The innovative solar energy conversion technologies: solar convective-vortex power systems

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Abstract. The article provides an overview of the existing problems arising in the conversion of radiant energy into the energy of currents, as well as in the transformation of electrical energy in solar convective-vortex power plants. On the practical example of a pilot industrial solar aerobaric power plant, the possibility of implementing solar-convective-vortex power systems is illustrated. As a result of a comprehensive analysis, factors have been determined that allow creating optimal conditions for controlling the processes of concentration of thermal energy of solar radiation into the power of tornado-like flows.

1. Introduction

Today, more and more attention is paid to the problems of developing the use of renewable energy sources, which is confirmed by a significant number of publications in this area. Also, this fact is primarily due to the need to ensure the environmental safety of energy technologies, as well as the real prospect of depletion of reserves of fossil resources [1].

In the period from 2012 to 2020 in the international database Scopus for the keywords "renewable energy sources" recorded over 50,000 research works (Fig. 1).

At the same time, the largest number of publications relates to the field of knowledge - energy - 25400, engineering - 25347, environmental science - 10,037 and computer science - 9,389.

The research leaders are countries such as India (6900 publications during the specified period), the United States (5843) and China (5165). Russia takes only the 18th place by the number of publications (1064).

In the field of research on unconventional energy for the period under review, a little more than 1150 publications - the largest number in the field of knowledge - energy (731), engineering - 462, Earth and Planetary Sciences - 406. The leaders are also the USA - 532, China - 198 and India with 93 publications.

Only 6 publications were recorded for the keyword "solar convective-vortex power systems" during the period under review. Only 2 publications each in 2018 and 2013, as well as one each in 2020 and 2017. This indicates that the technology presented in the article is at the stage of its development.
Publications [2–6] are attractive within the framework of the research. For example, in the research work [2] the convection vortex theory is combined with the existing solar chimney power plant and desalination, moreover, in this research work, a solar vortex power desalination system is proposed. The publication [3] focuses on upgrading existing solar energy systems. The research which is presented in [4] shows us a vertical wind resource model that is comparable in resolution to NREL’s solar and horizontal wind resource models and uses the model for estimating power output for the SoV. In the research work [5] a numerical model with simplifications due to general complexity of alternative renewable energy concept based on the possibility of utilizing an artificially created and maintained convective vortex system in the surrounding atmosphere was developed. The atmospheric vortex engine is proposed as a device for producing mechanical energy using the artificially generated vortex in the research work [6].

Thus, the technology of converting the infrared component of solar radiation into current energy and electrical energy is relatively unadvanced. During using this technology, conditions are created for the localization of heating in the surface layer with a unidirectional permeability of the short-wave component of solar radiation through the collector surface.

In the presence of a vertical temperature gradient in the chimney located in the centre of the solar collector, gravitational instability of air masses is formed, leading to an upward convective flow. The energy of this flow is converted into electricity by means of a wind wheel connected to the shaft of an electric generator. Such technologies are called "solar fireplace" or "solar tube" [7].

The use of the Carnot principle, which establishes that the power of the generated flows is directly proportional to the dimensions of the collector, the height of the pipe and the vertical temperature difference in it, makes it possible to estimate the efficiency of converting thermal energy into the energy of movement of air masses.

At the same time, an obstacle to the practical implementation of the technology is the thermodynamic limit of converting solar energy into the energy of currents, which is determined by the second law of thermodynamics for closed, equilibrium systems. A possible solution to this...
problem of increasing energy transfer of thermal energy to flows can be the creation of conditions under which energy conversion in the system "flows of thermal energy - flow" is carried out with nonequilibrium, irreversibility and openness of transfer processes.

This fact confirms the expediency of considering the basic concepts of conversion by thermal energy flows initiated by solar radiation, which should proceed from the principles of nonequilibrium thermodynamics.

In the presented work, according to the nonequilibrium and irreversibility of energy exchange processes it is suggested a possibility to create practical ways to overcome the limiting values of mechanical work with aerodynamic technology for converting solar energy.

2. Methods and methodology
The method of converting solar energy, which is characterized by the occurrence of fluid movement under the influence of wind and short-wave components of solar radiation, has been known for a long time [8]. However, until now, it is based on an ineffective approach to the conversion of solar energy - the principle of a windmill and direct thermal contact. Today it is becoming evident that for the transition to efficient solar energy based on the use of the power of hydrodynamic movements, it is necessary to move away from direct copying and statement of established technological principles. An essential element of the new scientific and technical ideology on the way of transition to highly economical solar energy should be the application of the principle of hybridity and personality of energy sources [9]. In this paper, the authors consider the extent to which the above considerations can be implemented in practice.

"Solar chimney" in the classic version is a collector (greenhouse) with a pipe in the centre. For the first time, such a converter of thermal energy from solar radiation was patented in France in 1929. The wind flow was formed due to the convection of air masses heated in the collector by solar radiation. For the concentration of convective currents in the centre of the collector, a tube with a turbine was installed, which converts the energy of the flow into electricity.

The Solar Chimney power plant, built in Spain in the late 1980s [10], was the first practical implementation of the direct conversion of the infrared component of solar radiation into the kinetic energy of convective air currents.

The solar collector in this power plant was installed at 1.85 m from the ground and had a radius of 122 m. The heated air entered a cylindrical tube 10 m in diameter and 194.6 m high, located in the centre of the greenhouse. The flow in the pipe ran into the wind wheel. The station operated for seven years but was destroyed during a thunderstorm in 1989.

The main disadvantage of the power plant was the high cost of energy (60 cents per kWh), but scientists also pointed to the fragility of the structure, a constant dusting of the transparent surface of the collector, as well as temporary fluctuations in electrical power due to the inconstancy of solar radiation and the variable magnitude of the surface wind. Thus, the experts came to negative conclusions regarding the prospects for its further use.

At the same time, in the Spanish pilot power plant, instead of the expected generated power of 100 kW, only 36 kW was obtained with a conversion efficiency of 0.26%.

There were also other modifications of the "Solar Chimney" power station, where it was proposed to use the heat of water coolers of nuclear power plants as a heat source causing convection in a pipe [11]. Later, construction of a power plant with fiery tornado-like vortices appeared, developed by a Canadian researcher [12], the advantage of which was the fact that to obtain high values of electrical power there was no need to create a high pipe. According to preliminary estimates, a vortex with a transverse size of 100 m and a vertical length of 1 km; generated in a tower with a diameter of 400 m and a height of about 100 m, is enough to obtain an output electrical power of 100 MW.

However, the presented variations of technical solutions of modifications of the "Solar Chimney" power plant did not increase the efficiency of solar power plants. And the scientists decided to build
higher and less expensive sea-based systems with inflatable collectors and pipes of the "Floating solar chimney-FSC" type (fig.2) [13].

![Scheme of Floating solar chimney-FSC operation](image)

**Figure 2.** Scheme of Floating solar chimney-FSC operation [13]

According to preliminary estimates, a floating solar thermal power plant with a pipe of two kilometres in height and 50 m in diameter, receiving a heat flow from a collector with a transverse size of 2000 m, will produce about 100 MW. A kilowatt of installed capacity in such a plant is estimated to cost 700 euros.

In Russia in the 80s of the 20th century, studies were carried out on low-potential wind flows initiated by non-uniform heating of the surface by solar radiation [14,15]. It was found that when converting solar energy into mechanical energy, solar tubes that use the rotation of convective currents are the closest to solving the problem of increasing energy output [16]. Later, laboratory facilities were created, on which various modifications were tested that contribute to an increase in the efficiency of heat conversion into the energy of convective-vortex flows [17].

The most suitable means of increasing the intensity of energy generated during aerodynamic conversion of solar energy turned out to be a two-collector version of a greenhouse power plant developed at Moscow University, in which the increase in the rotation was provided not only by the vortex nature of the flow but also by external turbulization of movements, leading to the emergence of coherent structures [18].

The practical implementation of the idea of enhancing the effects of solar energy conversion initiating low-pressure, thermally ascending vortex flows is being developed in the project of helioarobaric thermal power plants "Helioaerobaric thermoelectric station-HTES" [19].

The article proposes a design that provides cyclotron acceleration of helically screw flows with nonzero vorticity using the interaction of a convectively swirling flow with heaters that receive heat from solar heating.

### 3. Methods for assessing the thermodynamic limit of the conversion of solar energy into energy flows

Within the framework of classical thermodynamics, the process of converting thermal energy into the energy of moving media is expressed in the following axiomatic positions:

1) In the process of aerodynamic transformation, energy transfers from one form to another, undergoing dissipation.
2) In isolated aerodynamic energy converters, there are no ways to ensure the transition of energy from a small amount to a large one.
3) Absolute zero heat energy is unattainable.
4) The equilibrium of the system in the process of energy conversion under the external influence is shifted in the direction in which the effect of external force is weakened.

The listed axioms characterize the processes of aerodynamic energy transformation of isolated systems in equilibrium. In open systems, for nonequilibrium and unsteady flows, irreversibility acquires functions unusual for it [20]. If in an equilibrium state the production of entropy, due to irreversible internal processes, reaches a minimum, then in nonequilibrium situations, irreversible processes can lead to an increase in the production of entropy. For such cases, the concept of energy...
conversion of thermal energy into the energy of currents should be supplemented with one more axiom, which considers the self-organization of aerodynamic movements:

5) In nonequilibrium currents open to external energy supply, the production of entropy by thermal motion tends to a minimum, due to the limited rate at which energy dissipates into heat. In this case, the function of increasing the production of entropy begins to be assumed by the intermediate (irregular) movements of the particles of the medium, which carry out energy exchange with the principal, regular activities:

\[ dS = dS_e + dS_i + dS'_i < 0, \]

Here \( dS_e \) — change in entropy flow (\( dS_e \neq 0 \)), \( dS_i \) — change in entropy due to irreversible internal processes (\( dS_i \geq 0 \)), \( dS'_i \) — change in entropy produced by irreversible processes associated with irregular movements (\( dS'_i < 0 \)).

Considering the nonequilibrium and irreversibility of energy exchange processes leads to the possibility of overcoming the limiting values of mechanical work in the process of aerodynamic conversion of solar heat energy [21]. Axiomatically, this is determined by the fact that the transformation of energy in open flows, when the transfer processes are not in equilibrium, leads to an increase in the minimum amount of work that is performed by the movements of the particles of the medium due to energy exchange between large-scale, basic and small-scale turbulent motions of the particles of the medium. In this case, there is reason to believe that an increase in the specific power of currents initiated by the greenhouse effect should be due to a change in the degree of ordering of aerodynamic movements. The motions of a medium with a wide range of random frequencies with a spatial variation of the external pump power can acquire the ability to transform into a single-frequency coherent one. The flow instability regime and nonlinear interaction between motions of different scales with selection and competition should lead to the disappearance of rare fluctuations and the strengthening of the main ones [22]. Practical implementation of coherent hydrodynamic motion inflows and a change in the ratio between viscous dissipation and turbulent energy generation should be carried out by transferring flows into an unstable state with a finite amplitude of perturbations of a given frequency [17].

4. Results

The stated basic concept and theoretical results were used in the construction of the first Russian experimental scientific and industrial solar aerobaric thermal power plant in Berdsk, Novosibirsk region.

The station is designed for a power of 50 kW. The draft tube is 18 meters high. The light-absorbing areas are in the form of glass corridors 4 m wide and 18 m high, which diverge radially from the pipe.

At the Research Laboratory of RES, Moscow State University MV Lomonosov Moscow State University for the study of hydrodynamic processes, an experimental model of a solar-vortex power plant "solar tube" with a two-tier collector, consisting of six sectors of a greenhouse, joined to each other was created.

Technical characteristics of the experimental small-scale installation "solar fireplace with chimney" are presented in Table 1.

| Table 1. The characteristics of a small-scale installation "solar fireplace with chimney" |
|-----------------------------------------|
| Collector radius, m | 2 |
| Pipe height, m | 1.2 |
The experiments were carried out with different levels of air heating in the collector when the radiation intensity of the lamps illuminating the greenhouses was changed. It was found that with an increase in the temperature of the underlying surface, the rotation speed increased. The flow velocity in the pipe was also measured at various combinations of angles of air entry into the body and above-ground sections of the greenhouses. It was found that the effect of the upper-level angular momentum on the rotation intensity was selective. To the greatest extent, the flow rate in the pipe increased at the angles of flow entry into the upper header equal. The resulting flow velocity in the line for these entry angles turned out to be one and a half times higher than at other upper-level swirl angles. The total flow rate of the flow entering the pipe in the presence of above-ground swirling was noticeably increased in comparison with a single-tier collector. The maximum level of intensification of the radiant energy exciting the convectively swirling flow in the pipe was achieved by optimizing the peripheral angular momentum over the height of the vortex near the underlying surface. The swirling flow made it possible to significantly increase the conversion of radiant energy in comparison with the direct-flow convective jet flow.

In small-scale power plants "solar fireplace with chimney", the increase in flow due to turbulence and multi-tiered air mass movement caused by solar heating is carried out with lower energy costs than in large-sized plants. The results of the analysis of the performed experiments showed that the most significant increase in the length of air movement in the collector was achieved by selecting the optimal swirl angles, without increasing the size of the system.

5. Conclusion
The solution to the problem of generating artificial wind by radiant heating of the surface layer confirms the prospects for creating power plants, in which the principles of creating nonequilibrium turbulence with the self-organization of vorticity under conditions of nonlinear interaction of vertical and horizontal convection are used as a basic concept for converting solar energy. It has been established that the relationship between the increase in the specific power of currents initiated by the greenhouse effect may be due to a change in the degree of ordering of aerodynamic movements.

It should be noted that the main limiting factor on the path to the practical use of renewable energy sources is their high capital intensity.

At the same time, personal power plants of the "solar fireplace with chimney" type, which can be equipped with batteries and voltage converters of 12/220 volts, are devoid of the indicated drawbacks typical for large-scale projects. According to the estimates, the annual electricity generation in the climatic conditions of Russia by power plants "solar tube with fireplace" can be 15,000 w/h.

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