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Carbon free electricity production from the alternative energy concepts based on the utilization of the convective vortex systems as a heat engines: Review of the current status and perspective

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ABSTRACT

The idea of using convective vortices as heat engines as the source of useful mechanical work for carbon free electricity production is really intriguing one. On the other side technical realisation of assumed alternative energy concepts represents an exceptional engineering challenge, but with huge potential benefits to society. Foundations and motivation for proposal of the herein elaborated alternative energy concepts lies in the existence of the natural vortex phenomena's, such as tornadoes, waterspouts and dust devils. Namely, they are clear and obvious proof that it is possible to obtain and maintain vortex in specific surrounding circumstances. The main energy source for the herein assumed energy concept is heat input that can be ensured in the form of waste industrial heat, for example from convectional power plants, or even solar energy as a renewable energy source. Therefore in the recent decades alternative energy concepts have been proposed, where the main feature is a specific fluid flow (vortex) that is assumed to be produced and maintained artificially from available heat input. By proposed alternative energy concepts it is possible to obtain significant increase in the energy efficiency of the existing convectional power plants or even to produce carbon free electricity. Thus, this paper provides insight in the main research outcomes from recent decades (a state of the art), where all important issues have been addressed together with the discussed perspective for future research activities in this challenging and demanding research topic.

1. Introduction

There is no doubt that fossil fuel era is already behind us from certain aspects and that we are seeking for other renewable energy concepts that are less harmful to the environment (or not harmful at all and stable as an energy source). Previous target is not easy to achieve as we have certain history and also developed infrastructure for utilization of fossil fuels. However, renewables today are slowly but surely penetrating more and more to the global energy market. For example in EU around on third of electricity supply is already from renewables and target for 2030 is around 46% (energypost.eu, 2017). Thus expansion of renewables has already begun in EU region but certainly more efforts are needed in order to set the main goals from the Paris agreement (ec.europa.eu, 2017). Energy transition, sustainable energy strategies came to focus of certain countries. For example in the case of Asia as well as beyond, the useful data can be found in Lee et al. (2017) or general guidelines related to the sustainable energy planning in Nemet et al. (2016). Urbanization impact on the greenhouse gases and general role of the population density was considered in Liu et al. (2017) for the case of the China.

Renewable energy technologies that are currently available on the market are those related to the production of the heat solar thermal systems Thirugnanasambandama et al. (2010) or electricity from solar energy photovoltaics, Singh (2013), or wind turbine facilities, Herbert et al. (2007). In the case of the photovoltaic technology still there is an issue with the relatively low efficiency and finally high initial investment. Wind energy is also related to the high investment cost and usually economically questionable without governmental subsidies (however it has got an economic potential with respect to the fluctuating prices of the oil but in some countries it is a reasonable option). Further, in the case of the economic viability of solar thermal systems they are strongly

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dependent from the level of sufficient demands for hot water (issue with the production and realistic demand).

As already emphasized Energy transition, energy planning and sustainability in general Wan Alwi et al. (2016) are important issues that are currently in the focus of the research community Lund and Østergaard (2011). However, crucial issue is development of the novel energy technologies that will ensure to reach targeted goals related to the energy sustainability. Therefore in this paper alternative energy concepts are elaborated and discussed where considered concepts are based to the general possibility of utilization convective vortices (gravitational fluid structures) as the source of the useful mechanical work for electricity production.

The initial thoughts, i.e. initial ideas for possible utilization of convective vortices were raised by Dessoliers (1913) and later Dessens (1962, 1969) where they first started to analyse natural vortex phenomena's as an intensive convective vortex systems. Previously mentioned authors have been more focused on the meteorological aspect and they didn't analysed aspect related to the potential technical utilization of the vortex systems as a heat engines, and which is important to emphasize. The first research who has proposed possible technical utilization of the convective vortices as heat engines was Michaud, L.M. Namely, in his first paper Michaud (1975) he has elaborated general idea, i.e. sketch of the vortex station that would be able to produce electricity via horizontally mounted turbines. He has also obtained a simple experiment were he has managed to produce convective vortex that was very similar to the small tornado (i.e. small scale tornado). Later he has developed and enhanced his idea into the Atmospheric Vortex Engine (AVE) concept (vortexengine.ca, 2017). In general Michaud has contributed a lot in the research of the concepts that deals with the vortex systems (as a potential energy sources), as well as on some other aspects related to the herein considered research topic Michaud (1995a,b, 1999) and in fact he was a pioneer in this research field. For instance in the reported study Michaud, (1995a and 1995b) the specific process during upward heat convection was analysed in detail from the thermodynamic point of view. In Michaud (2000) the thermodynamic cycle of the atmosphere during the upward air movement was address and in the Michaud (2012) the energy issue related to the case of the hurricanes was elaborated.

The current progress in the research of the AVE concept was addressed in detail in the upcoming sections of this paper.

The second concept for the possible utilization of the vortex engines as heat engines was proposed by Ninić and Nižetić (2007) and named solar power plant with short diffuser (SPD). Proposed SPD concept Ninić and Nižetić (2007) in conceptual approach was identical with the AVE concept where main difference was in the assumed energy source (required heat input into the system needed for the operation of the system). In the case of the AVE concept energy input in the system could be in the form of the waste heat (for example industrial waste heat), while in the concept Ninić and Nižetić (2007) the solar energy was considered as a renewable energy source (i.e. as the heat input into the system). In both cases, i.e. mentioned concepts, we are dealing with the energy solutions that can either ensure increase in energy efficiency of convectional energy systems or even better, they could produce carbon-free electricity.

A meteorological aspect related to herein analysed research topic is also important one and crucial for development of the technical aspects which are in the focus of herein reported research. Namely, as already addressed, the meteorologists are dealing with the general preconditions for occurrence and general structure of natural convective vortex phenomena's (in order to predict their magnitude and possible site of appearance and by that to reduce potential harmful impact). However, in the previously addressed alternative energy concepts Michaud (1975) and Ninić and Nižetić (2007) the specific vortex structure is not identical one when compared to the vortex systems that could be found in the nature. Namely it is assumed that vortex systems would be artificially produced in controlled conditions and successfully maintained (thus there is a certain limitation of metrological findings, i.e. applicability of gained results for here in assumed alternative energy concepts as in general we are not comparing the same vortex systems). Still, certain findings obtained by meteorologists are important one and they could be used for the research of the alternative energy concepts addressed in this paper. More detail regarding the main meteorological findings and issues was addressed in the separate section of the paper.

A main advantage of herein prosed energy concepts is a potential benefit to the society and that could be achieved only if those energy systems would be successfully developed and putted under operation. It doesn't needs to be mentioned that we are dealing with the research of the complex physical phenomena's, which represents demanding engineering challenge. However, the best engineering solutions are coming from the nature and it is just an question if we are somehow capable to copy already existing natural phenomena's, i.e. to artificially create them, in controlled conditions (i.e. to be able to create specific vortex structures that are crucial features of the herein elaborated energy concepts). Certainly, it worth's a try to work, and to make a progress in this specific research topic, due to significant potential general benefits. Finally, significant research efforts, both in human and technical resources would be needed to ensure major steps towards the development of the prototype plants, and after that their further upgrade to real application.

The main objective of this paper was to present a current state of the art related to the investigation of the herein considered alternative energy concepts. All major findings related to the investigation of the proposed alternative energy concepts were address and discussed. Finally, main research outcome of this study is gathering of the data as a useful base, i.e. starting point for other researchers who are planning further to contribute in this demanding and challenging research topic.

2. A general theoretical basis related to the proposed alternative energy concepts

In the essence the convective vortex system (CVS) can be considered as the heat engine which is able to deliver useful mechanical work. The basic scheme of the convective vortex, i.e. a comparison with the convectional heat engine concept was provided in Nižetić (2011), Fig. 1. It is noticeable from Fig. 1, that CVS can deliver a useful mechanical work, similar as in the case of a convectional heat engine. However, in the case of the natural vortex

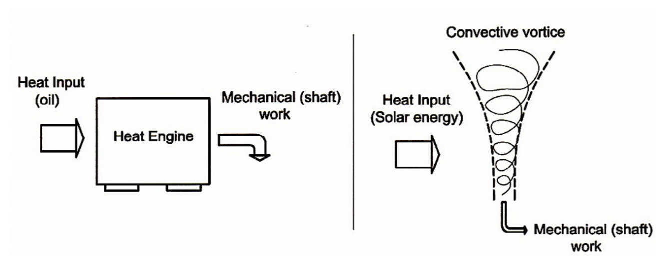


Fig. 1. The conceptual similarity between convectional heat engine concept and convective vortex system, Nižetić (2011).

phenomena's Bluestein (2005) the available mechanical work, in fact, is a destructive work, which brings hazard's and damage in general. Thus, main idea is to extract useful work from the CVS and use extracted work to drive, for example, turbines and finally to produce electricity.

However, CVS can be potentially a significant "energy consumer" that requires certain (considerable) available heat input in order to be able just to occur in the surrounding atmosphere. Secondly, beside the energy needed for the genesis of the CVS, the considerable energy is also required for the maintenance of the CVS in the specific surrounding atmospheric conditions (usually stochastic). Therefore, the overall heat input into the system needs to be sufficient to ensure genesis and maintenance of the CVS and finally to ensure available mechanical work.

From general thermodynamic point of view the Frist and second law of thermodynamics can be applied for considered CVS, respectively,

$$dq_{\text{overall}} = Tds = dh_{\text{tot}} + dw_{\text{overall}} \tag{1}$$

Overall heat from Eq. (1) is consisted from the general heat input into the CVS but also and from the other possible heat sources (thermal radiation, released heat due to intense friction with the ground, etc.). The specific enthalpy difference dh_{tot}, is related to the total enthalpy (latent heat included, kinetic energy, potential energy). Specific difference is set between point (section) inside the central region (zone) of the CVS and point outside the CVS (far away from the influence zone). Further, overall work is one related to the intense friction work, dw_f (dissipation friction work) and to the available useful mechanical work to drive the turbines, dw_{mw}. Thus, overall efficiency of the CVS as a heat engine could be written as follows,

$$\eta_f = \frac{dw_{overall}}{dq_{overall}} \tag{2}$$

However, the effective efficiency, i.e. one related to the available useful work that could be extracted from the CVS and that can be calculated as follows,

$$\eta_{fe} = \frac{dw_{mw}}{dq_{overall}} \tag{3}$$

If we examine rather simple equations' Eq. (2) and Eq. (3) the crucial question that can be raised is one related to the availability, and in general, the available magnitude of the useful mechanical work dw_{mw} (that could be extracted from the CVS system at all). Namely, maybe we are dealing with the pure energy dissipation systems were all converted work from the available heat input is spent to overcome intense friction (i.e. dissipation), i.e. in order to be successfully maintained in the surrounding atmosphere. Finally, it could happen that CVS would not be able to deliver useful mechanical work at all. Previous issue is still not solved and it is under speculations, as probably in certain circumstances CVS would be able to deliver certain quantity of the dw_{mw} and in some not at all, but for sure potential for exists. Certainly, it is an important issue that needs to be cleared and solved through upcoming research activity.

If we analyse theoretical efficiency of the CVS as the heat engines, i.e. Carnot base efficiency, then in general we have limitation. Namely, according to the Suoza, Suoza et al. (2000), the upper limit for the thermodynamic efficiency was defined as follows (and which corresponds with the Carnot value),

$$\eta_c \approx \frac{\Gamma_a Z}{2T_a} \tag{4}$$

Further, the main parameters that can affect efficiency of the CVS in general are; ambient temperature lapse rate Γ_a, depth of the convective layer, Z and finally surrounding air temperature, T_a. Calculation of thermodynamic efficiency, as well as other important parameters related to natural convective systems, was obtained in Renno (2008) (observed values for pressure are set in the table after backslash, Table 1).

From Table 1 it is clear that theoretical thermodynamic efficiency of the natural CVS ranges from about 5% to 20% according to the calculations, depending from the intensity of the CVS. Although previously specified thermodynamic efficiency of the CVS is relatively modest one, the considered energy concepts are assumed to be working with large installed nominal power outputs. Usual pressure potential for natural CVS ranges from the few hPa and more than 100 hPa for intense natural CVS (as for example tornadoes or hurricanes). The depth of the convective layer is around a few km for weak natural CVs and up to 15 km for intense CVS (basically the upper limit is a height of the troposphere level, after which buoyancy effect vanishes, so there is no possibility for extension in a depth of the convective layer). Renno (2008) provided valuable general data related to the theoretical analysis of the convective vortex systems as heat engines as the important base for herein assumed alternative energy concepts.

An intensity of the CVS depends significantly from the CAPE value (convective available potential energy) as the general measure of the convective circulation intensity, Eq. (5). CAPE in physical terms corresponds with the buoyancy work needed to lift air from the ground level to the upper levels of the atmosphere. A theory for calculation of the CAPE value has been proposed by Renno and Ingerssol, Renno and Ingersoll (1996). An alternative thermodynamic point of view related to the CAPE analysis given in Renno and Ingersoll (1996) was provided in Ninić et al. (2006) (where authors by using thermodynamic calculations, have proved that as a convection intensity criterion total work capacity should be used).

$$\text{CAPE} = \int_0^{z_{\max}} (\rho_a - \rho) \upsilon g dz \tag{5}$$

CAPE value usually ranges from few hundred J/kg and over 6000 J/kg in the case of the most intense CVS that are above already mentioned. Analytical definition of the CAPE value by Renno and Ingersoll (1996) was important step towards the determination of the general magnitude of the convective vortex systems.

A genesis of the CVS is rather complicated and unpredictable one as there is no unique mechanism, but they are specific theories that are supported by available observation data Bluestein (2005), Sinclair (1973). However, some mechanisms are discovered (and corresponds with the observation data) they provides realistic scenario, i.e. defines general conditions for genesis of the CVS. For example Renno, Renno (2008) has provided a general theory for convective vortices and also a sketch of the one possible general mechanism for the genesis of the GVC, Fig. 2. According to Fig. 2, the pressure potential between specific points "a" and "b" (caused directly by the certain heat input into the CVS) is generating intense

Table 1
Calculated values for different natural CVS, Renno (2008).

	γ	η	ΔT_{na}(K)	Δq(g kg^{-1})	Δp_{nh}(hPa)
Dust devils	1.0	0.05	5.0	0	2–5/3
Weak waterspouts	1.0	0.1	1.0	0.002	3–6/6
Strong waterspouts	1.0	0.2	4.0	0.005	30–60/65
Tornadoes	1.0	0.2	6.0	0.01	50–100/100
Hurricanes	1.0	0.2	10	0.01	60–120/90

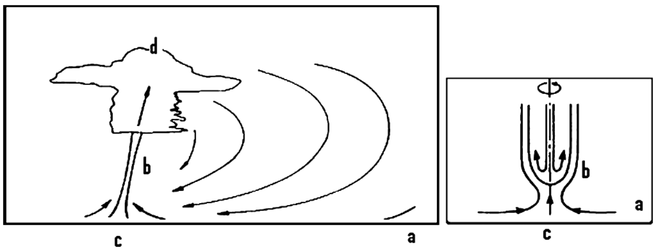


Fig. 2. Scenario of the convective circulation in order to generate CVS, Renno (2008).

air circulation from surrounding to the central zone of the CVS and finally towards the upper sections of the atmosphere. The most critical and important zone for genesis of the GVC is ground level region where friction with the ground makes an important role for genesis of the GVC.

Kerry Emmanuel also has set the theory Kerry (2005), related to the specific airflow circumstances which are leading towards the vortices genesis and maintenance in the surrounding atmosphere, Fig. 3. Namely, from Fig. 3 it is noticeable that for the vortex genesis we need high and low pressure zone (i.e. pressure gradient) and in essence a collision of the warmth and cooled air (which finally is causing rotational movement of the air and genesis of the specific vortex shape). Obtained analysis in Kerry (2005) provided important insights related to the genesis of the vortices with respect to the specific circumstances.

As already emphasized vortex is begin formed on the ground surface due to intense friction with the ground. The specific vortex genesis mechanisms were not considered in this paper as it was above the main scope of the paper.

The meteorologist scientists are more dealing with the specific mechanisms for genesis of the natural CVS and findings related to that can be easily accessed in the existing literature.

Finally, the main, i.e. crucial questions related to the theoretical issues related to the CVS are further one;

1) Are we able to generate CVS by artificial way?
2) Do we know controlling mechanism's for CVS control?
3) Are we able to extract useful mechanical work and simultaneously not to threaten the stability of the CVS?
4) Do we have available and sufficient heat sources to drive CVS based power plants?
5) Are we are dealing with the economical viable energy concepts?

All above raised question are not just important from the theoretical point of the view, i.e., they are also important for potential technical realisation of the herein considered alternative energy concepts. However, the first step is to develop theoretical models and to check general preconditions and requirements for eventually realisation of the serious prototype power plant. Therefore, in the continuation of the paper ongoing activity will be briefly elaborated for the most viable energy concepts that are under ongoing research activity.

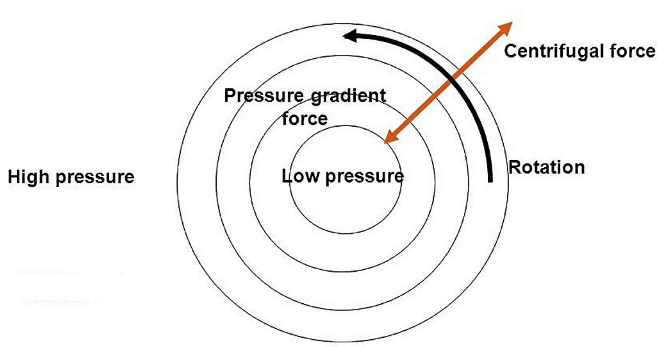


Fig. 3. Airflow circumstances in a vortex at the altitude, Kerry (2005).

3. Current ongoing research activity

In this section of the paper the AVE concept Michaud (1975) and solar power plant with short diffuser concept Ninić and Nižetić (2007) were discussed in detail, i.e. current progress related to the development of the considered energy concepts was elaborated. Mentioned concepts are currently the only one that are under research activity and that are based on the utilization of the convective vortices as heat engines.

3.1. The AVE concept

As already mentioned in the introduction section the AVE concept was proposed by Michaud (1975) and currently there is ongoing research activity at the Lambton College in Canada, where upgraded prototype of the AVE, i.e. LM-9, was successfully developed and tested, Fig. 4.

The AVE is a vortex generator that is capable by artificially way to create and maintain vortex (CVS), where finally useful mechanical work could be extracted from the CVS. A brief sketch of the AVE concept and base operation principle is presented on Fig. 5 (as well as plane view). To be able to create vortex AVE needs heat input in the form of the warm air that tangentially enters (Fig. 5) into the cylindrical wall of the AVE concept. Primary heat source for the AVE is assumed to be industrial waste heat (for example one from cooling towers), solar energy or any kind of the heat flow that is in the form of the warm humid air (which has got potential to ensure the work during the upward motion due to buoyancy effect). In the case if, for example, the industrial waste heat would be used as the heat source, the significant increase in efficiency of conventional power plants could be achieved by utilization of the AVE concept. Therefore, there is a huge potential benefit if we would

Fig. 4. AVE prototype LM-9 in operation (vortexengine.ca, 2017).

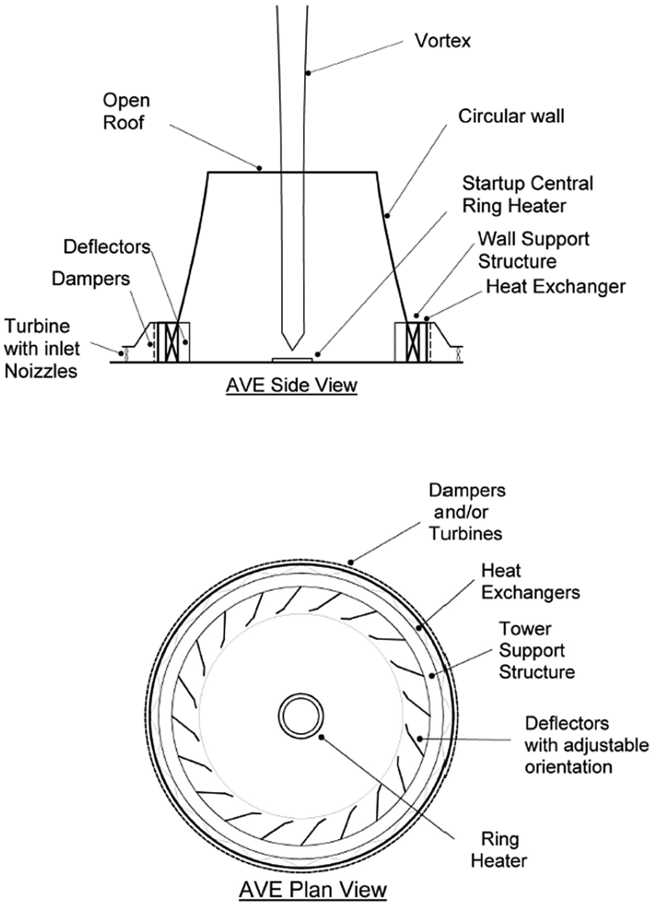


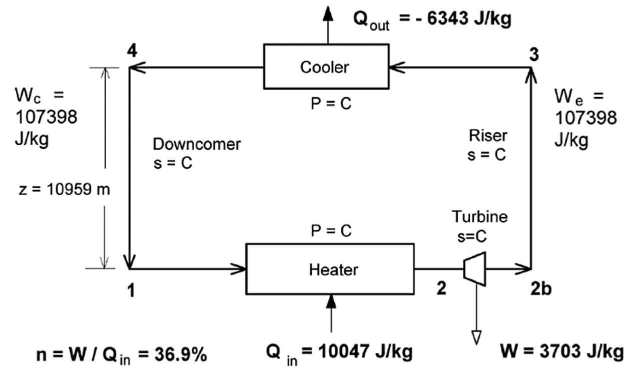
Fig. 5. A basic sketch of the AVE concept, (vortexengine.ca, 2017).

obtain successful development of the AVE concept to the stage of the market applicability.

Michaud reported that typical expected dimension of the large scale AVE generator will range from 50 m to 200 mm for circular wall diameter and from 30 to 80 m of its' height. Further, vortex base diameter would range from 20 m to 100 m and vortex height from 1 km up to maximal 20 km. Required heat input for plant of around 200 MW of electric power output is around 1000 MW. Estimated airflow would range from 20 Mg/s up to 100 Mg/s (with inlet air temperatures between 50 °C and 60 °C and water flows from 40 Mg/s up to 200 Mg/s). Expected heat to work efficiency of the AVE generator was estimated to be around the 20% (very close to the theoretical maximal efficiency).

Detail thermodynamic calculations of the AVE concept have been obtained and reported in several literature sources, Michaud (1999, 2000). Michaud compared Brayton cycle with so called gravity power cycle, where general thermodynamic calculations of the main parameter are presented on Fig. 6. The gravity power cycle is very close to the Brayton cycle as it is assumed that heat is begin received at the ground level and rejected to the upper levels of the atmosphere (where in general maximal level is at around 11,000 mm, after which environmental lapse rate is equal to zero, i.e. there is no available buoyancy force to lift the air). Air lifting from the ground level (i.e. air updraft) represents the expansion stage in the cycle and air downdraft (cooled air) represents compression stage.

Therefore, a difference when compared to the Brayton cycle is basically existence of the combustion chamber and turbine to take over produced technical work. Working fluid is assumed to be the



State	P (kPa)	T (K)	s (J/ K kg)	h (J/kg)	gz (J/kg)	h+gz (J/kg)
1	100	290	60.14	16929	0	16929
2	100	300	94.20	26975	0	26975
2b	95.77	296.31	94.20	23272	0	23372
3	20	189.42	94.20	-84126	107398	23372
4	20	183.10	60.14	-90467	107398	16929

Fig. 6. An example of the base thermodynamic calculations of the Gravity Power Cycle (vortexengine.ca, 2017).

air as an ideal gas and for specific example presented on Fig. 6, heat to work efficiency is calculated to be around 37%.

The CFD simulations of the AVE concept have been also obtained at University of Waterloo in Canada Natarajan (2011) using the CFD Fluent software. On Fig. 8 the specific vortex velocity streamlines have been presented (results are obtained using the OpenFOAM CFD software and obtained by Michaud group in AVTEC corporation) More detail regarding the CFD modelling of the AVE concept can be found in the Natarajan (2011). Developed CFD model was obtained on the way to take over the geometry from the small scale developed model, i.e. for the case presented on Fig. 7.

The first important outcome of the CFD modelling (related to the AVE concept), was prove that it is possible to generate and maintain CVS in the surrounding atmosphere (i.e. for the similar surrounding general conditions). The second important finding was related to the temperature difference between the temperature of the inlet air into the AVE system and surrounding air. Namely, it is found that previously mentioned temperature difference is important parameter that controls vortex intensity and by that also controls delivered power output (i.e. it controls intensity of the CVS). Mentioned finding is somehow expected as temperature difference

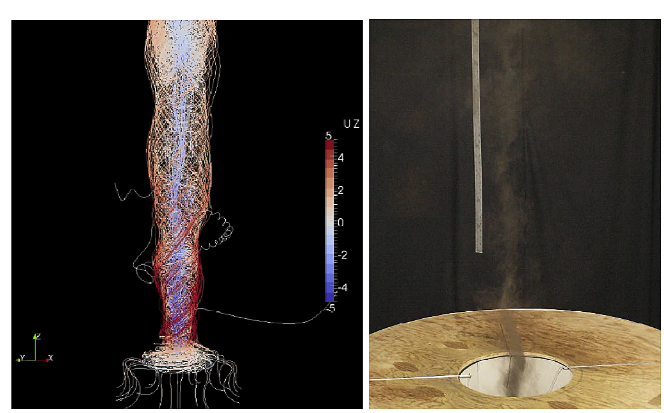


Fig. 7. The specific velocity streamlines (CFD) and comparison with the realistic model (vortexengine.ca, 2017).

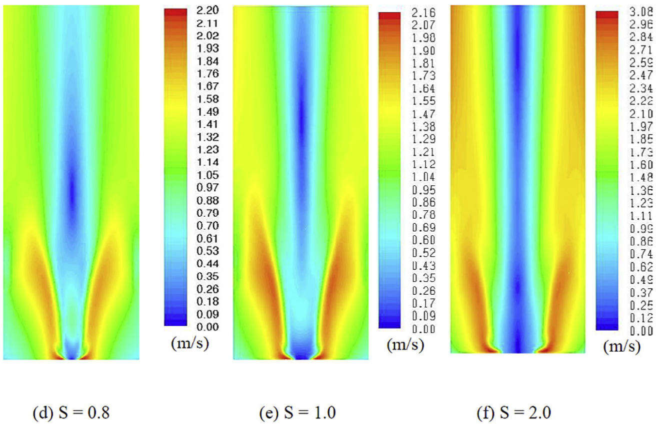


Fig. 8. Velocity contours for different swirl ratios (S), Natarajan (2011).

means difference in the air densities, and finally it has got an effect to the pressure potential (in the analytical approach, Nižetić et al. (2017) the same conclusion was obtained). The third interesting finding is related to the cross wind issue and according to the CFD obtained results, the cross wind doesn't have effect on the vortex stability.

The specific velocity contours for different swirl ratios are presented on Fig. 8 as well as interesting detail of the vortex evolution (genesis) on Fig. 9. From Fig. 9 it is clearly noticeable complex general nature of the vortex genesis for specific surrounding circumstances.

Beside the already above presented prototype model of the AVE concept, i.e. LM-9, Michaud's team has developed several prototypes (LM-1,LM-2,LM-3,LM-6,EM-1,TF-1,LFS). Some of them are showed on Fig. 10 in the operation mode. It is important to emphasize that all developed prototype models are small scale models and majority of them were not designed to deliver useful

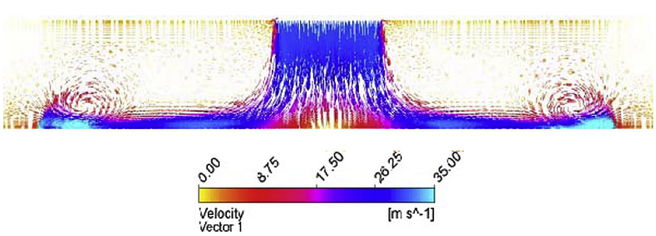


Fig. 9. A detail of the vortex evolution, Natarajan (2011).

work to drive turbines. Goal of the developed prototypes was to prove by experimental that is possible to create, and maintain vortex in she surrounding atmosphere, which was successfully obtained.

Regarding the potential business case the first it will be useful to detect potential benefits by successful development of the AVE concept that could lead to the final market applicability. On Fig. 11 the conceptual approach is presented, where AVE plant is assumed to be coupled with the conventional thermal plant (with fossil fuel as the primary fuel). According to the Michaud's calculations the overall efficiency of the convectional thermal plant can be significantly improved by integration of the AVE concept to the whole energy system, Fig. 11. While typical efficiency of the conventional thermal plants ranges from 30% to 35%, with integration of the AVE concept the overall efficiency could reach about 50%. Therefore, a potential for increase in the energy efficiency through implementation of the AVE concept is a significant one.

A detail business plan for large scale AVE plant is provided and elaborated in (vortexengine.ca, 2017). Namely, according to the calculations provided in (vortexengine.ca, 2017) the estimated overall investment cost for the AVE plant of 200 MWe in electric power output (which requires thermal input around 1200 MW_t) is approximately 60 Mio.USD. Previously means that specific assumed unit cost for the AVE plant is around 0.3 Mio.USD/kW_e. If we compare AVE unit cost with other technologies (that approximately ranges from 0.37 Mio.USD/kW_e to 1.9 Mio.USD/kW_e), we can see that AVE concept has got an economic potential and from this perspective it could be competitive with other current available energy technologies. More detail regarding the business plan for AVE, i.e. O&M cost, capital, energy production cost, return of investment can be found in (vortexengine.ca, 2017) under the section ''Business case''.

Above addressed and elaborated research activity obtained by Michaud and his team showed a realistic potential for realisation of the AVE concept in the reasonable future. AVE concept is reasonably investigated from the theoretical point of view with conducted experimental attempts but realisation of the experimental approach (mid-size or large scale plant) is necessary crucial.

3.2. Solar power plant with short diffuser concept

Beside the AVE concept the second considered alternative energy concept, and that is still under research, is a concept the solar power plant with short diffuser (SPD), Ninić and Nižetić (2007). The main difference when SPD concept is compared with the AVE concept is a type of the heat source but also in some other technicalities. While, as already mentioned, in the case of the AVE

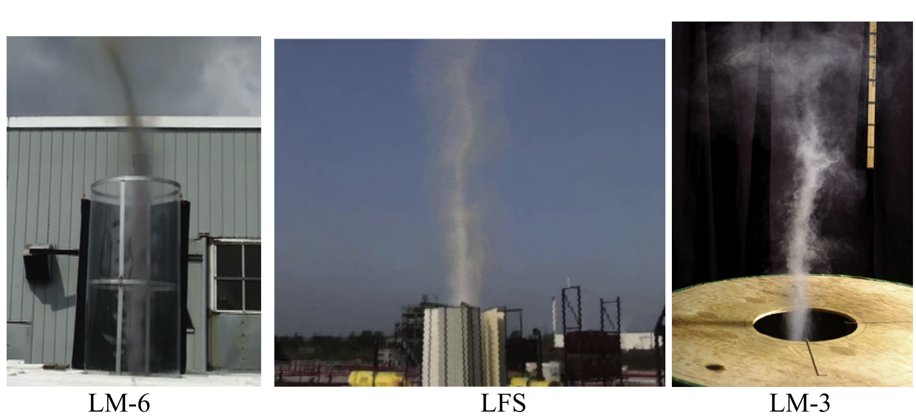


Fig. 10. The examples of the developed prototype models related to the AVE concept, (vortexengine.ca, 2017).

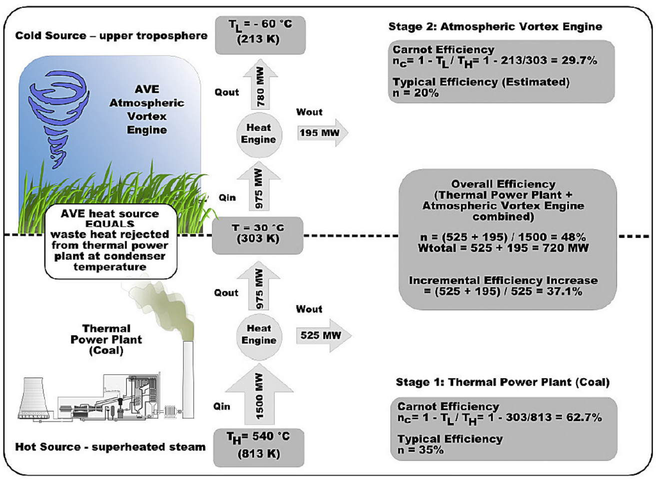


Fig. 11. The concept of the integration of the AVE plant with the conventional thermal power plant (vortexengine.ca, 2017).

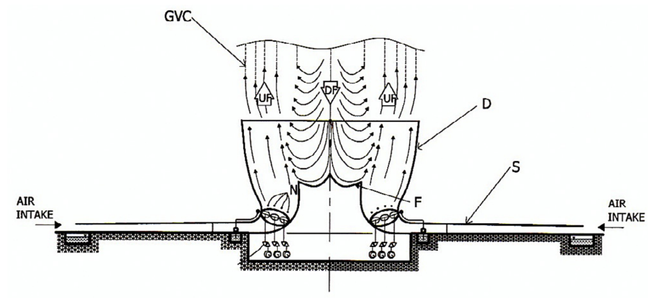


Fig. 13. The concept of the SPD power plant, Nižetić et al. (2017).

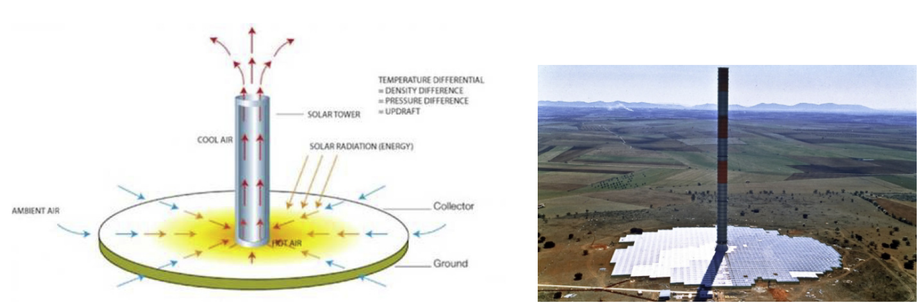
concept it is assumed that heat input is the waste heat in general, in the case of the SPD concept, the solar energy is considered to be used as the heat source. Therefore, the SPD concept basically can produce carbon-free electricity, which is an important advantage in nowadays general efforts to reduce implementation of the fossil technologies and harmful impacts to the environment.

The main idea for the SPD concept came out from the already developed and tested solar chimney power plant technology (solar updraft tower plant), Schlaich (1995). Solar chimney power plant technology (SC) is rather simple energy technology (collector roof, chimney, turbine assembly) that is able to produce carbon-free electricity from the available solar energy, Fig. 12.

Main issue with the SC technology was low overall efficiency (for the case of the prototype plant in Spain had overall efficiency about 0.5%, Schlaich (1995)). They were plans to build a first commercial SC plant in the dessert area of Australia (Mildura, Victoria), with nominal power output of 200 MW_e and with expected overall efficiency to be around 1.5%, (data.solar-tower.org.uk, 2017). However, due to high initial investment, and probably due to global economic crisis, this plan to realise considered SC plant was postponed. Currently they are plans to build a first commercial SC power plant in India (cleantechnica.com, 2017), 50 MW_e of nominal electric power output with thermal storage (to ensure night operation). The main cause for low overall efficiency of the SC plant is limited height of the chimney as chimney efficiency is directly proportional to the chimney height. Thus the idea of the SPD concept was to replace physical chimney with the fluid chimney which can be significantly higher one than for example concrete chimney. In one way SPD plant is a kind of modified SC power plant where basic sketch of the SPD concept is presented on Fig. 13.

According to Fig. 13 central part of the SPD plant is characteristic gravitational vortex column (GVC) that consists from the air updraft (UF) and air downdraft (DF). Air downdraft in the central part of the GVC represents cooled air and according to the Markovski (Markowski et al., 2003) this airflow is crucial for vortex genesis and maintenance. To boost up the intensity of the cooled air downdraft (UF), the water nozzles (N) are assumed to be installed in the central section of the vortex generator. Namely, water addition in the initial stage of the plant operation could ensure more intense air downdraft (later water addition could be disabled, however that should be verified by experiments and numerical analysis).

Working principle of the SPD power plant is based on the way that required heat input would be ensured from available solar irradiation that falls on the collector roof (collector roof can be made of the same materials that are assumed to be used in the solar chimney power plant technology, Schlaich (1995)). Air is being heated inside the solar collector, and passing through collector air becomes less dense than the surrounding air which finally is causing intense air flow inside the collector. Typical temperature of the air at the collector input is estimated to be from 30 °C to 35 °C and at the collector output between the 50 °C and 60 °C. At the collector outlet heated air enters to the central section of the GVC which has curved geometry (spiral blades) that are causing rotation movement of the air. Passing through the turbine section air is rotating the wind turbines and electricity is being produced. SPD plant could be only suitable for operation in the geographical regions with the highest solar irradiation levels more than 2000 kWh/m^2year (dessert areas in general). Finally, in combination with the relatively large collector geometry (due to in general available space resources in the dessert areas), high solar



(a) (b)

Fig. 12. Solar chimney power plant concept: (a) simplified scheme of the concept, (edisonmuckers.org, 2011): (b) prototype plant in Manzanares (50 kW_e), Schlaich (1995).

irradiation the sufficient heat input should be ensured to drive SPD.

The basis for the research of the SPD concept started in 2006 when Ninić et al. (2006), has analysed available energy in the solar chimneys. In that paper he also discussed general energy potential for ground level exergy contraction and elaborated general idea of possible alternative energy concept that could be able to utilize this working potential. Based on previous findings, Ninić (2006) the first elementary model of the Elementary theory of stationary vortex columns for solar chimney power plants was proposed in Ninić and Nižetić (2009). A simplified three-layer physical model of the GVC was developed, Fig. 14., where whole and complex thermodynamic process was analysed in the Mollier *h-s* diagram. Numerical results have been presented for a specific case based on the realistic expectations of the main input parameters. For considered case it was calculated that for the 60 MW of turbine power heat to work efficiency would be about 8.7%.

Developed three-layer model was further improved and upgraded in Nižetić (2010) by introducing the influence of the internal friction. Introduction of the internal friction in the upgraded model Nižetić (2010) was important one, however structure of the internal friction work was not analysed. Beside the introduction of the internal friction work a variable vertical velocity (variable by height) was also introduced as well as variable angular momentum of the downdraft shell. Final general physical structure of the vortex systems was defined in Nižetić et al. (2017), as already addressed and which was based on the previous research work related to the modelling of the vortex system for SPD plant.

Important contribution to the research of the physical nature of the vortex systems was provided in Nižetić et al. (2015) where simulation chamber was developed, Fig. 15. The influence of the water vapour addition on the pressure potential was also analysed by experimental way as well as also a change in the specific internal friction work by addition of the water vapour through experiments carried out in the vortex simulation chamber.

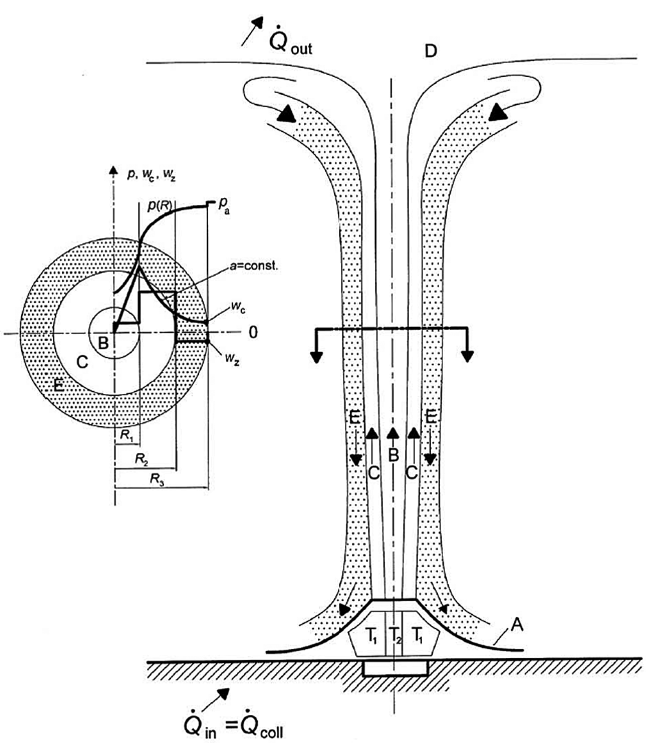


Fig. 14. The simplified scheme of the three-layer model of the GVC, Ninić and Nižetić (2009)

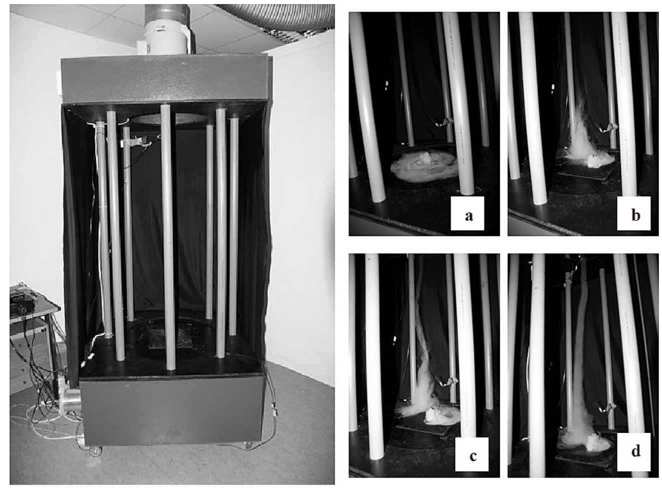


Fig. 15. Simulation chamber for vortices and characteristic stages in the vortex genesis, Nižetić et al. (2015).

It was found that that addition of the water vapour has unfavourable influence to the pressure potential as it has been reduced (however this outcome was gained for constant radial velocity). Second important finding in Nižetić et al. (2015) is a proof that it is possible to extract certain mechanical work from the convective vortex system and to maintain the stability of the vortex system (it was done by calculations based on experimental findings).

Proposed SDP plant is currently under CFD experiments where base simplified model was already developed and preliminary results are obtained. The example of the specific simulation result, i.e. velocity contours are presented on Fig. 16.

CFD experiments are still under progress and different influential parameters are examined (pressure potential, specific temperatures, the rate of the air mass flow, general dimensions of solar collector roof as well as diffuser, etc.) and in general their response to the vortex shape, stability and velocity magnitudes. Namely, velocity magnitudes need to be in reasonable range which is acceptable for application of the convectional based wind turbine technologies. Furthermore, other physical parameters also needs to be in the realistic range as currently we don't have developed experimental setup for the SPD concept (available observation data for similar natural vortex systems are used as an indirect validation of the developed model). The most similar vortex system to one proposed in the SPD concept is dust devil with respect to the intensity, shape and way of the genesis. There are available observation data for dust devils that can be used as a base for comparison with the numerical results of simulated GVC system as above mentioned. For example, Bluestein (2005) provided a review based on the data collected by W-band Doppler-radar for tornadoes and dust devils, while Sinclair (1973 and 1969) reported field based measurements and observations of dust devils. In reported study, Lorenz et al. (2016) a historical data are elaborated for the dust devils.

Namely, the GVC in the SPD plant is also assumed to be generated at the ground level while passing through characteristic geometry of blades and in general inlet section (dust devil also occurs in the ground level due to intense friction with the ground). Further, the shape of the GVC looks like characteristic shape of the dust devil. Finally, the pressure potential for dust devils is usually between the 2 hPa to 5 hPa which is something that also needs to be taken into the account during the numerical modelling in order to obtain realistic numerical results. Therefore, numerical modelling of the SPD power plant is still under progress and certainly gained

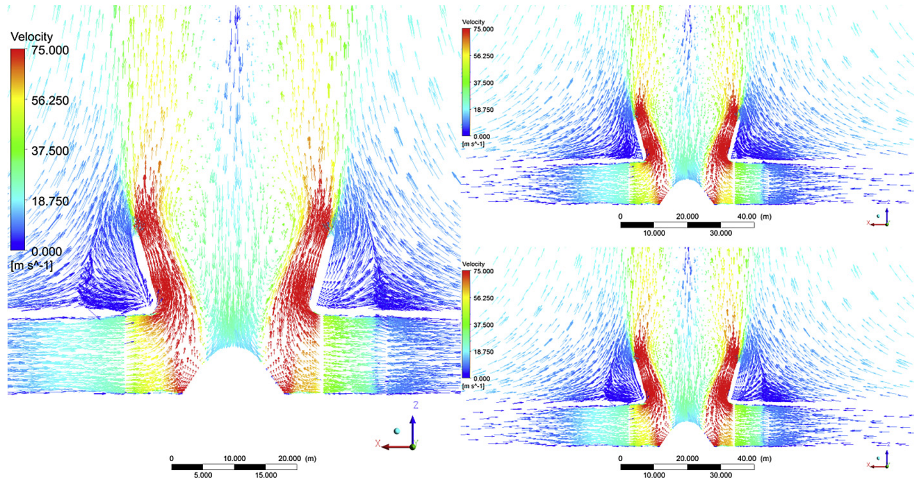


Fig. 16. The results of the CFD simulations related to the SDP concept (typical velocity vectors), Nižetić et al. (2017).

results would represent an important step towards the consideration of the prototype plant.

Based on the above conducted overview of the research activity related to the SPD concept it was found that there is an important progress in the numerical analysis as well as theoretical elaboration. Further experimental efforts are necessary in order to be able to get clear physical insight, i.e. to detect possible technical issues related to the practical realisation of the SPD energy concept.

4. Research contribution obtained by meteorologists

The meteorological aspect related to the natural vortex systems is focused on their prediction and occurrence in order to prevent fatal consequences and damage in general (in the case of the intense vortex systems as hurricanes, tornadoes and waterspouts). Meanwhile, in the previously elaborated alternative energy concepts, the focus of the research was oriented on the technical possibility to utilize vortex systems and to extract useful mechanical work to enable electricity production.

Majority of the research work obtained by meteorologists were reports and analysis of gained observation data for natural vortex systems as for example works of Bluestein (2005) related to the Doppler observations of tornadoes and dust devils, field observations of Sinclair (1973, 1969) related to dust devils and tornadoes field observations in Florida reported by Martinaitis (2017). Research studies obtained by meteorologists, and related to the numerical modelling of the natural vortex systems as heat engines, are mostly limited on the papers from Renno and Ingersoll (where it is important to emphasize that their research work is valuable and presents a significant progress in understanding complex phenomena related to the convective vortex systems). In the paper Renno and Ingersoll (1996) authors have proposed calculation framework for assessment of the CAPE value for convective vortex systems as the heat engines (developed calculation framework showed good agreement with available observation data. Further, Renno et al. (1998) developed simplified model for dust devils using the heat engine framework). They have compared results of their modelling with available observation data and provide physical interpretation of the observed characteristics of the dust devils. They have also found important analytical expression for pressure potential of the dust devils as well as thermodynamic efficiency. Later Renno et al. has expanded his approach to the waterspouts and in Renno and Bluestein (2001) provided simple theory for waterspouts. Again authors in Renno and Bluestein (2001) have developed analytical relations for pressure potential, thermodynamic efficiency and wind speeds by using the heat engine framework. Finally, Renno in Renno (2008), presented general thermodynamic theory for convective vortices as heat engines, where he has set general analytical expression for the pressure drop along streamlines and provided insight to the important features of the convective vortices. Therefore, previously briefly presented research efforts by meteorologist are certainly important one as they represents significant progress in the fundamental understating of the complex nature of the CVS.

Beside the theoretical analysis, experimental attempts were also provided in order to create by artificially way natural vortex systems. For example research group developed large scale tornado simulation chamber, Fig. 17, Fred et al. (2008). Simulation chamber was in diameter around 5.5 m, with height of 3.35 and it was used for experimental investigations of the different influential physical parameters on the vortex system. Other experimental attempts were also obtained to produce convective vortex systems that could be found in the nature like for example Meteotron experiment, Church et al. (1980) or other attempts, Refan and Hangan (2016) and Noda et al. (2014).

Beside the experimental attempts there are also numerical studies, i.e. large eddy simulations related to the tornado based

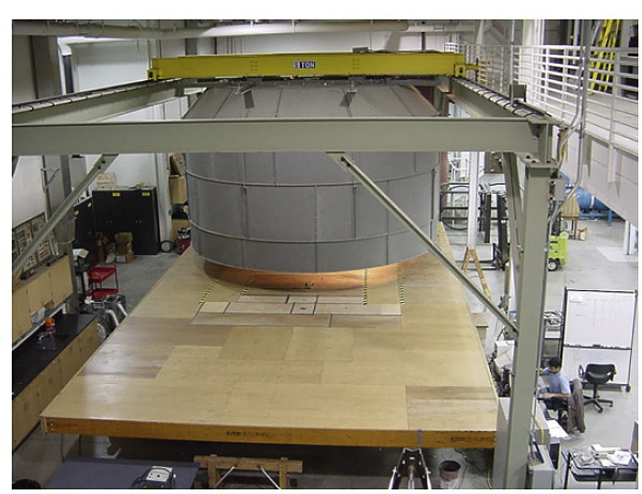


Fig. 17. The large scale tornado simulation chamber, Fred et al. (2008).

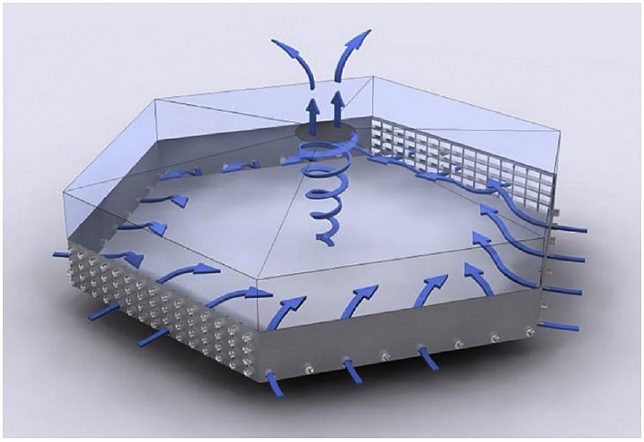


Fig. 18. The concept of the WindEEE Dome vortex simulator, Refan and Hangan (2016)

vortex systems Liu and Ishihara (2016). Finally, in this paper a focus of the research was not related to the meteorological aspect directly (but certainly indirectly for sure). On the important experimental setups is one reported in Refan and Hangan (2016) where they have successfully obtained experiments in the developed vortex simulator which is presented on Fig. 18 on the conceptual level.

Research efforts obtained by meteorologists are certainly important and valuable for the herein assumed alternative energy concepts. The main contribution of the reported research studies by meteorologist are valuable field observation data that are crucial for the numerical modelling of the convective vortex systems.

5. Issues and challenges

From previous elaboration of the vortex based alternative energy concepts (that are still under investigations) it can be concluded for sure that there are still not prepared to occur in the close future as the commercial plants. Namely, there are numerous issues that need to be solved, and in general both funding and human resources would be necessary to be able to come to the stage where commercial plants would be finalized and considered for utilization.

An AVE concept is on a good way towards its commercial realisation as already several prototypes are being developed and tested with CFD analysis carried out (and not to mention the already developed business plan). The latest developed prototype plant LM-9, at the Lambton College, is the most important one as it was rather large AVE prototype when compared to the previous AVE prototypes. However, the main issue related to the developed prototypes is one that in the majority of the cases the small scale models were considered (with vortex columns of the modest height). Furthermore, the magnitudes of the potential useful delivered work from the vortex system were not reported. Therefore, it is not clear if developed prototypes are able to deliver useful work at all or they are just using available heat input for maintenance of the vortex in the surrounding atmosphere (there is no data about turbines used in the experimental attempts or quantity of the delivered work). Therefore previous issues should be solved and clarified in order to prepare AVE concept to the commercial application (concept has got the high potential for possible implementation in the close future).

The SPD concept is still in the phase of the intense numerical investigations that are based on the general data specified in the patented application Ninić and Nižetić (2007). Numerical experiments by using the CFD analysis are in the progress and preliminary results are promising, and they are crucial to define a general geometry of the SPD plant (i.e. its range in order to provide realistic operating circumstances). The major outcome of the CFD modelling would be also a definition of the reasonable range of the working general condition's that will ensure secure environment for operation of the SPD plants. Still there is an issue how to control and maintain vortex system in the surrounding atmosphere BUT CFD experiments will be crucial contribution to provide insight in the complex physical picture. At this moment SPD concept is not close to its' experimental consideration, however outcome of the numerical investigations will shape future development of considered alternative energy concept.

6. Conclusions

This paper has elaborated currently two alternative renewable energy concepts (AVE and SPD concept) that are based on the possibility of utilization of the convective vortices as a heat engines. Both concepts were described in detail from the beginning of their development and in general their historical progress was addressed. Additionally, as this research field is also related to the meteorological aspect a main contribution from meteorologists was also briefly elaborated, i.e. those research studies that were dealing with the heat engine framework applied on the natural convective vortex systems. Regarding the present research activity related to the herein considered alternative energy concepts it can be concluded that currently AVE concept is reasonable close to the realisation of the serious prototype plant as the last major step towards the first commercial plant. The SPD concept is still in the stage of the intense numerical investigations that should define preconditions for possible realisation of the SPD prototype plant. The both considered concepts can contribute either in the overall efficiency improvement of the convectional power plants or to enable carbon free electricity production. However, there are still some open issues related to the general understanding of the convective vortex systems from the technical utilization point of view. Namely, additional workload is needed for sure to clear out range of the specific physical operating parameters. Previous is important in order to be able to detect circumstances where convective vortex system is able to deliver useful mechanical work and in the same time to be successfully maintained in the surrounding atmosphere. Further, reasonable operating conditions are also important to be detected, i.e. their range from the realistic limitations related to the assumed energy technologies (for example speed limitations of the wind turbines, mechanical stress of the constructional components due to intense air flow, etc.). Finally, in both cases, as already emphasized, the serious research work is necessary with demanding both human and funding resources. Potential general benefits are significant by successful realisation of the considered alternative energy concepts.

Nomenclature:

dz	Differential element of convective vortex height (height differential), m
g	Acceleration of gravity, m/s^2
z	Height above the ground, m
v	Specific volume of air, m^3/kg
q	Heat flux, J/kg
T	Temperature of the air, K
w	Specific work, J/kg

Greek symbols

η	Energy conversion efficiency

ρ_a Density of the ambient air, kg/m^3
ρ Density of the air updraft, kg/m^3
dh_{tot} Total enthalpy difference, J/kg

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