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NUMERICAL MODELING OF CYCLOTRON FLOW ACCELERATION MODES IN AERODYNAMIC MODULES OF SOLAR AEROBARIC POWER PLANTS

***Alexander A. Soloviev* [1], *Dmitry A. Soloviev* [2,3], *Liubov A. Shilova* [4]**

[1] Moscow State University named after M.V. Lomonosov, Moscow, RUSSIA
[2] Institute of Oceanology named after P.P. Shirshov of Russian Academy of Sciences, Moscow RUSSIA;
[3] Joint Institute for High Temperatures RAS (JIHT RAS), Moscow, RUSSIA
[4] National Research Moscow State University of Civil Engineering (NRU MGSU), Moscow, RUSSIA

Abstract. When constructing solar aerobaric power plants, it is necessary to develop effective ways to accelerate convective flows initiated by the action of a high-temperature working fluid heated due to the concentration of solar radiation, accumulation of dissipated heat losses and the use of the greenhouse effect. As an option for organizing the flow in the aerodynamic module of the solar aerobaric power plants, article considered a diagram of the cyclotron acceleration of the flow during horizontal and vertical transfer of convective air currents formed in cells containing alternately located cold and hot side boundaries and differently heated upper and lower bases.

Keywords: numerical modeling, RES, aerodynamic modules, solar radiation.

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ РЕЖИМОВ ЦИКЛОТРОННОГО УСКОРЕНИЯ ПОТОКА В АЭРОДИНАМИЧЕСКИХ МОДУЛЯХ ГЕЛИОАЭРОБАРИЧЕСКИХ ЭЛЕКТРОСТАНЦИЙ

***А.А. Соловьев* [1], *Д.А. Соловьев* [2,3], *Л.А. Шилова* [4]**

[1] МГУ имени М.В. Ломоносова, Москва, РОССИЯ
[2] Институт океанологии имени П.П. Ширшова РАН, Москва, РОССИЯ
[3] Объединённый институт высоких температур РАН (ОИВТ РАН), Москва, РОССИЯ
[4] Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ), Москва, РОССИЯ

Аннотация. При строительстве гелиоаэробарических электростанций необходима разработка эффективных способов ускорения конвективных потоков, инициированных воздействием высокотемпературного рабочего тела, нагретого благодаря концентрации солнечной радиации, аккумулированию рассеиваемых теплопотерь и использованию парникового эффекта. В качестве варианта организации потока в аэродинамическом модуле ГАБТЭС на основе методов численного моделирования рассматривается схема циклотронного ускорения потока при горизонтальном и вертикальном переносе конвективных воздушных течений, формирующихся в ячейках, содержащих попеременно расположенные холодные и горячие боковые границы и различно нагретые верхние и нижние основания.

Ключевые слова: численное моделирования, ВИЭ, аэродинамические модули, солнечная радиация.

INTRODUCTION

Traditional renewable energy technologies include direct photovoltaic converters of electrical energy [1]. Also, it is known the usage of the parabolic mirrors which concentate solar rays and heat a high-temperature coolant. The energy of this coolant is directed to Stirling engines [2].

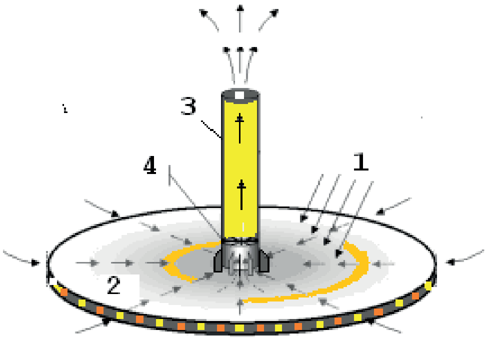

Figure 1. Scheme of generating artificial wind in the 'Solar Chimney' power plant. 1- solar radiation; 2- solar collector; 3- draft pipe; 4- turbine with an electric generator.

Wind turbines use natural wind flows without any modernization. In solar aerobaric power plants (SABPP) of the Solar Chimney type shown in Fig. 1, the artificially generated air flow is created due to the ascending convection of air heated in a solar greenhouse (collector) [3]. The technology for solar energy converting to electricity through the energy of artificial wind is less known in world practice than semiconductor and wind power plants or geothermal plants with a steam-gas thermodynamic cycle. However, in recent years, more and more works have appeared related to the study of issues of increasing the efficiency of this type of power plants [4] - [6]. These works also include the assessment of the effectiveness of such power plants' combined use not only for generating electricity, but also for obtaining fresh water [7], and for the removal of man-made pollution from the air of large cities [8], [9]. At SABPP of the "Solar Chimney" type, air heating and heat accumulation is carried out in a solar collector (greenhouse), which is formed by a horizontal soil surface and a translucent roof (Fig. 1). A draft tube is installed along the central axis of the greenhouse, where a turbine generator is placed, which converts the energy of convective movements of heated air into electrical energy. The main amount of thermal energy released by the infrared component of solar radiation goes into the atmosphere above the draft tube through the inner cavity of it and the turbine. The accumulation of thermal energy for the night period is carried out, in particular, due to the installation of containers with water on the surface of the solar collector.

The physical foundations of the conversion of solar energy in this case are as follows. The temperature difference between the air mass at the base and at the top of the pipe creates a steady-state convective air flow velocity. The magnitude of this speed is determined by the internal resistance of the air outlet duct, the main value of which falls on a turbine with a coupled electric generator. The inclination of the turbine blades during the axial flow of the stream, its friction against the surface of the blades and the generator load determine the air resistance of the turbine mainly. The flow rate in the pipe is constant during axial vertical movement of air masses due to the continuity of the flow. The temperature can also be considered practically the same throughout the movement of air in the pipe with low heat losses. As a result, the main amount of heat energy is released through the turbine into the atmosphere.

An analysis of such structures using solar energy with transformation into a laminar-convective flow of ascending air flows indicates a relatively low value of the coefficient of utilization of solar radiation energy entering the collector territory [10], [11]. This is due to the fact that the process of converting the energy of radiant heating of the greenhouse air environment into the energy of streams is carried out in the Solar Chimney structures only within the framework of vertical convection, without using the energy formed during horizontal advection. This is the basis of all known to date "greenhouse" solar energy complexes. Therefore, in the estimates of the solar energy conversion coefficient, it is necessary to state the relatively low efficiency of generating of artificial wind, which is a source of electricity [12].

FORMULATION OF THE PROBLEM AND METHODS FOR INVESTIGATION

Among the possible decisions that can ensure an increase in the efficiency of energy generation of currents excited by solar heating, the most important is to transform air flow into a controlled tornado rotating the turbine [13], [14]. With an appropriate trajectory, such a flow will contain two components of motion and velocity - axial (vertical) and tangential (rotation in a plane perpendicular to the pipe axis). A feature of an artificial tornado should also be local vortices in the form of a system of high-speed rotating air vortex bundles filling the cross-section of the flow in the pipe before entering the turbine. These vortices cause the hydrodynamic instability of turbulent flow in the pipe and collector and can significantly increase the energy of the process and the efficiency of converting thermal energy into useful energy generated by the turbine [15].

One of the tasks in the construction of solar aerobaric power plants is the development of effective ways to accelerate convective flows initiated by the action of a high-temperature working fluid heated due to the concentration of solar radiation, the accumulation of dissipated heat losses and the use of the greenhouse effect. As an option for organizing the flow in the aerodynamic module SABPP, we further consider the scheme of cyclotron acceleration of the flow during horizontal and vertical transfer of convective air streams formed in cells containing alternately located cold and hot side boundaries and differently heated upper and lower bases. Fig. 2 shows a diagram of such a method for accelerating a convective flow.

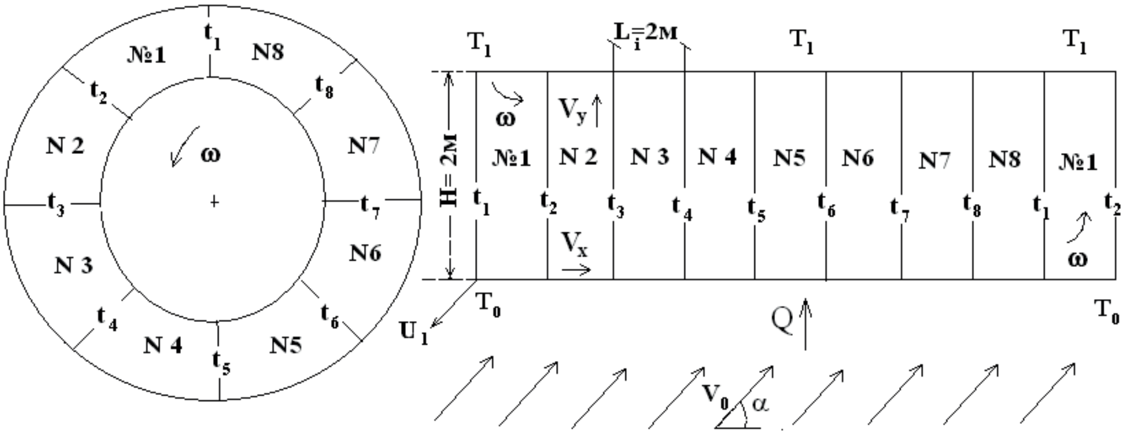

Figure 2. Scheme of the acceleration of the convective flow during the passage of air masses swirling with an angular velocity ω *through the cells with alternately heated and cooled side walls. The wind flow entering the cells has a velocity* $V_0(V_x, V_y, U)$*. The heat flux entering the channel from the lower boundary equals* Q*, the temperature of the lower boundary is* T_0*, the upper boundary is* T_1*. The cold side walls of the convective cells of the module have a temperature* t_{2i+1}*, the hot side boundaries are* t_{2i}*, the numbers of the cells are* $i = 0, 1, 2 \ldots n$*.*

The following system of differential equations [12] was used for the model theoretical calculation of the parameters of the convectively swirling flow arising in the annular channel of the aerodynamic module SABPP.

$$\frac{\partial V_i}{\partial t}+V_j\frac{\partial V_i}{\partial x_j}=-\frac{1}{\rho_0}\frac{\partial P}{\partial x_i}+\nu\frac{\partial^2 V_i}{\partial x_j\partial x_j}+g\frac{(T-T_\infty)}{T_\infty}\delta_{i3}-2\omega(V_1\delta_{i2}-V_2\delta_{i1}), \tag{1}$$

$$\frac{\partial T}{\partial t}+V_j\frac{\partial T}{\partial x_j}=\lambda\frac{\partial^2 T}{\partial x_j\partial x_j}, \tag{2}$$

$$\frac{\partial V_i}{\partial x_i}=0. \tag{3}$$

Here Ui is component of velocity vector (i,j=1,2,3); ω is angular swirling of vortex at the periphery of the system; T is an internal temperature; T_∞ is an external temperature; P is a pressure; ρ0 is an air density under normal conditions; ν and λ are viscosity and thermal conductivity factors respectively; δ_{ij} is Kronecker delta. The density depends on the temperature as follows (4):

$$\rho(T)=[1-\beta(T-T_0)]. \tag{4}$$

In this equation, the properties of the medium were characterized by the coefficient of thermal expansion: $\beta=-1/\rho_0\,(\partial\rho/\partial T)$.

The boundary conditions of the problem were formulated as follows:

1) The heat flux between the lower and upper boundaries, respectively heated to temperatures T_0 and T_1, was taken equal to $Q=-c_0\rho\lambda\,\partial(T_0-T_1)/\partial X_3$, where c_0 is heat capacity of air.

2) a wind velocity flow V_0 was introduced into the system of cells at an angle α to the horizon through the lower surface of the module.

3) At the lateral odd boundaries of the cells of the energy-dynamic channel, temperatures t_{2i+1} were set that were lower in absolute value with respect to the temperatures t_{2i} of the lateral even sides of the numbered cells $i=0,1,2...n$.

At the initial moment of time, the movement in the system was assumed to be absent, and the temperatures outside T_∞ and inside T were known.

An additional rotation with an angular velocity ω was imparted to the air flow in the system of cells. The momentum exchange coefficients were determined according to the well-known Kolmogorov relation obtained from the averaged equation of the balance of turbulent energy.

The problem has been solved numerically using the MATLAB software, which is a fourth-generation high-level programming language and an interactive environment for numerical calculations, visualization and programming. The calculation was carried out for an aerodynamic channel with a length of 10 m, a height of 2.0 m, an outer radius of 2.0 m and an inner radius of 1.0 m. The system of equations (1) - (3) was transformed to a dimensionless form. All values were normalized to the scale of length H, temperature - $\sqrt{\frac{1}{\beta}}$, speed - $\sqrt{gH}$, time - $\sqrt{\frac{H}{g}}$.

Numerical analysis was performed using the finite difference method.

Table 1 presents the main parameters of the problem, which remained unchanged in numerical calculations.

Table 1. The main parameters of the problem.

Parameter	Designation	Value
Vertical dimension	H	2 m
Horizontal dimension	L	10 m
Channel outer radius	R	2,0 m
Internal radius of the channel	r	1,0 m
Dimensionless vertical step	Δz	0.0625
Dimensionless horizontal step	Δx	0.052
Dimensionless time step	Δt	1
Peripheral vorticity	ω	0.05 s^{-1}
Air density	ρ	1,29 kg/m^3
Heat capacity of air	c_o	1007 J//kg degree
Number of time steps	N	1000

In the first series of calculations, the conditions for the formation of a flow through the cells in 18 hours were analyzed. Table 2 shows the conditions of the first series of numerical experiment.

Table 2. Initial conditions of the problem (the first series of numerical calculations).

Parameter	Value
t11	20 °C
t12	80 °C
t13	18 °C
t14	100 °C
t15	16 °C
t16	120 °C
Q	500 W /m^2
To	100 °C
T	20 °C
T_1	40 °C
T_∞	20 °C
α	30°
Vo	5m/s
n	5

The numerical calculation grid includes the number of points along the X3 axis equal to N = 16 and the number of points along the horizontal axis M = 96. The dimensionless step of dimensions in the vertical direction was designated Δz and Δx horizontally. The dimensionless time step was denoted as. The total number of time steps Δt_{Σ} varied depending on the specific conditions of the problem.

NUMERICAL SIMULATION RESULTS

Fig. 3 shows the distribution of the temperature established over time inside the channel along the flow.

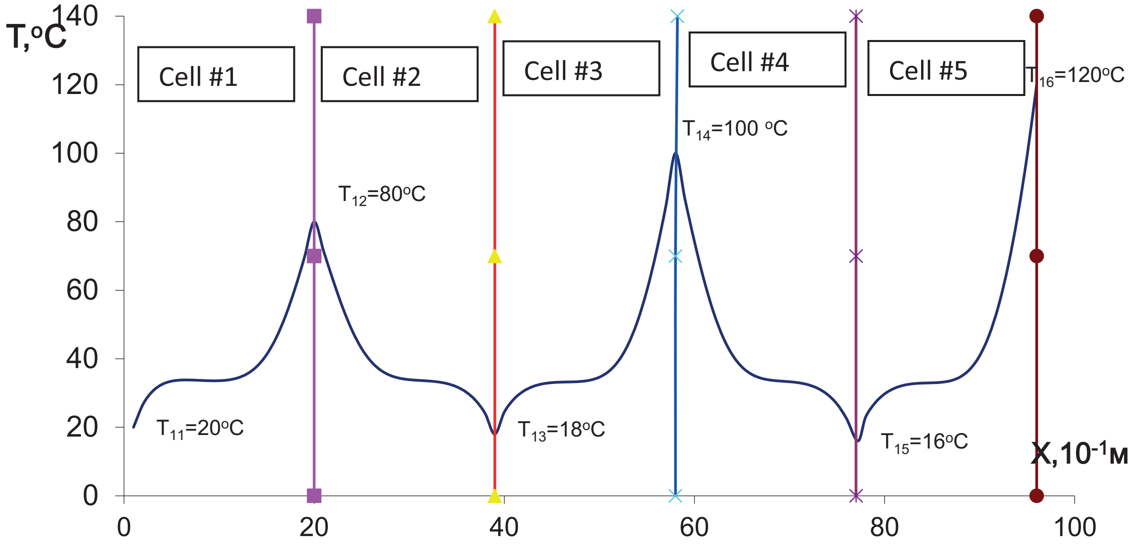

Figure 3. The temperature distribution in the cells convective SABPP aerodynamic channel in the first series of numerical experiment

Speed change along the direction of horizontal convective transport is given in Fig. 4. The figure shows that the steady-flow mode exiting aerodynamic cellular module completed through almost 5 hours after start heating. Subsequently the flow rate, which is formed at the outlet of the module, remains unchanged.

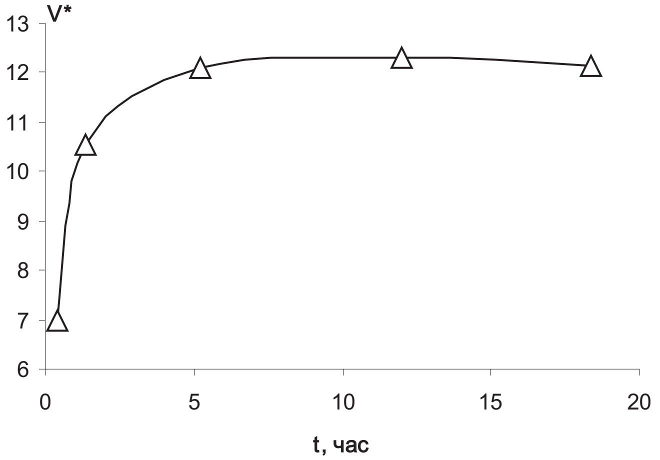

Figure 4. Numerical experiment data (series 1). The speed was normalized to a value in the incoming wind flow module

The transfer rate of air masses noticeably increases when they move through convective cells between cold and hot walls. For example, see Fig. 5.

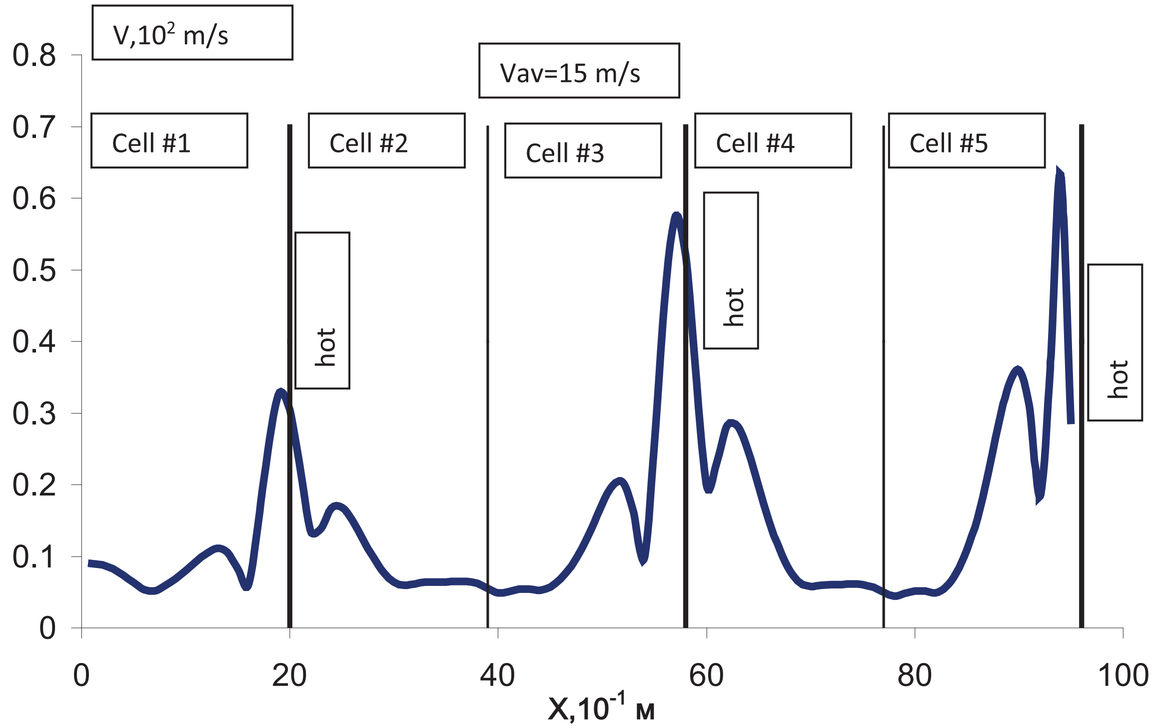

Figure 5. Change in flow rate when moving through alternately heated and cooled convective cells. The numerical calculation data refer to the moment 26 minutes after the heating is turned on

Fig. 6 illustrates the nature of air movement between the cells. It shows streamlines. At the cold wall, circulation occurs in a vertical plane with counterclockwise rotation. Near the heated wall, the circulation movement changes direction (Fig. 6).

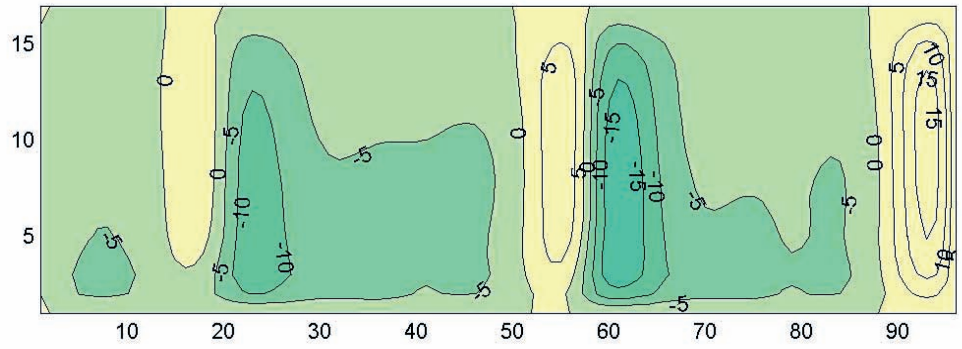

Figure 6. Streamline pattern in a vertical section of an aerodynamic module with alternately heated and cooled side walls. The values given on the isolines correspond to the circulation of the speed, expressed in normalized units, referred to the value of the circulation of the wind speed at the radius of the channel

An essential sign of a circulating increase in velocity in an aerodynamic channel with convective cells is the acceleration of the flow. This is evidenced by the calculation results shown in Fig. 7.

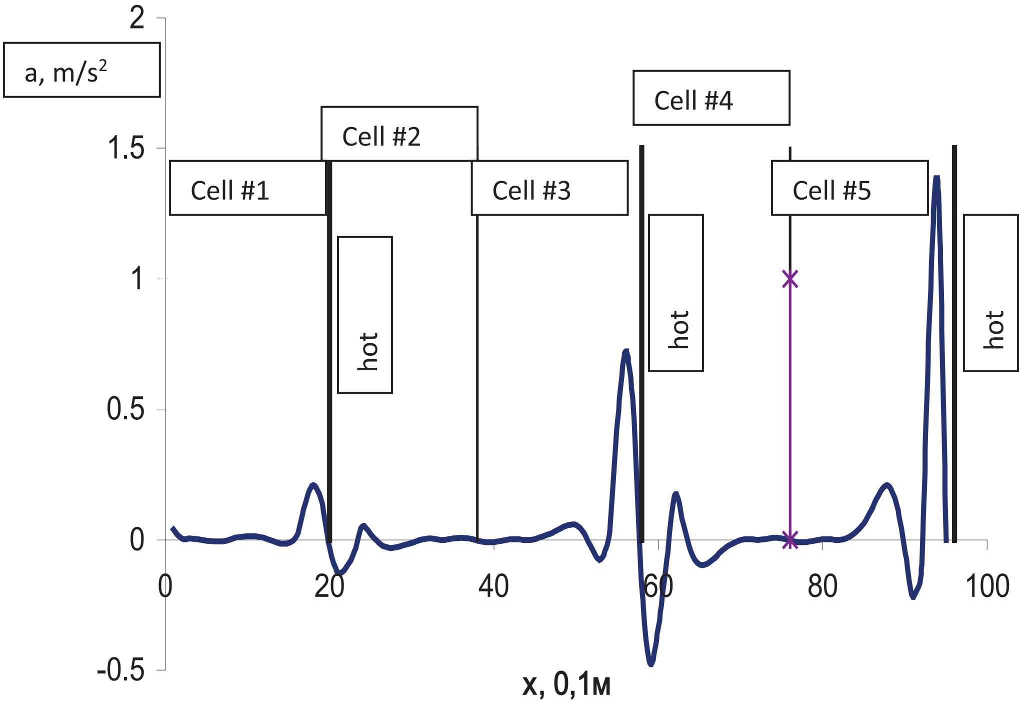

Figure 7. Change in the flow acceleration along the path of air movement through the convective cells of the aerodynamic module

It is accelerated in odd cells, in which the transfer movement of air masses goes in the direction from the cold side wall of the channel to the hot one. Moreover, as the cell number grows, the acceleration value increases. According to the calculation results for the conditions of series 1 of the numerical experiment (see Table 1), the change in acceleration a in odd cells ($i = 0,1,2....n$) of the SABPP aerodynamic channel separated by hot and cold partitions is determined by the following relation

$$a = 0,303 \cdot (2i+1) - 0,163 \qquad (5)$$

If the number of cells in the channel is 8, then the flow acceleration will reach a value equal to 2.6 m / s^2 in the last section.

In cells, where convective flow is transferred from a hot wall to a cold one, the air movement downstream slows down. However, in general, the tendency to accelerate the flow in the direction of convective transfer prevails over deceleration. The empirical trend formula for calculating the acceleration **a** (m / s^2) in the channel with the outer radius **R** (m) is as follows:

$$a = 0,094 \cdot R - 0,0355 \qquad (6)$$

From the relation (6), it follows that with the outer radius of the aerodynamic channel with the height H = 2m and the outer radius R less than 0.37 m, the flow will practically slow down.

CONCLUSIONS

Numerical modeling of the approach for acceleration of convective flows initiated by solar heating of air masses in the aerodynamic module of helioaerobaric power plants with horizontal and vertical transfer of convective air streams formed in cells containing alternately located cold and hot side boundaries and differently heated upper and lower bases has been carried out. An analysis of several series of numerical experiments was carried out. This shown the optimal conditions for the intensification formed in the flow cells with a decreasing and increasing temperature difference between the walls along the flow were determined.

According to the results of experiments, it can be concluded for the studied heating and cooling options that the proposed method for intensifying flows in the SABPP aerodynamic module divided into differently heated and side walls allows to increase the speed of the forming current an order in relation to the natural wind speed and obtain a cyclotron flow acceleration of the order of 2.6 m/s^2. The variant of the aerodynamic module SABPP with a multicellular structure of heating and a convective flow passing through it can be recommended for practical implementation.

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Alexander A. Solovyev, professor, academician of the RIA, MV Lomonosov Moscow State University, Faculty of Geography, Renewable Energy Research Laboratory, 119991, GSP-1, Moscow, Lenin Hills, d. 1, Bldg. 19, Moscow State University, e-mail: asolovev@geogr.msu.ru

Dmitry A. Solovyev, Senior Researcher, Candidate of Physical and Mathematical Sciences, Shirshov Institute of Oceanology, Russian Academy of Sciences, 36, Nahimovskiy prospekt, Moscow, Russia, 117997; Senior Researcher (part-time) of Laboratory No. 12, Joint Institute of High Temperatures of the Russian Academy of Sciences (JIHT RAS), 125412, Moscow, Izhorskaya Street, 13, building 2, solovev@ocean.ru, Tel.: +7(499)1247928

Liubov A. Shilova, Candidate of Technical Sciences, Senior Lecturer Department of information systems technology and automation in construction, Moscow State University of Civil Engineering (National Research University) (MGSU), 26 Yaroslavskoye Shosse, Moscow, 129337, Russian Federation, ShilovaLA@mgsu.ru

Соловьев Александр Алексеевич, д-р физ.-мат. наук, профессор, академик РИА, заведующий НИЛ возобновляемых источников энергии географического факультета МГУ им. М.В. Ломоносова, 119991, ГСП-1 г. Москва, Ленинские горы, д. 1, корп. 19, e-mail: asolovev@geogr.msu.ru, +7 (495) 939-42-57

Соловьев Дмитрий Александрович, кандидат физ.-мат. наук, научный сотрудник лаборатории взаимодействия океана и атмосферы и мониторинга климатических изменений, Институт океанологии имени П.П. Ширшова РАН, 117997, Москва, Нахимовский проспект, д. 36; старший научный сотрудник (по совместительству) лаборатории №12, Объединённый институт высоких температур РАН (ОИВТ РАН), 125412, г. Москва, ул. Ижорская, д.13, стр.2, solovev@ocean.ru, +7-499-1247928

Шилова Любовь Андреевна, канд. техн. наук, доцент кафедры ИСТАС Национального исследовательского Московского государственного строительного университета (НИУ МГСУ), 129337, г. Москва, ул. Ярославское ш., д.26, ShilovaLA@mgsu.ru, +7(495) 287-49-14