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Специальные стационарные течения плазмы

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Аннотация. *В физике плазмы большая часть основных вопросов лучше всего освещаются при изучении группы конфигураций, каждый из которых способен к стабильному удержанию в плазме. Поведение плазмы во многом определяется пространственной структурой, ограничивающей магнитное поле. В результате исследований получали семейство связанных конфигураций, которые в дальнейшем можно использовать для контролируемого изучения научных вопросов. На протяжении долгого времени были исследованы различные конфигурации. В настоящее время активно исследуются конфигурации для изучения множества важных вопросов в физике плазмы. Для построения специальных равновесных и стационарных конфигураций плазмы в данной работе рассматриваются течения в потенциально-силовом магнитном поле с плоской геометрией. Обсуждается специфическая симметрия выделенного класса стационарных конфигураций и связь специального множества равновесных конфигураций со стационарными течениями. Результаты исследования можно использовать при изучении движений несжимаемой плазмы.*

Ключевые слова: стационарная конфигурация, идеальная несжимаемая плазма, плоская геометрия

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Research article

Special stationary plasma flows

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Abstract. *In plasma physics, most of the basic questions are best covered when studying a group of configurations, each of which is capable of stable plasma retention. The behavior of the plasma is largely determined by the spatial structure that limits the magnetic field. As a result of the research, a family of related configurations was obtained, which can then be used to study scientific issues in a controlled manner. Various configurations have been investigated over time. Configurations for studying a variety of important questions in plasma physics are currently being actively explored. To build special equilibrium and stationary plasma configurations, this work considers currents in a potential-force magnetic field with a flat geometry. The specific symmetry of the selected class of stationary configurations and the connection of a special set of equilibrium configurations with stationary flows are discussed. The results of the study can be used to study the movements of incompressible plasma.*

Keywords: stationary configuration, ideal incompressible plasma, flat geometry

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Introduction. This work is due to the active development of research in the field of complex plasma, which over the past 30 years of research has turned not only into a separate type of plasma, but also become an interdisciplinary field of research. And, of course, the study of plasma and its properties is a topical problem of the world scientific community, the study of plasma is an important aspect of modern science. Let us give a review of the literature. The monograph [1] presents the basic concepts, facts and some applications of the theory of algebraic properties of differential equations; with rare exceptions, all the results are original. The following points are considered: algebra of equations, namely, a differential equation of general form, evolution equations of general form, equations in a Banach space; symmetry and separation of variables in the Hamilton-Jacobi equations, in the Dirac equation in Minkowski space, in the Weyl equation; linear equations of the 2nd order of non-parabolic and normal parabolic type. For an ideal plasma, symmetric stationary (equilibrium) states, as well as equilibrium states of general form are considered. The paper presents the basic concepts and the metric of Steckel spaces. The papers [2, 3, 4] study symmetric states of plasma in an external potential field. The general scheme for calculating solutions that are invariant with respect to a given subgroup of the geometric symmetry group of a differential equation was indicated by Sophus Lie more than 100 years ago.

Materials and research methods. The paper uses the parametric symmetry group of the MHD system of free ideal plasma induced in a natural way, that is, by shifts along the coordinate axes and the time axis, as well as by rotations in three coordinate planes. Solutions or more precisely, equilibrium configurations invariant with respect to a certain one-parameter subgroup of motions of the Euclidean space are obtained. The paper considers the set of Killing vectors of the group of motions G divided into three equivalence classes with respect to G: vectors of the 1st class determine translationally invariant states, those of the 2nd class determine axially symmetric states, and those of the 3rd class determine states with helical symmetry. The criterion of invariance of the configuration ($\mathbf{v}$, $\mathbf{H}$, p, ρ) with respect to a one-parameter group of motions with the Killing vector **w is formulated. The system of MHD stationary flows** is also formulated in covariant form.

The system of differential equations is reduced to one differential equation with partial derivatives of the second order for the plasma density; the Euler potential of the magnetic field is an arbitrary function of two variables, the pressure is specified by quadrature; the magnetic field strength and velocity are specified. In [5] it is shown that if the system of differential equations under study has a certain type of symmetry (translational, axial or helical), then when constructing equilibrium magnetoplasma configurations that have symmetry of one type or another, and in the presence of gravity that does not violate this symmetry, then it is possible to solve a direct magnetohydrostatic problem: for a given dependence of gas pressure on magnetic flux A (r, z), a second-order partial differential equation (an equation of the Grad-Shafranov type) is solved under certain boundary conditions and A is found as a function of coordinates, that is, in this way the magnetic structure of the system is determined. It is possible to consider the inverse problem, when, considering the magnetic structure of the system to be known, the corresponding equilibrium distributions of pressure, density and temperature are calculated.

The rationale for this approach is that, when we start modeling active solar formations, the global field of the Sun, or the field of magnetic stars, we usually have an idea in advance of what type of magnetic configurations we may encounter, i.e. we know in advance the approximate form of the flow function A(r, z), but, as a rule, we have absolutely no idea what spatial distributions of pressure, density, and temperature these magnetic configurations of interest to us correspond to and what observational consequences they may lead to. The inverse problem of magnetic hydrostatics provides an answer to these questions, which are of the utmost importance for observational astrophysics. It is important to emphasize that for systems with translational and axial symmetry, this inverse problem admits a general solution for pressure, density, and temperature in the form of integrals of combinations of derivatives of the flow function with respect to coordinates. This eliminates the need to solve a second-order differential equation and finds a solution for virtually any function A (r, z) given in advance. In the work [6] special stationary configurations of an ideal plasma in an external potential field are studied, in which the surfaces of constant density are magnetic, and the velocity and magnetic field strength fields are collinear; the relationship between such nonequilibrium configurations and equilibrium ones is indicated.

All special equilibrium and nonequilibrium configurations with a flat geometry of the potential-force magnetic field are obtained. In the article [7] special equilibrium configurations of plasma in an external field are considered; for each such configuration a method for constructing stationary flows is shown. The corresponding theorems are proved. In the work special stationary configurations of an ideal plasma in an external potential field are studied, in which the surfaces of constant density are magnetic, and the velocity and magnetic field strength fields are collinear; the relationship between such nonequilibrium configurations and equilibrium ones is indicated. All special equilibrium and nonequilibrium configurations with a flat geometry of the potential-force magnetic field are obtained. In the article by V.N. Shapovalov, O.V. Shapovalova "On the Question of Stationary Invariant Configurations of Ideal Plasma" [8] considers the behavior of plasma in a magnetic field. Definitions are given and such plasma properties as ideality and equilibrium are considered. A magnetohydrodynamic system for invariant states of compressible plasma is derived. Stationary configurations of ideal plasma are described. Also, the problem for systems that have symmetry, translational, helical or axial, is solved using the Killing vector. In the work of K. V. Brushlinsky "Mathematical Models of Plasma in Morozov's Projects" [9], a detailed review of mathematical models and calculations of plasma processes in various scientific and technical projects written and largely implemented by A. I. Morozov is presented.

The equations of magnetogasdynamics, on which the plasmadynamic models are based, are also considered. This work is devoted to the study of plasma flows in the channels-nozzles of plasma accelerators. The results of the obtained calculations made a significant contribution to the theory of the MHD analogue of the Laval nozzle and significantly influenced the success in the development and reconstruction of a quasi-stationary high-current plasma accelerator of high power. Plasmastatic models in terms of boundary value problems with the Grad-Shafranov equation are implemented in the calculations of equilibrium magnetoplasma configurations in traps with current-carrying conductors immersed in plasma. A.I. Morozov called such traps Galateas. The results of the calculations relate to the geometry, quantitative characteristics of the considered configurations and a number of regularities in matters of plasma confinement by a magnetic field. This work also discusses topical issues related to the mathematical model of the interaction of reaction and diffusion processes. Also, calculations of the geometry of the magnetic field in a vacuum, forming magnetic surfaces, which are intended to hold the plasma in traps, are carried out. In the article by Grossmann W., Saltzman J. "Adiabatic compression of the magnetic field configuration in a three-dimensional plasma" [10] the calculation of adiabatic compression of plasma in a realistic geometry is formulated and considered step by step. The plasma equilibrium equations, the flux conservation law are described, and calculations for the boundary conditions are made.

The article can be used as a teaching and reference material for students of physical and technical fields. It describes in sufficient detail and clearly the main calculations performed to determine the characteristic properties of plasma in a magnetic field. The nonlinear equilibrium equations represent the volume averaged over the surface of the flux and are recalculated from the partial differential equations. This allows one to take into account the adiabatic boundary conditions arising from the flux conservation law. The calculations are given for a plasma configuration with a reversed field, limited or finite length - a pinch. Compression occurs by increasing the current of the external confining coil (in other words, compression of the magnetic flux) and, consequently, increasing the clamp field, or by compressing the outer wall if the magnetic flux is constant. It is more often assumed that compression occurs on a time scale exceeding the pressure equilibration time. The results of radial and accompanying axial contraction are presented for a series of initial plasma profiles and beta for various compression schemes.

In the work of Morozov A.I., Solovyov L.S. "Stationary plasma flows in a magnetic field" [11] stationary plasma flows in a magnetic field are presented. Examples of emerging flows are given and their processes and phenomena are considered in detail. Magnetohydrodynamic equations of an ideal plasma are also formulated. The book "Stationary plasma flows in a magnetic field" very clearly reflects the attitude of the authors to the issues raised and their interest in the study. This book is a teaching aid for postgraduate students and specialists studying plasma processes and properties in physics. In the work of N. M. Zueva, L. S. Solovyov “On the nonlinear theory of gas-dynamic instability” [12] it is said that all changes in the state of the medium can occur in the case of unstable equilibrium and also under the influence of uncompensated forces, when the motion is caused by a small initial disturbance. As a result of instability development, the equilibrium configuration passes into a new stationary state, characterized by a lower level of “unstable” potential energy. In conservative systems with a large reserve of internal energy, the development of instability is a strong process leading in a short time to the transformation of a significant part of the energy of the initial state into other forms of energy and, in particular, into the kinetic energy of matter motion. The development of large-scale gas-dynamic instability in the general case is of a co-conservative nature, since it is accompanied by an affective rearrangement of the outer and inner layers of gas inside the unstable region.

The nonlinear stage of instability development also has a number of other common properties that do not depend on the physical mechanism causing instability, which allows us to consider various physical problems from a unified point of view. This paper is devoted to the issues of nonlinear development of gas-dynamic instabilities within the framework of a two-dimensional boundary value problem with initial data. In [13], a model of sunspot formation is considered based on the development of axially symmetric convective instability in the presence of a uniform magnetic field. The physical mechanism responsible for the instability is assumed to be the growth of entropy in the direction of gravity. There, gas-dynamic models of tornado formation in the atmosphere are also studied, based on the movement of the rotation moment from the entire region of instability development to the center. Here, both the convective mechanism in the gravity field and instability caused by the non-potentiality of the initial stationary flow can act as a physical mechanism causing instability.

In addition, a model of a supernova explosion is considered, based on the development of a two-dimensional axially symmetric convective instability inside it. In the article by V.N. Shapovalov, L.N. Dzhimbeeva, B.V. Umkeeva " Some translation-invariant plasma configurations" [14], translation-invariant equilibrium configurations are constructed in a modified cylindrical coordinate system. The system of magnetohydrodynamic equations is analyzed. The symmetry of the system and its invariance are also described. The article describes and considers the simplest equivalence classes. A definition of a translation-invariant configuration is also given. This work describes in detail the general solution of the equations and their integration. Graphic support, performed in the MAPLE 2019 mathematical package [15], helps to study the constructed translation-invariant configuration in more detail.

Research results and their discussion. Let's consider the definitions and theorems, lemmas that we use in our work.

Definition 1. A stationary nonequilibrium configuration $(\vec{v}, \vec{H}, p, \rho)$ плазмы в поле $U$is called special if there exists a scalar λsuch that$(\vec{H}, \nabla\lambda) = 0, \vec{v} = \lambda\vec{H}/\sqrt{4\pi\rho}$.

Note: The above conditions are equivalent.

$$(\vec{H}, \nabla\rho) = 0, [\vec{v}, \vec{H}] = 0$$

Definition 2. An equilibrium configuration $(\vec{H}, p, \rho)$in a field $U$is called special if$(\vec{H}, \nabla\rho) = 0$.

Theorem 1. If a stationary nonequilibrium configuration $(\vec{v}, \vec{H}, p, \rho)$in a field $U$is special with a scalar λ, then a configuration $(p', \vec{H}', \rho')$of the form $\vec{H}' = \vec{H}\sqrt{1-\lambda^2}$,$\rho' = \rho$,

$$p' = p + \frac{\rho v^2}{2} - p_0 \qquad (p_0 - const)$$

is a special equilibrium in this field.

Proof. From the equalities $div\,\vec{H} = 0, (\vec{H}, \nabla\lambda) = 0$ we immediately find

$$div\,\vec{H}' = 0. \quad (1)$$

It is obvious that in the case under consideration, $(\vec{v}, \nabla\,\lambda) = 0$;now from the condition $div\,\rho\vec{v} = 0$by direct calculation we find $(\vec{v}, \nabla\,\rho) = (\vec{H}, \nabla\rho) = 0$;thus, we have

$$(\vec{H}', \nabla\rho') = 0. \quad (2)$$

In this case, the identity is valid

$$\rho(\vec{v}, \nabla)\vec{v} = \lambda^2[rot\,\vec{H}, \vec{H}]/4\pi + \lambda^2\nabla\vec{H}^2/8\pi;$$

Taking this into account, the equation

$$\rho(x)v^k(x)\{v_{i,k} - v_{k,i}\} + \rho(x)\{\vec{v}^2(x)/2\}_{ji=} \\ = H^k(x)\{H_{i,k} - H_{k,i}\}/4\pi - p_{,i}(x) - \rho(x)\,U_{,i}(x);$$

you can write it like this

$$(1-\lambda^2)[rot\,\vec{H}, \vec{H}]/4\pi - \lambda^2\nabla\vec{H}^2/8\pi - \nabla p - \rho\nabla U = 0.$$

Taking into account (2) and the definition of a vector, $\vec{H}'$,it is easy to prove the identity

$$(1-\lambda^2)\left[rot\,\vec{H},\vec{H}\right]+\vec{H}^2\nabla\lambda^2/2=[rot\,\vec{H}',\vec{H}'];$$

Taking this into account and the definition of a scalar p', the previous equation can be written as follows

$$\left[rot\,\vec{H}',\vec{H}'\right]/4\pi-\nabla p'-\rho'\nabla U=0.(3)$$

Equalities (1) – (3) mean that $\left(\vec{H}',p',\rho'\right)$is a special equilibrium configuration in the field, U;which is what was required to be proven.

Theorem 2. If $\left(\vec{H},p,\rho\right)$ −a special equilibrium configuration is in a field, U,then with any scalar λ: $\lambda\neq 0,\ \lambda(\lambda^2-1)\neq 0,\ \left(\vec{H},\nabla\lambda\right)=0$a configuration $\left(\vec{v}',p',\vec{H}',\rho'\right)$of the form $\vec{v}'=\lambda\vec{H}/\sqrt{4\pi\rho(1-\lambda^2}$, $\vec{H}'=\vec{H}/\sqrt{1-\lambda^2}$, $p'=p_0+p-\frac{\lambda^2\vec{H}^2}{8\,\pi\,(1-\lambda^2)}$, $\rho'=\rho$is a special stationary configuration in this field.

The proof of this statement is similar to the previous one and is omitted.

Let us discuss the symmetry with respect to the “permutation” of the vectors $\vec{v}$ и $\vec{H}$of the equations for a certain class of stationary configurations.

Lemma 1. If a configuration $\left(\vec{v},\vec{H},p,\rho\right)$is stationary in a field $U$and satisfies the conditions

$$(\vec{v},\nabla\rho)=0,\left(\vec{H},\nabla\rho\right)=0,\ (4)$$

then the configuration is $\left(\vec{v}',\vec{H}',p',\rho'\right)$of the form $\vec{v}'=\vec{H}/\sqrt{4\pi\rho}$,$\vec{H}'=\sqrt{4\pi\rho}\vec{v}$,$\rho'=\rho$, $p'=p_0-p-\rho\vec{v}^2/2-\vec{H}^2/8\pi$is stationary in the field $U'=U_0-U$ $(U_0=const)$and satisfies conditions (4).

Proof. It is clear that the quantities $\vec{v}'$, $\vec{H}'$, ρ'satisfy conditions (4); we will show that the primed configuration is stationary in the field. U'.It does not require any effort to verify the conditions

$$div\,\rho'\vec{v}'=0,\ div\,\vec{H}'=0;(5)$$

the fairness of equality is obvious

$$rot\left[\vec{v}',\vec{H}'\right]=0(6)$$

Using (4) and the definition of primed quantities, direct calculations verify the validity of the equalities

$$\rho'(\vec{v}',\nabla)\vec{v}'=\left[rot\,\vec{H},\vec{H}\right]/4\pi+\nabla\vec{H}^2/8\pi,$$

$$\left[rot\,\vec{H}',\vec{H}\right]/4\pi=\rho(\vec{v},\nabla)\vec{v}-\nabla(\rho\vec{v}^2/2);$$

with the help of these identities and expressions for we can p' и U'easily verify that the relation is true

$$\rho'(\vec{v}',\nabla)\vec{v}'=\left[rot\,\vec{H}',\vec{H}'\right]/4\pi-\nabla p'-\rho'\nabla U'. \quad (7)$$

The validity of equalities (5) – (7) means that the primed configuration is stationary in the field, U'; which is what was required to be proven.

Let us consider examples of special equilibrium configurations and construct special stationary flows.

Example 1. $a=\frac{1}{2}x_1^2+x_2,\ \Psi=a+\frac{1}{2};$

$$\vec{H}=[\nabla a,\vec{e}_3]=\left[\nabla(\frac{1}{2}x_1^2+x_2),\vec{e}_3\right],$$

$$\Psi=-4\pi p\ \ =>p=\frac{\Psi}{-4\pi}=\frac{a+\dfrac{1}{2}}{-4\pi},$$

$$\left(\vec{H},\nabla\rho\right)=0!\ \ =>\ \rho=\rho(a,z)\forall=>\ \rho=a^2z.$$

We obtain a system of equations

$$\vec{v}'=\frac{\lambda\vec{H}}{\sqrt{4\pi\rho(1-\lambda^2)}},$$

$$\lambda(\lambda^2-1)\neq 0,\qquad \left(\vec{H},\nabla\lambda\right)=0\ \ =>\ \lambda=az,$$

$$\vec{v}'=\frac{(az)[\nabla\mathrm{a},\vec{e}_3]}{\sqrt{4\pi\rho(1-a^2z^2)}},$$

$$\vec{H}'=\frac{\vec{H}}{\sqrt{1-\lambda^2}}=\frac{[\nabla\mathrm{a},\vec{e}_3]}{\sqrt{1-a^2z^2}},$$

$$p'=p_0+p-\frac{\lambda^2\vec{H}^2}{8\pi(1-\lambda^2)}=p_0+p-\frac{(a^2z^2)[\nabla\mathrm{a},\vec{e}_3]^2}{8\pi(1-a^2z^2)},$$

$$\rho'=\rho=a^2z.$$

Using the Maple program We plot graphs of density and magnetic force lines.

Density graph.

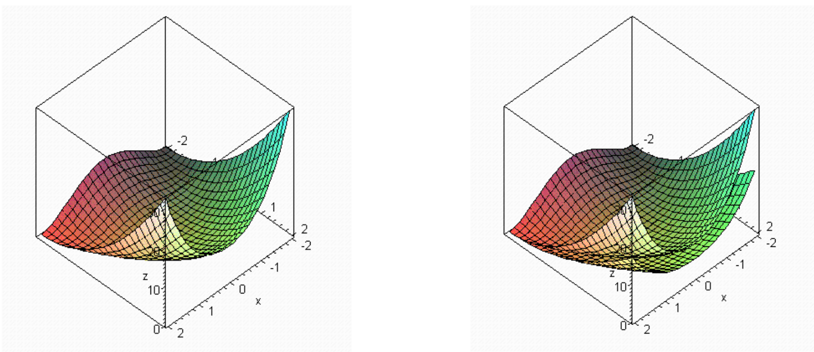

Figure 1 – Density graphs

Magnetic field line graph.

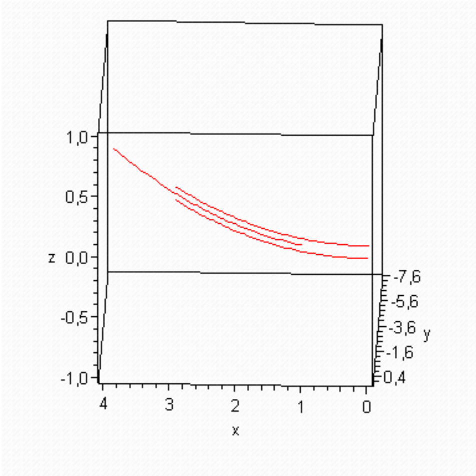

Figure 2 – Graph of magnetic field lines

The results can be used in studying the motions of incompressible plasma. Particular special equilibrium configurations of ideal incompressible plasma, possessing translational and axial symmetry, are considered in the work [1].

Keeping in mind the above, let us consider one of the free (U =0) special equilibrium states, namely, the state with flat geometry: the surfaces z =0 are magnetic. Let us consider the state:

$$H = [grad(a), grad(z)].$$

where $\rho = \rho(a.z)$ is an arbitrary function,

$$a = \exp(y - z^2) * \cos(x) * \exp(-z^2),$$

$$p = (\exp(2 * z^2) - 1) * a^2/2.$$

Below are shown in Figure 3 the graphs of the squares of the field strengths, in Figure 4 – the isobaric surfaces, in Figure 5 the pressure on the corresponding surfaces is presented.

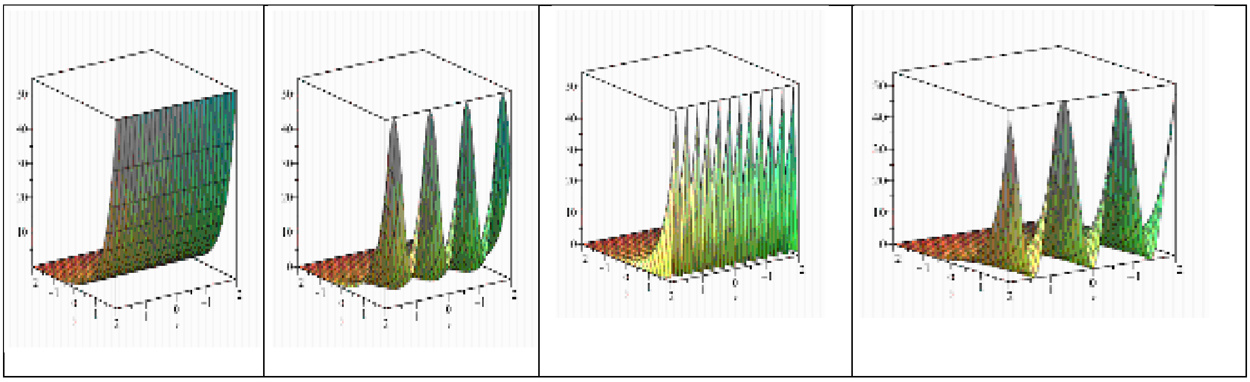

Figure 3 – Square of the stress on the surface z = const

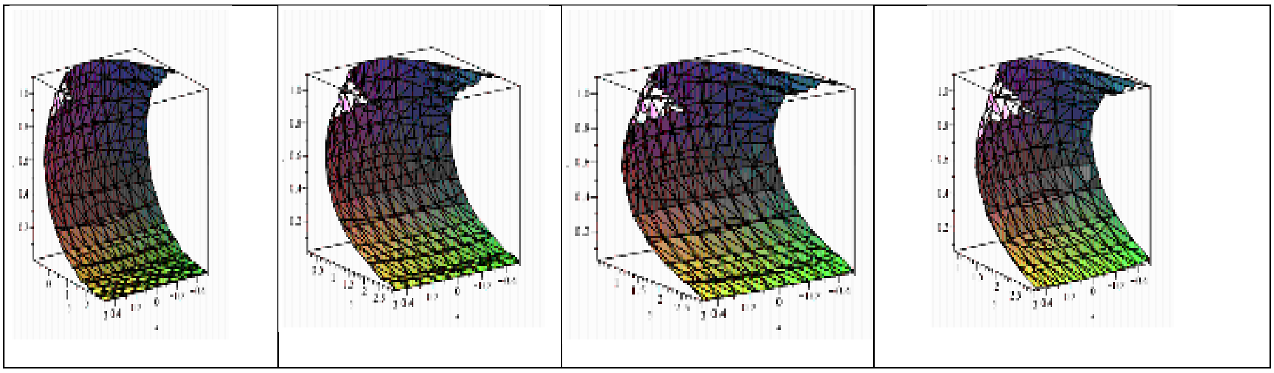

Figure 4 – Isobaric surfaces

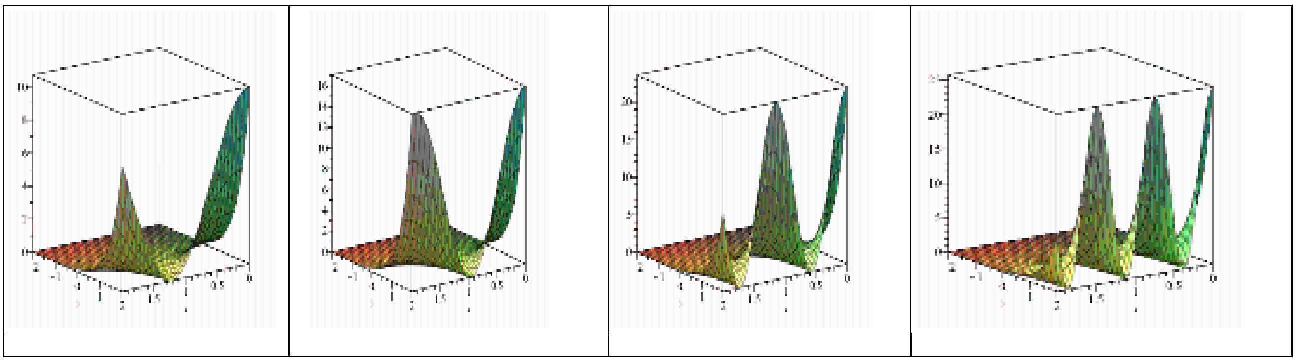

Figure 5 – Pressure on surfaces z = const

Graphic support is provided in the mathematical package MAPLE 2019.

Conclusion. In this article according to the described methodology One of the free (U = 0) special equilibrium states is considered, a state with flat geometry: surfaces z = 0, which are magnetic, at a certain value of the magnetic field strength.

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