24] presented a summary review of the tornado; they revisited and updated data on tornado occurrences throughout the world. This was carried out by accessing the relevant literature, analysing, reanalysing, and comparing the data on tornado occurrence from various sources. The investigation was aimed at those countries/regions for which no or little information was available.

3 GENERATION OF CONVECTIVE VORTICES

3.1 Analysis of the vortex

The heating rates of the underlying surface and air temporal and spatial temperature shear which lead to the stable genesis of wall-free nonstationary vortices were estimated. These vortices were generated over the underlying surface of an aluminium sheet due to its controlled heating from below as a result of the development of unstable stratification of air. The resultant data enable one to estimate the rate of heating of the air and the values of horizontal and vertical gradients of temperatures at which the unstable stratification of air leads to the generation of wall-free nonstationary vortices. The Rayleigh number was used for the generalization of measuring air temperature distributions on the subject of finding thermal modes for the stable generation of wall-free vortices. The Rayleigh number defines the correlation between the buoyancy and viscous forces, for different thermal modes. This criterion was determined as eqn (1) [25]:

$$Ra = \frac{gh^3\beta\Delta T}{va} \tag{1}$$

where *Ra*: Rayleigh number, *g*: acceleration of gravity, *h*: vertical dimension, *β*: the coefficient of volumetric expansion, ΔT: the temperature difference, *υ*: the coefficient of kinematic viscosity, and *a*: the thermal diffusivity.

Navarro *et al*. [26] presented convective instability as the mechanism for generating vertical vortices in a cylindrical annulus nonhomogeneously heated from below. They assume axisymmetric, thermal, and geometrical conditions under which stable vertical structures are found. The structure of these vortices appears to be qualitatively similar to that of dust devils.

Michaud [27] revealed closed ideal thermodynamic cycles are used to analyse the atmospheric upward heat convection process which is compared to the Brayton gas-turbine cycle. The heat to work conversion efficiency of the atmosphere is shown to be close to the Carnot efficiency calculated using the average temperatures at which heat is received and given up for hot and cold source temperatures, respectively. The efficiency is independent of whether the lifting process is discontinuous or continuous, and nearly independent of whether the heat is transported as sensible or as latent heat. Most updraft properties were predicted and explain how work of buoyancy is dissipated by using the model of one-dimensional thermodynamic entrainment–detrainment [28]. Mechanical energy is produced when heat is carried upward by convection in the atmosphere. Processes for controlling and concentrating where the mechanical energy is produced could be a method of harnessing solar energy. A process for producing and controlling a tornado-like vortex and thereby concentrating the mechanical energy where it can be captured is proposed. The work produced when air rises from the bottom to the top of the troposphere is typically 1500 J/kg, about the same as the work produced when a kilogram of water is lowered 150 m [29].

Long [30] utilized similarity arguments, which lead to a reduction of the equations of motion to a set of ordinary differential equations. These are integrated numerically. A uniform feature is the constant circulation *K* outside the vortex core, which is also a viscous boundary layer. The circulation decreases monotonically towards the axis. The axial velocity profiles and the radial velocity profiles have several characteristic shapes, depending on the value of the nondimensional momentum transfer. The solution has a singular point on the axis of the vortex. The radius of the core increases linearly with distance along the axis from the singularity, and, at a given distance, is proportional to the coefficient of viscosity and inversely proportional to *K*.

Kuo [31] presented the investigation of the dynamics of convective atmospheric vortices through a simple model with unstable stratification, by expanding the flow variables in powers of two small parameters, χ and α, defined by the percent variance of the equivalent potential temperature and density equations. Two buoyancy-driven similarity solutions of these equations are also presented: the first is of a two-cell type, with descending motion in the centre and ascending motion in the outer part, while the second is of a one-cell type. These solutions show that the vertical velocity is proportional to the square root of the equivalent potential temperature lapse rate and increases linearly with height, while the tangential velocity is proportional to the quartic root of the lapse rate and to the momentum supply, and is nearly irrotational outside the core.

Takhar [32] shows that two ways of driving vertical flow in the core of a vortex could be (1) by the direct action of buoyancy acting on hot air and (2) by producing a vertical pressure gradient along the axis of a vortex because of core development involving the lateral spread of the vortex with height. Order-of-magnitude analysis applied to the nonbuoyant equations of motion leads to flow regimes depending upon the Rossby number [inertial forces/Coriolis forces] and the axial Reynolds number [inertial forces/viscous forces]. Further Takhar and Bég [33] developed a mathematical model of the geophysical vortex flow using an order-of-magnitude analysis based on a laminar, steady axisymmetric vortex motion in a cylindrical frame of reference. Similarity solutions are considered for the regimes (1) Rossby number > 1, (2) Rossby number ~ 1, and (3) Rossby number < 1.

It is also shown that a true similarity solution does not exist for the regime of Rossby number ~ 1, as it leads to the physically absurd conclusion that the fluxes of radial momentum and the angular momentum are both equal to zero [32,33].

Davies-Jones and Wood [34] utilized exact solutions of the Navier–Stokes or Euler equations of motion and the continuity equation in cylindrical coordinates for 3D, axisymmetric, inviscid, or laminar flows to represent evolving vortices that roughly model tornado cyclones or misocyclones contracting to tornadoes. These solutions are unsteady versions of the diffusive Burgers–Rott vortex and the inviscid Rankine-combined vortex. They satisfy the free-slip condition at the ground. Different vortices are obtained by choosing different values of the constant eddy viscosity and uniform horizontal convergence while holding the circulation at infinity constant. Because the flows are axisymmetric and uniformly convergent, all the solutions have the same radial and vertical velocities as given by eqn (2):

$$\frac{dr}{dt} \equiv u = -ar, \ \frac{dz}{dt} \equiv w = 2az \tag{2}$$

where (2a) is the horizontal convergence, and all components satisfy the pressure equation as in eqn (3):

$$p(r,z,t) = p(0,0,t) + \rho_0 \int_0^r \frac{v^2(r,t)}{r} dr - \frac{\rho_0 (u^2 + w^2)}{2} \tag{3}$$

where (u, v, w): the wind components in cylindrical coordinates (r, θ, z), t: time, ρ_0: constant mean value of density, P: the nonhydrostatic pressure.

Kolář [35] presented a brief survey of popular vortex-identification methods on the background of other vortex-identification and relevant discussions on vortex definition, and further suggests that a specific portion of vorticity provides a proper physical quantity for the kinematic identification of a vortex. On the basis of the triple decomposition of the relative motion near a point, the vorticity is decomposed into two parts, shear vorticity and residual vorticity. Berson *et al*. [36] deals with the identification and tracking of vortices in a time-resolved unsteady flow. The approach is based on the combination of two existing post-processing tools that are Galilean invariant functions: feature flow field, ***f*** and vortex identification algorithm, $\gamma 2$. An analytical development shows that the joint use of $\gamma 2$ and the streamlines of ***f*** allows identifying and tracking the location of the centre of a vortex core with a nonzero convection velocity.

Arsen'yev [37] presented recent advances in modelling of tornadoes and twisters consisting of significant achievements in mathematical calculation of occurrence and evolution of a violent F5-class tornado on the Fujita scale, and four-dimensional mathematical modelling of a tornado with the fourth coordinate time multiplied by its characteristic velocity. Such a tornado can arise in a thunderstorm supercell filled with turbulent whirlwinds. A theory of squall storms is proposed. The squall storm is modelled by running perturbation of the temperature inversion on the lower boundary of cloudiness. This perturbation is induced by the action of strong, hurricane winds in the upper and middle troposphere, and looks like a running solitary wave (soliton), which is developed also in a field of pressure and velocity of wind. Equations (4) and (5) give a solution of the problem about a mathematical description of the wind velocity and the air pressure in a developing tornado:

$$v = \sec h\left(\frac{x+Gt}{\Delta}\right)\sqrt{\frac{2g\beta r}{G\Delta} th\left(\frac{x+Gt}{\Delta}\right)} \tag{4}$$

$$P = p_0 + g\rho H - g\rho \frac{\beta}{\sqrt{gH}} \sec h^2 \left(\frac{r + Gt}{\Delta} \right) \tag{5}$$

where v: azimuth wind velocity, P: air pressure, t: time, r: the radial coordinate directed from the centre of rotation to outside, g: acceleration of gravity, ρ: air density, p_o: pressure at level ($z = \zeta$), H: highest tornado level ($z = H$), G: velocity determined by $G = (g\ H)^{1/2}$, Δ: the width of the soliton, $x = r$, $\beta = (3/2)(f/\alpha)$, where f is the frequency of friction and $\alpha = C_g/k^2H^2$, C_g is the coefficient of resistance, and k is the wind coefficient.

Emanuel [38] presented a simple numerical tropical cyclone model (Hurricane model) for a convective representation. The numerical model suggests that subcloud layers are nearly in thermodynamic equilibrium, with heat fluxes from the surface nearly balancing convective and small-scale turbulent fluxes of entropy through the subcloud-layer top. Results show that thermodynamic quasi-equilibrium of the subcloud layer may provide an important and useful closure condition in the representation of the ensemble effects of cumulus convection.

Mustafa *et al*. [39] reviews the present state of the convective vortex engine, and the fundamentals of the atmospheric vortex engine (AVE). Furthermore, the paper discusses an idea on utilizing the solar energy as the heat source to operate the system. In conclusion, the system is feasible and promising for electrical power generation.

3.2 Experimental approach

An AVE is a device for producing mechanical energy by means of a controlled tornado-like vortex. The vortex is produced by admitting air tangentially at the base of a circular wall which produces a convective vortex that acts as a dynamic chimney. The vortex is started by temporarily heating the air near the centre of the station with fuel or steam. The operation of the AVE is based on the fact that the atmosphere is heated from the bottom and cooled from the top and that more mechanical energy is produced by the expansion of a heated gas. An embodiment of the vortex engine is shown in Figs 2 and 3. The AVE has the same thermodynamic basis as the natural draft cooling tower; the total energy equation is used to calculate the energy received and produced in each process, as in eqn (6) [40]:

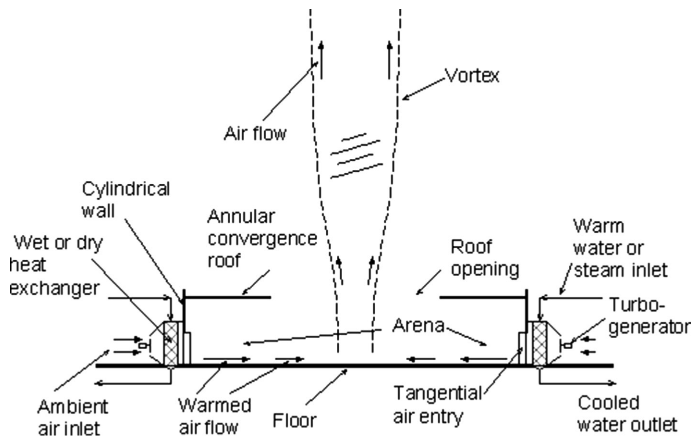

Figure 2: Schematics of the AVE – side view [40].

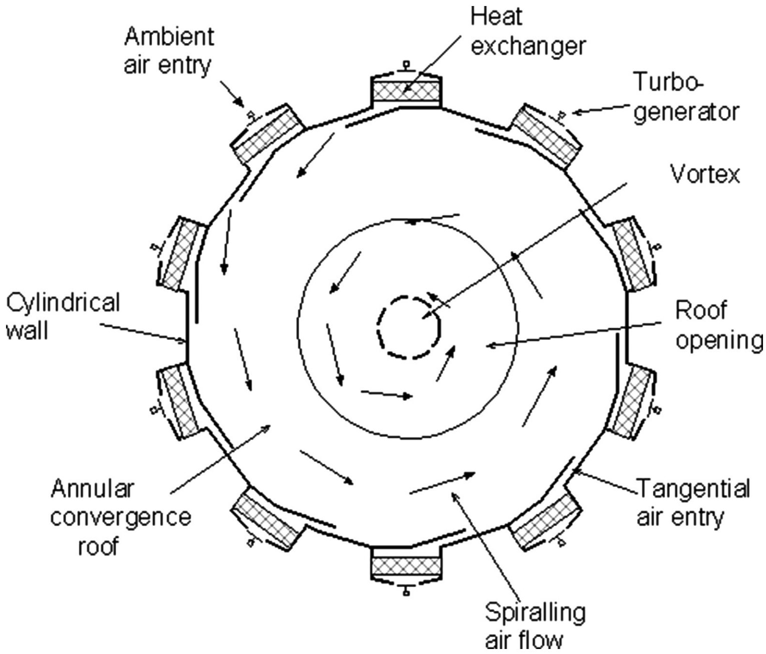

Figure 3: Schematics of the AVE – plan view [40].

$$w = q - \Delta h - \Delta gz - \frac{\Delta v^2}{2} \tag{6}$$

where w is the work given up, q is the heat received, h is the enthalpy of the air including the enthalpy of its water content, g is the acceleration of gravity, z is the height, and v is the velocity [40]. Louis M. Michaud received the United States Patent for the design of an AVE with Patent No: US 7,086,823 B2 in August 2006 [41].

3.3 Simulation of the vortex

Natarajan [42] performed numerical simulation of an AVE by the CFD analysis of a model-scale AVE. The results show that the AVE can generate a vortex flow in the atmosphere much above the AVE and the vortex acts as a physical chimney limiting the mixing of surrounding air into the rising plume of hot air. A parametric study was conducted, and it provides a good starting point for future designs. For a given geometry, the physical parameter ΔT (temperature difference between the inlet air to AVE and ambient air) is the main parameter that controls the strength of the vortex and in turn the power output. The full-scale simulations subjected to cross wind show that the power generation capacity is not affected by the cross winds. The current full-scale simulations do not consider actual temperature gradient present in the atmosphere. Figure 4 shows the contour plot of the tangential velocity in the YZ plane and the vector plot of velocity magnitude at the Z = 0.4 m plane (at the exit of AVE). It can be seen from these plots that a tornado-like vortex flow was generated inside the AVE and the flow extended into the atmosphere till the top of the domain. Natarajan and Hangan [43] studied the effect of surface roughness on tornado-like vortices using Fluent 6.2 software.

The investigations were carried out for swirl ratios between 0.1 and 2.0, covering a broader range of values than hitherto. Introducing roughness increases the radial, axial, and tangential velocities inside the core region. Outside the core region, introducing roughness decreases the tangential velocity for all swirl ratios. For swirl ratios 0.28 and above, roughness increases the radial velocity outside the core. A fractional decrease in axial velocity is seen outside the core for all swirl ratios. The limitations in fluent software restrict this study to only the low roughness case.

Park and Kim [44] present a method for visual simulation of gaseous phenomena based on the vortex method. This method uses a localized vortex flow as a basic building block and combines those blocks to describe a whole flow field. As a result, computational efficiency is achieved by concentrating only on a localized vorticity region while generating dynamic swirling fluid flows. Vorticity equation can be described as in eqn (7):

$$\Omega(x,t)=\frac{1}{2}\nabla\times u(x,t)=\frac{1}{2}\begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ u & v & w \end{vmatrix} \quad (7)$$

where Ω: angular velocity, $u(x, t)$: a velocity field of (u, v, w), and the curl operator.

Further, based on the Lagrangian framework, various boundary conditions are resolved. By exploiting the panel method, the no-through boundary condition is satisfied in a Lagrangian way. A simple and effective way of handling the no-slip boundary condition is also presented [44].

Qian and Zhang [45] performed numerical simulations of cyclones with various geometries and operating conditions to study the natural vortex length. The numerical solutions were carried out using commercial CFD code Fluent 6.1. A prediction model of the natural vortex length was obtained based on response surface methodology by means of the statistical software program (Minitab V14). The results show that inlet velocity, cyclone length, and vortex finder insertion depth also play an important role in influencing the natural vortex length other than the factors mentioned in publications. Compared with some experimental conclusions, the results indicate that the present prediction

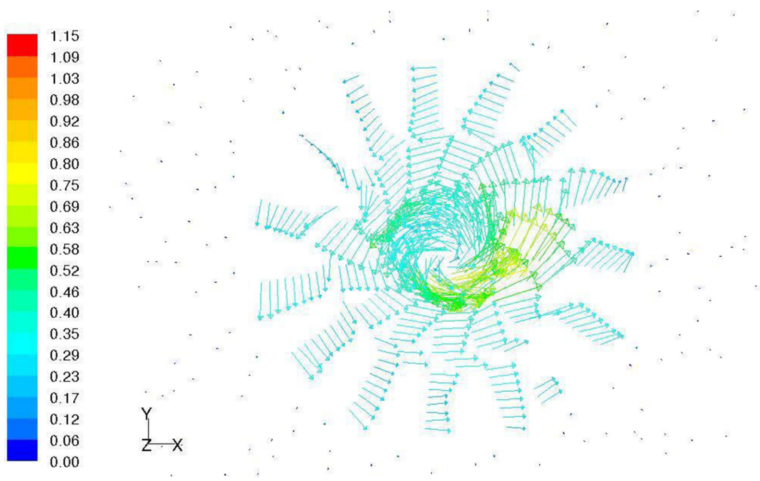

Figure 4: The vector plot of velocity magnitude (m/s) in the Z = 0.4 m plane for model-scale AVE (laminar simulations) [42].

model can estimate the effects of different geometries and operation conditions on the cyclone's performance more acutely than other models.

Kuai *et al*. [46] verify a CFD model to capture the flow characteristics of both full-scale and laboratory-simulated tornadoes. The sensitivity of computational simulations of a tornado to geometric parameters and surface roughness within a domain based on the Iowa State University laboratory tornado simulator was investigated. The tornado was found to be sensitive to a variety of geometric parameters used in the numerical model. Increased surface roughness was found to reduce the tangential speed in the vortex near the ground and enlarge the core radius of the vortex. The core radius was a function of the swirl ratio while the peak tangential flow was a function of the magnitude of the total inflow velocity.

Hashemi *et al*. [47] conducted an experimental simulation of tornado-like vortices in a small tornado-vortex simulator in order to study the effect of swirl ratio on flow characteristics. Particle Image Velocimetry (PIV) method is employed to quantitatively determine the tornado-vortex velocity field for swirl ratios ranging from 0.08 to 1. The radial and tangential components of velocity as well as the core radius of the tornado increase with increase in swirl ratio. The location of the maximum radial and tangential velocities is adjacent to the ground where the tornado vortex interacts with the surface. The values of normal and shear turbulent stresses indicate the existence of a laminar core for small swirl. As expected, the shear stresses increase with swirl ratio as the vortex becomes turbulent. The highest turbulent production corresponds to the critical case of vortex touchdown.

Maruyama [48] generated a tornado-like vortex numerically by Large Eddy Simulation. The calculation region was designed to reproduce the wind flow in a tornado simulator. A numerical tornado simulator was constructed by using the unsteady flow calculation method with Large Eddy Simulation. The configuration of calculating domain was designed to reproduce a tornado-like vortex following the laboratory tornado simulator. The simulator consists of a convection region and a convergence region. The horizontal shear was supplied by the inflows on the side walls of the convergence region. The strength of vortices was controlled by the wind speed and the distribution of inflow conditions. A series of tornado-like vortices were generated with varying the calculating conditions. The characteristics of unsteady flow field in the vortex were examined. The variation of the velocity and the pressure in the vortex with the dimension of the convection region, a vortex with

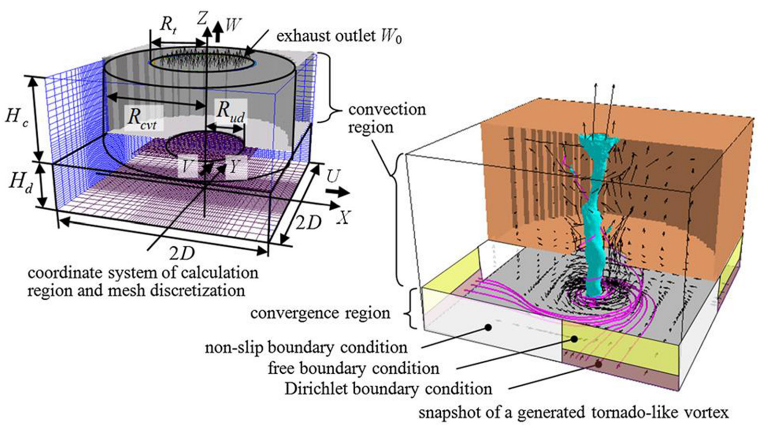

Figure 5: Numerical tornado simulator [49].

multicells, and a wind field of vortex near a building were presented. Further, Maruyama [49] carried out a study on the trajectory of flying debris in a tornado-like vortex by numerical simulation. A numerical tornado simulator was developed, which had the equivalent configuration to that of the laboratory experiment with a convection region and a convergence region; see Fig. 5. Numerical calculations were done by Large Eddy Simulation and a series of unsteady flow fields of a tornado-like vortex were generated. Finally, 3D trajectories of flying debris were computed and the statistical distributions of the maximum horizontal speed of debris were obtained [49].

Schecter [50] investigates the infrasound of an ordinary tornado in a numerical experiment with the Regional Atmospheric Modelling System, customized to simulate acoustic phenomena. The simulation has no explicit parameterization of microphysical cloud processes, but creates an unsteady tornado of moderate strength by constant thermal forcing in a rotational environment. Despite strong fluctuations in the lower corner flow and upper outflow regions, a surprisingly low level of infrasound is radiated by the vortex. Infrasonic pressure waves in the 0.1 Hz frequency regime are less intense than those which could be generated by core-scale vortex Rossby (VR) waves of modest amplitude in similar vortices. Higher frequency infrasound is at least an order of magnitude weaker than expected based on infrasonic observations of tornadic thunderstorms. Suppression of VR waves (and their infrasound) is explained by the gradual decay of axial vorticity with increasing radius from the centre of the vortex core; the azimuthal velocity distribution is given by eqn (8). Such a non-Rankine wind structure is known to enable the rapid damping of VR waves by inviscid mechanisms, including resonant wave-mean flow interaction and ‘spiral wind-up’ of vorticity:

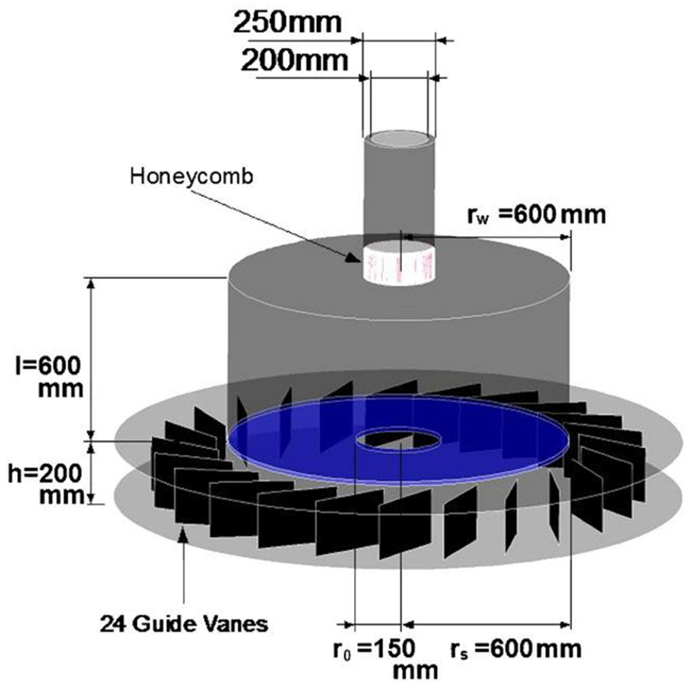

Figure 6: Overview of the numerical tornado simulator [51].

$$v = \frac{r / r_m}{1 + \left(r / r_m\right)^2} \sqrt{\frac{2B\theta_a z_m}{\pi} \left\{ \left[cos\left(\frac{\pi z}{z_m}\right) + 1 \right] - \frac{1}{8} \left[cos\left(\frac{2\pi z}{z_m}\right) - 1 \right] \right\}} \tag{8}$$

where θ_a: the surface value of the ambient potential temperature, r: radius from the centre of the vortex core, z: height of the vortex, $\beta = 3\times10^{-4}\ m/s^2K$, the initial cyclonic circulation is confined to $z \leq z_m$.

Ishihara *et al*. [51] investigated flow fields of tornado-like vortices generated by a numerical tornado simulator using the LES turbulence model for two typical swirl ratios. The core radii of simulated vortices with swirl ratios of 0.31 and 0.65 showed favourable agreement with visualized vortices by a laboratory tornado simulator. Mean velocity fields were examined to obtain detailed corner flow patterns. It was found that a one-cell type vortex with a central upward flow appears for the case of low swirl ratio and vertical velocities show peaks at the centre of the vortex, while a two-cell type vortex with a central downward flow emerges for the case of high swirl ratio and the maximum tangential velocity appears near the ground. The formations of one-cell and two-cell type vortices were investigated by examining the axisymmetric time averaged Navier–Stokes equations. The vertical pressure gradient generates vertical velocities at the centre of the vortex in the one-cell type vortex, whereas the centrifugal force balances with the radial pressure gradient and the vertical advection term of the radial velocity in the case of the two-cell type vortex. Figure 6 shows the overview of the numerical tornado simulator used in the study [51].

4 PROPOSED MODEL OF SVE

The SVE, proposed by the authors, is a vortex creation engine capable of utilizing a solar air collector to capture the solar energy. An artificial AVE is proposed to replace the physical chimney wall of SUTPP by the centripetal force produced by the spiralling updraft air flow. The proposed SVE in this work has novel developments as below:

1. Overcomes the conventional energy used in previous models by utilizing renewable energy through a solar air collector for the purpose of heating air and creating a vortex.
2. Utilizing a new design for the guide vanes or deflectors inside the vortex engine by using curvature deflectors to smooth and enhance the vortex generation in the engine.

The dimensions of the proposed SVE model are 1 m in diameter of the vortex engine with 1 m height which builds in the centre of a solar air collector of 9 m in diameter with 0.15 canopy slope towards the centre. An axial flow turbine is located immediately upstream of the air flow leaving the solar air collector at the base of the SVE. The kinetic energy of warm air is captured by the rotating blades of the turbine and converted to mechanical energy in the turbine shaft. The air flow through the turbine is then directed to flow in a narrow passage and to the core of the engine through deflectors imposing rotational motion. Then, the air flows up through a small opening in the upper cover of the core and moves up to the open atmosphere in swirling motion, as a vortex.

The process of power generation by the SVE with a solar air collector can become a major source of clean energy. The efficiency of the SVE could be higher than the efficiency of the conventional solar chimney power plant because the created vortex extends to levels higher than a physical chimney. Developments in the SVE can be revealed by comparisons with previous patents, as shown in Table 1.

Table 1: Differences of SVE with respect to AVE and solar power plant with short diffuser.

Criteria	AVE [41]	Solar power plant with short diffuser [18]	SVE [proposed technique by authors]
Published type	Patent + theoretical + experimental	Patent + theoretical	Proposal
Input energy	Burning fuel	Solar energy	Solar energy
Output	Electrical energy	Electrical energy	Electrical energy
Solar collector	No utilization	Utilize	Utilize
Solar chimney	No utilization	Short chimney	No utilization
Vortex air technique	Swirl updraft air	GVC	Swirl updraft air
Vortex air type	Warm updraft air	Warm updraft air + cold air stream down	Warm updraft air
Vortex establishing	Less complex	Complex	Less complex
Warm sir guide	Ribs air guides	Spiral air guides	Curved vanes air guides
Other supporting units	Heat exchanger	Water circulation by pumping, with nozzles	None

5 CONCLUSIONS

There are two ways of driving vertical flow in the core of a vortex: (1) by the direct action of buoyancy acting on hot air and (2) by producing a vertical pressure gradient along the axis of a vortex because of core development involving the lateral spread of the vortex with height.

Mechanical energy could be produced when heat is carried upward by convection in the atmosphere, as in the form of a natural tornado. A convective vortex engine is a technique using a created tornado-like vortex to convert the thermal energy to a mechanical energy during upward heat convection motion of air. It is possible to utilize this fact to compensate the long chimney in the solar chimney power plant by the vortex engine. Hence, it is highly cost-effective to reduce the high investment costs of installing the solar updraft tower by this replacement, where the physical chimney is replaced by the centripetal force produced by swirly upward air flow out from the vortex engine.

An AVE is a device for producing mechanical energy by means of a controlled tornado-like vortex. For a given geometry, the physical parameter ΔT (temperature difference between the inlet air to AVE and ambient air) is the main parameter that controls the strength of the vortex and in turn the power output.

A novel model of the SVE has been proposed by the authors, which operates on the same principles of vortex generation, but utilizing the solar energy as the heat source. The proposed technique is compared with the other reported atmospheric vortex base power generation systems.

ACKNOWLEDGEMENT

The authors express their appreciation to Universiti Teknologi PETRONAS for providing the research fund under I-Gen scheme and for the technical support to implement the experimental model of the proposed SVE.

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