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Contribution to the research of an alternative energy concept for carbon free electricity production: Concept of solar power plant with short diffuser

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ABSTRACT

In this paper, an alternative renewable energy concept, i.e. concept of solar power plant with short diffuser (SPD) was investigated through the development of a numerical model with simplifications due to general complexity. The mentioned alternative energy concept is based on the possibility of utilizing an artificially created and maintained convective vortex system in the surrounding atmosphere. Finally, it is assumed that the specific vortex system would able to deliver useful mechanical work which then can be used to produce carbon-free electricity via turbine assembly. Preliminary numerical results were presented as a case study for SPD plants using a solar collector diameter of 600 m with a diffuser of 30 m in maximal and 25 in minimal diameter. According to the obtained numerical simulations, for the considered case, it was found that pressure potential should be below 5 kPa in general (with mass air flow rates less than 31 t/s) in order to enable reasonable operating conditions for commercial wind turbine technologies (a specific pressure potential range was defined in order to provide reasonable parameters related to the vortex system). Namely, for pressure potentials ranging between 3.5 kPa to 5.0 kPa, and mass air flow rates from 26 to 31 t/s, the plant would be able to deliver between 5.17 MW to 16.95 MW of nominal electric power output with an associated range of wind turbine operating air velocities from 30 m/s to 50 m/s. A comparison of the numerical results was obtained by using available observation data and reasonable matching was achieved, i.e. partial validation of the developed numerical model due to the non-existence of an experimental plant. Current research related to SPD concept development is still in the stage of numerically based experiments, which are crucial and important towards the consideration of a prototype plant. Therefore, the gained and presented findings in this paper are certainly valuable for the further development of the herein analyzed alternative renewable energy concept and provide a base for the final experimental realization of a prototype plant.

1. Introduction

The idea of using an artificially produced atmospheric vortex (i.e. convective vortex) for carbon-free electricity production, in controlled conditions, is a really intriguing one. If we could be able to realize the previously mentioned energy concept, great benefits to society would be achieved (novel renewable energy source, increase in energy efficiency, greenhouse gas emission reduction, etc.). Further, well-known natural phenomena (tornadoes, waterspouts, dust devils, etc.) prove that it is possible to create and maintain the previously mentioned fluid structures (vortex systems) in the surrounding atmosphere (in special circumstances). Hence, the real question is, are we ready to simulate vortex systems as natural vortices in relation to our present general knowledge and capabilities. It is certainly possible to create a convective vortex artificially but significant contribution is needed to achieve this when considering different aspects (as we still have unsolved issues) and especially in relation to the herein assumed energy concept.

The final goal is to utilize the artificially produced vortex system for electricity production through a specially designed power plant (i.e. through novel energy concept). Michaud was the first to propose the possibility of technically utilizing convective vortex

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Nomenclature

f_i	specific body forces
h	sensible enthalpy, J/kg
$h_{vortex.max.}$	maximal vortex height, m
k	turbulence kinetic energy, m^2/s^2
$\dot{m}$	mass flow rate of the air, kg/s
p	pressure, Pa
r	specific vortex radius, m
R_{ij}	Reynolds stress tensor
S_h	volumetric heat source, W/m^3
v	circumferential velocity, m/s
SST	shear-stress transport
T	temperature, K
Q	heat flow, W
W	available mechanical work, J/s
Z	depth of the convective layer, m

Greek symbols

Γ_a	ambient temperature lapse rate, K/m
δ	Stefan-Boltzmann constant, $W/m^2\,K^4$
η_{max}	thermodynamic efficiency,
μ	molecular viscosity, kg/ms
μ_t	turbulent viscosity
ρ	density, kg/m^3
Δp	pressure potential, hPa

as a heat engine [1], and further developed the concept in the form of an Atmospheric Vortex Engine (AVE) [2]. AVE is assumed to use waste heat from conventional thermal plants (or other heat sources as heat input in general), which means that the integration of the AVE in conventional energy systems (that are currently driven by fossil fuels) can boost overall efficiency and reduce harmful emissions into the environment. In general, Michaud has significantly contributed to research regarding his proposed concept [3–7] and has developed a few prototypes as well as small-scale models. His general work in the research field of convective vortices was crucial for their technical utilization and development, i.e. to transform available heat input into useful mechanical work that is assumed to be used for electricity production.

A second concept considered for the technical utilization of convective vortices when producing electricity was proposed by Ninic and Nizetic [8,9], where solar energy is used as a low-temperature energy source (solar power plant with short diffuser-SPD concept). The previous authors proposed an elementary theoretical model for their concept [10], which was later improved by taking another influential parameter into consideration [11]. Additionally, they also provided experimental work in order to investigate the general behavior of convective vortices in different circumstances [12,13] and to establish a base for further progress in this complex research topic. A detailed review of convective vortices and their possible utilization for carbon-free electricity production was provided in [14].

Regarding meteorological aspects, a crucial research outcome was the one obtained by Rénno and Ingersoll, where, for the first time, a detailed theory of natural convective vortices as heat engines was presented [15]. The previous paper was an important base for further investigations of convective vortices as heat engines and their analytical modelling. Rénno provided a significant contribution to this field with his research findings [16–18] that were, in general, related to the development of analytical models for natural convective vortices (but meteorological aspects were more considered).

All the above mentioned proposed technical concepts are still under investigation, and we can conclude that they are well developed regarding their conceptual phase as well as their theoretical models. However, a large scale prototype development is still premature. The development of a large scale prototype requires a detailed numerical analysis, where the most suitable option is CFD analysis, which would enable the determination of crucial and useful data, i.e. findings and conclusions needed in the design phase related to the specific considered energy concept. Michaud's concept was numerically analyzed at the University of Western Ontario using CFD analysis and the results can be found in [19]. The main goal of their research was to determine optimal AVE parameters (geometrical and process parameters). Regarding the provided CFD analysis, they concluded that AVE can generate a vortex flow in the atmosphere, and that the major parameter defining convective vortex strength is the temperature difference inside the AVE fluid structure when taking surrounding air and regional air into account (i.e. indirect pressure potential). However, they did not consider the influence of actual temperature and absolute pressure distributions, i.e. variable atmospheric conditions that can generally affect the stability of convective vortices in the surrounding atmosphere. They also found that the influence of cross wind is not significant for electricity production.

The main objective of this paper was to develop a simplified numerical model for the proposed SPD concept [8] as further research progress related to the development of the considered alternative energy concept. The obtained preliminary numerical results turned out to be useful as they have defined a range of crucial operating parameters for the SPD plant. Finally, the research outcome in this study represents an important base for future developments of the SPD concept in order to get into the stage where prototype plant realization would be considered.

2. Concept overview and general theoretical basis

The main motivation for the herein addressed energy concept [8] was the solar chimney power plant technology (SCP), [20] that was developed by a group of German scientists, and successfully tested on a prototype plant in Spain [21,22]. There are also other SCP based energy concepts that are under investigation, [23–25]. The main disadvantage of SCP technology is its low overall system efficiency, as its limited chimney height is the main reason for this (which finally affects overall SCP efficiency as chimney efficiency is proportional with chimney height). Thus, regarding the previously mentioned chimney efficiency issue, in the proposed concept [8], the chimney is replaced with a specific fluid flow structure (called gravitational vortex column system-GVC) that acts in fact as a fluid chimney. In the previous case, the flow structure is considerably higher in comparison to conventional chimneys in SC power plants, therefore, an increase in overall system efficiency is a reasonable expectation (maximal expected increase in overall efficiency, i.e. Carnot efficiency, would be at around 22% for any kind of energy concept that utilizes convective vortices as heat engines). However, maximum, i.e., Carnot efficiency, depends on the available maximum temperature difference between the heat source, at ground level, and the heat sink at the top of the troposphere level (general buoyancy limit), [26].