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CONTENTS

A SECOND-ORDER WINDING FOR MAGNETIC TUBES

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The Hopf invariant for braids with 4 strings is introduced in [1] using an approach by J. Wu that describes homotopy groups of 2-sphere. Specifically, this invariant is well-defined for braids with 3 strings. In this particular case, the Hopf invariant of braids coincides with a well-known invariant, called a second-order winding number and introduced by M. Berger [2, 3]. The main result is the resultant theorem. The Berger's second-order winding number is a totally well-defined asymptotic ergodic invariant of magnetic tubes with respect to volume-preserving diffeomorphisms. Definitions of asymptotic ergodic invariants are given in [4]. As a corollary, we proved that the Berger's invariant is generalized. The generalized second-order winding number gives a new lower bound of energy of magnetic tubes. Examples and elementary introduction are given.

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OSCILLATORY INSTABILITY OF PRIMARY CONVECTION FLOW IN VERTICAL AND INCLINED LAYERS OF STRATIFIED MAGNETIC FLUIDS

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Experiments on stability of primary thermogravitational flow were performed with vertical and inclined layers of magnetic fluids heated from one side and cooled from the other. Magnetic fluids are complex colloids containing nanoparticles (with the average size of 10 nm) and their aggregates suspended in a carrier fluid. Therefore there exist various interacting mechanisms in ferrocolloids such as thermodiffusion of liquid phase components, thermophoresis of solid particles and their gravitational sedimentation may significantly influence the stability of convection flow induced by buoyancy force [1, 2].

The magnetic fluid layer with the dimensions of 375 × 180 × 6.0 mm was sandwiched between 0.8 mm thick textolite and 15 mm thick aluminum plates. The infrared camera was used to observe temperature fields on the textolite side of a chamber. The flow stability in two types of magnetic fluids, namely, surfacted kerosene-based and non-surfacted undecane-based ferrofluids, was examined. The density and viscosity of the former fluid were $1.44 \cdot 10^3$ kg/m^3 and $7.66 \cdot 10^{-3}$ kg/(m·s) and of the latter were $1.23 \cdot 10^3$ kg/m^3 and $7.7 \cdot 10^{-3}$ kg/(m·s), respectively. The volume concentration of magnetite particles was 10 % in both fluids.

In contrast to mono-fluids with similar properties, where the instability of the primary buoyancy-driven flow occurs in the form of a pair of counter-propagating thermal waves appearing at sufficiently large values of Grashof number [3], our experiments revealed that in ferro-nanofluids isolated travelling rolls appear at much smaller values of Grashof number. Namely, in a vertical layer a single moving roll was observed in the lower part of the chamber for approximately 340 hours. As time progresses the diameter of the roll increases and the roll is eventually destroyed by what appears to be hairpin instability. Subsequently, a new roll appears and the process repeats with a period of about 5.5 hours.

In the chamber forming the angle of 80° with the direction of gravity, several rolls emerged near both the top and bottom edges of the layer. The total number of rolls and their sizes changed with time. While the upper rolls travelled down and were periodically destroyed, the lower rolls survived for the duration of the experiment.

The fascinating behavior of ferrofluid flows observed in the absence of magnetic field indicates that the application of magnetic field is likely to produce even more complicated fluid motion patterns that will require careful and systematic studies.

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CONCENTRATION EFFECTS ON PARTICLE SIZE DISTRIBUTION VARIATION IN $CoFe_2O_4$/DDS-NA/LA/WATER FERROFLUID

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Ferrofluids, ultrastable dispersions of magnetic nanoparticles in liquids, find a wide range of applications in many technical and industrial fields, as well as in medicine and biotechnology.

Cobalt ferrite nanoparticles ($CoFe_2O_4$) have received increasing attention for the combination of their bulk magnetic properties (high coercivity at room temperature, moderate saturation magnetization) with the magnetic properties typical of nanoparticles (superparamagnetism) that make them ideal materials for technological and medical applications.

In the paper the results obtained from the studies on concentration effects in a new non-ionic $CoFe_2O_4$/lauric acid/DDC-Na/H_2O ferrofluid investigated by means of small angle neutron scattering (SANS) are presented. The ferrofluid was prepared by coprecipitation of $Fe(OH)_3$ and $Co(OH)_2$, ferritisation of hydroxide mixture in 1M alkali aqueous solution, adsorption of lauric acide on ferrite particles and peptisation of hydrophobic precipitate in aqueous solution with sodium n-dodecyl sulphate.

Small angle neutron scattering (SANS) experiments were performed at the time-of-flight YuMO spectrometer in function at the high flux pulse IBR-2 reactor, JINR Dubna.

STRUCTURE FACTOR INVESTIGATION OF Fe_3O_4/POLYDIMETYLSILOXANE MAGNETIC ELASTOMERS BY MEANS OF SAXS

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Small angle scattering is a well-established technique suitable for studies of the microstructure in the nanometer length range of condensed matter objects [1, 2, 3].

The scattered intensity on an absolute scale for any interacting particulate systems of scatters can be expressed as [1]:

$$I(Q) = \phi P(Q) S(Q)$$

where: Q is the modulus of the scattering vector defined as $Q = (4\pi/\lambda)\sin(\theta/2)$, with the scattering angle being θ; $\phi = N/V_0$ is the density of particles in the volume V_0 of the sample, $P(Q)$ concerns each particle and is related to its form factor, $F(\overline{Q})$, by

$$P(Q) = \left\langle \left| F(\overline{Q}) \right|^2 \right\rangle$$

were

$$F(\overline{Q}) = \int_{\text{Volume of particle}} (\rho - \rho_0) \exp(i\overline{Q}.\overline{r}) dV$$

ρ and ρ_0 are the coherent lengths densities of the particle and respectively of the matrix. $S(Q)$ is the interparticle term-the structure factor-related to the spatial distribution of the centers of mass

$$S(\overline{Q}) = \left\langle \sum_{\alpha,\beta} \exp i\overline{Q}(\overline{R}_\alpha - \overline{R}_\beta) \right\rangle$$

$\langle .... \rangle$ denotes a statistical average and is taken over the available positions and orientations of the particles.

By means of small angle neutron scattering specific variations of the structure factor and interparticle correlation length with the particle concentration and the magnetic field magnitude, imposed during polymerization of a Fe_3O_4/polydimetylsiloxane magnetic elastomer samples, were reported earlier [4].

The present work analyzes results on the experimental structure factors determination for polydimetylsiloxane magnetic elastomers polymerized in transversal and parallel magnetic field to the elastomer sample surface.

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ULTRASONIC FOUNTAIN ON THE SURFACE OF THE MAGNETIC FLUID

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The paper studies the influence of magnetic field on the processes on the free surface of a magnetic fluid caused by ultrasonic field.

It is known that at a certain intensity threshold of ultrasonic waves falling up from inside on a fluid free surface, emission of drops begins from a surface – «ultrasonic fountain» [1]. On the other hand, it is known that the magnetic field provides an effective mechanism that influences the processes occurring on the free surface of a magnetic fluid [2].

In this paper the «ultrasonic fountain» from the free surface of a magnetic fluid in the presence of uniform magnetic field is studied experimentally.

A kerosene based magnetic fluid and a magnetite with saturation magnetization of 72 kA/m and 1 MHz ultrasound generator are examined. The pressure created on the free surface of fluid by ultrasound wave can reach 70 Pa, and the threshold of the beginning of «ultrasonic fountain» is 48 Pa.

It is shown that vertical magnetic field with intensity of 20 kA/m directed along the fountain jet stabilizes it, thereby increasing the length of the continuous part of the jet from 6 mm to 24 mm, and also increasing the height of the drops raising. Simultaneously this field decreases the threshold of the beginning of «ultrasonic fountain» more than 5 times from 48 Pa to 9 Pa.

On the other hand the horizontal magnetic field prevents the development of a fountain and reduces its height.

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PROBE SIMULATION IN MHD FLOW

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The work is devoted to the problem of flow around the probe in a mercury flow under the action of transverse magnetic field [1]. In this study, an important problem is to provide experimental accuracy and safety taking into account the probe durability. The influence of probe disturbances on our experimental data is defined based on CFD simulations.

The probe, which is a micro thermocouple with head diameter of 0.25 mm moves in the tube with diameter of 20 mm. The probe model was constructed using the CAD program. It is an elongated cone with the sphere at the end (head of thermocouple). We investigate the behavior of the flow depending on the distance of the probe to the tube wall for two cases: 1) probe is close to the wall; 2) probe is in the center of the tube.

Our calculations were performed with the non-commercial CFD code ANES20XE [2] using the control volume method. The code was adapted for 3D MHD flow problem: a mercury flow in a tube heated from one side in the transverse or longitudinal magnetic field. We use the non-structural mesh with density of ~3 million control volumes.

A series of calculations have been performed. We have obtained 3D fields of temperature, velocity and potential. The results of calculations allowed us to estimate temperature and velocity field deformations near the probe and propagation of the upstream perturbations and to verify to first approximation the accuracy of our heat transfer experimental data.

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RESEARCH OF THE LOCAL VELOCITY COMPONENTS VIA MICROTHERMOCOUPLE SENSOR IN A MHD FLOW OF LIQUID METAL

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Thermal hydraulics investigations in support of liquid metal (LM) cooling systems involve experimental research on modeling LM facilities for finding out the laws of heat exchange in conditions close to real, and for verification of numerical codes. In connection with this, the measurement of the local characteristics of fluid flow and heat transfer in the LM flow channels is an important theme. Measurement of the velocity components in the dense, chemically active, conductive, non-isothermal fluid is a complicated task. Methods widely used in non-conductive environments are often inapplicable. In this case, for measuring the local velocity components a microthermocouple sensor consisting of two thermocouples is offered.

The liquid metal MHD heat transfer investigations were carried out at mercury facility. This facility was put into practice because of scientific collaboration between and MPEI (Moscow Power Engineering Institute). The facility consists of two parts. The first one is a LM (mercury) loop for investigations of hydrodynamics and heat transfer affected by a LONGITUDINAL magnetic field (MF). The second part is generally very similar to the LM loop in a TRANSVERSE MF [1]. The flow in vertical, horizontal or inclined tubes and channels is the object of study [2].

The work is devoted to measuring longitudinal component of the averaged velocity using temperature correlation velocimetry (TCV) method and at the same time components of the averaged and fluctuating velocity by the conductive method due to the presence of a strong external MF. Simultaneously with the measurement of the velocity, the sensor can be used to measure averaged and fluctuating temperatures to obtain full information on the heat transfer and to amend the measurement of velocities. For primary signals processing we used a variety of analog and digital media applications. Measurement systems based on serial GPIB, PXI/SCXI module systems and LabVIEW, CVI software were used to provide local measurements in automated mode.

With the combined sensor, the single and two-point moments of temperature fluctuations and velocity components in LM flow under the influence of a strong coplanar MF were investigated.

Fundamental research of three-dimensional statistical characteristics of turbulence in a MF is necessary for the development of simplified turbulence models in the fields of mass forces (electromagnetic and thermogravitational).

The work is supported by RFBR Grant No 15-08-06207 A.

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BEHAVIOR OF FERRONEMATIC LIQUID CRYSTAL IN ELLIPTICALLY POLARIZED ROTATING MAGNETIC FIELD

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It is known that orientational structure of nematic liquid crystal (NLC) may be involved in the motion by the rotating magnetic field. There are two qualitatively different regimes of rotation of the NLC structure in circular polarized rotating magnetic field: (i) synchronous regime, when the director of NLC rotates with constant angular velocity of the magnetic field, and (ii) asynchronous regime, when the director follows the magnetic field with a time-dependent phase lag [1].

The physical properties of nematic liquid crystals are sensitive to different external fields, but like most of organic materials liquid crystals are diamagnetic, i.e., their magnetic susceptibility is negative and very small. The embedding of anisometric single-domain magnetic particles in a nematic liquid crystal can significantly increase the magnetic susceptibility of the liquid-crystalline suspension [2]. This low concentrated magnetic suspension based on a nematic liquid crystal is usually called ferronematic liquid crystal, or ferronematic (FN). Dynamic properties of the orientational structure of FN in a rotating magnetic field with circular polarization have been studied earlier in Ref. [3].

In this work within the framework of generalized Ericksen-Leslie continuum theory [4] we have analyzed the behavior of the orientational and magnetic structures of the ferronematic liquid crystals under the influence of elliptically polarized rotating magnetic field. We consider the case of soft planar anchoring between director and magnetization, so that in the absence of external magnetic field the minimum of FN free energy corresponds to parallel orientation of the director and magnetization. A non-stationary system of equations for planar director and magnetization fields describing the orientational structure of ferronematic has been obtained. We have performed numerical calculations of the angles of the director and magnetization for different values of magnetic field strength, angular velocity, anchoring energy and ellipticity parameter. It has been shown that alteration of the ellipticity parameter changes the rotational regimes of the FN structure.

We have found two modes of rotation of the FN orientational structure: synchronous oscillatory and asynchronous oscillatory regimes, which are similar to rotational motions of pure NLC in elliptically polarized rotating magnetic field [5]. In the synchronous oscillatory regime the director and the magnetization do not simply rotate with angular velocity of magnetic field, but oscillate near the average phase lag from the field. In the asynchronous oscillatory regime the director and the magnetization oscillate near the time-dependent phase lags. We have derived analytical expressions for the angles of the director and the magnetization rotation for synchronous oscillatory regime at strong anchoring between NLC-matrix and magnetic particles. We have obtained numerically and for some specials cases analytically the critical velocity of magnetic field rotation, which determines the boundary between synchronous and asynchronous regimes of rotation as a function of magnetic field strength for different values of ellipticity parameter.

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SEGREGATION OF PARTICLES IN THE SQUARE CAVITY UNDER THE JOINT ACTION OF MAGNETIC AND GRAVITATIONAL FIELDS

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This paper focuses on the spatial redistribution of dispersed particles in magnetic fluid that fills a long cylindrical cavity with square cross-section having impermeable boundaries in external magnetic and gravitational fields. Segregation of particles under the influence of the gravitational field is much weaker than particle segregation driven by magnetophoresis, and it is usually not taken into account. However, important exceptions are the processes of sedimentation in magnetic fluid during prolonged storage of magnetic fluid, centrifugation and thermal convection. In the latter case even a very slight liquid separation associated with particle concentration gradients can lead to qualitatively new effects [1].

The 2D problem is numerically solved in the absence of convection. The magnetic field within the fluid is settled by an iterative method and the original algorithm described in [2]. The characteristic diffusion time is many orders of magnitude larger than the relaxation time of the magnetic moment of particles, so the magnetization of fluid is assumed to be equal. Its value is calculated within the framework of a modified “effective field model” [3].

Most calculations were performed for relatively low volume-averaged concentration. It is shown that particle segregation can be either amplified or attenuated depending on the relative orientation of the two fields.

The generated finger-like long-living structures are discussed in detail as well. These patterns are formed in the transition from the initial homogeneous state to the stationary inhomogeneous state. The equation is supplemented by an additional Cahn-Hilliard term to limit the wavenumber in the mass transfer equation. The appearance of finger-like structures is explained by the competition between gravity and magnetostatics in the diffusion layers with low and high particle concentrations. The phenomenon observed is the analogue of the Rosenzweigs diffusion instability on the free boundary of magnetic fluid in a vertically oriented magnetic field.

This work was supported by RFBR (grant No 13-02-00076, 13-01-96041, 14-01-96007).

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DEFORMATION OF FERROFLUID DROPLET ON A LIQUID SUBSTRATE UNDER THE ACTION OF VERTICAL MAGNETIC FIELD

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The evolution of ferrofluid drop laying on a liquid substrate as an element of drop structure [1] was experimentally investigated. It was found that a change in drop shape under the action of a magnetic field exhibits hysteresis. In particular, in the absence of magnetic field the drop has a shape of two vertical axisymmetric semi-ellipsoids of different height, which are joined at the interface between air and liquid substrate. After applying the field, the height of the bottom semi-ellipsoid increases until a peak of instability occurs at a critical value of magnetic field strength. With increasing field intensity, the size of the peak increases, and the bottom semi-ellipsoid turns to a cone submersed into the liquid substrate. With further growth of field intensity on a free surface of the drop (the top semi-ellipsoid), instability occurs which manifests itself in the form of the second peak in the upward direction. The critical values of field intensity peaks do not depend on the drop diameter and the liquid substrate thickness, but they depend on the initial magnetic susceptibility of magnetic fluid. The quantitative relation between two critical values of magnetic field strength is given by the square root of the ratio of the surface tension on the free surface to that at the interface of the drop.

A comparative analysis is performed to determine the specific features of deformation of an individual drop and drop structures formed from the decay of a horizontal ferrofluid layer under the influence of a uniform vertical magnetic field.

The work was supported by the RFBR projects No. 13-01-96041 and No. 14-01-96007.

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UNDERWATER GAS TORNADO AS A POSSIBLE DRIVE FOR DYNAMO EXPERIMENTS

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For magnetic field excitation in rotating liquid Na one needs to reach the Reynolds number about 10^6 [1]. Such a problem has not been solved yet. Recently, a new hydrodynamic phenomenon, the underwater gas tornado, has been observed at rather small scale – in a cylinder of height 100 cm and diameter 15 cm filled with water and pumped by atmospheric air through a hole in the center of the floor covered by a mesh [2]. The air vortex core rotates as a solid body (ω = const) while the surrounding liquid water rotates as a Rankin vortex; its angular velocity depends on radius as $\omega(r) \sim r^{-2}$ at $r > a$. The tornado core radius a occurs to be rather small; it increases proportionally to the gas flow j raised to the power 2/5 theoretically, and 0.36 experimentally. An experimental estimate of the gas velocity at a = 0.2 cm was $U \sim$ 5 m/c and for the gas flow $j = \pi U a^2 \sim 60$ cm^3/s.

For tornado experiments with Na one should use some noble gas instead of air. (It could be either He, Ne or Ar. Hydrogen use is questionable since it could react with liquid forming solid hydrides NaH.) I am far from being certain that this design will lead to a magnetic field self-excitation. Anyway, new geometry needs its own approach in dynamo estimations; they will be provided later. One should keep in mind that Rankin vortex is non-dissipative; it means that sufficient energy losses exist near walls and mainly in a narrow turbulent surface layer between gas and liquid. This fact explains the long life of an underwater tornado vortex without external rotation. However, it will be rather difficult to reach the proper level of Reynolds number in Na liquid, but it is easy in a gas flow that moves spirally. One possible attempt to improve dynamo conditions is initial gas ionization, another – the Na-tornado in rotating Hg.

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MHD DYNAMO IN UNCONSTRAINED FLOWS INSIDE A TORUS

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A stationary flow of conducting incompressible fluid (liquid metal) inside an empty rotating toroidal channel is considered. Direct numerical simulation was undertaken in order to know if magnetohydrodynamical action in such flows is realisable. The mere possibility of the dynamo is based on the fact that the flow consists of 2 oppositely screwed Dean-like [1] vortices each of which can act as a separate Ponomarenko-like [2] screw dynamo.

Indeed the simulation has shown that the stream component of the flow stretches and the secondary component twists magnetic lines thus providing necessary mechanism for magnetic field self-generation. The threshold of the generation strongly depends on intensity and geometry of the flow and relative electric properties of fluid and walls of the channel [3]. For example, the flow, where the secondary component reaches half-maximum of the stream Poiseuille-like component and electric conductivities of the fluid and wall are equal, shows the dynamo action at magnetic Reynolds number Rm ~ 150. Magnetic field is generated at region with highest velocity gradient and then carried away by a stream along helical trajectories.

At the conference a thorough search for the minimum dynamo threshold will be presented. Specific features of generated dynamo waves at different velocity profiles and wall conductivities will be discussed.

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ELECTROVORTEX CENTRIFUGAL PUMP

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Special requirement of the available technologies for pumping liquid metal through pipes is that the pumped metal should not come into contact with the environment. The fulfillment of this requirement is necessary to prevent oxidation and contamination of liquid metal during its pouring in foundry and to avoid contact with the environment in chemical and nuclear industries. For these purposes MHD pumps having sealed channels and working without moving parts are particularly well suited. For instance, in France traveling magnetic field MHD-pumps with high capacity are used to pump a sodium carrier in nuclear reactors. Such MHD-pumps are also essential for nuclear-powered sea crafts.

Scientists are currently exploring the possibility of using liquid lead as a carrier. Application of MHD-pumps has some restrictions, which are mainly due to the high density and poor electrical conductivity of the molten metal. A convenient way to transport metal with the aid of traveling field pumps causes a significant increase in their sizes. This paper describes an electrovortex centrifugal MHD-pump developed by the authors and tested under laboratory and real production conditions.

The pump works on the principle that the pumping effect is created by an electrovortex flow generated in a flat disk channel [1]. The main part of the channel is a disk channel having an inlet branch in its center and outlet branches at its diametrically opposed sides. The outlet branches form a closed loop, where an electrical current is generated by electromagnetic induction. Electric current flowing through a disk channel excites a magnetic field, which is enhanced by two C-shaped cores. Magnetic field and electrical current produce a vortex force that rotates liquid metal in the channel and causes the occurrence of a pumping effect. The pump of such a design is able to develop pressure up to 300 kPa. At pressure of 70 kPa the pump capacity reaches 5 ton per hour.

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EXPERIMENTAL EXPLORATION OF INCORPORATION OF REINFORCING BORON NITRIDE PARTICLES INTO MOLTEN ALUMINUM IN THE PRESENCE OF MHD-STIRRING DURING DIRECTIONAL SOLIDIFICATION

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Manufacturing processes that include the incorporation of reinforcing particles into molten aluminum to produce composites with improved mechanical properties are a relatively recent development, which predominantly involves four methods of introducing particles into the melt: mechanical mixing of particles in the melt; mixing of powders and their sintering under pressure; plasma deposition of metallic and ceramic particles; incorporation of reinforcing particles into a molten metal using a plasma jet. The first three methods are inefficient and expensive; large waste volumes are associated with metal production in those cases. The fourth is a very promising method, but it requires special equipment [1–2].

In our paper we describe the results obtained during the experimental study of the incorporation of reinforcing boron nitride particles into an aluminum ingot in the presence of two-directional MHD-stirring. We used a cylindrical crucible with heated side walls and a bottom cooled by flowing water. Liquid aluminum (4.2 kg) was poured at 750 °C into the crucible, which was in a bore of the MHD-stirrer generating toroidal and poloidal flows [3]. Boron nitride powder was placed in an aluminum tube of inner diameter of 4 mm. The tube was inserted slowly into the molten aluminum in the crucible. The end parts of the wall of the tube were melted inside the crucible with the molten metal, and the releasing amount of powder was spread by mixing flows throughout the molten metal with simultaneous directional solidification of the ingot.

Boron nitride powder used in the experiment had a hexagonal structure of particle diameter of 2–4 mm and a cubic structure of particle diameter of 15–20 mm. Boron nitride powder introduced into the liquid aluminum comprised 2 % by the weight of an aluminum ingot. After solidification of the metal, the ingot was cut to obtain samples for recording mechanical characteristics and visualizing the crystalline structure of the ingot.

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PECULIARITIES OF MOTION OF A MAGNETIC FLUID DROP WITH MAGNETIZED AGGREGATES IN ROTATING MAGNETIC FIELD

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A lot of works have been devoted to the peculiarities of motion of magnetic fluid drops under the action of magnetic fields [1, 2]. Most of these studies are concerned with studying the drop motion in stationary fields [3]. In the present work, the investigation of falling magnetic fluid drops with magnetized aggregates and non-aggregated magnetic fluid drops in the liquid medium under the action of a rotating magnetic field are considered.

Under the action of a rotating magnetic field a drop of non-aggregated magnetic fluid is set in rotation and deviates from the vertical direction during the freefall owing to the Magnus effect. It was found that the rotation of such drop is a consequence of the drop deformation and the change of drop shape from spherical to ellipsoidal. The dependencies of the drop deviation on the rotating magnetic field strength and frequency have been measured. The measurements showed that the dependence of the droplet deviation value on the external field frequency has a maximum at some critical frequency. With further increase of the field frequency the deviation value diminishes to zero, and at high frequencies the drop deviation has not been observed. It has been concluded that the observed phenomena is not associated with the internal rotations of colloidal particles.

The analogous investigations have been performed for magnetic fluid with spontaneously magnetized aggregates. It has been determined that at low external field frequencies the dependencies of the drops deviation from the vertical on the field frequency for aggregated and non-aggregated magnetic fluids are closely approximated. But in the range of high frequencies the linear growth of the drop deviation value with increasing frequency has been observed for the fluid with magnetized aggregates.

The analysis of experimental results leads to the conclusion that in both cases at low rotation frequencies the drop rotation is associated with the shape deformation and depends on the external field frequency and strength. At high frequencies for magnetic fluid drops with magnetized aggregates the drop deformation has not been observed but the deviation of the drop from the vertical increases. This indicates that the drop rotation mechanism is different. It is likely that in this case the drop rotation is associated with the internal rotations of aggregates.

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STRUCTURE FORMATION IN SYSTEM AGGREGATES WITH UNCOMPENSATED MAGNETIC MOMENT UNDER THE ACTION OF ROTATING AND CONSTANT MAGNETIC FIELDS

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The study of magnetic ordering in magnetic colloids is still a poorly understood problem. We have observed the occurrence of a well-developed system of aggregates with uncompensated magnetic moment in a magnetic fluid under the certain conditions. This paper presents the results of a study of structure formation processes in systems of such aggregates at the same time exposed to constant and rotating magnetic fields.

The structural formations were studied by observations using an optical microscope equipped with three pairs of Helmholtz coils. A thin layer of the test sample was placed in a rotating horizontal magnetic field. The constant magnetic field was produced in the perpendicular direction of the layer and experimentally varied smoothly from 0 to 50 Oe. The maximum amplitude values of each component of the rotating magnetic field were equal to 23 Oe. The behavior of aggregates was recorded by high-speed shooting (at 300 frames/sec), which allowed determining the frequency of aggregates with high accuracy.

The dependence of the system aggregates behavior on the uncompensated magnetic moment of the frequency of the rotating field, as well as on the magnitude of further applied constant magnetic field was determined.

It has been found that, when exposed to the rotating magnetic field, larger aggregates by combining with the adjacent ones, form a "tangles", while smaller aggregates remained distinct. At low frequencies the rotating field (3 to 30 Hz) aggregates frequency coincides with the field frequency. The action of a constant magnetic field directed perpendicular to the rotating, in this case, led to the separation of "tangles" into separate aggregates, which continue to rotate with the frequency of the rotating field.

When the rotating field frequency of 30 Hz high in the absence of a constant magnetic field aggregates are also combined in the "tangles", rotating with a frequency below the frequency of the field. With increasing frequency of the rotating field the aggregate frequency decreased. Additional action of constant magnetic field in this case, initially led to a decrease of the frequency of individual aggregates, and the "tangles" to a certain value, depending on the frequency of the rotating field. With further increase of the constant field there occurred separation "tangles" in the individual aggregates, the frequency of which increased to a certain limiting value, independent of the value of the constant field. Interestingly, the rotation aggregates and "tangles" were observed for the rotating field frequency ranging from 500 Hz to 2 kHz.

The studies may have relevance to understanding similar structural organization considered in modeling molecular systems or self-induced by the moving particles in alternating or rotating fields observed in biological systems.

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THE STUDY OF SELF-DIFFUSION IN QUASI-TWO-DIMENSIONAL SYSTEMS

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Ferrofluids are the systems consisting of single-domain magnetic particles (a particle of dispersed phase) suspended in a carrier liquid. It is very important to investigate diffusion properties of magnetic fluids as they form the basis for medical applications. The complex microstructure of magnetic colloids makes the study of diffusion rather complicated. There were several attempts to study diffusion [1–4], but the detailed theoretical description is still missing.

We studied three-dimensional systems and know that the self-diffusion coefficient decreases with growing particle volume fraction in a monodisperse case. In the bidisperse system the coefficient increases with rising small particle volume fraction. Also we performed the computer simulation to check our theoretical method. We observed a good agreement between results of the theory and the data of computer simulations.

Now we can use the theoretical approach to describe the self-diffusion in the quasi-two-dimensional ferrofluids. Also we will compare the theoretical results with the data of computer simulations.

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STUDY OF A WINDING FREE MHD-PUMP HAVING A FLAT CURVED CHANNEL

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MHD-channels have many applications in the foundry industry because they assure high-quality castings and improve foundry environments. Hence, the development of reliable pumps for liquid metals that are inexpensive and easy to use is a topical problem. The present work is a continuation of a cycle of researches devoted to studying processes in flat curved MHD-channels that have in plane a curved configuration composed of tetragons connected to each other. An alternating current passes through the channel placed in the gap between the C-shaped ferromagnetic cores used to produce a magnetic field of required configuration and intensity. Vortex flows and pressure drop between input and output are generated. In the case of an open channel this initiates a transit flow. Such an effect is used in the MHD-pump of the proposed design. We describe the experimental results obtained in the study of the MHD-pump model for three variants of flat zigzag-shaped stainless steel channels having different design features. Measurements were carried out on a gallium circuit. Pressure drop-flow rate characteristics were determined for various values of the electric current in the channel. The MHD-pump of the developed design is proposed as a submersible pump for pumping fusible metals and alloys.

COMPETING DIRECTIONALITY IN SYSTEMS OF CUBE-LIKE MAGNETIC PARTICLES

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Systems whose magnetic response can be finely tuned using control parameters, such as temperature and/or external magnetic field strength, are extremely desirable both in research and in an industrial setting. Magnetic nano/micro-particles, in particular suspensions thereof, offer opportunities for this controllability to be realised. Traditional ferrofluids composed of spherical nanoparticles have been developed over many years to realise useful, magnetically controllable liquids. Nowadays, in order to provide systems that respond in a different manner, modifications to the particle structure have to be made. These changes can be in terms of the magnetic structure or indeed the particle shape. We have considered the effect of the latter. The manufacture of nonspherical magnetic particles, ranging from the nano to microscopic regimes, is now a reliable technique of colloidal synthesis [1]. Cube-like particles are particularly monodisperse examples, which together with their favourable packing behaviour make them interesting to study [2, 3, 4]. We have used analytical theory in combination with molecular dynamics simulations to study the behaviour of permanently magnetised dipolar cubic particles. Most notably, we have elucidated the ground state microstructure of these particles for a number of different preferred magnetization directions [5]. As well as, detailing the zero-field magnetic properties of isolated clusters, we have begun to address the effects of particle curvature on these structures [6, 7]. The phenomena we observe can be directly attributed to the fundamental interplay between the anisotropy of the magnetic interaction and the anisometric geometry of the particles.

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GRADIENT DIFFUSION IN FERROFLUIDS: THE ROLE OF POLYDISPERSITY

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It is well known that in the course of time an initially homogeneous ferrofluid, filling a cavity of arbitrary shape, becomes spatially inhomogeneous with respect to the magnetic phase concentration due to gravitational sedimentation. In the absence of convective motion, the only factor that prevents the concentration stratification of the fluid is the gradient diffusion of ferroparticles. Stationary concentration profile of the ferrofluid in the external gravity field can be obtained from a condition of equality of the diffusion and sedimentation fluxes. This problem has been solved [1, 2] for the simplest model of ferrofluids that is monodisperse dipolar hard spheres. Theoretical results have been compared with the computer simulation data [2], and they have had a good agreement even for concentrated systems with intensive interparticle dipole-dipole interactions. However the real ferrofluids are polydisperse. The influence of the polydispersity on the mass transfer processes has been studied in this work on the basis of bidisperse model of dipolar hard sphere fluid. The choice of a bidisperse system is quite obvious: being, on the one hand, still rather simple, it appears to be the first step on the way to full polydispersity, on the other hand. The system of mass transfer equations for describing sedimentation and gradient diffusion of ferroparticles in concentrated magnetic fluids has been derived. These equations take into account steric and dipole-dipole interactions between particles of different fractions. Steric interactions have been investigated using the bidisperse Carnahan-Starling approximation for the hard sphere fluid [3]. In order to study the dipole-dipole interaction, the free energy of the dipolar hard spheres is represented as a virial expansion with accuracy to the terms quadratic in ferroparticle concentration [4]. Analysis of the concentration profiles of the ferroparticles from different fractions has shown that the large particles are mainly accumulated in the bottom of the cavity; the small fraction particles are pushed out from the bottom by large particles. This leads to the fact that the concentration profile of the small ferroparticles is nonmonotonic. Knowing the concentration profiles, it is a simple matter to calculate static initial magnetic susceptibility as a function of cavity height. It has been shown that the theory describes well the initial magnetic susceptibility profile of the real polydisperse ferrofluid under the action of the centrifugal forces [5].

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PATTERN ANALYSIS OF EXTRAGALACTIC MAGNETIC FIELDS: MAGNETIC AND GASEOUS ARMS IN M83

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Radio polarization observations show that magnetic field configurations in several nearby spiral galaxies contain magnetic arms, sometimes located between the material arms, with NGC6946 being the clearest case. The phenomenon of magnetic arms may be common to spiral galaxies. It was first observed in the spiral galaxy IC342 [1]. However, the relation between magnetic and gaseous arms in IC342 and other galaxies is not as simple and well-defined as in NGC6946 [2]. Another example is provided by M51where the ordered magnetic field is maximum at the spiral arms traced by dust lanes in some regions and displaced from them to other locations [3]. The nature of magnetic arms is a topic of intensive discussion. An expansion of sampling of galaxies with various relations between the spiral patterns visible in magnetic and material tracers is required to clarify the situation.

We consider the spatial distribution of magnetic fields in the nearby barred galaxy M83 and their relation to the material spiral arms, with emphasis on spatial analysis based on quantitative methods and without reference to restrictive global ad hoc models such as logarithmic spirals with a fixed number of arms.

Isotropic and anisotropic wavelets are used to decompose the images of M83 in various tracers and to quantify the structures identified in the range of scales from 0.2 to 10 kpc. We use the ATCA radio continuum observations at $\lambda = 13$ cm and APEX sub-mm observations at 870 μm, together with data at $\lambda = 6$ cm and maps of emission of warm dust, ionized gas, molecular gas and atomic gas.

The spatial power spectra for tracers of dust, gas and total magnetic field are similar, while the spectra of the ordered magnetic field are significantly different. As a consequence, the wavelet cross-correlation between all material tracers and total magnetic field are high, while the structures of the ordered magnetic field are poorly correlated with those in other tracers. The magnetic field configuration in M83 contains pronounced magnetic arms. Some of them are displaced from the corresponding material arms, while the others overlap with the material arms. The pitch angles of the magnetic and material spiral structures are generally similar, but some parts of the magnetic arms show larger pitch angles. The polarization angles of radio emission are aligned with the outer material arms, although significant deviations occur in the inner arms and in particular in the bar region, probably due to non-axisymmetric gas flows.

One of the main magnetic arms in M83 is displaced from the gaseous arms similarly to the arrangement observed in the galaxy NGC6946, while the other main arm overlaps a gaseous arm in an arrangement similar to that observed in M51. We briefly discuss the physical nature of the results in terms of dynamo action and compression in the large-scale spiral shocks.

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KINEMATIC DYNAMOS RESULTING FROM THE INTERACTION OF HIGH PERMEABILITY MATERIAL AND FLOWS OF LIQUID SODIUM

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We perform numerical simulations of the dynamo effect driven by various flow fields of a conducting liquid interacting with "magnetic material" characterized by a large relative permeability. The examinations are motivated by the key role of soft iron impellers for the Von-Kármán-Sodium (VKS) dynamo [1] and by the repeatedly expressed idea to make use of Oxide Dispersion Strengthened (ODS) ferritic/martensitic alloys in the core of a fast reactor which may exhibit a permeability much larger than one [2].

The results of our simulations that consider a localized distribution with finite permeability clearly differ from computations using simplifying pseudo-vacuum boundary conditions (vanishing tangential field conditions) in order to mimic the impact of infinite permeability. Our kinematic simulations of an axisymmetric model of the VKS dynamo show a close connection between the exclusive occurrence of dynamo action in the presence of soft iron impellers and the observed axisymmetry of the magnetic field [3]. We qualitatively explain this effect by paramagnetic pumping at the fluid-disk interface and propose a simplified analytical model that quantitatively reproduces numerical results. In order to fully explain the observation of growing magnetic fields in the VKS dynamo, we resort to mean-field dynamo theory [4] in terms of an α-effect caused by helical outflows between adjacent blades attached to the impeller disks. Italics should be used for the name of the organization, city, and country.

In order to examine the properties of the α- and β-effect (which is closely related to the turbulent diffusivity) under the influence of magnetic material [5], we use an idealized helical flow field (a modified Roberts flow). We compute the mean-field coefficients using the test-field method [6] and proof that the corresponding mean-field models are indeed capable to reproduce growth-rates and principle field structure of the fully resolved model by requiring much less computational efforts.

Further remarkable results are the observed reduction of the critical magnetic Reynolds number by roughly 30 percent independently of configuration or flow geometry when the permeability is sufficiently large. However, this universality is not reflected in the behavior of the mean-field coefficients. In particular, the β-effect strongly depends on the geometry and the permeability. A striking feature is the occurrence of negative β which has previously been observed in simulations [7] and, more recently, in experiments [8].

Our results for the mean-field coefficients allow the development of dynamo models for nearly arbitrary systems of various sizes consisting of a large number of helical small scale flow cells embedded into some large flow structure.

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TEMPERATURE DEPENDENCE OF INITIAL MAGNETIC SUSCEPTIBILITY OF POLYDISPERSE FERROFLUIDS

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Lately a new theory describing the initial magnetic susceptibility for ferrofluids with particle-size polydispersity has been developed [1]. In the resulting expression there is a parameter that plays the part of dipolar coupling constant and is defined in a form of double averaging of high powers of particle sizes over the granulometric distribution. For real particle size distribution this effective parameter exceeds at least twice the commonly defined polydisperse dipolar coupling constant. The systematic comparison of this theory and computer simulation results for the initial susceptibilities was carried out in [2], and it was shown that the particle-size distribution significantly affects the initial susceptibility, and therefore it must be accounted for correctly in theoretical studies and in magnetogranulometric analyses of ferrofluids. In works [3, 4], the results of experimental measurements of the magnetic susceptibility for magnetite-based ferrofluids over a wide temperature and concentration range were examined against well-known theories [5–7], which are based on a monodisperse model of ferrofluid. Using novel corrections to the temperature dependence of particle magnetization, a new interpretation of the experimental results was proposed. However the agreement between experimental data and each of these theories [5–7] was achieved only in a fixed concentration range. This work is devoted to comparison of experimental data [3, 4] and new polydisperse theory [1].

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SHOCK WAVE ACCELERATION IN A NON-HOMOGENEOUS MAGNETIC FIELD

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Shock wave acceleration at the expense of a decrease in the initial density can occur in the stellar and planetary atmospheres exposed to local heating or ionization. Within the framework of gas dynamics this effect was detected by L.I. Sedov in solving the problem of strong explosion in a variable-density medium in the absence of counterpressure. On the other hand, when an initial constant pressure is taken into account, the density decrease automatically leads to an increase in the speed of sound and, therefore, in the shock wave velocity, thus producing the preconditions for the loss of the medium inertia, the instability, and the development of different dynamic processes.

An exact solution of MHD equations with plane waves describing the solid-body motion of an ideally conducting gas in a given uniform gravitational field is derived. The motion is due to a piston producing a shock wave propagating throughout the initial equilibrium state with a decreasing density. The solution involves an arbitrary function of the Lagrangian variable, whose choice influences the flow pattern.

The solution is constructed by the inverse method. If the solutions ahead of and behind the shock wave involve, at least, two arbitrary functions of one variable, then, together with the law of motion of the shock wave, they are determined by three conditions at the discontinuity. In this study, we consider the case of the solid-body motion of a medium with a frozen-in magnetic field which makes it possible to construct a solution with one more arbitrary function of the Lagrangian variable, whose behaviour has a considerable effect on the motion.

Typical cases of plasma motion are considered. Shock wave acceleration is investigated in acoustic approximation by series expansion in characteristic variable. An analogous class of solutions in the framework electrohydrodynamics with frozen-in specific charge is presented.

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PULSE INJECTION IN SEPARATION ZONE AT HYPERSONIC MHD FLOW OVER ROTATION BODY

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Pulse injection of cold gas into the separation zone occurring at the surface of a rotation body subject to hypersonic MHD overflow is simulated. Previously (see, in particular, [1, 2]), we have shown that in dipole configuration of the magnetic field generated by currents flowing in the body, the MHD interaction may give rise to extensive separation zones with substantially quiescent medium. The flow streamlines skirt the separation zone along the magnetic lines of force. It is significant that the density of the heat flux to the body surface decreases in the separation zone. It has been found that the position and size of the separation zone at the body surface can be controlled by changing the direction and intensity of the dipole magnetic field moment. In this regard, it is of interest to affect directionally the medium in the separation zone without its destroying, for example, via its cooling by a cold gas pulse injection.

The problem is solved in two formulations. In the first formulation, the body is an infinite cylinder with its axis perpendicular to the incident flow velocity vector. Two parallel wires are disposed in the cylinder. The electric currents in the wires flow in opposite directions closing at infinity. The moment of the dipole magnetic field generated by the currents is normal to the incident flow velocity vector, as well as to the cylinder axis. In the second formulation the body is a sphere, in which a circular current coil is located. The magnetic dipole moment is directed along the incident flow velocity vector. The initial conditions for the corresponding unsteady problems are the stationary solutions without injection obtained in the framework of the MHD model taking into account the induced magnetic fields, viscosity, thermal conductivity and real thermodynamic properties of air. The incoming flow pressure and density correspond to the atmosphere parameters – an altitude of 65 km, the body velocity is 7 km/s. The injected gas (air) has the wall temperature (2000 K). Its velocity is 300 m/s, the pressure is equal to the pressure in the separation zone. The mass of the gas injected per pulse is close in magnitude to the mass of medium in the separation zone.

The solutions obtained show that the injection of cold gas deforms the separation zone without its destroying. The injected gas partially flows out of the separation zone into the external flow, but the remaining part is sufficient to maintain the cooling effect of injection for a long time after its completion. The effect observed may be of interest for aerospace applications.

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SPECIAL ASPECTS OF MAGNETIZATION OF THE MAGNETIC COLLOIDS WITH DIFFERENT SIZE OF DISPERSED PARTICLES

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The magnetic properties of magnetic colloids have been discussed at various stages of development of physics of magnetic nanocolloids. Initially it was thought that description of their magnetization is possible on the basis of the Langevin theory [1], but later researchers focused on the interaction effect of dispersed particles [2]. In the present study we conduct a research of magnetization characteristics and magnetic susceptibility of the two samples of kerosene-based fluid, which differ in particle size distribution in order to clarify its effect on the magnetization characteristics of such systems.

Having done the research, we drew a graph showing the magnetization curves of two samples of kerosene-based magnetic fluid, having the same volume concentration of the dispersed phase, particles of which, however, have a different average diameter (9 nm and 13 nm, respectively). Whereas the magnetization curve of a colloid having a larger particle lies above the magnetization curve of the colloid with smaller particles in the range of low values of the field gradient. At sufficiently strong fields the curves combine due to the same saturation magnetization of samples. It is obvious that the difference between the curves is caused by the difference in the magnetic susceptibility of the samples determined by the slope of the curves in their initial sections, which is confirmed by direct investigation of this characteristic. Then we drew another graph comparing the concentration dependences of the dynamic magnetic susceptibility of the samples measured at a vertical frequency of 320 Hz.

The second graph revealed that both dependences are nonlinear. This indicates limited application of a Langevin theory to describe magnetization of the investigated colloids. At that, if the dependence $\chi(c)$ of the colloid with smaller particles is smooth, then a similar dependence for a sample with larger particles undergoes a break in concentration c = 11.9 %. It has been found that anomalies in the concentration dependence of the magnetic susceptibility of the colloid with larger particles are connected to the appearance of aggregates, when diluted with kerosene, which have non-zero magnetic moment. Additional studies of the complex magnetic susceptibility of the sample revealed the dependence of the magnetization relaxation time on its concentration of the dispersed phase, analysis of which is carried out taking into account the interaction between the particles and the processes of aggregation.

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TEMPERATURE-INDUCED STRUCTURAL TRANSITIONS IN SELF-ASSEMBLING MAGNETIC NANOCOLLOIDS

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In order to control the self-assembly of magnetic nanoparticles, one needs to gain a fundamental understanding of the interparticle interaction. Here, we reveal two scenarios of hierarchical self-assembly induced by cooling. Unlike nanomaterials with central interactions, magnetic dipole-dipole interaction leads to the formation of particular structures in which the head-to-tail or antiparallel orientations of the dipoles are favorable. This can be realized by forming chains, rings, or various branches. The interplay between energy gains and entropy losses determines the internal structure of the self-assembling system and, as such, drastically influences the macroscopic responses of the systems. Even though nanoparticle rings have lower energy, at moderate temperatures, linear chains are predominant owing to their higher entropy. This changes on cooling. As a result, if the system of magnetic nanoparticles is highly diluted, the rings with a vanishing dipole moment turn out to be dominant. The same happens to the Y-type junctions, which form in the systems at higher nanoparticle concentration. However, the entropy gain of forming a Y-junction does not compensate for the energy decrease gained from the ring formation, thus making the structural behavior of magnetic nanocolloids much more complex than expected.

In this work, using a combined novel analytical-numerical approach, we discover a series of fascinating structural transitions. Indeed, we find that the system of magnetic nanocolloids exhibits two different scenarios of the hierarchical self-assembly. At low particle concentrations, first highly magnetically responsive linear chains are formed, which further close in rings, thus making the whole system barely susceptible to an external magnetic field. The weak interaction between nanoparticle rings increases on cooling, which leads to the formation of a particular type of defects, playing the part of ring cross linkers. In contrast, at higher nanoparticle concentration, at moderate temperature, chains are replaced by entropy-induced branched structures, which can be described by only three types of defects, depending on the amount of segments connected by the defect: four-way X junctions, three-way Y junctions and two-way Z junctions (Z-defects are intracluster ones). On cooling Y and Z defects disappear, and the X-type defects dominate, merging together nanoparticle rings, keeping the system weakly magnetically responsive. The defect structures observed here can be considered as the precursors to the network formation, ushering in the next step in the hierarchical self-assembly of magnetic nanocolloids. The drastic changes in magnetic and thermodynamic responses of the magnetic nanocolloids found in this work can be exploited as a tool to bottom-up design of medical and microfluidics applications.

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ON FREE SOLUTAL CONVECTION IN FERROCOLLOIDS

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An experiment was carried out to investigate natural solutal convection in a magnetic fluid caused by non-homogeneous initial distribution of colloidal particles in a vertical Hele-Shaw cell. For experiment we used a dilute magnetic fluid of the “magnetite-kerosene-oleic acid” type. The initial distribution of particles was formed by magnetophoresis of the drop-like aggregates and their sedimentation on the surface of the diamagnetic ball located in the center of the cell. Application of the magnetic field on the system led to the onset of the Rayleigh-Taylor instability and formation of descending convective jets. The velocity of the flow at the front of descending jets was measured for different values of cell thickness (up to 0.18 mm) and strength of the magnetic field generating the drop-like aggregates (up to 21 kA/m). The solutal Rayleigh numbers

$$Ra = \frac{g\beta\Delta\varphi L^3}{\nu D},$$

varied in the range $Ra = 50 - 10^5$. Here L is the characteristic dimension of the cell with magnetic fluid (the thickness of the Hele-Shaw cell in our work), φ is the volume fraction (concentration) of magnetite, $\Delta\varphi$ is the characteristic concentration difference, g is the gravity acceleration, β is the solutal density coefficient, D, ν, ρ are the diffusion coefficient, kinematic viscosity and density of the fluid, respectively.

It was shown that the intensity of the convective flow characterized by the Reynolds number Re, increases with the Rayleigh number according to the power law: $Re = 1.16\cdot10^{-5}Ra^{0.86}$.

Thus, the solutal convection increases the rate of mass transfer in dilute magnetic fluids by two orders of magnitude. In concentrated magnetic fluids the influence of the gravitational convection should grow weak by two reasons. First, one should expect a multiple decrease of the initial concentration difference, because the coefficient of particle segregation rapidly decreases with the growth of the concentration cell of average volume [1]. Second, with the growth of concentration the effective viscosity of the solution increases which leads to a decrease in the solutal Rayleigh number, all other factors being equal.

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HIGH TEMPERATURE MHD-PUMPS DESIGNED AND PRODUCED IN IPUL

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The system of MHD-pumps as a significant part of MEGAPIE-target was developed at the Institute of Physics based on the unique experience of designing high temperature pumps for nuclear power systems used in space vehicles.

Successful implementation of the MEGAPIE experiment has quickened interest in the use of liquid metals for targets. The experience in designing MHD pumps in targets of nuclear disintegration of heavy liquid metals is currently in great demand. In our paper we describe several concepts of using MHD-pumps for these purposes (the LIMETS, LIEBE projects, megawatt target concepts).

The development of MHD-pumps for studing liquid-metal blankets, limiters and divertors of thermonuclear reactors, including corrosion of materials in PbLi-flows and MHD-effects in channels passing through strong magnetic fields is the other in-demand line of IPUL research.

WAYS TO INTENSIFY THE PROCESS OF TITANIUM PRODUCTION BY MAGNESIUM THERMAL REDUCTION OF TITANIUM TETRACHLORIDE

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At present, most titanium is produced by the Kroll method as titanium sponge in steel reactors. The reactor temperature is limited to 900 °C due to the formation of fusible TiFe eutectic under temperatures exceeding 1085 °C, which results in worsening of titanium sponge and in weakening of the reactor walls' strength. Such temperature limitation is avoided by using a material more resistant to high temperatures – NbZr (1 %), along with the reactor shielding from the contact with the atmosphere. In this case, the reactor is considered appropriate for the reaction progress under the most favourable temperature range of 1200–1400 °C (for thermodynamic analysis of titanium as the end product) [1] to achieve a more effective reduction process in the gas phase for the production of a cleaner titanium sponge or a titanium powder. New possibilities for the titanium production arise.

The reactor is a vessel made of niobium-zirconium alloy with locking valves for three pathways for

- magnesium alloy supply,
- titanium tetrachloride supply,
- removal of reaction gaseous products (mostly $MgCl_2$) into a cooled and periodically evacuated vessel (condenser).

Supplying small amounts of reagents in a stoichiometric proportion makes possible the reaction in the gas phase. Because of the reaction exothermic nature, the rapid heating of the reaction zone and the ejection of the reaction products onto the relatively "cold" walls of the reactor take place. When the pathway to the condenser is open, vacuum separation and evacuation of vapors of magnesium dichloride and magnesium (if an excess of magnesium is supplied) into the water-cooled condenser take place, where the pressure of their vapors corresponds to "good" vacuum. Therefore, the evacuation velocity is high, but the time takes fractions of a second. This is accompanied by considerable reaction heat losses, which greatly decreases the need in intensive cooling of the reactor walls. Periodically, as magnesium dichloride and magnesium accumulate, they are melted and removed from the condenser for recycling.

As both the reaction duration and the evacuation duration occur in a second and in fractions the completion of these phases makes the reactor operative for a new cycle, the total time is much smaller than when the Kroll method is applied despite of the fact that many cycles must be carried out to fill half of the reactor to its unloading. A system of quickly locking valve mechanisms is needed to conduct the process in the automated mode. In this case, it is possible to consider the MHD doser or stopper.

Additionally, a version of vacuum-arc melting with a system for ingot pulling in the reactor is also considered [2].

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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF THE ELECTROVORTEX FLOW HYDRODYNAMIC STRUCTURE UNDER THE ACTION OF THE EXTERNAL MAGNETIC FIELDS

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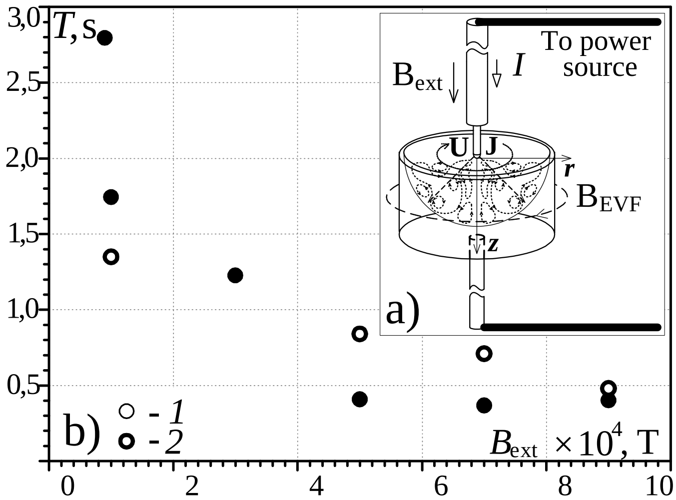
An electrovortex flow is formed under the action of electromagnetic force generated as a result of the interaction between the electric current and the electric current's own magnetic field when the non-uniform electric current passes through the liquid metal volume [1]. The results of the experimental and numerical investigations of the EVF structure appeared due to the influence of the external magnetic fields on EVF are presented.

Experimental setup is shown in fig a). A hemispherical hollow container with a diameter 188 mm made of copper was filled with eutectic indium – gallium – tin alloy and served as a large electrode. A small electrode made of stainless steel in the shape of a hemisphere with a diameter of 5 mm was immersed into liquid metal. When a direct electric current was passed through the alloy, continuous or pulsed external axial magnetic field was generated by a solenoid. The velocity and temperature measurements were carried out at various depths on the symmetry axis with original fiber-optical velocity transducers and thermocouples.

The numerical calculations were carried out by the finite volume method and the equation of motion was solved using the following source term: $\mathbf{F} = \mathbf{J}\times(\mathbf{B}_{EVF} + \mathbf{B}_{ext})$, where **F** – electromagnetic force, $\mathbf{B}_{EVF}$ is the own magnetic field of the current in hemisphere, $\mathbf{B}_{ext}$ is the external magnetic field and **J** is current density.

The experiments and calculations show that flow evolves as follows. At first the descending flow in the shape of torus is formed. Also a swirling flow is generated due to the influence of the axial magnetic field and the upward flow arises. Depending on the value of the external magnetic field three kinds of curl structures are possible. First – the structure with one downward curl, when the external magnetic field is rather weak, second – the structure, in which the secondary curl fills almost the entire flow area and third is the case when the interaction of upward and downward flows leads to a complicated multivortex picture. In this case high amplitude velocity oscillations are observed at the axis. At the current $I = 400$ A the oscillations occur in the range of external magnetic field of $9\times10^{-5} – 10^{-3}$ T wherein the axial velocity is varied in the range of 0.05–0.5 m/s and the value of the axial velocity is about 0.3 m/s while the external magnetic field is absent at the point. At lower currents even weak Earth's magnetic field leads to the appearance of oscillations. The period and amplitude of velocity oscillations decreased with increase in the value of the magnetic field (see fig. b). The area of oscillations depends on the magnetic field value: when it is smaller than 5×10^{-4} T the oscillations appear near the bottom of container and also near a small electrode.



Experimental setup (a) and the dependence of velocity oscillation period on the external magnetic field (b), depth 10 mm, I = 400 A. *1* - Simulation, *2* - experiment

The supposition that velocity oscillation effect is caused by weak magnetic fields comparable with Earth's field should be taken into account in simulations of mixing, crystallization and welding processes, because it can affect the grain structure, mixing quality and welding rate.

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STATISTICS OF GEOMAGNETIC DIPOLE REVERSAL ACCORDING TO PALEOMAGNETIC DATA AND TO SIMPLE GEODYNAMO MODELS

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The geomagnetic field reversal data [1] allow us to judge the mechanisms of the generation and maintenance of the magnetic field. These mechanisms include [2] the differential rotation, mirror-asymmetric convection, magnetorotational instability and other effects. To compare the scale magnetic polarity with the geodynamo theory, we investigated the simple geodynamo model [3]. This model is able to reproduce the real scale and some statistical characteristics of real scale. It is a dynamical system obtained by simplifying the equations of mean field electrodynamics. This system takes into account the statistical fluctuations of the geodynamo coefficients.

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INERTIAL WAVES IN A ROTATING LIQUID METAL AND FEASIBLE METALLURGICAL APPLICATIONS

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The use of electromagnetic methods, in particular electromagnetic stirring by means of a rotating magnetic field (RMF), is widespread in the metallurgy to homogenize the temperature and chemical composition of melts. With an applied rotating magnetic field, almost the entire melt volume rotates with a constant angular velocity; the only exception is a thin boundary layer near the vertical side wall of the vessel (ladle, crucible, etc.).

The existence of a quasi-solid rotation core characteristic of turbulent azimuthal flows serves as a reason for studying the possibility of using inertial waves observed in rotating fluids [1] for heat transfer intensification and dopant concentration homogenization in the melt.

The inertial wave frequencies are described in the general case by the formula [2]:

$$\omega_{klm} = u_z k_z \pm 2\Omega / \sqrt{1+\lambda_k \delta_z / m^2\pi^2}$$

where u_z is the mean axial flow velocity; k_z is the wave number vector component; Ω is the angular rotational velocity of the quasi-solid core region; $\delta_z = Z_0 / R_0$, Z_0 is the melt column height, R_0 is the melt quasi-solid core radius; λ_k are the roots of the equation $\lambda_k J_{l-1}(\lambda_k) - l \cdot J_1(\lambda_k) = 0$; l = 0, 1, 2..., m = 0, 1, 2,.... At $l = 0$ the inertial waves are axisymmetric.

Some features of forced inertial waves and their dynamics in magnetic fields were studied, for example in [3–4], where certain relations between waves and field parameters were derived.

In the present study, we analyze the properties of inertial waves versus the influential electromagnetic parameters and consider one of the feasible variants of their use in the ladle-furnace metallurgical processes. It is shown that relatively minor changes in a ladle and a support platform design may reduce significantly the stirring time and improve the melt quality with a simultaneous decrease in the energy input.

The results of our investigation can be used both in ferrous and nonferrous metallurgical processes.

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GRANULAR RAYLEIGH-TAYLOR INSTABILITY IN MAGNETIC SEPARATION OF RED BLOOD CELLS

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Direct magnetophoretic separation of submagnetic microparticles, especially biological particles based on their intrinsic magnetic differences and high-gradient magnetic fields has recently attracted much attention in connection with diagnostic applications of microfluidic analytical systems, for the purpose of which it is more suitable than traditional centrifugation or flow cytometry [1]. The most attractive subject of these studies is blood, which is extensively used for diagnostics, and stands out among other biological matters because of the noticeable difference in magnetic susceptibilities of the white and deoxygenated red blood cells (RBCs). The magnetic force of magnetophoretic minidevices that can be applied to RBCs, though higher than the gravity force, is still small, which makes the search for efficient magnetic schemes of microseparation the problem of immediate concern for current studies, which rely on the theory of single particle motion. The problem of collective behavior of magnetically driven cells has never been posed and represents a live research issue of both practical and scientific relevance. To tackle this problem, we have upgraded our experimental setup [2], developed for studying individual magnetic properties of cells as a microfluidic model that ensures simple deterministic experimental conditions, the possibility of measuring the relevant physical properties of microparticles, their time-varying distribution in diluted samples and visualization of the processes in the concentrated samples. Also, we have formulated the concept of magneto-gravitational analogy allowing us to consider the collective magnetophoresis of submagnetic microparticles as a sedimentation process in predetermined force field. To stress this point, we represent the magnetophoretic cell separation as magnetic sedimentation, – a specific problem at the border of magnetism and fluid mechanics. Both, local (particle-particle) and global (solid-liquid phase) hydrodynamic interactions are of the same fundamental interest for magnetophoretic separation as the gravitational sedimentation due to its debated problems of mesoscopic hydrodynamic fluctuations [3] and the hydrodynamic (granular) Rayleigh-Taylor instability [4] that can crucially affect the successful separation. On the other hand, the possibility to control the driving force field brings about a new intrigue into the classical sedimentation problem. On this basis, we study magnetic separation of red blood cells from deoxygenated diluted blood. We have found that the single-particle separation mode is destroyed at cell volume concentration of only about 0.002, and, with increasing cell concentration generates an intensive hydrodynamic vortex motion, which, however, does not influencing the time and the purity of the magnetic separation of red blood cells. Our observations led us to conclude that the hydrodynamic magnetophoretic instability should be related to mesoscopic swirls caused by cell concentration dispersion. Our experimental model and the obtained results are of considerable importance for designing the advanced microfluidic analytical system technologies and for mechanics of suspensions in whole.

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NUMERICAL AND ANALYTICAL ANALYSIS OF A MAGNETO-RHEOLOGICAL DAMPER

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Magneto-rheological dampers have already found wide practical applications, but there is no a fairly complete theory of the influence of magnetic fields and hydrodynamic processes on their power and dissipation parameters.

The requirements to the parameters of hydraulic dampers are clarified. Often the magneto-rheological dampers (MRD) do not contain real magneto-rheological fluid (MF), using instead, pseudo-MF, with the size of magnetic particles more than 1 micrometer. The use of nanodispersed magneto-rheological fluid (NMF) allows saving the operating parameters of the damper for a long time.

The analysis of patent information on available sources was made. The largest number of patents in the countries of Southeast Asia, USA. Russia lags behind. The number of patents in 2009–2013 years has increased dramatically [1].

The flow MF in the magnetic field differs from the flow of non-magnetic fluids. In the hydraulic calculation it is necessary to take into account structuring of MF in a magnetic field. The results of simulation of the magnetic field are analyzed. In the MRD the fluid flow is used in the gap between the piston and housing. Here it is necessary to consider only the pressure head of the liquid in the gap. The strike slip is not determinative in this case. MF research shows good stability.

The analytical study of the flow MF in the gap MRD has been conducted. It has been found that the velocity field has three characteristic regions. In the center of the flow there is a body without a shift between the layers. On both sides of the body there are flow regions with decaying structures. At the walls of the gap the flow velocity changes abruptly. Formulas obtained in [2] allow us to calculate the variation of MF.

Finite element modeling of the flow of NMF in the slot of the channel in the transverse external magnetic field has been performed. The simulation demonstrates typical flattening of the central part of the stream, which confirms the analytical results. The experimental setup for studying the flow of MF in a narrow channel has been developed.

The effect of concentration of the magnetic phase and intensity of the external transverse magnetic field on the flow of NMF has been investigated. In the development of MRD one needs to take into account the mutual influence of thermal, electromagnetic and other processes on the fluid hydrodynamics. Numerical models of MRD have been developed in [3]. The characteristics of this model have been investigated taking into account the mutual influence of magnetic and hydrodynamic processes.

The MRD design has been improved. The refined design of the MRD with magnet-controlled working fluids has been developed. The patents and patent applications have been made.

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CALCULATION OF EDDY CURRENTS IN INDUCTION PLASMAS

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Eddy currents (or Foucault currents [1]) are widely used in plasma chemical technologies. The simplest plasma torch consists of a quartz cooled tube encircled by copper coils [2]. The coils carry current supplied by a radio-frequency generator. Gas flowing through the tube is heated and partially ionized by inductive coupling to the coil current.

Induction plasmas have applications in aerospace research, processing of materials and treatment of waste materials, atomic emission spectroscopy and mass spectrometry techniques.

Some results for turbulent flow of viscous heat conducting plasma are reviewed in [2]. Recent numerical modeling and experimental studies of heat exchange in the under-expanded jets of dissociated carbon dioxide produced by radio frequency plasmatron are available in [3].

Mathematical modeling of a steady axisymmetric laminar flow of induction plasma under local thermodynamic (including thermochemical) equilibrium is based on the conservation equations of mass and momentum with regard to the Lorentz force and the energy equation with regard to the Joule heating and loss due to radiation [4, 5]. This also requires the application of the MHD approach for calculation of the alternating electric field in the plasma and Ohm's law for motionless medium. In addition, the vector potential **A** of the magnetic field with regard to Coulomb's gauge invariance condition is introduced and the solution of the Poisson vector equation [1] for **A** is used to calculate the electric field at the entry, exit and walls of the torch [4, 5].

The boundary condition in the electric field calculation involves the sum of two terms, one of which is due to a given external current in the coils, and the other is due to Foucault currents $\mathbf{j}_F$ in the plasma [4, 5]. Since the Foucault currents are not known *a priori*, the total power dissipated in the plasma and torch efficiency should be given as integral constraints to find an iterative solution to the whole system of equations for gas dynamics and electrodynamic equations. In the framework of the mathematical approach used above the question of uniqueness of the obtained solution arises.

In contrast to [3–5] we suggest to use conceptually more natural procedure for calculation of the electric field **E** in plasma. The distributions of magnetic fields $\mathbf{H}_1$, $\mathbf{H}_2$ in nonmagnetizable conducting and insulating adjacent media with interface Σ are found by solving the boundary value problem

$$\frac{\partial \mathbf{H}_1}{\partial t} - \nu_m \Delta \mathbf{H}_1 = 0,\ \ rot\mathbf{H}_2 = \frac{4\pi}{c}\mathbf{J}_c,\ \ div\mathbf{H}_i = 0,\ \ i = 1, 2,\ \ \nu_m = \frac{c^2}{4\pi\sigma},$$
$$\mathbf{r} \in \Sigma:\ \mathbf{H}_1 = \mathbf{H}_2;\ \ r \to \infty:\ \left|\mathbf{H}_2\right| \le const,$$

where $\mathbf{J}_c$ is the current density in the coils, c and σ are the light velocity and conductivity, respectively. After calculation of $\mathbf{j}_F = c / (4\pi)\, rot\, \mathbf{H}_1$ we obtain $\mathbf{E} = \mathbf{j}_F / \sigma$.

As a model example, we consider the isothermal plasma filling a coaxial tube inside a long AC solenoid. An exact solution to the initial boundary value problem of Foucault current evolution at $t \to \infty$ after switching on a radio-frequency power supply at time $t = 0$ has been found in the form of convergent series.

One of the co-authors (V.M.K.) acknowledges RFBR for support (project No. 14-01-00056).

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TESTS OF THE INSTRUMENTATION AND EQUIPMENT FOR LIQUID METAL COOLANTS ON THE IRS-M CALIBRATION FACILITY

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The IRS-M calibration facility is designed for metrological support of developed and supplied flowmeters as well as for tests of other instrumentation and equipment for liquid metal coolants.

The calibration facility consists of 2 loops. The maximum coolant flow is 20 m^3 per hour in the primary loop with the SIP spiral induction pump 8/20 and 100 m^3 per hour in the secondary loop with the CIP cylindrical induction pump 4/80. The range of sodium operation temperature is 250–450 °C; a short-term increase in the temperature is allowed to 500 °C.

The flow up to 20 m^3 per hour is measured by the volumetric method, with the help of a gauge tank having 2 level indicators mounted in its nozzles. The gauge tank is filled by transferring the coolant from the supply tank.

Five parallel pipes are used to extend the range of the flow measured by means of the facility to 100 m^3 per hour (secondary loop). The pipes are Ø 48×4 and have BZ1 – BZ5 monitoring electromagnetic flow transducers linked by 2 headers and connected in series with the secondary circulation loop of the facility. Each of the monitoring flow transducers is pre-calibrated by the volumetric method.

The facility modes are monitored by an automated measurement system developed on the basis of I-7018Z analog input modules, I-7059 digital input modules, USB-RS485 I-7563 interface converter modules and a mainframe computer. Signals are recorded from flowmeters, level meters, and temperature and pressure sensors.

Based on the metrological tests of the facility, which were done at the FSUE «All-Russian Research Institute of Metrological Service», the following facility parameters were defined:

– the permissible relative error of sodium flow in the primary loop does not exceed ± 0,3 %;
– the permissible relative error of sodium flow in the secondary loop does not exceed ± 0,8 %.

The calibration facility has Pattern Approval Certificate (of Measuring Instruments) RU.E.29.004.A № 46579 and is entered in the State Register of the Russian Federation.

The IRS-M calibration facility is used to investigate and test different types of the flowmeters developed at the SSC RF-IPPE, including magnetic, correlation, vortex, combined ones. Acceptance tests of flowmeters for RCP-1 and FA of the BN-800 reactor have been done; flowmeters for the BN-1200 reactor are currently being developed. Also, tests of the flowmeters with low-frequency alternating magnetic field, which were developed at NIITEPLOPRIBOR plc, have been done. Among the mare IRMU-100 apparatuses for the EHRS of BN-600, over 80 IRMU units of different dimension types (D 25.40.80) for the BN-800 reactor.

Tests of a series of electromagnetic induction pumps for BN-600 are a new direction. So far NEI 8/2, 4/10, 4/125pumps have been tested and delivered to the Customer.

MODES OF CONVECTION AND THE POSSIBILITY OF MHD PROCESS IN THE EARTH'S CORE AT THE STAGE OF THE PLANETARY ACCUMULATION

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The study of different convection modes at the Earth's accumulation stage has not yet been carried out in detail. Regarding convection realization inside the initial core of the growing proto planet, we can distinguish some qualitatively different stages. The earliest among them for the Earth's planetary group was realized for pre planetary bodies, when the energy dissipation by the decay of the short living radioactive, first of all ^{26}Al, provided the melted state of the inner areas of the proto planet. Hence, the masses and relative velocities of body impacts during the process of accumulation were small. This stipulated the low temperature values of the growing proto planetary surface [1] and the background of Raleigh heat convection realization. At the next stage of the planetary accumulation the contribution of short living isotopes to the energetic process during the decay ^{26}Al decreased, but the energy contribution from the body impact increased. The energy balance on the surface of the proto planet led to the melted state of the upper envelope and the inelastic character of the impact. Further during the increase of the proto planetary mass, and increase of the pressure and the melting temperature with the depth and decrease of the energy dissipation intensity by the body impact, which became more elastic because of its silicate part, the proto-planetary cloud of the Raleigh heat convection can be realized [2]. However the falling of accumulated bodies can lead to the random distribution of the heat anomalies [3–4]. For studying the MHD mechanism of geomagnetic field generation already developed at the stage of Earth's accumulation in this paper, the results of the numerical modeling carried out under the assumption that the random distribution of 3D thermal heterogeneities does not destroy the thermal convection and MHD process during the outer Earth's core formation are presented.

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CONVECTION IN THE ROTATING CYLINDER WITH A GROWING DIMENSION LOCATED IN THE MAGNETIC FIELD

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During last years, much progress has been made toward an understanding of Earth’s modern structure of geomagnetic field and the mechanism of its generation. This has proved possible first of all due to the progress in the development of new super computers and new numerical algorithms for solving the systems of nonlinear vector differential equations of parabolic type. Among the undoubted achievements are the proposed numerical models which have long been known and newly installed after numerous inversions of the dipole structure of geomagnetic field formed during the hydro magnetic dynamo process.

Significantly less detail are the studies on the problem of the time of geomagnetic field occurrence at the stage of Earth’s formation [1]. Thus, in paper [2] the authors present the numerical results about the possibility of geomagnetic field generation obtained in the framework of the model of Earth’s core growth at the stage of planetary accumulation in a spherical sector rotating with a constant angle velocity.

In our paper we present the results of numerical modeling of a rotating circle cylinder with growing dimensions in the homogeneous magnetic field in the framework of the Boussinesq thermal convection model.

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INDUCTION PUMP FOR LIQUID SODIUM

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This paper presents the main parameters and characteristics of a liquid sodium stand and induction MHD-pumps for circulating liquid sodium. The stand is designed to mix two liquid sodium flows having different temperature.

The liquid sodium stand consists of a flow mixing section, a heater, a cooler, MHD-pumps for liquid sodium circulation, pipe conduits, and gages. The elements of the stand form the main circuit and are connected by the stainless pipes of diameter 68 mm. In addition, the liquid sodium stand contains a minor (cleaning and pouring) circuit. The minor circuit includes a liquid sodium storage system, an entrainment filter, valves, and gages. The main circuit has low internal flow resistance. This can be attributed to the fact that there are no stop and expansion valves in it. The flow rate of liquid sodium can be changed by adjusting the rate of operation of the MHD-pump, which provides more stable control of a broad range of flow rates.

In the main circuit, there are two branches: hot and cold. One contains a heating system of a capacity of 27 kW, and the other a cooler for sodium. The heating system is a cylindrical vessel with embedded electrical heaters washed by the sodium flow. The cooler consists of finned tubes blown from the outside by air. The maximum operating temperature of the circuit is 250 °C. The maximum temperature difference between the hot and cold sodium flows is 100 °C. The circuit comprises the following elements: a 300 L sodium storage system, vacuum and gas filling and discharge systems, a measuring system, and a cleaning system.

The sodium stand is located in a special-purpose room of 36 m^2, which is equipped with a ventilation system, a fire signal system, and fire-extinguishers meant for sodium. In the room, there is sodium storage and cleaning tank, which is a $6 \times 2 \times 2$ m concrete pit. Also, the room has a separate space for controlling and measuring equipment.

Experience gained during the design, development and application of a cylindrical traveling field pump for liquid sodium is described. A mathematical model of the device has been developed and verified. The effects of various parameters on the pump capacity have been investigated. Based on the results of simulations, we developed and manufactured a single-section pump tested in gallium circuit experiments. Test data supported the validity of the mathematical model developed in our study. Simulations allowed us to develop and manufacture multiple-section pumps with required characteristics. All the pumps have successfully passed the tests conducted on a sodium circuit and can be found today in a wide variety of applications.

MEASUREMENT OF LIQUID SODIUM FLOW RATE

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The structure and performance of a device for measuring the flow rate of liquid sodium in a cylindrical channel are described. The device consists of three elements based on independent flow rate measurement methods: conduction, induction and thermocorrelation. It has been designed to be integrated into the liquid sodium stand located at the experimental facilities of the Institute of Continuous Media Mechanics UB RAS and is meant for temperature up to 250 °C.

All the elements of the flowmeter are assembled on the straight section of a stainless steel tube of 68 mm inner diameter and 500 mm length, which is built in a general circuit using flange mounting.

The conduction system for flow rate measurement comprises two neodymium magnets that embrace the tube and generate a magnetic field up to 0.3 T applied transverse to the flow direction and four symmetric couples of electrodes that record an electromotive force produced by the interaction between the conducting medium and the magnetic field. Electrodes are placed in a circular cross-section of the tube at different angles to magnetic field directions: 0, 45, 90, 135, and 180°. The use of several couples of electrodes makes it possible to take into account velocity profile asymmetry [1].

The induction system for flow rate measurement is based on the magnetic field drift due to the flow of a conducting medium: an alternating magnetic field aligned with the flow direction is generated by a central coil comprising 260 turns. Two measurement coils, whose EMF amplitude ratio is dependent on the flow direction and velocity, are placed symmetrically on both sides of a generating coil.

The thermocorrelation system for flow rate measurement contains two rapid-response thermocouples. The thermocouple junctions are located inside the metal flow and aligned along the tube axis. When temperature fluctuations takes place, the analysis of thermocouple signals shows the time it takes for temperature inhomogeneities to transfer from one thermocouple to the other. What is more, knowing the distance between these thermocouples, it is possible to restore the mean flow velocity in the center of the velocity profile.

Calibration of flowmeters has been performed in the experiment on pumping liquid sodium from one vessel to the other under pressure drop. For calibration purposes, use was made of an integrated flow rate determined by the conduction system for measuring liquid sodium level in the vessels.

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EXPERIMENTAL STUDY OF MIXING OF LIQUID SODIUM FLOWS HAVING DIFFERENT TEMPERATURES

[1] Khalilov R., [1] Kolesnichenko I., [1] Shestakov A., [2] Krylov A., [2] Pakholkov V.,[1] Pavlinov A., [2] Rogozhkin S., [1] Mamykin A., [1] Vasiliev A., [1] Frick P.

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In designing of fast sodium reactors, in which liquid sodium is used as a heat transfer medium, the researchers face the problem of mixing the flows, which are at different temperatures. Mixing of heat transfer liquid flows gives rise to temperature pulsations, which impose additional thermal cyclic loads on the equipment and may exert considerable effect on the operating life of the structure. Such was the case with the operating reactor Phenix, in which decompression of the main pipe connecting two of the three loops of the reactor occurred due to temperature pulsations [1]. The reason of decompression was temperature pulsations initiated by the alternate impacts of the "hot" heat-transfer liquid coming from the inlet pile and cold liquid circulating in the main pipeline. Thermal pulsations occurred at the BN-600 reactor were the reason for crack formation on the outer surface of the upper tubesheet and adjacent shell of the heat exchanger in the first and second circuit [2].

Since experimental studies of the mixing process were performed mainly in the circuits filled with water, it is impossible to apply the obtained results to liquid metals, in which the process of heat transfer is quite different. The objective of this work is to explore experimentally the process of mixing liquid flows having different temperatures and to obtain data, which will allow verification of the CFD codes.

For experimental study we used a three-branch structure, which is a T-shaped pipe made of stainless steel tubes 1.45 mm thick. The "hot" heat-transfer liquid circulates through the entire length of the circuit and the "cold" heat transfer liquid is fed through the inlet pipe. The nonstationary turbulent mixing of hot and cold flows of heat-transfer liquid metal gives rise to temperature pulsations in the flow core. However, few vortices of hot and cold liquid sodium reach the internal surface of the pipeline, which causes temperature pulsation in the metal frame of the T-shaped structure. The thickness of the pipe wall specified for the model provides low rate of response to temperature, which allows measurement of temperature pulsations on the external surface of the circuit with the aid of thermovision camera. The circuit is additionally equipped with thermocouples to measure temperature pulsations in liquid sodium and on the surface of the T-shaped pipe.

The paper presents the results of a series of experiments at different combinations of flow rates and temperatures of "hot" and "cold" liquid sodium. A stationary regime of liquid sodium flow was obtained in each experiment for a certain combination of the corresponding parameters. The obtained experimental data will be used to verify CFD codes, which are intended for implementing project computations for BN reactors.

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EFFECT OF ROTATING MAGNETIC FIELD ON HEAT AND MASS TRANSFER AND DOPANT SEGREGATION DURING DIRECTIONAL SOLIDIFICATION OF SEMICONDUCTORS

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The problem of studying the processes of heat and mass transfer during the growth of semiconductor single crystals is of great importance due to the rapid development of semiconductor microelectronics. The worldwide semiconductor industry is in demand for the ever-growing volumes of high-quality semiconductor single crystals with high dopant distribution uniformity, which are the basis of all modern semiconductor hardware. For optimal control of convective heat and mass transfer within the solidification process the various methods are used, such as rotation, axial and rotational vibrations, stationary and non-stationary magnetic fields.

The paper presents the results of numerical simulation of the rotating magnetic field (RMF) effect on mass transfer and dopant segregation during directional solidification of semiconductors [1]. The simulations were performed for two directional solidification methods: the vertical Bridgman method in form of the Vertical Gradient Freeze (VGF) setup [2] and the submerged heater method in form of the Axial Heating Process (AHP) setup [3], for similar parameter sets (materials, crystal diameter, growth rate etc.).

The aim of the work is to evaluate the rotating magnetic field as a means to control the mass transfer within the melt and ultimately the dopant segregation in the grown crystal.

The problems are solved in a two-dimensional non-steady axisymmetric formulation. The simulation of convective flow in the melt is carried out using the Navier-Stokes equations in the Boussinesq approximation. The rotating magnetic field is assumed to be spatially uniform; the melt boundaries are treated as electrically insulated. Both diffusion and convective mechanisms of heat and mass transfer in the melt are taken into account. The shape and position of the solidification front is unknown a priori and is subject to determination from the instant temperature distribution.

The growth simulations are performed for Gallium-doped Germanium crystal with 3.2 cm in diameter for both VGF and AHP setups. The rotating magnetic field of 50 Hz frequency and up to 0.4 mT intensity is employed. It is shown that the RMF poses considerable effect on the meridional flow pattern and consequently on dopant distribution within the melt. Also, the RMF decreases of the radial dopant concentration non-uniformity in the grown crystal by order of two in the AHP case and, to lesser extent, in the VGF case. The onset of azimuthal flow instability within the melt due to RMF [4] and its consequences on the dopant distribution is discussed.

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PREDICTABILITY OF SOLAR ACTIVITY (WOLF NUMBERS) BASED ON NONLINEAR DYNAMO

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A one-dimensional nonlinear dynamo model (no R-model) is used to study the predictability of solar activity (Wolf numbers). The nonlinearity includes the dynamical equation for the magnetic helicity (the magnetic part of the alpha effect) and algebraic nonlinearity of the total alpha effect. The diffusion flux of magnetic helicity is taken into account. The Gnevyshev-Ohl rule works when only the algebraic nonlinearity is taken into account. This model reproduces well enough the Maunder Minimum of the solar activity. The properties of the nonlinear dynamo model were studied carefully: limit cycle, and amplitude-period-asymmetry relations. Lyapunov exponents were found and compared with the results of solar observations.

PARAMETERS OF ELECTRICAL DISCHARGES UNDER FREE SURFACE OF LIQUID METAL

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The work is devoted to investigation of parameters of high current electrical discharges forming under the free surface of liquid metal in problems of melting and mixing intensification using electrovortex flow control. The significance of our study is that it will allow researchers to solve fundamental [1, 2] and applied problems related to improving the performance of technical devices used in power engineering and industry as well as the environmental situation. One of the practical applications of research results is metallurgy. Systems with electric arcs under liquid metal surface are used in many electrometallurgical processes such as electro-arc melting, remelting, casting, welding, getting of liquid metal heat transfer agent, melt purification, and waste recycling. The purpose of the work is experimental investigation of the parameters of high-current electric arcs and the characteristics of heat exchange in modeling the configuration a system with rode and liquid metal electrodes under conditions taking place in electrometallurgical facilities and reactors of waste recycling [3, 4]. Electrical, thermodynamic, spectroscopic and magnetic characteristics were measured, and formation, evolution and structure of the high-current arc were visualized under the following conditions: pressure – 1 Atm, ambient gas – air, nitrogen, electric current values – from 1 to 30 kA, liquid electrode – lead, tin, and eutectic alloy of indium-gallium-tin. The electric arc was initiated in the electrode gap of a rode electrode of various diameters and a bath of melt of model metal (lead, tin, and indium-gallium-tin). Special heaters provided the formation of the bath of model molten metal. Capacitor banks of following parameters: voltage – 50 kV, power 100 kJ, duration of a current pulse – up to 100 mks and 10 kV, 6 MJ, up to 3 ms, were used as an energy source for electrical discharge burning. Use of high-speed optical techniques made it possible to carry out a comprehensive diagnosis of the formation and evolution of the electric arc and to determine parameters of the arc channel. High-speed photo recording enabled visualizing a liquid metal constriction forming between the electrode and the liquid metal, electrical explosion of the constriction, and subsequent ignition of the discharge. The temperature of the plasma channel was determined from the spectral measurements, and the temperature of molten metal surface in vicinity of the arc was measured by a high-speed pyrometer.

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EXPERIMENTS ON INTERACTION OF JETS OF LIQUID GALLIUM WITH SOLID SUBSTRATES IN APPLICATION TO TOKAMAK

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The controllable thermonuclear reactor Tokamak, i.e. a reactor that uses the energy of plasma from the reactions of light particles' nuclei fusion, has been known for about 60 years. Due to many reasons, the problem of energy production (extraction) from high-temperature plasma has appeared very complicated. From the point of view of stability control and necessity to keep it away from the reactor walls, plasma is a complex issue. The requirement to keep plasma away from the walls is determined by its very high temperature. Though the problems of nuclear heating and stable suspending of the plasma rope in the Tokamak toroidal chamber have been solved, the problem of energy extraction from the plasma still remains unsolved. Anyway, the energy which accumulates in the plasma particles must be extracted into devices in the reactor walls, i.e. the blanket, which entraps the flux of neutrons and transforms their kinetic energy into thermal, and a special target – the divertor intended for catching tritium – the product of the nuclear fusion reaction, which should serve as a renewable fuel for the long-term operation of the reactor. In some projects, the divertor has been proposed to be used as a device capable to control the plasma density [1]. However, it is not possible and necessary to avoid completely the plasma particle flux onto the walls. The reactor walls, or their parts, receiving the fluxes of neutrons and tritium, must be highly durable against the action of the fluxes of particles with high energy (to 50 MW/m^2 for divertors) and effectively remove the heat from the energetically loaded zones of the reactor, e.g., limiters of the plasma rope [1]. To solve these problems of heat removal and control, it is proposed to use a liquid metal as a most realistic and already utilized in nuclear reactors version. Lithium, gallium and tin are considered as most suitable for this purpose [2].

That is why an urgent issue in the design of the European experimental thermonuclear DEMO reactor started in 2014 is the development of a liquid metal, pumped through divertor with a renewable target surface. The experimental studies of potential versions of a liquid metal surface moving over the substrate performed at the Institute of Physics, University of Latvia (IPUL) are reported. The data on the observation of an InGaSn liquid metal film formed at the interaction of jets with the substrate surface in strong (~4 T) magnetic fields transverse to the flow direction are presented. Possible design solutions of the jet-film module of the divertor are proposed.

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WAVELIKE TEMPERATURE PERTURBATIONS PROPAGATING ALONG STATIONERY CONVECTIVE ROLLS IN A HORIZONTAL LAYER OF MAGNETIC FLUID

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Gravitational convection in a horizontal layer of magnetic fluid heated from below has been investigated experimentally. Special attention has been paid to the wave regimes of convection.

Since the magnetic fluid is a multicomponent two-phase medium, the convective motion in such medium (even if a magnetic field is absent) can be caused by several mechanisms: thermal convection, thermal diffusion, barometric separation of particles and etc. [1–5]. In the case of competition of a few mechanisms the convection becomes oscillatory.

During the experiment the thermal imaging measurements of temperature field of the magnetic fluid surface were carried out. Previously, the fluid had been motionless for some time. After that the temperature difference at layer boundaries was gradually increased.

The oscillatory regime of convection was detected in the range of the Rayleigh numbers equal to $(1.6–2.2) \times 10^3$. In our opinion, it can be caused by the competition between two mechanisms: barometric separation of magnetic particles in the fluid and thermal diffusion. The revealed regime is that of convective rolls, along which the temperature perturbations unevenly move.

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NUMERICAL STUDY OF INTERACTION BETWEEN THE FLOW OF LIQUID SODIUM AND HELICAL MAGNETIC FIELD

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We investigate peculiar features of initially homogeneous flow of electrically conducting liquid (liquid sodium) through a cylindrical channel in a helical magnetic field. The magnetic field with non-zero helicity is generated in the channel with the aid of magnetic system. The conducting liquid while flowing through the channel interacts with the magnetic field and produces the EMF and electric current. The appearance of azimuthal component of this force is responsible for the formation of the azimuthal velocity component of initially homogeneous liquid flow. Then it follows that hydrodynamic helicity of the fluid velocity field is nonzero.

The interaction between the magnetic field and the turbulent flow of conducting liquid with high level of helicity plays a decisive role in many models of the MHD-dynamo. Most of the mean-field models that are currently used to describe the process of generation of large-scale magnetic field in a turbulent conducting medium involve the so-called alpha effect, which implies that a turbulent flow with nonzero hydrodynamic helicity generates an electromotive force directed along the large-scale magnetic field. In this case, the induced electric current is directed along the imposed magnetic field and the total magnetic field acquires a helical structure. This paper is concerned with studying the inverse problem – the flow of conducting liquid in a helical magnetic field. It is originally conjectured that in the flow of conducting liquid, the magnetic field with non-zero helicity can initiate vorticity directed along the velocity vector, which accounts for the generation of hydrodynamic helicity.

The calculations have shown that the flow of conducting liquid through the region subject to the magnetic field with nonzero helicity gives rise to a vortex flow and its hydrodynamic helicity is other than zero. The value of hydrodynamic helicity increases with flow rate and parameters of the magnetic field. This effect can be observed in real flows of liquid sodium through the cylindrical channels inside the sodium loop.

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TURBULENT FLOW AND EDDY-CURRENT HEATING IN EXPERIMENTS ON CONTAINERLESS SOLIDIFICATION OF PERITECTIC ALLOYS: SPACE EXPERIMENTS PERITECTICA AND MAGHEPHAS

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In 2015, a series of space experiments onboard of the International Space Station will be conducted on the rapid solidification of pure metals and alloys levitated and heated by induction coils using the new MSL-EML facility. In these experiments, samples will be heated and then cooled down at high rates in order to achieve the formation of metastable phases.

In electromagnetic levitation, samples are suspended by an alternating electromagnetic field from an induction coil surrounding the sample. In order to have stable levitation, frequencies between 100 and 400 kHz and currents between 20 and 200 A are used. Therefore, a correct description of the fluid flow and the eddy-current heating is essential for analysis of the actual experimental conditions.

The SEPOS coil set used in MSL-EML has a single-coil/dual-current design where the positioning and heating currents use a single coil but different modulation schemes and frequencies. The positioning current has a quadrupole modulation while the heating current has a dipole type. In the international space experiments PERITECTICA and MAGNEPHAS [1], the effect of convection on the delay time between the formation of the metastable and stable phases is studied for Fe-Co and Nd-Fe-B alloys.

A magneto-hydrodynamic model for axisymmetric samples with heat transport and solidification was developed by us using the theory of continuum electrodynamics [2, 3]. The model was thoroughly tested and validated with experimental [4] and theoretical data [5, 6] and showed good quantitative agreement. A transition from laminar to turbulent flow is predicted for the experimental conditions on the ISS. The structure of the flow field in the sample was found to depend on the heating current with a transition from clock-wise to counter clock-wise vortices. This provides a minimum flow velocity of about 5 cm/s at intermediate heating currents. Depending on the heating current, the maximum flow velocity varies between 5 and 25 cm/s.

Eddy-current heating is due to both the positioning and heating magnetic field but the heating field prevails due to the higher frequency. The typical skin layer thickness was found to be about 1/3 of the sample radius which leads to intensive inductive heating of the bulk of the molten droplet. The relation between processing parameters and observed thermal modes will be discussed in the talk.

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PROXIES OF THE MEAN MAGNETIC FIELD FROM OBSERVATIONS OF SOLAR ACTIVE REGIONS AND ITS DYNAMICS WITH 22 YEAR CYCLE

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Observational proxies of the mean magnetic field are very important for developing the hydromagnetic mean field dynamo theory. We have used the systematic long term observations of vector magnetograms of solar active regions obtained at Huairou Solar Observing station over 1988–2005. The magnetic field vector has been de-projected to the solar surface. This enabled us to compute mean values of the asimuthal, meridional and radial components of the magnetic field averaged over magnetograms. The asimuthal component can be considered as a proxy of the toroidal field and the meridional one as the poloidal field. We grouped the magnetogram data by sampling bins 7 degree in latitude and 2 year time intervals, so that each group contains at least 30 independent magnetograms. In our investigations we are especially interested in samplings where the mean values exceed 90 % confidence interval of Student's criterion.

We have found that Hale's polarity law for all three-components of the mean magnetic field is well confirmed with these observations. We have also found some (10 out of total 88) samplings where Hale's law is significantly violated. Such samplings tend to occur near the edges of wings of time-latitudinal butterfly-diagram for sunspots. We can impute this phenomenon to:

1. Presence of the mechanism of sunspot formation related not to magnetic flux buoyancy but to the effect of draining of the flux into Sun (effective negative magnetic pressure).

2. Peculiarities in the solar-cycle evolution of the phase shift between the toroidal and poloidal components of the magnetic field.

EQUILIBRIUM STRUCTURE OF A FLEXIBLE DIPOLAR CHAIN

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Equilibrium behavior of a single flexible chain of dipolar hard spheres is numerically investigated in the framework of the Langevin molecular dynamics. Particles interact pairwise through steric and dipole-dipole interactions. In addition, the chain integrity is maintained by artificial «bonds» – center-to-center distance of the first nearest neighbors in the chain is not allowed to exceed some predetermined value r_{max}. Furthermore, the particles have full orientational and translational freedom. The control parameters of the simulation are the particle number, r_{max} and the dipolar coupling constant λ (the ratio between the dipole-dipole interaction energy of two particles and the thermal fluctuation energy).

Simulations show that for $r_{max} \approx \sigma$ (σ is the particle diameter) and $N > 4$ the dipolar chain at $\lambda \approx 6$ undergoes the structural transition from a random coil to a closed ring with the «head-to-tale» alignment of dipolar moments. This result is in good qualitative and quantitative agreement with the recent study on supramolecular magnetic filaments [1]. However, in the case $r_{max} \geq 2\sigma$ the diversity of possible system morphologies is much greater. At $\lambda \approx 4$ the chains collapse into dense quasi-spherical formations, which do not have the overall magnetic order («globules»). At $\lambda > 6$ only small globules ($N < 20$) are transformed into rings. Larger globules take toroidal («donut-like») shape and stable circulating magnetic order.

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THE INFLUENCE OF INTERPARTICLE INTERACTION ON DYNAMIC SUSCEPTIBILITY OF MAGNETIC FLUIDS

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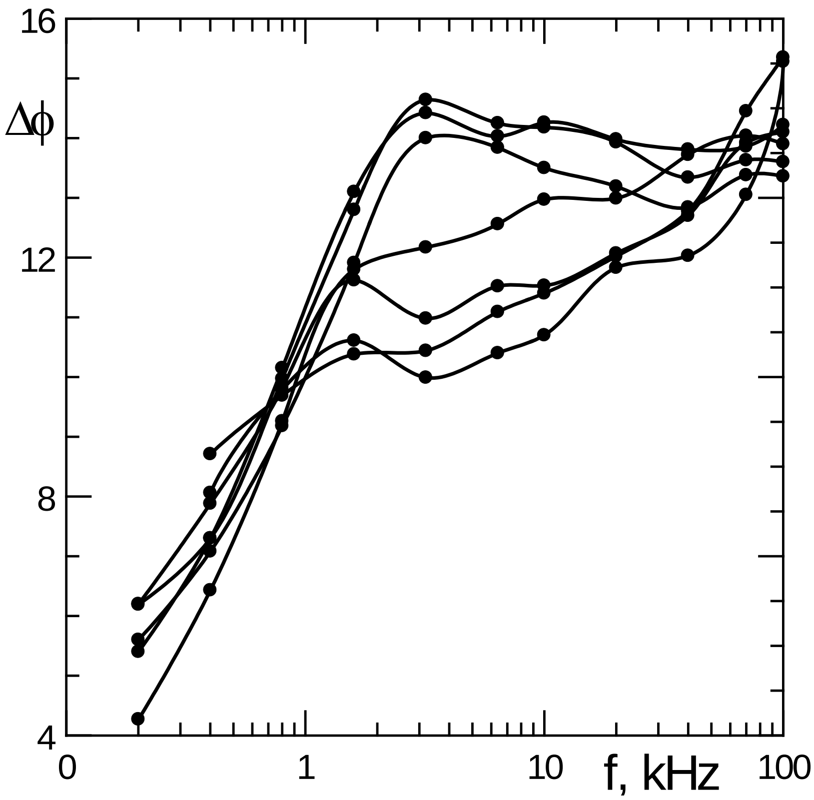
The problem of the influence of interparticle interactions on the magnetic properties of magnetic fluids is one of the main problems in physics of magnetic fluids. In the case of constant fields some progress has been made in solution of this problem [1, 2]. As for alternating fields we practically don't have any ideas of how to describe theoretically this influence. Moreover, at present time we don't have any experimental results, which can substantiate the influence of interparticle interactions on dynamic susceptibility. In our early work [3], dynamic susceptibility of magnetic fluids was compared with theoretical predictions obtained in one-particle approximation. The dynamic susceptibility was normalized to the initial susceptibility of fluids. Good agreement between the theory and the experiment was observed. This suggests that the influence of interactions to the susceptibility can be taken into account through the initial static susceptibility.

In this work we present new results on dynamic susceptibility of magnetic fluids in relation to its concentration.

The dynamic susceptibility was measured with the help of Mutual Inductance Bridge. The output voltage of the bridge was recorded by a multi-channel AD converter. A difference in the phases of signals was measured separately. In this series of our experiments we measured the susceptibility of 7 samples with different concentrations at 5 different temperatures. The most informative parameter reflecting the influence of interparticle interactions is the phase difference. In the case of constant phase difference in the dependence of concentration the interparticle interaction changes only the scale of susceptibility. But the real situation is more complex.

The figure shows the results for frequency dependence of the phase difference at different concentrations of fluids. We can see that this difference is not constant for any of the frequencies. In the range from 1 kHz to 50 kHz the difference in phase changes and the maximum change is half of that at the frequency of 4 kHz. What is more important, the increase of concentration leads to a decrease of phase difference. In other words, the interparticle interaction improves conditions of particle relaxation. In the figure the higher concentrations corresponds to the lower curves.



This work was supported by the Russian Foundation Basic Research, grant No 13-01-96041 and 14-01-96007.

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TURBULENT CONVECTIVE HEAT TRANSFER IN CYLINDRICAL ENCLOSURES WITH LIQUID SODIUM

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The interest in heat and mass transfer in liquid metals is largely stimulated by their application as coolants in nuclear reactors [1], fusion reactors and space power plants. Sodium is used as a coolant in a fast neutron reactor plants. In the design analysis of heat and mass transfer processes occurring in these systems during a shutdown of forced coolant circulation, the numerical codes must be verified using experimental data on natural convection of metal in cylindrical enclosures having different orientations with respect to gravity. Experimental data on cylinders with $L \gg D$ (L is the cylinder length, D is the diameter) are rare.

The natural turbulent convection of liquid sodium in two cells with end heat exchangers providing fixed temperature drops is investigated experimentally for different orientations with respect to the gravity ($\alpha = 0$–$90°$ form vertical). The cells are thermally isolated cylinders with inner diameter $D_1 = 168$ mm and length $L_1 \approx 5D_1$ for the first one and with inner diameter $D_2 = 96$ mm and length $L_2 \approx 20D_2$ for the second one. Both ones have an expansion tank. The cylinders are placed on a frame, on which it can be mounted at a given angle ($\alpha = 0$–$90°$ form vertical). For inclined and vertical positions, the heater is below the cooler, i.e. we study the case of heating from below. Chromel-alumel thermocouples with an isolated junction of diameter 1 mm are used for temperature measurements. Sampling rate for each thermocouple is up to 75 Hz. Cross-correlation velocimetry are applied for estimation the mean velocity of LSC. In this technique the temperature-time records from a pair of thermocouples, one downstream of the other, are cross-correlated to determine the flow's preferred mean velocity [3].

The Rayleigh number, which is determined by the superimposed temperature difference and the cylinder diameters D_1 and D_2, varies within the range of $Ra_1 = (2 – 10) \cdot 10^6$ and $Ra_2 = (1 – 6) \cdot 10^6$. Dependence of the Nusselt number on Rayleigh and Prandtl numbers for both cells and for $\alpha = 0$, 45 and 90° is discovered. A strong dependence of power transferred along the cylinder on the inclination angle is observed: Nusselt number varies by an order in the investigated range of angles with a maximum approximately at 65° to the vertical. Obtained characteristics of the large-scale circulation (LSC) and turbulent temperature fluctuations demonstrate the fact that the convective heat transfer is mainly determined by the velocity of the LSC. In the horizontal cylinder, the LSC is less intense, the flow can be characterized as transient to turbulent, and the Nusselt number is significantly lower. In the vertical cylinder the convective heat transfer is provided by turbulent mixing only (the large-scale circulation is absent, but the energy of turbulent fluctuations is maximal) and the Nusselt number has the lowest value (less than in case of inclined cylinder by an order). For the first cylinder (short) in power laws for the Nusselt number of the form $Nu \sim (RaPr)\lambda$ the exponent also has a maximum value for the inclined cylinder ($\lambda_1 = 0.84$), and a minimum for the vertical cylinder ($\lambda_1 = 0.6$), while for the horizontal $\lambda_1 = 0.75$ [3]. For the second one (long) the exponent has the maximum value for the horizontal cylinder ($\lambda_2 = 1.05$), and is less and similar for the vertical ($\lambda_2 = 0.84$) and inclined ($\lambda_2 = 0.8$) cylinder. The range of considered Rayleigh numbers is below a decade, thus the accuracy of scaling exponents estimation is low. However the values obtained indicate that the value of the scale exponent is essentially above then "2/7", confirmed for the short and flat vertical cylinders, and even above then "1/2", suggested for "ultrahard" regime.

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MAGNETIC FIELDS IN THE OUTER RINGS OF GALAXIES

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It is believed that in the inner parts of the spiral galaxies there are regular fields of several μG. Their generation is described by so-called αΩ-dynamo that works because of the differential rotation of the galaxy and the alpha-effect [1]. Some galaxies have outer rings containing some ionized gas, so that there is an opportunity of generating the magnetic field.

To model these magnetic fields we use so-called no-z model, which takes into account the probability that the galaxy ring and the disc are rather thin and so the component, which is perpendicular to the galaxy plane, is quite small and can be neglected [2]. The dynamo mechanism is a threshold effect and can operate even at some values of the turbulent velocity, angular velocity of the galaxy and its half-thickness. As for the galaxy ring, the mechanism can operate if the width of the ring is quite large: it should be more than 2 kpc. Otherwise, the magnetic field will decay because of the dissipation effects.

However, the magnetic field can be generated not only *in situ*, but it can pass through the gap between the main part of the galaxy and the ring. This mechanism is called Kolmogorov – Petrovsky – Piskunov effect [3] and it occurs provided that the gas density in the gap is not very small.

We have modeled the magnetic field for several galaxies with outer rings. There is a list of objects that can have regular magnetic fields and we recommend to study them in an observational way by radiotelescopes.

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MAGNETO-HYDRODYNAMIC EFFECTS IN FAST NUCLEAR REACTORS

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The purpose of our investigations and computer simulation is to determine physical conditions for generation of coherent vortex structures and to study their influence on the hydrodynamics of turbulent flows of liquid-metal coolants in the complicated channels of nuclear-power installations. The possibility of prediction of large-scale vortex generation leading to occurrence of magneto-hydrodynamic (MHD) effects allows us to prevent the dangerous operation conditions and to optimize the collector array of shell-type fast-breeder reactors.

The present work demonstrates a new approach for prediction of conditions for formation of steady-state vortex structures. It is shown that the main mechanism for appearance of steady-state vortex structures in swirl and curved flows is connected with the process of helicity generation. The original equation of helicity generation rate for dynamical liquid system was obtained in dimensional and dimensionless forms in work [1].

Application of the developed model of liquid vortex motion can be demonstrated for coolant flow in collectors of nuclear reactors. The prevention of flow regimes with spontaneous appearance of large-scale vortices is a significant problem for nuclear power plants with heavy liquid-metal coolants.

The objects of investigation in the present work are three-dimensional flows of liquid sodium streaming under conditions of the applied magnetic field in the curved and straight cylindrical channels with internal obstacles of different geometry, which leads to generation of the large-scale vortex motion. Particular attention is paid to so-called alfa-effect, which takes place in the presence of helical-screw motion and promotes to self-generation of the magnetic field resulting in coolant flow interrupt [2].

For carrying out a theoretical analysis, determination of governing dimensionless criteria and their influence the distributions of the velocity and magnetic fields, and evaluation of the influence of boundary conditions, primarily the simplified Hartmann two-dimensional flow problem was considered. A solution to this problem gave analytical dependences for the distribution of dimensionless fields of velocity, vorticity and magnetic induction. In addition, the change of pressure drop was determined as a function of the Hartmann number, the magnetic Reynolds number and the parameter of MHD-interaction for the examined two-dimensional channel was determined.

For 3D numerical modeling of high-velocity vortex flows in the tested complex channels, the k-omega SST turbulence model was used. The mesh size in a zone near the wall was chosen taking into account the given Reynolds number, geometrical data and transport properties of sodium (viscosity, density). As a result of modeling, zones of the highest intensity of the induced magnetic field for the considered cases of a Hartmann three-dimensional flow were found. Spatial distributions of fields of velocity, pressure and magnetic induction were obtained taking into account the arrangement of a flow disturbance source.

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MAGNETIC ENERGY AND MAGNETIC HELICITY CASCADES IN MHD TURBULENCE

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MHD turbulence is an important part of astrophysical processes, which gives rise to global cosmic magnetic fields. Over the last few decades, the peculiarities of MHD turbulence have attracted the interest of researchers in astrophysics and fluid dynamics, significant attention has been paid to the role of magnetic helicity in fully developed MHD turbulence. Magnetic helicity, together with the energy and cross-helicity, is one of the three integrals of motion in ideal MHD. The purpose of the work is to investigate the influence of magnetic helicity on the cascade properties of the developed MHD turbulence. To provide an extended inertial range (4 decades in our case), we use a helical shell model [1], which cannot take into account the spatial complexity of turbulent flows but reflects spectral distributions of real MHD turbulence [1]. Shell models are low-dimensional dynamic systems that are derived from the original MHD equations by a drastic reduction of the number of variables.

Here, we try to highlight the role of magnetic helicity by separating its source from the source of energy. We consider MHD turbulence that is stationary forced at the largest scale, with a source of magnetic helicity that is localized at a scale inside the pronounced inertial range. In our research, we focus on the possibility of a simultaneous direct cascade of energy and oncoming inverse cascade of magnetic helicity and examine the influence of magnetic helicity on the standard Kolmogorov energy cascade.

We demonstrate that, in the inertial range in fully developed MHD turbulence with small-scale sources of magnetic helicity, oppositely directed fluxes of energy and magnetic helicity coexist. Three inertial ranges with different scaling properties were obtained. In a short range of scales larger than the scale of magnetic helicity input, a bottleneck-like effect appears, which results in a local reduction of the spectral slope. The slope changes in a domain with a high level of relative magnetic helicity, which determines that part of the magnetic energy is related to the helical modes at a given scale. In the infrared part of the spectra, we observe a simultaneous inverse cascade of energy and magnetic helicity. Our results indicate that a large-scale dynamo can be affected by the magnetic helicity generated at small scales. The kinetic helicity, in particular, is not involved in the process at all [2].

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PECULIARITIES OF THE MOTION OF MAGNETIC FLUIDS IN POROUS MEDIA

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In this study, the features of the behavior of magnetic fluids in porous media consisting of sands, sediments, and single capillaries are investigated experimentally. We investigate the potential for controlling fluid emplacement in porous media using magnetic fields. We have developed the previously undertaken studies presented in works [1, 2]. In our experiments, we used a kerosene-based magnetic fluid in which magnetite particles stabilized by the oleic acid were dispersed.

We have studied the flows of a magnetic fluid under the action of vertical gravitational forces and magnetic forces acting simultaneously. The speed of the magnetic fluid rise in the vertical cylindrical capillary has been measured in the presence of non-uniform magnetic field with gradient directed upward and downward. The maximal rise has been measured.

The similar experiments have been performed to study the flow of a magnetic fluid in a porous media. For this purpose a cylindrical tube filled with sand has been used. The speed of the magnetic fluid rise in sand has been measured in the presence of non-uniform magnetic field with gradient directed upward and downward. The maximal rise has been measured.

On the basis of obtained results a new method of determining the porosity and other characteristics of porous media by means of the use of magnetic fluids and magnetic measurements has been proposed.

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THE STRUCTURAL PROPERTIES OF A BIDISPERSE MAGNETIC FERROFLUID IN THE ABSENCE OF A MAGNETIC FIELD

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The structural properties of a ferrofluid modeled by a bidisperse system of dipolar hard spheres are studied theoretically for the case of a zero external field. Analytical expressions are provided for the pair distribution function (PDF) and structure factor (SF) to the first order in number density and the second order in dipole-dipole interaction strength. The data obtained can serve as a basis for interpreting the experimental small-angle neutron scattering results and determining the regularities in the behavior of the structure factor, its dependence on the fractional composition of a ferrofluid, interparticle correlations. The influence of the granulometric composition on the behavior of the PDF and the position of the first peak of the SF is analyzed. The constructed theory is compared with the results of computer (Monte Carlo) simulations [1] and with the results of small angle neutron scattering [2] to determine the range of its validity.

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THE INFLUENCE OF ELECTROMAGNETIC STEERING ON THE MAGNESIUM MELT DYNAMICS IN INDUSTRIAL REACTOR OF TITANIUM SPONGE PRODUCTION

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In the largest Russian titanium producer Avisma-Berezniki, branch of VSMPO-AVISMA Corporation, titanium sponge is produced by the metalothermic method in industrial reactors with diameter of 1.5 meters and height of about 4 meters. The reactor capacity per production cycle is 4.8 tons. Titanium is produced in exothermic recovery reaction from titanium tetrachloride (TTC) in melted magnesium medium. The TTC is supplied to the surface of molten magnesium with temperature of 750…800 °C. The heat of 642.4 kJ/kg is emitted in the reaction, and 188.2 kJ/kg is absorbed because of evaporation reaction products. It leads to rapid overheating of chemical reaction zone to 1000 °C and greater. To maintain the reactor operating temperatures, the reactor bottom is heated, and its upper part has to be cooled. Full recovery cycle takes about 3 days, after which the reaction products are separated: the magnesium chloride is drained, and the titanium sponge is subjected to further technological processing. To obtain one ton of titanium sponge, it is required to spend more than 18 GJ of electricity. Low productivity and the high cost of technology restrict titanium production.

Titanium producing processes in the existing technology is controlled by varying the TTC feeding frequency and the heat transfer intensity selection in the heating and cooling reactor areas. Taking into account the fact that a titanium reduction reaction proceeds in conditions of non-isothermal free convection in the molten magnesium (conductive medium), it can be assumed that the electromagnetic stirring (EMS) will allow one to control flows and, therefore, a transfer of reaction products to the magnesium melt, and to form the desired temperature distribution.

The aim of the present work is to develop a mathematical model of heat and mass transfer in a titanium production reactor with EMS and to analyze possible effects.

The mathematical model contains dimensionless equations: 1) energy equation for convective heat transfer and Joule heat release; 2) mass transfer equation written in terms of vortex ω and stream function ψ in the Boussinesq approximation takes into account the effect of electrodynamic forces generated by an external field on the melt; 3) equations for current induced magnetic fields and volume forces in the non-inductive approximation; 4) velocities and temperatures boundary conditions for industrial devices.

To solve the problem of non-equilibrium heat and mass transfer, a numerical algorithm is implemented. The system of ω-ψ-T equations is approximated on a regular grid using finite difference method and solved by a tridiagonal matrix algorithm. The Poisson equation is solved by successive over relaxation.

Based on the numerical experiments performed using this model, the possibility of effective control over the flow intensity and structure in the reactor for titanium sponge production is shown. Thus, the EMS may be useful 1) to reduce exothermic reaction zone overheating, to eliminate vortex flow in the upper part of the reactor; 2) preventing separation pure magnesium and reaction products; 3) to enhance energy efficiency of the process of production of the titanium sponge.

The results of flow dynamics at TTC serving volume varying, joint variations of modes of TTC supply and electromagnetic steering is given.

MATHEMATICAL MODEL OF HEAT AND MASS TRANSFER IN CONDUCTIVE FLUID UNDER THE ACTION OF HIGH FREQUENCY MAGNETIC FIELD

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Induction heating is widely used for different metallurgical tasks, in precision production of semiconductors and dielectric elements: induction melting, zone melting, surface hardening of metal products, crystal growth, and optical fiber production. The basic idea of induction heating is utilization of joule heat eddy currents, induced in conductive material by alternation external magnetic field. The energy released leads to local heating of material and therefore changes density and concentrations of equilibrium elements and other effects.

The objectives of the present work are: 1) to develop a mathematical model of heat and mass transfer in metal melt located in an alternating non-uniform magnetic field, which takes into account both the "slow" free-convection flows and the "fast" vibration processes; 2) to study the mechanisms of magnetic field diffusion in the melt, eddy currents generation and volume heat source distribution; 3) to model convective flows in the melt.

A vertical cylinder filled by a paramagnetic $\mu \approx 1$ conductive melt is considered. This cylinder is placed in an external non-uniform magnetic field alternating harmonically with frequency of 1…2 kHz. It is suggested that the dielectric crucible walls are not affected by magnetic fields.

The governing equations include Maxwell's equations, Ohm's law and the equations of free convection in the Boussinesq approximation, including electrodynamic force and joule heat.

Based on the estimations made, it is shown that the complex magneto-thermo-convective problem can be reduced to two subproblems: 1) subproblem of magnetic field diffusion in the melt (its solution gives distributions of heat source, eddy currents and magnetic fields); 2) subproblem of convective movement of conductive paramagnetic fluid in alternating field (its solution provides determination of the flow structure, its stability and evolution when the governing parameter changes).

The boundary conditions of second subproblem are given for velocities and temperatures: at the crucible walls the velocities equal to zero, at free unyielding surface normal component of velocity and tangent component of viscous tension tensor equal to zero.

The flows in the melt and magnetic field distributions are axisymmetric, and this allows us to solve the problem in the half-plane. The symmetry condition is used for velocities measured along the cylinder axis. The radiation heat flux at the free surface of the melt is calculated by the Stefan-Boltzmann law, and for the side surface of the melt the steady heat flux through the cylindrical crucible wall is determined. The bottom of the crucible is insulated.

The results of modeling alternating magnetic field diffusion, temperature field and averaged flows are given. The model proposed can be useful for studying of the mechanisms of convective melt movement under induction melting, and it can be applied to determine effective modes and to design measurement and control automatic systems.

METASTABLE STATES IN SYSTEMS OF COLLOIDAL PARTICLES WITH A MAGNETIC COATING

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Ferrofluids are stable colloidal suspensions of ferromagnetic nanoparticles of typical diameter 10–20 nm. Ferroparticles of such small sizes can be considered as uniformly magnetized; so each particle has a permanent magnetic dipole moment. In the past decades, ferrofluids have become relevant in many applications ranging from engineering to medicine, and have attracted the interest of scientists from many fields. In order to fine-tune various aspects of the interactions in the system and to build tailored structures, in recent years, magnetic nanoparticles and colloids that deviate from the model of a spherical particle with a dipole moment at its center were examined. Among them are dumbbells, magnetic core-shell particles, elongated ferroparticles, and colloidal particles with a magnetic cap. In this contribution, we introduce and examine systems of colloidal particles with a magnetic coating using analytical calculations and molecular dynamic simulations. We consider one model system, namely, magnetic particles where three dipole moments are shifted from the center of mass towards the particle's surface. In this way, an additional anisotropy is introduced to the particles, which results in quite different and surprising microscopic properties of suspensions. Here, we mainly concentrate on ground states of small clusters of magnetic coating particles. We are particularly interested in the metastable state found by Gabi Steinbach (Institute of Ion Beam Physics and Materials Research, Dresden) and named Mickey, because of the visual resemblance to Disney Mickey Mouse. It is interesting that such a condition does not occur if we consider particles with a one shifted dipole [1].

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POLYDISPERSE MAGNETIC FLUIDS: CHOOSING BIDISPERSE APPROXIMATION USING THE EXPERIMENTAL STRUCTURE FACTORS

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Real-world commercial ferrofluids are polydisperse stable suspensions of single domain magnetic particles. Ferroparticles of such small sizes (typical diameter 10–20 nm) can be considered as uniformly magnetized; each particle has a permanent magnetic dipole moment. The magnetic cores are usually stabilized with a surfactant shells to prevent particle agglomeration. We choose bidisperse system as the first step to take into account polydispersity of ferrofluids when studying thermodynamics of magnetic fluids in the paper [1]. Using molecular dynamics simulations, we calculated polydisperse structure factor and compared it to a model bidisperse structure factor, with the bidisperse parameters chosen in such a way that the initial susceptibility and the saturation magnetization of a poly- and bidisperse systems are the same. It emerged that even though the magnetization curves are the same, the structure factors of the aforementioned systems differ significantly. This led us to an important conclusion: the bidisperse approximation based on matching the magnetic properties is not appropriate for the description of the structure factor in polydisperse systems.

Consequently, in the future we will investigate different approaches to solve this problem, for example, taking into account those form-factors carefully which are always used in real experiments [2]. Another way is to use different properties of magnetic fluids rather than magnetic, to choose the bidisperse parameters. It might be that obtained results will allow us to conclude that bidisperse system is not suitable to describe structure factors of real ferrofluids and one has to unavoidably use complex to three- or four-partial models.

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SIMULATION STUDY ON THE APPLICABILITY OF TRAVELLING MAGNETIC FIELDS IN METALLURGICAL FURNACES FOR REDUCING TEMPERATURE DIFFERENCE IN THE MOLTEN METAL

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Metals are melted in electrical and gas metallurgical furnaces by heating metals in proximity to free surface. This leads to overheating the upper layers of the metal; temperature difference between the upper and lower layers may achieve 100 °C. Such non-uniform heating causes the loss of quality of metals, expulsion of alloys, and growth of the amount of slag. No natural convection may occur in the metal heated from above. The overheating of metals can be reduced in the case of forced convection, which promotes interchange between the upper and lower layers of molten metal.

The present paper is a continuation of previous studies [1]. The aim of the paper is to explore the applicability of travelling magnetic fields for generating and controlling liquid metal flows in order to reduce temperature inhomogeneities typical of the process of metal melting in metallurgical furnaces. Numerical and experimental results obtained in the course of our investigation are presented.

The study was performed by the RFBR (grant No 14-08-96002).

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RESULTS OF ITER TEST BLANKET MODULE DEVELOPMENT IN RUSSIAN FEDERATION

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Since 2007 in Russian Federation the leading organizations JSC “NIIEFA” and JSC “NIKIET” collaborating with some other scientific organizations have developed ITER test blanket module (TBM) with ceramic breeder and lead-lithium eutectic (LL). In this concept proposed by Indian TBM-team the double cooling of blanket is used – LL cools breeding zone, helium cools the first wall and the outer structure; tritium breeders are lithium containing ceramics and LL. Preliminary estimations fulfilled for Russian design of DEMO-S reactor proved the availability of this blanket type and possibility to obtain high tritium breeding and high outlet temperature of LL.

R&D on this topic includes both design and experimental works.

Implementation of neutron, thermal, MHD and mechanical calculations enabled one to optimize arrangement of the test blanket module and DEMO-S blanket. Based on the fulfilled calculations, the Russian conceptual design of TBM with ceramic breeder and LL has been developed.

Experimental works are carried out in the following directions: thermohydraulic studies of TBM models in magnetic field; development of LL handling technology; corrosion tests of materials in LL; study of blanket materials permeability for hydrogen isotopes; development of the technology of tritium extraction out of LL and lithium ceramics.

Till the present time the thermohydraulic investigations of TBM models were carried out with NaK alloy in NIIEFA and mercury in MPEI. Results of these experiments were used for development of numerical codes and TBM design. At the same time the preparation for studies with original material, eutectic lead-lithium alloy, is carried out. For this purpose two facilities have been designed and are being manufactured: the first one in IPPE – for development of LL technology, which may be used for corrosion tests later, and the second one in NIIEFA – for MHD and thermal tests of TBM models.

The main results of MHD tests of TBM mock-up with NaK alloy and thermo-gravitational convection experiments with mercury in rectangular duct with coplanar magnetic field are given in the report.

TURBULENT LIQUID METAL FLOW UNDER THE INFLUENCE OF ALTERNATING MAGNETIC FIELD

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A liquid metal flow driven by a rotating magnetic field in a cylinder is investigated. Measurements of the average and pulsation characteristics of the flow close to the cylinder wall were made using two-component conduction velocity sensors. The flow of liquid metal was created inside the MHD-stirrer, which produced traveling and rotating magnetic fields of different intensity [1]. Volumetric forces were generated due to the interaction between the external magnetic field and the vortex alternating electrical current induced by this field. Current industrial demands for the quality of metals require creation of flows of specific configuration producing a stirring action in continuous casting crystallizers to assure the homogeneous structure of ingots [2]. In addition, the existence of turbulence in these flows has a profound effect on the stirring process. The present paper includes information about the effect of magnetic fields of different intensity and frequency on the flow structure. Experimental studies were performed with low-temperature eutectic alloy Ga-Zn-Sn at room temperature. The effects of electromagnetic interference on conduction sensor readings cause the necessity to determine accessible frequencies intervals within which sensors provide true information about the pulsation characteristics of flows. The wavelet cross-correlation analysis assessed a direct impact of magnetic fields on sensor's signal [3]. The use of a Pacific 360-ASX power source for feeding stirring coils made it possible to create high-frequency fields (up to 200 Hz) and to measure turbulence factors in the low-frequency band correctly.

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LORENTZ FORCE VELOCIMETER

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A prototype model of a probe for determining the velocity of a conducting medium has been designed and manufactured for use under real industrial conditions. In order to calibrate the probe, measurements were made in an intensive turbulent liquid sodium flow. The results justify that the proposed techniques can be applied to most industrial flowmeters and take into account induction effects that may appear during processing of measured values.

Lorentz force velocimetry (LFV) is a non-contact technique for measurement of the velocity or mass flux of a conducting fluid [1–3]. It is appropriate for many industrial applications because a probe should not be immersed in a hot metal in view of non-intrusive measurements [4]. The key idea of LFV is that the force depends linearly on the velocity. However, in the case of high-speed flows this linear dependence is unsuitable due to eddy currents, and a corresponding induced magnetic field b_i becomes high enough to alter the imposed magnetic field B_0. Velocity measurement errors in metallurgical applications may lead to an excessive or insufficient amount of alloy ingredient and consequently to the undesirable properties of metal slabs. Therefore it is important to conduct a study on the applicability of Lorentz force velocimetry to turbulent high-speed liquid metal flows. A setup for generating such flows is located at the experimental facilities of the Institute of Continuous Media Mechanics in Perm (Russia) [5]. It consists of a toroidal titanium channel filled with liquid sodium. The channel rotates with frequency up to 50 Hz and can be broken within 0.3 seconds. The maximum velocity of the sodium at the end of the braking phase is 50 m/s, which leads to the high magnetic Reynolds number ($\mathrm{Re_m}$ = 40).

The primary purpose of our experiments was to calibrate the probe prototype. A permanent magnet was used to create the magnetic field B_0. The electromagnetic force acting on this field on the side of a moving medium was measured with a tensiometric or piezoelectric transducer. The probe housing also contained a magnetic field transducer for assessing the interaction force in terms of the value of the induced field b_i and temperature sensor data. An internal space of the probe was blown with cold air to provide a temperature regime appropriate for probe operation. The probe was fixed in close proximity to the rotating channel.

For precise measuring of induced fields, a miniature construction containing only a permanent magnet and a Hall probe for magnetic field measurement was manufactured. The probe was mounted directly on the toroidal channel wall and rotated together with it. At the same time, the distance between the measuring system and the moving medium was kept minimum.

The measurements of the Lorentz force and the induced magnetic field are represented as a function of time and $\mathrm{Re_m}$. It has been found that at $R_m > 1$ the electromagnetic force differs significantly from the linear relationship.

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GEOMAGNETIC REVERSAL FREQUENCY IN PRECAMBRIAN AND THE EVOLUTION OF THE REVERSAL PROCESS THROUGH THE EARTH HISTORY

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Only very few continuous magnetostratigraphic sequences are currently available to constrain the geomagnetic field behavior during the Precambrian. However, several differences between the Precambrian and Phanerozoic field have been tentatively proposed, including a higher contribution of non-dipole field components, a different secular variation regime or the occurrence of asymmetric magnetic reversals perhaps as a consequence of a less dipolar field during the Precambrian. On the other hand, several authors have argued for a dominantly dipolar field in the early Earth's history less prone to polarity reversals. Each of the above characteristics clearly requires further investigation and close scrutiny of any potential effect that might be related to the late growth of the inner core and/or long-term changes at the core-mantle boundary. In this respect, the Proterozoic era appears as a vast domain of research. Our recent magnetostratigraphic studies show that the Siberian platform possesses many sedimentary sections that are suitable for constraining the geomagnetic field behavior during the Precambrian. We will present a synthesis of these studies with a particular focus on the detection and the frequency of superchrons during the Proterozoic.

MODEL OF THE EARLY PALEOZOIC GEOMAGNETIC POLARITY TIME SCALE (GPTS)

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GPTS represents the distillation of our knowledge on the character of changes in polarity of the Earth magnetic field through the geological history. Geomagnetic reversal chronology is well known from the Upper Jurassic (approximately 150 Ma), mostly due to the study of oceanic magnetic anomalies. The magnetostratigraphic studies of Late Paleozoic and Early Mesosoic sections promoted significant advancement in the understanding of the reversal history of the Late Paleozoic and Early Mesosoic (i.e. beginning from ~320 Ma). At the same time our knowledge on the magnetic reversal sequence of more ancient epochs rests to be scarce and restricted. In our talk we represent the model of the Geomagnetic polarity time scale of Early Paleozoic (~540–440 Ma), which have been constructed on the base of synthesis of magnetostratigraphic data obtained by us and our colleagues during the last two decades, mainly from Siberian type sections.

BRIDGE OF MAGNETIC FLUID CONTAINING FERROMAGNETIC CYLINDER, BETWEEN TWO HORIZONTAL PLANES IN A UNIFORM VERTICAL FIELD

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Magnetic fluid bridges and valves in magnetic fields are studied experimentally in several works. In [1], the experimental study of a magnetic fluid bridge located between the poles of an electromagnet was carried out. The behavior of the magnetic fluid bridge between two cones and a cylinder in the magnetic field of a line conductor was studied theoretically in [2]. A theoretical investigation of the fixed volume of the magnetic fluid between horizontal plates in the magnetic field of a line conductor with current was made in [3].

In this work the surface shape of a magnetic fluid that contains a cylindrical ferromagnetic body in the applied uniform vertical magnetic field is studied experimentally and theoretically. The magnetic fluid volume is located between two horizontal planes (the distance between the plates d = 12 mm). Uniform vertical magnetic field is generated by the Helmholtz coils. The current in the coil is controlled by a LabView virtual instrument.

In the experiments constant and stepwise (quasi-static) vertical magnetic fields are considered. Two water-based magnetic fluids with magnetite particles are used. Magnetic fluids have different initial susceptibility (MF № 1 – $\chi_0 = 0.011$, MF № 2 – $\chi_0 = 0.03$) and different contact angle on the vessel wall (MF № 1 does not wet the wall, for MF № 2 the angle varies depending on the process). Transformer and silicone oils are used as the surrounding liquids.

Various stable forms of the magnetic fluid consisting of one, two or three volumes are obtained in the constant magnetic field. The magnetic fluid can shut the gap between the planes.

In the quasi-static magnetic field abrupt changes of the shape and a change in the number of magnetic fluid volumes are observed. In the alternating magnetic field the hysteresis of the shape was found. In the increasing magnetic field magnetic fluid with sufficient volume (V > 1.5 mL for hydrodynamic cell under investigation) rises above the cylinder and shuts the gap between the planes for some field value, and the magnetic fluid bridge is formed. In a decreasing field the magnetic fluid bridge breaks at another small value of the magnetic field. The hysteresis can occur due to the existence of several stable shapes of the magnetic fluid (MF № 1), and due to the hysteresis of the wetting angle (MF № 2).

Statics of fixed volume of MF № 1 is studied theoretically. Various types of the magnetic fluid shape consisting of one, two and three volumes, both symmetric and asymmetric, are obtained. The values of the problem parameters (the magnetic fluid volume, the magnetic field value) at which the bridge is formed between the planes are calculated. The obtained parameters depend on the shape of the bridge. Theoretical and experimental results are in good agreement.

The obtained results may be useful in the development of new types of valves, without the use of motors and moving parts, which allows creating micro-sized devices based on magnetic fluid.

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INFLUENCE OF FLEXOELECTRIC EFFECT ON ORIENTATIONAL STRUCTURES OF FERRONEMATIC LIQUID CRYSTALS

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In the framework of continuum theory the distortions of orientational structures in suspensions of nanosized ferroparticles induced by the magnetic and electric fields were investigated based on nematic liquid crystal (ferronematics). It was assumed that the flexoelectric deformations of director structure appeared under the action of electric field. We considered soft planar anchoring between the director and boundaries of the ferronematic cell and soft homeotropic coupling between the liquid crystal matrix and magnetic particles. The static electric and magnetic fields were applied across the layer perpendicular to the axis of easy orientation in the plane of the layer. In this case, the fields induced deformations of orientational and magnetic structures corresponded to the combinations of splay and bend distortions. We considered ferronematic with low volume fraction of magnetic impurity, so that we can neglect the interparticle magnetic dipole-dipole interaction in a suspension. We took into account the following contributions to the bulk free-energy density of a ferronematic: free-energy density of the director field elastic deformations in nematic liquid crystal (the Oseen-Frank potential); the interactions of magnetic field with liquid crystal matrix and magnetic moments of the ferroparticles; the mixing entropy of the ideal particle solution; the surface coupling energy of the magnetic particle coupling with liquid crystal molecules; the interaction of dielectric liquid crystal with the external electric field and finally, flexoelectric polarization of the director field.

By minimizing the free energy functional of a ferronematic the system of equilibrium state equations for the angles of orientation of the director and magnetization, as well as for spatial distribution of the volume fraction of magnetic particles was obtained. We have shown that there are two uniform states of ferronematic in nonzero magnetic and electric fields. The first one is homeotropic phase, in which the director is parallel to the axes of easy orientation and magnetization is parallel to the external fields. Other state corresponds to the planar phase, in which the director and magnetization are parallel to external fields. We obtained the equations for threshold fields of transitions between the corresponding orientational phases as the functions of material parameters. We have shown that flexoelectric polarization of liquid crystal decreases the threshold electric field of the transition between homeotropic phase and distorted state and increases the threshold electric field of the transition between the planar phase and nonuniform state.

In the vicinity of the transition fields between the homeotropic phase and nonuniform state and planar phase and distorted state the free energy of ferronematic was written in the form of Landau expansion. We showed that such transitions could be the first- or the second order transitions. We have obtained the analytical expressions for the tricritical values of the segregation parameter as the functions of material parameters.

We have studied the spatial distortions of the orientational structures of the director and magnetization, and the concentrational distributions of the magnetic impurity and the phase lag of light passing through a layer of ferronematic as the functions of applied magnetic field and material parameters of a ferronematic. It was shown that the deformation of ferronematic orientational structure essentially depends on flexoelecric polarization, in particular, on the surface polarization changes in the symmetry of director deviation from the easy orientation axes even for equal energies of surface coupling between the liquid crystal matrix and the boundaries of the layer, i.e., the maximum angle of director deviation shifts from the middle of the layer to the boundary.

TRICRITICAL BEHAVIOR OF COMPENSATED FERROMEMATIC WITH NEGATIVE MAGNETIC ANISOTROPY

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The orientational transitions induced by magnetic field between different phases of ferronematic, i.e. suspension of nanosize ferroparticles in a nematic liquid crystal, were studied. We assumed compensated suspension, i.e. in the absence of magnetic field such system has equal numbers of ferroparticles with magnetic moments oriented parallel and antiparallel to the director, so that this ferronematic is not magnetized. We considered a planar layer of ferronematic placed between two parallel plates. We assumed soft and planar coupling between liquid crystal molecules and surface of magnetic particles and rigid planar anchoring of the director with boundary plates. We considered the ferronematic based on nematic with negative anisotropy of diamagnetic susceptibility. In this case the director tends to orient orthogonal to the external magnetic field (quadrupolar mechanism of orientation), but magnetic particles tend to be parallel to the field (dipolar mechanism of orientation). Thus there is a competition between two mechanisms of the field induced orientational response which determines the orientational behavior of a suspension.

By minimizing of the free energy functional with respect to the director, magnetization and volume fractions of both types of ferroparticles with magnetic moments aligned parallel and antiparallel to the director, we obtained the set of differential equations for equilibrium state of ferronematic. These equations can be integrated and we obtained the set of integral equations for the director and magnetization angles deviation from the easy orientation axis and for distributional functions for magnetic particles. The system of equations was solved numerically and in limiting cases analytically.

We have shown that there are two uniform states of ferronematic in nonzero magnetic fields. The first one with the director aligned parallel to the easy orientational axis and compensated magnetization. The second one with the same director orientation and magnetization oriented along the magnetic field (magnetic saturation phase). We found analytical expressions for threshold fields of transitions between uniform and nonuniform states of ferronematic as functions of material parameters.

We have shown that Freedericksz transition can be only the second order one but the transition between nonuniform state and magnetic saturation phase can be the first- or the second order transition. We found analytical expression for the tricritical point where the change of phase transition character takes place.

WALDMEIER'S RULES IN THE SOLAR AND STELLAR DYNAMO CYCLES

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The Waldmeier rules establish [1] the empirical relations between the general parameters of the solar cycle, such as the amplitude, period, the growth rate and the shape of the cycle (ratio between durations of the growing and decaying phases). Some of the Waldmeier rules were established for the stellar cycles in the solar-type stars [2]. The distribution of the magnetic cycle parameters over the solar type stars depends on the properties of the dynamo processes operating in the stellar convection zones. We employ (see details in [3]) the nonlinear mean-field axisymmetric dynamo models and calculate the magnetic cycle parameters, such as the dynamo cycle period, amplitude of the magnetic flux and the Poynting flux from the surface for the solar analogs with rotation periods from 15 to 30 days. The dynamo models take into account the principal mechanisms of the nonlinear dynamo saturation, which include the magnetic helicity conservation, the magnetic buoyancy and the magnetic feedback on the angular momentum balance inside the convection zone. Also, we consider two types of the dynamo models. The D-type models employ the standard α–effect distributed over the whole convection zone. The BL-type models employ the non-local α–effect. Both the D- and BL-types of the dynamo models show the growth of the dynamo-generated magnetic flux with increasing rotation rate. It has been found that for a given range of the rotational periods the magnetic helicity conservation is the most feasible effect for dynamo saturation both for the D and BL-types dynamos. The quenching of the dynamo by the magnetic helicity conservation is even more efficient for the BL-type dynamo than for the D-type dynamo. The D-type dynamo reproduces qualitatively the dependence of the cycle period on the rotation rate for the Sun analogs. For the Sun rotating with period 15 days we have found regimes with multiple cycles. The stars with multiple periods form the second branch in the dependence of the dynamo cycle period on the rotation period of the star.

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GENERATION, ROTATION AND HELICITY OF THE LARGE-SCALE NONAXISYMMETRIC MAGNETIC FIELD IN SOLAR DYNAMO

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It is known that the set of the basic solar parameters such as the rotation period, the typical convective turnover time, and the differential rotation profile do not promote the linear instability for the large-scale non-axisymmetric magnetic field. However, the nonlinear coupling between the global magnetic fields and the non-axisymmetric modes, e.g., due to the magnetic feedback on the alpha-effect, can maintain the large-scale non-axisymmetric dynamo (see, e.g., [1]). The non-axisymmetric random fluctuations of the dynamo parameters can give another source for the non-axisymmetric dynamo on the Sun. Such fluctuations transfer the magnetic energy from the global field to the non-axisymmetric modes. We develop the nonlinear 3D mean-field dynamo model and show some preliminary results about rotation and magnetic helicity of the non-axisymmetric field. It is shown that the solar spectrum of rotation periods for the non-axisymmetric modes corresponds to the field generated in the subsurface shear layer, which is located in the range of depths 0.85–0.95 R. We find that the magnetic helicity of non-axisymmetric field reverses the sign for the high azimuthal number. It is concluded that the 3D mean-field dynamo models can be used for the diagnostics of dynamo processes inside the Sun.

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RESEARCH OF DOWNWARD FLOW OF LIQUID METAL UNDER ONE SIDE WALL HEATING IN COPLANAR MAGNETIC FIELD IN RECTANGULAR DUCT

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Liquid metal is used as a coolant in a few ITER Test Blanket Module projects [1, 2]. It is well known that the hydrodynamic parameters of liquid metal flow with magnetic field and without it differ significantly. The main goal of our investigation is to study the hydrodynamics and heat transfer of a liquid metal downward flow in a rectangular duct. The MPEI-JIHT experimental MHD facility [3] has been used to investigate the flows of mercury in a vertical rectangular duct in the presence of a strong coplanar magnetic field.

The results of measuring the wall temperature, the fields of average and fluctuating components of the flow temperature, the statistic characteristics of temperature fluctuations and the downward flow velocity in the rectangular duct are presented in this paper. The results were obtained over a wide range of Reynolds numbers (Re) from 10 000 to 55 000, Grashof (Gr) numbers up to $5 \cdot 10^8$, and Hartmann (Ha) numbers from 0 to 800.

It has been found that the buoyancy effects have a strong effect on the averaged characteristics of heat transfer. In the magnetic field, this effect leads to generation of low-frequency temperature fluctuations of abnormally high intensity. For example, at Reynolds number Re = 40 000, the intensity of temperature fluctuations with increasing magnetic field does not become lower, as it would be expected, but it will increase and reach its maximum at Hartmann number, Ha = 800. The amplitude of temperature fluctuations can reach 15 °C.

A series of experiments has been performed to determine pressure drop of the downward flow in a coplanar magnetic field in the rectangular duct having conducting walls. The effect of an interaction of the magnetic field with the flow does not lead to a considerable increase in pressure drop.

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MAGNETIC FLUX AT THE BOUNDARY OF THE SOUND BEAM AND THE PULSATING SURFACE OF THE MAGNETIC FLUID

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The expression for the slope of the initial part of the acoustomagnetic effect (AME) curve, presented in relative terms, has the form:

$$tg\theta_A = \frac{\mu_0 m_*}{3k_0 T} \cdot \frac{(1-k')/(1+k''/3)+(\omega\tau)^2}{1+(\omega\tau)^2}, \qquad (1)$$

where m_* is the magnetic moment of the nanoparticles, μ_0 is the magnetic constant, k_0 is Boltzmann constant, M_S is the saturation magnetization of the magnetic fluid (MF), ω is the angular frequency of oscillation, N_d is the dynamic demagnetizing factor, the parameters k' and k'' are described in [1], and $\tau \equiv \tau_1 (1 + N_d M_H)^{-1}$ is the relaxation time of the magnetic moment [2].

The frequency of the variable component of the magnetic field in the radial oscillation of the air bubble in the magnetic fluid corresponds to the expression known in the theory of acoustic cavitation:

$$\nu = (2\pi R_0)^{-1}\sqrt{3\gamma P_0/\rho}, \qquad (2)$$

where R_0 is the bubble radius, P_0 is the hydrostatic pressure, $\gamma = C_p/C_v$ is the ratio of specific heats of the gas in the bubble, and ρ is the density of the breast.

The elastic coefficient of the Kneser-type oscillating system with an incompletely sealed air cavity is written as:

$$k = k_0 + \frac{k_1 \cdot \omega^2\tau^2}{1+\omega^2\tau^2}, \qquad (3)$$

where k_0 and k_1 are the elastic coefficients of the completely and partially sealed air cavities, and τ is the relaxation time of the oscillatory process in the system.

For the experimental study of the processes described by expressions (1)–(3), the alternating magnetic flux initiated by the sound wave and the pulsed surface of the magnetized magnetic fluid are used. The physical fields that are present in these processes are discussed.

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1D AND 2D FEEDBACK DYNAMO EQUATIONS WITH THE ALPHA-EFFECT, DIFFERENTIAL ROTATION AND MERIDIONAL FLOWS

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Basic solar magnetic activity is described by the dynamo equations, which couples magnetic field and fluid velocity. The simplest model of the solar dynamo was proposed by Parker in 1955 as follows. Differential rotation produces a toroidal magnetic field from the poloidal field while the transformation of toroidal magnetic field into poloidal field occurs due to the breaking of mirror symmetry by the plasma fluid convection in the rotating body. The action of the Coriolis force on expanding, rising (and compressed, sinking) vortices results in a predominance of right-handed vortices in the northern hemisphere and left-handed vortices in the southern hemisphere. After averaging over velocity pulsations, the electromotive force produced by Faraday electromagnetic induction acquires a component $\alpha\mathbf{B}$ parallel to the mean magnetic field $\mathbf{B}$. It is this component that closes the self-excitation loop in the Parker dynamo. Recall that usually the electromotive force and the electric current produced by it are orthogonal to the magnetic field.

Analysis of this model showed that the theoretical cycle duration is an order of magnitude shorter than the observed one. Later meridional flows have been entered into the equations dynamo, showing that meridional circulation can influence the wave period. An increase in the intensity of meridional flows resulted in deceleration of the propagation of dynamo waves. In this regard, an interesting question rises regarding the behavior of a self-consistent system where the flows of matter and magnetic fields influence each other. Based on the full system of MHD equation which combines the induction equation with the Navier-Stokes equations including the Lorentz-force we built Parker dynamo model with the feedback of the induced magnetic field on differential rotation and meridional flow. We discuss the results of 1D and 2D simulations.

A METHOD FOR MODELLING MHD FLOWS IN PIPES

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We consider the flow of an electroconducting viscous fluid in a pipe. The fluid moves under the action of a longitudinal pressure gradient. The z-axis of a Cartesian coordinate system is directed parallel to the pipe axis. The intersection of the conduit and xy-plane is the line Γ. The Navier-Stokes system in the presence of a transverse magnetic field can be written as

$$\begin{aligned} &Al\frac{\partial H}{\partial y}+\frac{1}{\mathrm{Re}}\left(\frac{\partial}{\partial x^2}+\frac{\partial}{\partial y^2}\right)V=\frac{\partial p}{\partial z},\\ &\frac{\partial V}{\partial y}+\frac{1}{R_m}\left(\frac{\partial}{\partial x^2}+\frac{\partial}{\partial y^2}\right)H=0, \end{aligned} \tag{1}$$

where H, V are the longitudinal components of velocity and magnetic field, and Re, Al, R_m are the Reynolds, Alfven and magnetic Reynolds numbers. For perfectly conducting walls the boundary conditions are

$$V=0\,,\ \frac{\partial H}{\partial n}=0\,. \tag{2}$$

There are many methods to solve hydrodynamics problems. All of them have some disadvantages. The search for a new method can be interesting in the area of Rvachev functions [1]. In works [2, 3], the authors investigated some problems of hydrodynamic stability using the R-function method and got nice results. It is possible to apply this method to magnetohydrodynamic flows.

The boundary distance function ω_Γ is considered as a function which should be equal to zero on the boundary Γ. This function changes sign only on the boundary. The boundary function can be guessed for simple geometrical figures such as lines or circles. For complex domains, this function is constructed by algebraic combination (conjunction or disjunction) of more simple figures by R-operations (see [1]).

The solution structure for conditions (2) takes the form

$$\begin{aligned} &V=\omega_\Gamma\Phi_1,\\ &H=\Phi_2+\omega^2\Phi_2+D_1\Phi_2, \end{aligned} \tag{3}$$

where Φ_1, Φ_2 are the indefinite components as $\sum_{ij} a_{ij}T_i(x)T_j(y)$, a_{ij} are the coefficients, $T_i(x)$, $T_j(y)$ are the Chebyshev polynomials of the first kind and powers i, j, and $D_1=\frac{\partial\omega}{\partial x}\frac{\partial}{\partial x}+\frac{\partial\omega}{\partial y}\frac{\partial}{\partial y}$. According to (3), the Galerkin method produces a linear algebraic system of equations for a_{ij}.

The proposed method can be used to study flows in pipes with arbitrary complex cross section, including inner elements. The R-function method is also suitable for flow optimization because it does not require mesh generation.

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CLUSTER ANALYSIS OF MAGNETIC FLUIDS

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The microstructure of magnetic fluid produced on the basis of kerosene with oleic acid as a stabilizer was studied. An analytical procedure based on the known dependence of the time of Brownian relaxation of the magnetic moment of the colloidal particle on its size and the expansion of a low-frequency spectrum of dynamic susceptibility into the series of Debye functions is used. Magnetic susceptibility is measured at frequencies from 10 Hz to 100 kHz and temperatures from 225 to 360 K for colloidal solutions with the volume fraction of magnetite from 0.08 to 0.17. The clusters with uncompensated magnetic moments and sizes varying from 50 to 70 nm that are three- or fourfold larger than the mean diameter of a single colloidal particle are found. The contribution of aggregates to the magnetic susceptibility of fluids grows exponentially with a decrease in temperature and becomes prevailing at temperatures below 300–320 K. Weak dependence of the results of analysis on the solution concentration can be considered as an indirect proof of the validity of such an approach. This assumption seems to be quite reasonable, although there is at present no rigorous theory describing the dynamics of fluid magnetization with the account of interparticle interactions and the formation of quasi-spherical clusters. For this reason, the problem of the applicability of the method to strongly concentrated solutions remains unresolved. The obtained temperature dependence of equilibrium susceptibility is compared with that predicted from current theoretical models.

Slight dependence of the aggregate size on temperature contradicts the conclusions drawn on the basis of chain models and can be considered as a confirmation of the hypothesis that the aggregates in magnetic fluids based on liquid hydrocarbons are formed mainly due to the defects of protective shells, and quasi-spherical shape of aggregates is the most probable. The formation of chains is the exception rather than the rule. This conclusion is complete agreement with the data obtained from diffusion experiments and data obtained from experiments with magnetic crossed fields. Apparently, the amount of aggregated particles strongly depends on the preparation technology of magnetic fluid and can vary over a wide range. Therefore, our results are not universal: a certain care must be exercised to extend these results to other types of magnetic fluids. However, it is beyond question that the account of aggregation is imperative for describing the dynamics of dipole systems with intense interparticle interactions.

MACROSCOPIC PROPERTIES OF THE FERROFLUIDS WITH NONSPHERICAL PARTICLES

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Nowadays, different nonspherical particles form the cutting edge of dipolar soft matter research as they correspond completely to the idea of fine tuning and designing new materials with controllable microstructure and as a result various microproperties via changing the properties of the particles. It is important to learn how to design magnetic soft matter in bottom-up manner, because this is the only way to develop nanotechnology and create new smart materials. This work deals with a complex investigation of the system of magnetic nonspherical particles (see, for example, [1, 2]) using different theoretical approaches and computer simulations.

We present results for macroscopic properties (initial susceptibility, radial distribution function, diffusion coefficient) of the systems of ellipsoidal magnetic particles with different dipole orientation and semiaxes ratio, partially investigated in our previous work [3]. An extensive comparison of our theoretical models with the results of molecular dynamics simulation for a wide range of system parameters demonstrated good quantitative and qualitative agreement. As a result, macroscopic responses of the systems significantly change with changing particles parameters (both the shape and orientation of the magnetic moments), which may prove to be very important in various medical and industrial applications, where a bottom-up design of materials plays a crucial part and strong magnetic response of particles should be combined with the absence of strong cluster formation.

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HYDRODYNAMICS AND HEAT TRANSFER FOR A DOWNWARD LIQUID METAL FLOW IN THE RECTANGULAR CHANNEL IN THE PRESENCE OF A COPLANAR MAGNETIC FIELD

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Liquid metals (LM) belong to promising heat transfer fluids for Tokamak fusion reactors where the flow is affected by a strong magnetic field (MF). Here, the governing factors that have effect on the flow include the magnetic field and thermogravitational convection (TGC) that tend to change the flow hydrodynamics and heat transfer.

The problem of verification of calculation codes arises in designing the channels in the newly built ITER reactor. This brings about the need for an extensive array of experimental data on velocity and temperature fields obtained under conditions simulating actual conditions in blanket channels to the maximum possible extent.

The experimental data were obtained at the joint mercury MHD test facility of MPEI & Joint Institute of High Temperatures of the Russian Academy of Sciences. A LM downward flow in a rectangular channel in the presence of a coplanar magnetic field was studied. The test section was a 17 × 56 mm rectangular channel installed between the poles of a DC magnet. The test section has a two-section tape heater that can provide one-side or two-side heating. Temperature fields in the channel were measured with a lever-type probe with a thermocouple.

The experiments were carried with one-side or two-side heating under the following flow conditions: Re = 10 000 ÷ 50 000, Ha = 120 ÷ 800, q_c = 20 000 ÷ 35 000 W/m^2.

The flow in the presence of a coplanar MF [1] is of certain interest as its effect differs from the effect produced by a transverse MF. Recall that the coplanar MF differs from the transverse MF in that it acts along the long channel wall but not along the short one.

As TGC and MF affect the LM flow, it is important to segregate the effect of these two factors. To do this, the model [2] modified to account for the effect of a coplanar MF was used. The temperature profiles calculated by this model include the effect of the coplanar MF only, but not the effect of TGC. Hence, it is the TGC which is considered to be responsible for difference between the predictions and the experiment. It is evident that under the experimental conditions the influence of TGC is considerable and manifests itself in the fact that the temperature profile becomes less elongated.

The results of the comparison of the experimental data with the predicted ones enable us to develop a more intricate computer model, which accounts for the effect of both factors (TGC and MF).

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MAGNETIC FLUID SEALING COMPLEXES OF VAO ELECTRIC ENGINES

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The most common devices that use magnetic fluid are the magnetic fluid seals (MFS). The MFS work well to seal vacuum, gases, vapors, but in more complicated cases to ensure long-term operation of MFS some steps must be taken to minimize contact of magnetic fluid in the seal with sealed medium. For these purposes, various preliminary seals are used.

It should be noted that most of the manufactured magnetic fluid seals "Ferrohydrodynamica" produces as a magnetic fluid sealing complexes (MFSC) – combined seal consisting of a placed in a single package magnetic fluid seal and preliminary compaction, reducing adverse effects of the sealed medium on the magnetic fluid. Usually MFSC are manufactured in regular dimensions of the existing seal assembly. The type and location of the preliminary compaction depend on the sealed medium, operating conditions and requirements for seal, forwarded by the customer.

So, the seals of high-speed electric motors sliding bearings consist of located on the side of the bearing inner optimized labyrinth seal and the outer MFS, placed in the same package as a single structure, the seals of low-speed engines sliding and ball bearings assemblies with liquid lubricants consist of inner lip seal and the outer MFS [1].

At the same time, there are cases when the bearing assembly of the electric motors must be protected by MFS of getting into the oil from the outside – for example, for mining combines, on which gears electric motors are installed. Liquid lubricant oil of gear or clutch coupling if it enters the motor bearing assembly blurs grease of ball bearings and further falls in housing on the motor winding. Here preliminary seal is installed on the outside of magnetic fluid seal.

Examples of devices, which bearing assemblies protect both the inside and the outside, are the VAO electric motors produced in Lysva at "ELECTROTYAZHMASH-PRIVOD" LLC.

The VAO-series explosive-proof asynchronous ventilated electric motors are used widely to drive mechanisms applied in the locations of operation in which the technology of production forms the explosive concentrations of gases, vapors and dust.

MFSC with an outer preliminary seal protected the leakages of clutch coupling oil were installed on the bearing assemblies of VAO-710 and VAO2-630S4U2 electric motors drive the methyldiethanolamine solution pump for the ammonia production at the PJSC "Severodonetsk Azot Association" (Severodonetsk, Ukraine). MFSC with an internal preliminary seal are provided for VAO5-560-2 motors, MFSC with sealing on the outer cylindrical surface of the nut with lock screw – for other models [2].

MFSC installing significantly improves the industrial safety and trouble-free operation of VAO series motors. Namely the use of MFSC increases the degree of protection up to IP 65, which corresponds to the best foreign analogues.

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EXPERIMENTAL INVESTIGATIONS ON MHD-HEAT TRANSFER APPLIED TO TOKAMAK–FUSION NEUTRON SOURCE

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Liquid metals (Pb-Li, for example) and molten salts (LiF.BeF$_2$, LiF.NaF.KF) are the prospective coolants and working media for fusion neutron source (FNS) [1–3]. The many-year experimental study and numerical simulation of liquid metal (LM) flow and heat transfer in a tube affected by longitudinal or transverse magnetic field (MF) under conditions close to FNS have been performed [4]. A specific feature of heat transfer under these conditions is the joint affect of strong MF and thermogravitational convection (TGC), which results in two dangerous effects:

a) the extremely non-uniform distribution of local heat transfer coefficients and wall temperatures along the tube perimeter, possibilities of "degraded" heat transfer and "hot spots";
b) the development of abnormally high low-frequency temperature fluctuations near the tube wall and inside the wall.

Recently, similar investigations have been performed in a vertical rectangular channel (with an aspect ratio of 3/1) in the presence of coplanar MF. Here, the effect caused by abnormally high low-frequency temperature fluctuations was observed in a wide range of flow conditions.

As these channels are of the most practical interest, the observed and investigated effect of extremely high temperature fluctuations must not be neglected as it is hazardous situation for the wall of cooling channels in a fusion reactor because it can result in a fatigue failure of the wall because of fluctuating thermal stresses.

Numerical simulation of MHD LM heat transfer is working out simultaneously with experiments. Good coincidence between the calculated and experimental results is observed.

So, the attempt of LM cooling system design for tokamak leads to previously unknown problems. One can treat molten salts (MS) as interesting alternative of LM for FNS. But the question is: couldn't the designers of MS heat exchangers meet the same problems mentioned above for LM? The results of preliminary analysis come to the conclusion about the real possibility of essential combined effect of strong MF and TGC upon molten salt MHD heat transfer under the conditions of tokamak – fusion neutron source. These phenomena should be considered in the future investigations.

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DYNAMO MODELING IN 2D PARKER'S MODEL

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To the moment there is no doubt that modern dynamo models can reproduce many features of magnetic fields observed on planets and stars. So far only a small part of physical fields (mainly, magnetic fields) penetrates outside of the origin of generation, where it can be measured, the problem of optimization of the model parameters is a crucial point of modern dynamo researches. There are two ways of such optimization: the first one is a solution of the inversed problem. This approach is only started to be considered in dynamo community, because optimization of the non-stationary process is a hard numerical problem itself, and it requires a lot of computer resources. The second possibility is a study of the direct dynamo problem for a various set of parameters. This approach is a good candidate for the clustered computer systems, where communication between the processors is absent, and it is the subject of this study. To test the approach, we considered 2D Parker's dynamo model with two varying parameters: amplitudes of the alpha- and omega-effects. Each processor simulated in time evolution of the system for the unique pair of these amplitudes that resulted in a phase diagrams for some physical quantities: magnetic energy distribution, amplitude of the magnetic dipole, and level of its oscillations. Information on such a phase space can be useful for modeling the transitional regimes, where the properties of the system change quickly, e.g. transitions from the regimes with constant polarity to the regimes with frequent reversals. Taking into account the fact that magnetic fields observed on many planets and stars have dipole structure, we focused our optimization efforts on selection of dipole-dominated fields. The other point is influence of rotation on the dynamo process. The analysis of this influence can be quite sophisticated, and it requires detailed information on the structure of the 3D flow. For this aim we used 3D thermal convection models for precomputing the distribution of differential rotation and kinetic helicity for the geotropic flow, which is related under some assumptions to the alpha-effect.

INFLUENCE OF THERMAL CONDUCTION ON PROPERTIES OF MHD WAVES IN THERMALLY UNSTABLE PLASMA

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In this paper, we describe the properties of MHD waves in the thermally unstable medium taking into account dissipative processes such as thermal conductivity. The thermally unstable state of the medium is a result of the non-adiabatic processes presence. These processes are generally described by the use of the generalized heat-loss function that depends on temperature and density of the plasma medium. It has been shown previously that three types of instabilities can be realized in the medium depending on the parameters of the heat-loss function [1]. The wave dynamics in such non-adiabatic medium can be described by the full set of MHD equations [2]. During our investigation the dispersion relation for magnetoacoustic and thermal modes has been obtained. It has been separated into the relation for the magnetoacoustic waves and the relation for the thermal mode using the approximation of the small thermal conductivity. The dispersion relation for Alfven waves has been derived as well. The condition for the amplification of the magnetoacoustic and thermal waves has been obtained analytically. It is important to emphasize that thermal conductivity does not affect the condition of wave instability presence but it determines the frequency range where amplification can occur. In the low-frequency limit dissipation processes are negligible and amplification is governed by isentropic instability condition that is equivalent to the negativity of the bulk viscosity [3]. In the high-frequency limit magnetoacoustic waves are damped due to dissipation processes caused by thermal conductivity. The threshold frequency of the MHD wave's amplification has been obtained during our investigation. Besides, we have analyzed the wave properties (phase velocities and wave increments) of magnetoacoustic waves propagating perpendicular to the external magnetic field under the solar corona conditions. The frequency dependences of the waves phase speeds and increments have been shown. The analysis has been conducted by the use of the modern cooling function models [4, 5] and various probable heating scenarios of the solar corona. As a result, we have found the heating scenarios which can lead to magnetoacoustic wave's amplification and the ranges of temperature and frequency where amplification can occur.

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MICROSTRUCTURE OF BRUSHES OF SUPRAMOLECULAR FERROMAGNETIC FILAMENTS

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Supramolecular magnetic brushes consist of a layer of permanent chains of magnetic colloids grafted with one end to a surface. Such permanent chains of magnetic colloids, known as magnetic filaments, are usually obtained by crosslinking the colloids with polymers or other molecules to form a supramolecular polymer-like structure [1, 2]. These systems represent a promising approach to make magnetoresponsive nanocoatings with several prospective applications [3, 4].

In this contribution we present our recent progress on the theoretical study of supramolecular magnetic brushes. In particular, we focus on brushes made out of magnetic filaments formed by ferromagnetic colloids with a permanent magnetic moment fixed with respect to their internal structure, and crosslinked by means of semiflexible polymers permanently attached to their surfaces. For this kind of magnetic filaments we recently introduced a coarse-grained bead-spring model [5, 6] that here we use to determine the equilibrium structural behavior of the brushes under different conditions. The study is based on a combination of extensive computer simulations and analytical theories. Our preliminary results show that, even in absence of external fields, the overall structure of the brush is significantly different from the one corresponding to a non magnetic polymer brush. We also pay a special attention to the microstructure of the brush, which is studied by means of connectivity clustering techniques.

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THE MAGNETOHYDRODYNAMIC PROCESSES WHEN FORMING NANOSTRUCTURES AT MAGNETIC PULSE

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Our previous experiments have revealed the formation of nanostructural layers in the gradient structures under the influence of heterogeneous streams of plasma. To explain the results of these experiments, we proposed a new mechanism and mathematical model describing the formation of nanolayers moving relatively each other within the zone of melted materials as a result of development of instability, (instability Kelvin-Helmholtz) [1, 2]. The influence of a magnetic field on the thermocapillary instability of suppressions is well known. The interaction of longitudinal magnetic fields with a layer of carrying liquid is poorly understood, and in the nanodimensional range is generally unknown. In this work, the dispersion equation is derived and its analysis in the nanodimensional range is carried out.

To form gradient structures with nanostructural layers we used a magnetic pulse field, generated in a specially developed device. The device operated on the energy of capacitor and consists of pulse high-voltage condensers and one round flat inductor. The maximum energy of the device was about 20 kJ.

This pulse causes metal fusion and generates the electromagnetic force non-uniformly distributed through the layer thickness, which leads to the development of magnetic and hydrodynamic instability (MHI) in the nanodimensional range. After crystallization of metal the gradient structure with a nanostructural underlayer of about 1 micron and of general depth up to 100 microns is formed. This gradient structure provides high durability of the products and specific superficial properties. For parameterization of our experiments we cannot use the known results on MHI because they were not studied in the nanodimensional range.

The condition for creation of superficial nanolayers, which was obtained from the developed mathematical model, can be used as a basis for determining the parameter range of magnetic-pulse effect. Preparation of nanolayers from technically pure titan will allow researchers to apply the new approach to production of implants. Besides, the creation of the strengthening layer on the surface of a product allows one to exclude the process of preliminary strengthening, which considerably reduces the cost of implants.

The parameter, defining positive indicators of osteointegration under the subsequent functional loading of the implants, is the quality of interaction between the biological fabrics and the implant surface. In our approach an improvement of these indicators is achieved by creating the required nanostructural surfaces on technically pure titan under the action of magnetic-pulse taking into account the specific properties of particular types of bone tissues and their biophysical characteristics.

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MHD MODELING OF PROCESSES IN NEAR-EARTH SPACE PLASMA: FROM THE PROCESSES AT THE BOW SHOCK REGION TO THE MAGNETOSPHERE–IONOSPHERE COUPLING PROCESSES

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It is clear that the primary energy source for magnetospheric processes is the solar wind, but the process of energy transfer from the solar wind into the magnetosphere, or rather, to convecting magnetospheric plasma, appears to be rather complicated. The solar wind energy also feeds the ion acceleration process, the generation of waves in the region of bow shock, and the energy necessary to build up the foreshock. Bow shock is a powerful transformer of the solar wind kinetic energy into the gas dynamic and electromagnetic energy [1]. A jump of the magnetic field tangential component at front crossing means that the front carries an electric current. The solar wind kinetic energy partly transforms to gas kinetic and electromagnetic energy during its passage through the bow shock front. The transition layer (magnetosheath) can use part of this energy for accelerating of plasma, but can conversely spend part its kinetic energy on the electric power generation, which afterwards may be used by the magnetosphere. Thereby, transition layer can be both consumer (sink) and generator (source) of electric power depending upon special conditions. The direction of the current behind the bow shock front depends on the sign of the IMF Bz-component. It is this electric current which sets convection of plasma in motion. The electric current from the generator at the bow shock front is responsible for the power needed to compress plasma tubes during their motion toward the Earth. The plasma tube volume constantly decreases, and this means that pressure increases at a uniform adiabatic compression.

Direct observations of plasma distribution in the magnetosphere are faced with large difficulties, because pressure must be known everywhere in the plasma sheet at high resolution, which in situ satellites have been unable to provide. As shown by Waters et al. (2001), a map of global field-aligned currents can be constructed with hourly resolution using magnetometer data from the Iridium System consisting of 66 satellites in circular polar orbits. Modeling of distribution of plasma pressure (on ~3–12 R_E) is very important, because the data from multisatellite magnetospheric missions for these purposes would be a very expensive project. Therefore, there is a necessity to model the processes of near-Earth space. Selecting and applying the correct initial system of equations are also very important [2]. A combined action of convection of plasma tubes and pitch-angle diffusion of electrons and protons lead to the formation of plasma pressure distribution in the magnetosphere. Specifying the initial pressure at the boundary, we can find the resultant pressure at any point on the flux line. In such a way, the field of plasma pressures in the magnetosphere is calculated. In this study we determined the more precise expression for plasma pressure distribution calculation. The expression takes into account particles with energy up to 300 keV.

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DEFORMATION OF FERROFLUID DROPLETS UNDER THE INFLUENCE OF AN EXTERNAL FIELD. COMPARISON BETWEEN THEORY AND COMPUTER SIMULATION

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A ferrofluid is a stable colloidal suspension of sub-domain magnetic particles in a liquid carrier. The particles of magnetic material have an average size of about 100 Å (10 nm). Due to the small size of the particles they are in constant thermal motion, which, in combination with different chemical stabilization methods, prevents their aggregation and precipitation. The feature of magnetic fluids is their ability to significantly interact with external magnetic fields and retain the properties of the fluid. One example of such interaction is the deformation of the magnetic fluid droplets suspended in a liquid medium under the influence of an external magnetic field: applied magnetic field tends to elongate the droplets along the field direction. This effect becomes more significant than less the interfacial tension at the boundary between the magnetic fluid and the liquid carrier.

In the theoretical investigation of the behavior of ferrofluid droplets under the action of external magnetic field, an approach to homogeneous magnetic media is used, and the droplet shape is an elongated ellipsoid of revolution [1–3]. The results of this approach show good agreement with experimental data in the case of sufficiently weak external fields.

With the development technology of computer simulation, it becomes possible to simulate macroscopic samples with regard to their complicated microstructure, which is a convenient way of understanding the properties of complex objects like droplets. This approach allows modeling the deformation of the magnetic fluid drop starting from the microstructural features of the material.

This work is devoted to a comparison of the theoretical approach to modeling the behavior of the magnetic fluid with the results of computer simulations based on modeling ferrofluid microstructure.

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SYMMETRIC PHASE OF THE EARLY UNIVERSE:
BARYON ASYMMETRY AND HYPERMAGNETIC HELICITY EVOLUTION

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We study hypermagnetic helicity and lepton asymmetry evolution in plasma of the early Universe before the electroweak phase transition (EWPT) taking into account the chirality-flip processes via inverse Higgs decays and sphaleron transitions, which violate the left lepton number and wash out the baryon asymmetry of the Universe (BAU).

This process is described by a system of integro-differential equations with some arbitrary parameters. So, we consider the monochromatic and continuous spectra of maximum and arbitrary helicity density and the large and small initial values of leptons.

In this work we calculate numerically baryon asymmetry, hypermagnetic helicity and evolution of right leptons.

MAGNETIC FIELD EVOLUTION IN A CONDUCTING FLUID WITH A JUMP OF THE VELOCITY FIELD

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We study asymptotic solutions of the MHD system for incompressible fluid. We assume that the velocity field is varying rapidly in a small vicinity of a moving 2D-surface. In the linear approximation we prove that the magnetic field grows instantaneously in the points of the surface, forming delta-type spatial structure. For the nonlinear system the behavior of the solution depends essentially on the influence of the magnetic field on the movement of the surface. If the surface moves along the trajectories of the velocity field, the small initial magnetic field grows instantaneously with respect to the small parameter. The leading part of the asymptotic solution satisfies the nonlinear system which is in certain sense close to the Prandtl equations of the boundary layer. However, if the surface moves along the trajectories of the sum of the velocity and the magnetic field, there is no growth and the leading term of the asymptotics satisfies the linear system.

COSMIC MAGNETIC TURBULENCE IN THE RANDOM WALK MODEL

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The most important factor determining the behavior of cosmic rays (CR) in Space is magnetic field, characterized by pronounced turbulent character. For this reason, many calculations of cosmic ray propagation are based on the diffusion model or its modifications. The common feature of approaches is the parabolic type equations, assuming the Markov character of the process. This implies statistical independence of points of particle interaction with environment, as in the case of diffusion of heavy particles in an ideal gas, where positions of molecules are truly independent. The environment in which cosmic rays propagate is arranged in a quite different way, intricately meandering magnetic field lines penetrate the space, and there can be no question about any independence (and, therefore, Markovian property).

The report focuses on the modeling of correlated inhomogeneous magnetic environment where simulations of CR particle trajectories are planned. If one applies the term "randomization" to this method, then the modeling of CR transport as "walk on walk" can be considered as a secondary randomization. Non-Markovian nature of the interstellar field is simulated by applying non-local operations to random processes such as Brownian motion, Poisson or telegraph process. The integrodifferential operator of fractional order [1] and some of its modifications are used. The simulation results are easily matched to the solutions of the Shalchi-Kourakis equations [2] for anomalous correlation functions that are sufficiently different from the correlation function of the Brownian motion. This indicates the fundamental difference of the class of particle trajectories in such environment from infinitely fractured Brownian prototypes. In contrast to those, the trajectories of particles moving along smoothly but writhing magnetic field lines lead to the non-Markov process.

The report provides technical details of the calculations and presents numerical results demonstrating the reliability and efficiency of the approach. The results are applied to interpretation of Ulysses and Voyager spacecrafts data on solar cosmic rays fluxes and to other problems.

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SIMULATIONS OF OSCILLATORY ELECTROCONVECTION IN A HORIZONTAL CAPACITOR WITH LARGE ASPECT RATIO

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Traveling wave structures are numerically investigated in a low conductive liquid layer subjected to an electric field and a thermal gradient. The following set of parameters is used: the Rayleigh number Ra = –1000, the Prandtl number P = 10, the parameter characterizing the mobility of charges M = 30, and the ratio of the concentration of residual and injected ions $C_0/C = 0.2$ [1, 2]. Two-dimensional spatially periodic electroconvective flows are analyzed in a horizontal capacitor with a large aspect ratio of 60. This computational domain corresponds to forty wavelengths of perturbations which are most dangerous in accordance with the linear theory. The trajectories of the vertical velocity nodes corresponding to the coordinate $z = 1/2$ are presented on the characteristic (x, t) plane. The inverse tangent of the trajectory slope defines the velocity of the corresponding node. The Fourier decompositions of the temporal evolution and spatial distributions of stream function were used for analysis of the traveling wave structures.

Near the instability boundary the main frequency of the stream function oscillations at a fixed point of the capacitor coincides with the frequency of neutral oscillations. It is found that the interaction of different spatial harmonics generates an amplitude-modulated traveling wave: the intensity of convective vortices in the traveling wave varies along the horizontal axis. It is shown that with increasing supercriticality (the electroconvective parameter) the traveling wave structure is complicated due to growth of the number of spatial harmonics.

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TOWARDS UNDERSTANDING OF DYNAMO ACTION IN M-DWARFS

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Intensive investigations of stellar magnetic activity already have about a 40 year history and many important results have been obtained here. On the one hand, this activity is believed to be similar to some extent to the solar cyclic activity. In particular, magnetic field of many types of stars is believed to be excited by stellar dynamo action driven by a joint action of differential rotation and an additional mirror-asymmetric driver which produces poloidal magnetic field from toroidal. The physical nature of this factor is still disputable for the Sun and maybe even more so for other stars. However we have no intention to enter this discussion at the instant and for the sake of simplicity refer this factor as alpha-effect whatever physical nature it has. On the other hand, magnetic activity in a particular star can look quite specific in comparison with the solar case: star spots on the most investigated magnetically active stars are much larger than the solar ones, cover a larger part of the surface rather sunspots, etc. These specific features should be somehow related to the properties of stellar dynamos; however in practice this relation is understood much less than it is desirable. In particular, the relation between magnetic phenomenology of M-dwarfs and underlying stellar dynamos is a topic of continuous discussions in the relevant scientific meetings. Experts in observational investigations of star spots on M-dwarfs stressed many times in such discussions that an instructive contribution from dynamo theory in the problem is highly desirable: there is a general feeling that there is a basic difference between dynamo action in M-dwarfs which are fully convective stars and the Sun with a relatively thin convective shell. Considering stellar dynamo theory, there are many stellar dynamo models that explore various details of stellar dynamo action for various stars including M-dwarfs. However experts in dynamo theory avoid taking risks in formulating clear predictions accessible for observational verification. As a result, we have arrived at a strange situation that the fantastic progress in observational and theoretical abilities in last 40 years has resulted in progress in the physical understanding of the problem which looks less optimistic than might have been expected. Our feeling is that a coordination of efforts between observers and dynamo modellers is highly desirable for further progress in the topic. We see the format of the coordination as follows. A risk has to be taken and a particular approach in dynamo models has to be accepted as a starting point, a list of magnetic configuration which can be expected for M-dwarfs in the framework of this basic model have to be described, together with observational tests sufficient to be distinguished observationally. If possible, the existing observational data have to be used to identify the configurations, and the perspective of future observations should be discussed. The point is that the full inspection of the list may (and will) be quite demanding on telescope time and other material resources, and the community have to make a reasonable decision how to manage the resources to achieve the goal. Further elaborations of the model have to be motivated by particular difficulties in interpretation of observations. Magnetic activity of M-dwarfs is far from being the only branch of knowledge where the coordination between observations and theoretical understanding is required for effective progress.

THE INFLUENCE OF POLYDISPERSITY ON THE MAGNETIC SUSCEPTIBILITY OF CONCENTRATED FERROFLUIDS

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Ferrofluids are stable colloidal systems of ferri- or ferromagnetic nanoparticles, which are suspended in a liquid carrier. The diameters of the magnetic cores generally fall within the 1–10 nm scale, but they are rarely uniform within a given sample, leading to considerable particle-size polydispersity. The theoretical analysis of magnetic properties allows us to describe the particle-size distribution more effectively than microscopy techniques.

The most important characteristic is the initial magnetic susceptibility χ determining the magnetic response of the ferrofluid to a weak applied magnetic field. The universal representation of χ is given by the known modified mean-field theory [1], which approximates the initial magnetic susceptibility as a series over the Langevin law χ_L:

$$\chi = \chi_L \left[1 + \frac{4\pi\chi_L}{3} + \frac{(4\pi\chi_L)^2}{144} \right]. \qquad (1)$$

But this simple expression is not able to describe properly the magnetic susceptibility of the super dense ferrofluid, which was synthesized by Perm researchers in early 2000s [2].

In the case of monodisperse ferrofluids [3], the representation (1) can be extended to include positive corrections for the order of the dipolar coupling constant λ, which is the ratio of the magnetic interaction energy of two particles at close contact with the perfectly co-aligned dipole moments m^3/d^3 to the thermal energy kT:

$$\chi = \chi_L \left[1 + \frac{4\pi\chi_L}{3} \left(1 + \sum_{i=1}^{\infty} c_i \lambda^{2i} \right) + \frac{(4\pi\chi_L)^2}{144} \right], \; c_i > 0 .$$

The calculation of these corrections for ferrofluids with particle-size polydispersity was outlined in [4]. It turns out that the effects of polydispersity on the initial susceptibilities of ferrofluids the parameter λ should be replaced by a different parameter, denoted by Λ, which contains a complicated double average over the particle-size distribution. This parameter Λ more than twice exceeds the commonly used effective polydisperse dipolar coupling constant λ for real particle size distribution.

Taking into account the polydispersity allowed us to achieve good agreement with the experiment data [2] for some fitting parameters. However, a comparison with computer simulations for highly polydisperse system shows the need to calculate the next correction for $\chi_L^{\,3}$, which was defined in this work:

$$\chi = \chi_L \left[1 + \frac{4\pi\chi_L}{3} \left(1 + \sum_{i=1}^{\infty} C_i \Lambda_i^{\,2i} \right) + \frac{(4\pi\chi_L)^2}{144} + (4\pi\chi_L)^2 \left\{ \frac{74}{24000} \tilde{\Lambda}_1 + \frac{3\ln 2 - 7}{360} \tilde{\Lambda}_2 \right\} \right].$$

The obtained term in curly brackets is negative and therefore it improves the agreement between the theory and computer simulation, where fitting parameters are absent.

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2D FRACTIONAL BROWNIAN MOTION-SIMULATION APPROACH FOR SAS NANOPARTICLE DISPERSION DATA

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Small-Angle X-ray Scattering (SAXS) is a non-destructive method for investigating nanostructures in liquids and solids. The method is very useful to analyze sample inhomogeneities on a length-scale of 1–100 nm and to determine the nanoscale structure of systems in terms of such parameters as averaged sizes, shapes, distribution, and surface-to-volume ratio.

This technique is one of the most important for investigation of the structural properties of fractal systems. In case of random fractals, different models for mass and surface fractals have been developed and applied to material studies.

The power law behavior of the scattering curve is

$$I(q) \sim q^{-\alpha} \quad ,$$

where α is the power law scattering exponent, indicate on scatterers fractal structure. $I(q)$ is the scattered intensity and $q = \frac{4\pi}{\lambda}\sin\theta$, where 2θ is the scattering angle, and λ is the incident wavelength. The exponent α contains information on the fractal dimension of the scatterers: $\alpha = D$ for mass fractals and $\alpha = 6 - D$ for surface fractals. In the particular case of a mass fractal $D_m = \alpha$, $2 < \alpha \le 3$ and, in the case of surface fractal $D_s = 6 - \alpha$, $\alpha > 3$.

Fractional Brownian motion (fBm), first introduced by Kolmogorov [1] and made popular by Mandelbrot and Van Ness [2], was proved to be quite useful in many applied areas including telecommunications, as well as signal and image processing. The constant parameter *H* called the Hurst parameter is directly related to fractal dimension, D such that $H = d + 1 - D$, where d is the dimension of the supporting space. The values of the Hurst exponent vary between 0 and 1, with higher values indicating a smoother trend, less unpredictability, and less roughness [3].

In the present work, a series of tests has been carried out to verify the capability of a 2D fractional Brownian motion (2DfBm) method to simulate microstructure configurations in several nanoparticulate samples, including biogenic particles [4], by calculating Hurst parameters from the experimental power law dependence of the SAXS scattering intensity.

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LIQUID METAL EXPERIMENTS ON DYNAMO ACTION, MAGNETOROTATIONAL INSTABILITY AND CURRENT-DRIVEN INSTABILITIES

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Magnetic fields of planets, stars and galaxies are generated by self-excitation in moving electrically conducting fluids. Once produced, cosmic magnetic fields can play an active role in cosmic structure formation by destabilizing rotational flows that would be otherwise hydrodynamically stable. For a long time, both effects, i.e. hydromagnetic dynamo action and magnetically triggered flow instabilities, have been the subject of purely theoretical investigations. This situation changed in 1999 when the threshold of magnetic-field self-excitation was exceeded in the two liquid sodium experiments in Riga and Karlsruhe [1, 2]. Since 2006, the VKS dynamo experiment in Cadarache has successfully reproduced many features of geophysical interest such as reversals and excursions. In the same year, the helical version of the magnetorotational instability (MRI) was observed in the PROMISE experiment in Dresden-Rossendorf [3]. More recently, the azimuthal MRI was found at the same facility [4]. First evidence of the current-driven Tayler instability in a liquid metal was obtained, too [5].

The lecture gives an overview about liquid metal experiments on dynamo action and magnetically triggered instabilities. It concludes with an overview about future experiments, including a precession driven dynamo and a large-scale Tayler-Couette experiment to be set-up in the framework of the DRESDYN project [6].

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MHD TURBULENCE IN SPACE, LABORATORY AND COMPUTER

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Magnetohydrodynamic (MHD) turbulence is characterized by nonlinear interactions among fluctuations of the magnetic field and flow velocity over a range of spatial and temporal scales. It is ubiquitous in space and astrophysical plasmas and plays an important role in physical processes like plasma heating, the transport of energetic particles, and radiative transfer. The solar wind and the diffuse interstellar medium (ISM) are both examples of plasmas that exhibit turbulent behavior, as evidenced by the power spectra determined from radio propagation observations. Also MHD turbulence is at the heart of the dynamo action generating magnetic fields in planets, stars and galaxies.

The theoretical understanding of magnetized turbulence suggested in the review can be subdivided in two parts: properties of cascades in the inertial range and turbulent transport confidents. The first part deals with the phenomenological description of the energy and helicity spectra under different conditions, i.e. global rotation or applied magnetic field. It is curious to compare these theoretical predictions with the results of direct numerical simulations and the shell models. The second part contains a review of turbulent effects involved in the dynamo process of the large scale magnetic field. It is discussed in relation to the results of laboratory experiments and possible interpretations of the astrophysical observations.

MAGNETIC NANOPARTICLE HYPERTHERMIA WITH ALLOWANCE FOR THE NÉEL AND BROWN RELAXATION MECHANISMS

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Nowadays magnetic hyperthermia is an issue of intense international research. The work, both theoretical and experimental, is developing inspired by the premonition that the method is close of being set into practice [1–4]. In this context, the challenge for magnetic science is to provide fundamental basis for predicting the amount of heat produced by the embedded single-domain nanoparticles. Such a particle, whose magnetic moment $\boldsymbol{\mu}$ has a constant length, dissipates the energy of the imposed ac field via two channels. First, the field makes $\boldsymbol{\mu}$ to rotate inside the particle, and the heat generated by internal friction is ejected outside by way of thermal conductivity. On the other hand, owing to the orientation-dependent anisotropy (bulk, surface and shape), the magnetic moment is coupled with the particle body. As a result, the internal motions of $\boldsymbol{\mu}$ make the particle to rotate with respect to the matrix. This motion induces a flow around the particle so that viscous dissipation heats the matrix directly.

Hereby we analyze the joint dissipation process under an ac field in a magnetic suspension. This is done by solving in full of the extended Fokker-Planck equation [5]

$$\frac{\partial}{\partial t}W = \left\{ \frac{1}{2\tau_B}\left(\hat{\boldsymbol{J}}_e + \hat{\boldsymbol{J}}_n\right) W \left(\hat{\boldsymbol{J}}_e + \hat{\boldsymbol{J}}_n\right) + \frac{1}{2\tau_D}\hat{\boldsymbol{J}}_e W \hat{\boldsymbol{J}}_e \right\} \left(\frac{U}{kT} + \ln W \right), \qquad (1)$$

for the probability density $W(\boldsymbol{e},\boldsymbol{n},t)$ of various orientations of the magnetic moment and the easy magnetization axis of a ferroparticle. Here, $\boldsymbol{e}$ and $\boldsymbol{n}$ are the respective unit vectors, $U(\boldsymbol{e},\boldsymbol{n})$ is the orientation-dependent part of the particle energy, $\hat{\boldsymbol{J}}_e = (\boldsymbol{e} \times \partial / \partial \boldsymbol{e})$ and $\hat{\boldsymbol{J}}_n = (\boldsymbol{n} \times \partial / \partial \boldsymbol{n})$ are the operators of infinitesimal rotations with respect to $\boldsymbol{e}$ and $\boldsymbol{n}$, while τ_B and τ_D are the relaxation times of the external and internal diffusion processes.

The results are given in terms of specific loss power (SLP) and applied to a model maghemite colloid with the reference particle diameter ~10 nm. The developed description renders SLP as a function of the main material parameters of magnetic nanodispersion: particle magnetization, fluid anisotropy, and so-called “magnetic” viscosities. A full solution of Eq. (1) for the linear case (weak field amplitudes) has been presented recently in [6]. The results obtained there were shown to unify several previously existing approximate models of SLP and to correct some of them. The frequency and temperature dependencies of SLP have been discussed in view of crossover of the absorption mechanism from the external (Brownian) to the internal (Néel) one under frequency or temperature increase/decrease. In the present work we report the effect of ac field amplitude on SLP.

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EXPERIMENTAL SETUP FOR MEASUREMENT OF THE TORQUE ON FERROFLUID SAMPLES IN ROTATING MAGNETIC FIELDS

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Magneto-hydrodynamics of ferrofluids include complex phenomena, and the understanding of fundamental effects of their dynamics as well as a quantitative characterization of material parameters are important both from a fundamental physics point of view as well as for application purposes. We are going to conduct a straightforward experiment to characterize the behavior of ferrofluids under the influence of an external rotating magnetic field. Earlier experiments with non-rotating oscillatory fields confirmed a thermal ratchet effect in ferrofluids [1], based on a rectification of Brownian motion. For a quantitative analysis and correct interpretation of this phenomenon, the understanding of the much simpler reorientation in a continuously rotating field is vital. Theoretically, the reorientation in uniformly rotating magnetic fields appears to be related to the model describing the dynamics of anisotropic fluids (nematics) in such fields, by proper substitution of the diamagnetic torque with that on magnetic dipoles. The magnetization direction of the particles in a rotating magnetic field follows the field with a certain phase lag, defined by the balance of magnetic and viscous torques.

The experimental method is basically similar to that used in [2]. Glass sphere with a diameter ~2 cm is completely filled with magnetic fluid and fixed on a long thin glass string. The obtained rotational pendulum is placed in Helmholtz coils system creating a rotating magnetic field. The size and shape of the magnetic field are determined by sensors SS94A1F, connected to a digital channel oscilloscope operating in parametric mode. Directly under the rotational pendulum we placed a web-camera, which records the rotation of the sphere with a magnetic fluid where a contrasting mark was pre-printed. The angle of rotation of sphere is calculated by special MatLab application which recognizes the start and the end positions of the mark. To prevent a sphere heating due to the Helmholtz coils, we put the sphere with a magnetic fluid into a water filled cell with a flat bottom.

Using this experimental setup we measured the torque on ferrofluid samples in rotating magnetic fields. A sphere was filled with various samples of magnetic fluids, the frequency and magnitude of the external magnetic field are in the ranges of 5–50 Hz and 0–20 kA/m. The experimental results can be used in interpreting experimental data [2] on ratchet effect observed in ferrofluid.

We have done this work according to the task of the Ministry of Education and Science of the Russian Federation. Project Code 3.1941.2014/K.

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NUMERICAL STUDY OF THE CONVECTIVE FLOW OF LIQUID METAL IN A VERTICAL CYLINDER

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This work was conducted to study the process of titanium production via metallothermic reduction. Control of the reaction during this complex physical-chemical process is one of the essential problems of metallurgical production. Large mass and dimensions of the retort as well as very high temperatures make difficulties for the direct experimental measurements inside the reactor. Therefore, there is the motivation for the numerical study of the process.

The purpose of the work is to develop a hydrodynamic model of the process and use this model to study the influence of convective flow on the reaction. All the previous studies devoted to the mathematical modeling of the process [1, 2] have used only stationary and axisymmetric statement of the problem. This is quite restrictive assumption given that the characteristic Grashof number of the process is $\approx 10^{12}$. In this work the mathematical model is based on the non-stationary equations of free convection written for three-dimensional case.

The retort for metallothermic reduction of titanium is a vertical cylindrical vessel filled with melted magnesium. During the process the titanium tetrachloride is fed into the reactor from the top. The chemical reaction on the surface of the liquid metal produces titanium sponge and magnesium chloride, which sink to the bottom of the retort. The reaction is exothermic, and therefore the area on the top surface of the magnesium layer has high temperature. In order to prevent overheating, the airflow is used for cooling side walls in the reaction zone. Heating from the top and cooling from the side walls lead to the substantial horizontal temperature gradient which generates convective flow inside the reactor. The structure of this convective flow may have the influence on the reaction process. In particular, change of the regime of the convective flow may lead to the "nonseparated regime", that is the situation when the magnesium chloride remains on the surface and does not sink to the bottom. In this case the process terminates.

In the present work we study the convective flow of only one phase in the reactor – liquid magnesium. We do not consider the contribution to the flow made by the second liquid phase – magnesium chloride and the porous medium – titanium sponge. The mathematical model is based on the Boussinesq equations for free convection of incompressible fluid in three-dimensional case. Discretization of the equations was done with finite volume method. The simulations carried out on numerical grid with 4.5 millions of nodes. The large eddy simulation (LES) approach was used for resolving of the sub-grid small scale turbulence. We used free and open source CFD software package OpenFOAM Extend 3.1. Numerical simulations were performed using «Triton» supercomputer of ICMM UB RAS, Perm.

The computational domain was a cylinder with the following dimensions: radius $R = 0.75$ m, height $H = 2.5$ m, the height of the cooled part of the side surface $h = 0.7$ m. The convective parameters of the medium correspond to the liquid magnesium at 850 °C. It was shown that at Grashof numbers up to $Gr = 10^7$ the fluid flow are stationary and axisymmetric. However with increasing of the Grashof number the flow becomes non-stationary and non-axisymmetric, the very pronounced boundary layer appears. The higher Grashof number leads to the thinner boundary layer. In case of the Grashof number corresponding to the real process in the titanium reduction reactor ($Gr = 2\cdot10^{12}$), the flow velocity in the boundary layer is 6 cm/s, and the velocity at the central part of the retort $\approx$ 4 cm/s.

Financial support from the RFBR (project No 13-01-96042) is gratefully acknowledged.

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THERMODYNAMICS OF DIPOLAR SQUARE-WELL FLUIDS IN THE EXTERNAL MAGNETIC FIELD

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The thermodynamic properties of a dipolar square-well fluid in the external magnetic field are studied theoretically. The theory is based on the virial expansion of the Helmholtz free energy. The second and third virial coefficients are calculated as functions of the dimensionless temperature, the reduced dipolar interaction parameter, and the potential well width. Following [1], the analytical expressions for the virial coefficients are incorporated into various forms of virial expansion for the Helmholtz free energy and the equation of state. Finally, predictions of the critical parameters for the condensation transition are obtained on the basis of the virial expansion of the Helmholtz free energy and compared with computer-simulation results available in the literature.

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EXPERIMENTAL STUDY OF LIQUID SODIUM HEAT TRANSFER IN A CYLINDRICAL VESSEL AT LOCAL HEATING OF ITS UPPER BOUNDARY

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Control of reactions during the process of recovering titanium sponge in a metal-thermal reactor is one of the acute problems of metallurgical production. A process for recovering titanium sponge employs an exothermic reaction between titanium tetrachloride (TTC) and molten magnesium, during which titanium tetrachloride is recovered to the state of sponge-like titanium with formation of a by-product, magnesium chloride. Liquid titanium tetrachloride is fed into the apparatus onto the surface of molten magnesium heated to 750…800 °C, where it enters into the exothermic reaction with heat generation and vapors, forming a gaseous phase inside the apparatus. Temperature in the reaction zone can exceed 1000 °C and therefore the upper part of the apparatus is cooled and its lower part is simultaneously heated. This initiates turbulent convective flows in the magnesium melt. A necessary condition for successful implementation and application of a hydrodynamic model is to create an experimental base for verification of a computational investigation.

In the present work, we study the flow of liquid sodium in a vertical cylindrical channel with a non-uniform temperature distribution on the upper boundary of the cylinder. The experimental setup for studying turbulent convection in liquid sodium with local heating and from above cooling is a cylindrical stainless steel channel. The channel wall is 8 mm thick, 700 mm long and has an inner diameter of 201 mm. The channel is mounted on the frame in a vertically aligned position. In the side wall of the channel there are ten gasket seats for thermocouples forming two vertical lines. A heat exchanger on the upper boundary of the channel is used for heating liquid sodium in the central part of the channel and for cooling around the channel periphery. Spiral heaters wound around a copper cylinder are used to generate high temperatures in these areas. One end of the cylinder comes into contact with liquid sodium in the central circular area of diameter 40 mm. Thus the heat generated by the spiral heaters is transferred through the copper cylinder into liquid sodium.

The main element of the cooling system is a 20 mm thick copper base frame. The copper plate of such a thickness equalizes fairly well temperature field inhomogeneities inside it. The plate is connected to the end of the cylindrical channel. An air needle-plate heat exchanger is attached to the plate. Measuring thermocouple junctions are at the copper frame/liquid sodium interface. With these thermocouples one can measure the temperature of liquid sodium on the boundary between heating and cooling regions. In experiments, an average temperature of liquid sodium and its volume may vary, which causes the necessity to use a heated expansion vessel. At some experimental stage a steady state can be achieved in the setup. This state is characterized by some temperature difference between heating and cooling regions. At the same time, the flow develops in liquid sodium, and temperature fluctuations may take place in these regions. Temperature is measured using all thermocouples, and the results are analyzed by spectral and cross-correlation analysis techniques.

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STATIC SHAPE OF THE MAGNETIC FLUID COVERED BY AN IMPERMEABLE FILM IN THE FIELD OF A LINE CONDUCTOR

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The free surface of a magnetic fluid changes its shape near a line conductor while a current is slowly changing. For some values of the current, a shape hysteresis and spasmodic phenomena may be observed. For small magnetic fields in [1], the spreading of a ferrofluid drop along a wire in case of wetting was studied theoretically and observed in the experiment. Taking into account the results obtained in [1], the behaviour of a ferrofluid drop on a line conductor for any values of wetting angles and magnetic fields was developed in [2]. The influence of a polymer film on the shape of the magnetic fluid containing a cylinder of ferromagnetic material exposed to a uniform magnetic field was investigated in [3].

In the present paper we consider a heavy, incompressible, homogenous, isothermal magnetic fluid on a line conductor with current. The magnetic fluid has a free axially symmetric surface. The magnetic field of the conductor is not deformed by the magnetic fluid in this geometry. The magnetic fluid of a constant volume, covered by a stretchable polymer film, is immersed in a non-magnetic liquid with the same density. The tension of the polymer film is considered to be equal to the surface tension of the magnetic fluid. We use the Langevin law to describe a magnetic fluid magnetization. We get the general analytical solution describing any axially symmetric shape of the magnetic fluid free surface in any axisymmetric magnetic field in case of hydroimponderability from the hydrostatic equation and the boundary condition on the free surface. The influence of the polymer film on the magnetic fluid shape is investigated.

Without the polymer film, on the contact lines of three media (magnetic fluid, non-magnetic liquid and conductor) the Jung condition should be satisfied and it yields the boundary conditions according to wetting angles. When the magnetic fluid is covered by the polymer film, the boundary conditions are different: the polymer film fixes the contact surface of the magnetic fluid and of the line conductor. This contact surface is taken initially due to the magnetic fluid shape for zero current. Static shapes of the magnetic fluid free surface were calculated numerically for different values of the magnetic fluid volumes and of the currents in the line conductor. The calculated shapes are compared with the calculation results of the magnetic fluid statics without polymer film. It has been found that the polymer film on the magnetic fluid surface significantly influences the magnetic fluid shape.

The changing of the magnetic fluid free surface should be taken into account for the construction of different devices with controlled magnetic fluid volumes, in which the magnetic field is changed periodically, such as seals, interrupters, valves, dispensers. The covering of the magnetic fluid by an impermeable film could prevent the mixing of a magnetic fluid and a surrounding liquid.

This work is supported by the Russian Foundation for Basic Research (projects 14-01-90003, 14-01-31146 and 13-01-00703).

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MHD-PUMPS FOR NEW GENERATION OF FAST NEUTRON REACTORS

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Russian atomic energetics strategy foresees putting fast neutron reactors (fast reactors) into operation. The use of such reactors provides for nuclear fuel breeding and formation of closed fuel cycle. As a result a power potential of nuclear fuel raw materials usage significantly increases.

At the present stage of fast neutron reactor construction, MHD pumps are considered as primary circulating pumps in reactor plants (RP) with lead coolant (RP "BREST" and BR-1200), secondary circulating pumps (such RP with sodium coolant as MBIR, BN-1200), pumps of integrally mounted in RP BN-1200 cold filter traps (IMCFT) and pumps for subsystems of above mentioned reactors.

Table. Main characteristics of pumps

Parameter	Type of pump, RP, coolant				
	CLIP 5/1300**, MBIR (Na)	CLIP C LeV 3.4/3600***, BREST-OD-300 (Pb)	CLIP 7.3/3600***, BR-1200 (Pb)	CLIP 4.8/13000****, BN 1200 (Na)	CLIP 0.6/4**, BN-1200 IMCFT (Na)
Temperature of coolant, °C	298	420	550	355	410
Nominal delivery (flow rate), $m^3 \cdot h^{-1}$	1268	3600	3600	13000	4.0
Pressure, $kg \cdot sm^{-2}$	5.1	3.4	7.3	4.8	0.61
Input power, kW	630	2233	5675	3557	0.7
Voltage phase/linear, V	360/620	1200/2100	578/1000	650/1125	25.0/43.3
Current phase/linear, A	1110/1110	1360/1360	5370/5370	3900/3900	19
Efficiency/Effective efficiency*, %	28/40	15/34	12.6/32.4	47.9/58	9.5/11.8
Cooling	forced,air	free	forced, Ar	free	forced, Ar
Pump diameter, m	1.7	1.2	1.5	1.7	0.236
Active part length, m	4.4	3.35	6.0	4.7	0.625
Life time, years	50	15	20	25	15
Weight of pump, kg	10500	18000	46000	37000	100

– Effective efficiency $\eta_{eff} = P_2/(P_1 - 0.33\ P_{22}) \cdot 100\%$; P_2 – output power, P_{22} –power passed to coolant, P_1 – input power; 0.33 – accepted value of thermal energy into electrical energy transformation ratio
** – Technical design; *** – Technical proposal; **** – Initiative of JSC "NIIEFA".

ON POSSIBILITY AND PRACTICALITY OF MHD MACHINES APPLICATION IN NUCLEAR POWER PLANTS AND PLASMA FACILITIES

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Development of up-to-date nuclear energetics is characterized by new approaches in fast breeder reactors (FBR) construction with different type of liquid-metal coolants (LMC): sodium (SFR), lead (LFR), lead-bismuth eutectic alloy (LBFR).

One of the main tasks related to reactor plant (RP) construction is to provide equipment with a lifetime of 50 years or more.

Coolant circulation in auxiliary liquid metal systems of RP is provided by magnetohydrodynamic (MHD) / electromagnetic (EMP) pumps. They, due to their advantages in hermetically sealed construction, maintenance and controlling, fully expelled mechanical pumps from auxiliary liquid metal systems.

The aspects of theory and calculation of induction EMPs are solved in JSC "NIIEFA", where the development of novel and elaboration of existing constructions of EMPs takes place, and new high temperature resistant electrotechnical materials are developed in cooperation with a number of Russian factories.

At the same time, application of mechanical pumps in primary circulation loops of RPs is still widespread. There are several reasons for this approach. The first is traditions based on the referentiality of this approach and in the absence of comparison methods of economic feasibility and safety of RP with appropriate type of pump. The second is a lack of "rundown" (gradual loss of flow during emergency power off) of EMP. This is provided in mechanical pumps by means of inertia of pump and electric motor rotating masses.

Choice of pump type method is carried out in collaboration with experts – developers of alternative types of pumps – JSC "NIIEFA" and JSC "Afrikantov OKBM".

The issues of EMP "rundown" and lifetime are solved in JSC "NIIEFA" in the following way.

EMP "rundown" is provided by energy storage devices (accumulators, capacitive or inductive energy storages) along with application of frequency inverters. This scheme makes it possible to implement practically any type of flow variation during emergency power off.

The required lifetime of EMP is assured by development of novel constructions and high temperature resistant materials. These materials resistant to ionizing radiation and high temperatures are able to guarantee the required lifetime of EMP at temperature of liquid-metal coolants of 450–550 °C without a forced cooling system and at 650 °C with a forced cooling system.

EMP pumps as well as other types of MHD machines: MHD throttles, MHD (electromagnetic) – pumps-throttles (EMPT) have been and will be applied as having no alternative in space borne reactor facilities and cold filter trap of SFR.

The application of EMP and EMPT has no alternative as well for providing a stable flow of working medium or ionizing additives in the delivery systems of plasma or ion plasma engines and facilities.

MODEL OF THE GEODYNAMO DRIVEN BY 6-CELLS CONVECTION IN THE EARTH'S CORE

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The main geomagnetic field is generated by a dynamo mechanism driven by convection in the Earth's core. Seismic data on density inhomogeneities in the liquid core can provide the information on the large-scale structure of convection. In [1], splitting-functions of free oscillations of the Earth after the strongest earthquakes were analyzed. A hypothesis was proposed that the convection spherical structure has 12 alternating zones of ascending and descending fluid.

The paper describes a large-scale model of the geodynamo driven by such convection. The above alternating structure is associated with spherical harmonic Y4, which defines the basic poloidal component of velocity. Coriolis drift of this mode determines the toroidal component of velocity. Thus, 6 convective cells are formed. The model takes into account the feedback effect of the magnetic field on convection.

It was ascertained that the model contains stable regimes of field generation. The velocity of convection and the dipole component of the magnetic field are close to the observed ones.

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THERMODYNAMIC PROPERTIES OF FERROFLUIDS WITHOUT EXTERNAL MAGNETIC FIELD

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The work is devoted to the thermodynamic properties of ferrofluids without applied magnetic field. In this work a new theory is constructed based on the transformation of the virial expansion for the Helmholtz free energy into a logarithmic form. The argument of logarithm is expressed in terms of second, third, fourth and fifth virial coefficients. The second and the third virial coefficients are known as serials expansions in dipolar coupling constant λ [1]. The forth and the fifth virial coefficients were calculated by straightforward application of the Mayer – sampling method [2]. Analytical expressions for the forth and the fifth virial coefficients were obtained by applying the least-squares approximation to the simulation data. The results for the thermodynamic properties are compared with the results of Monte Carlo simulation [1]. The results for Helmholtz free energy, chemical potential, pressure and compressibility factor agree well with simulation for $\lambda = 1$ and $\lambda = 2$ up to the rather high values of volume fraction $\varphi = 0.4$. For $\lambda = 3$ the new theory can predict correctly the behavior of ferrofluids up to $\varphi = 0.25$. For $\lambda = 4$ the new theory shows agreement with simulation up to $\varphi = 0.05$. The results for diffusion are also compared with the results of computer simulation. For $\lambda = 1$ and $\lambda = 2$ the theory works correct up to $\varphi = 0.1$, for $\lambda = 3$ and $\lambda = 4$ the agreement between theory and simulation is up to $\varphi = 0.05$.

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SIMULATION OF ELECTRIC VORTEX FLOWS AND HEAT AND MASS EXCHANGE IN DC ARC FURNACE BATH

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Mixing in DC arc furnaces (DCAF) is carried out with the help of electric vortex flows (EVF), initiating both the positive effects (return movement of heat from arc inside the metal, decrease of melt surface temperature, intensification of melt mixing, and heat exchange processes) and the negative ones (formation of steady toroidal vortices resulting in lining breakage in the area of hearth electrode).

A set of mathematical models, algorithms and programs is developed for the study of electric vortex flows and heat mass exchange in current-carrying melts of melting facilities, which enable numerical simulation of extensional electromagnet forces in current-carrying bath, electric and magnet spaces, as well as temperature and concentration spaces with different current contact jaws, and simulation modeling of nonsteady electric vortex flows in melt bath with axisymmetric current outflow [1]. Numerical researches of temperature spaces changes and FeS concentration in DCAF bathes with one-dross refining and parameters of desulphuration are performed. The minimum desulphuration time and parameters of melt and mass transfer were determined according to the averaged concentration of impurities.

To reduce bottom lining wearing in the area of hearth electrodes, the parameters of unsteady electric vortex flows in DCAF melt bath by arc current switching on and switching off are considered. Formation and movement of vortexes in the area of hearth electrode are analyzed, and conformity of transfer processes and typical time for electric vortex flows set up are determined. Mechanisms of formation and development dynamics of vortexes in the area of hearth electrodes in DCAF bath are shown. The main factors that influence EVF character in current-carrying melt bath are found.

A theoretical possibility of melt flow control is motivated, and the scheme of currents flowing through DCAF hearth electrodes control is offered, which allows one to intensify mixing and enforce suppression of electric vortex flows in the bottom area with constant arc power. Capabilities to control the melt flow intensity and the direction in DCAF due to changes in phase displacement between pulse currents flowing through hearth electrodes are shown [2].

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SIMULATION OF MAGNET SPACES BEHAVIOUR IN DC ARC FURNACE BATH WITH DIFFERENT DESIGN OF BUSBAR TO HEARTH ELECTRODE

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Metallurgical melts represent high-temperature current-carrying liquids. Their behavior is described by laws of magnet hydrodynamics, connected with the phenomena appeared while current flowing through the melt interacts with its own inner magnet space and outer magnet spaces.

The outer magnet spaces can influence the technological processes taking place in bathes with metallurgical melts either positively or negatively. On the one hand, under the influence of magnet space to current-carrying melt in DC arc furnace bath, extensional electromagnet forces appear which lead to conductive interfusion that intensifies heat-mass exchange processes. On the other hand, the outer magnet spaces can bring intensive flows, washing lining-up out, and also arc vertical deflection or its typical movement on the liquid melt surface. Thus, the correct usage of conductive interfusion increases the technical and economic characteristics of the metallurgical process and the quality of the metal produced and minimizes negative effects.

The given mathematical models are true for estimation of magnet space and extensional electromagnet forces in the arc furnace bath while using busbar to hearth electrode in the form of a helix or a plain or space Archimedean spiral. Patents of Russian Federation for possibility of magnet spaces in melt bathes control are issued [1, 2].

Dependencies of magnet spaces projections in bath radius and height are made by computer modeling for current contact jaws in the form of a helix with different number of coils, in form of plain Archimedean spiral or space Archimedean spiral [3].

Current contact jaws in the form of a plain Archimedean spiral are the most perspective ones, because, with all other things being the same, their compact design ensures high values of extensional electromagnet forces in melt treated.

The results of this work can be useful for projecting departments, which design DC arc furnaces for melting metals and alloys and modify the existing ones.

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BEHAVIOR OF MAGNETIC FLUID MICRODROPS IN UNIFORM DC AND ROTATING MAGNETIC FIELDS

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In this study, the features of deformation of a magnetic fluid microdrop immersed in a nonmagnetic liquid under the action of a uniform DC and rotating magnetic field are investigated experimentally; in addition, the behavior and dynamics of inverse system (nonmagnetic microdrop in magnetic fluid) is also studied. In our experiments, we used a kerosene-based magnetic fluid in which magnetite particles stabilized by the oleic acid were dispersed. We used AMG-10 oil as the nonmagnetic liquid material for obtaining the dispersion of microdrops. Such a choice was dictated by the fact that oil is insoluble in the magnetic fluid, and the interfacial tension at the boundary between the oil and the magnetic fluid is relatively small. Microdrops have a typical radius of 10 μm in zero field. Such droplets are easily deformable in weak uniform magnetic field of the order of a few 100 A/m.

Microdrops under study were contained in a thin gap between two glass plates (20 μm) with a simultaneously applied in-plane rotating magnetic field and a DC normal magnetic field. The microdrops were observed with an optical microscope and their behavior was recorded through a video camera system. The magnetic fluid microdrops in a nonmagnetic liquid and the nonmagnetic microdrops in a magnetic fluid exhibit a rich and complex behavior in response to both the frequency and magnetic field strength.

New flows and instabilities were observed for the studied microdrops. The studied droplets were first placed in the rotating magnetic field. In this case the observed droplet shapes were analogous to the previously described in works [1–3]. Then a DC normal magnetic field was gradually applied. This results in the droplets transformation into spirals or an abrupt transformation to many small droplets. New surface instabilities in the form of different traveling waves were observed.

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INVESTIGATION OF THE WAVE DYNAMICS IN OPTICALLY THIN THERMALLY UNSTABLE PLASMA

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This paper is focused on the wave dynamics of magnetoacoustic and Alfven waves in the optically thin plasma medium with thermal instability. The investigation of the wave evolution has been conducted using the modified full system of the magnetohydrodynamic (MHD) equations. The modification is done taking into account the influence of non-adiabatic heating and cooling processes in the medium. It is to be noted that non-adiabatic processes depend on the medium temperature and density. Moreover, it is because of this dependence that the various types of thermal instability [1] can be realized in the medium. During this research we have studied the wave dynamics in the medium with isentropic instability [2], isochoric and isobaric stability. In addition, the influence of thermal and finite electrical conduction has been taken into account. It has been found that the non-adiabatic processes results in the frequency dependence of MHD waves, phase speed and wave increment (or decrement). We have also obtained the nonlinear evolutionary equation describing the one-dimensional spatial-temporal dynamics of the weak fast and slow magnetoacoustic waves. The obtained equation is fundamentally different from the non-linear equations of Burgers-Fisher type [3] and describes the behavior of the entire wave spectrum. The possible wave structures and their parameters have been found analytically. The most interesting solution is the auto-wave solitary pulse with a shock front [4]. Furthermore, the wave dynamics has been studied by the numerical solution of the full system of the MHD equations. The results have shown that any initial weak perturbation is disintegrated into a sequence of self-sustained pulses. The numerical investigation has supported the view that the ability of the MHD pulse to emerge from the collision is unchanged.

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NUMERICAL ANALYSIS OF THE EFFECT OF THERMAL CONVECTION IN MHD DUCT AND PIPE FLOWS

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The recent results of the research collaboration between the MHD groups at the UM-Dearborn and MPEI are reviewed. In the course of the collaboration, high-fidelity numerical models are applied to analyze the experimental results obtained at the MPEI and Joint Institute for High Temperatures (JIHT) RAS and to extend the exploration of the convection effects to the range of parameters corresponding to typical conditions of liquid metal blankets for tokamak fusion reactors. Several idealized configurations in the form of flows through horizontal or vertical pipes and ducts with various orientations of the imposed magnetic field and various schemes of nonuniform heating are considered. The values of Hartmann and Grashof numbers are, correspondingly, up to 800 and $1 \cdot 10^{10}$ in three-dimensional simulations and reach the values $1 \cdot 10^4$ and $1 \cdot 10^{12}$ typical for a blanket of a large-scale tokamak reactor in the simulations, where two-dimensional approximation is taken.

The main conclusion of the analysis is that, in full agreement with the experimental data, the convection-induced instabilities in the presence of strong magnetic fields lead to development of large-scale, high-amplitude coherent flow structures, existence of which cannot be predicted on the basis of the understanding of the behavior of more conventional flows at smaller Hartmann and Grashof numbers. The high-amplitude (tens of degrees C) fluctuations of temperature associated with the dynamics of these structures render many currently pursued design concepts of liquid metal blankets potentially invalid and certainly in need of a thorough analysis of convection-related aspects. We also find that in one configuration, namely in a horizontal duct with axial magnetic field (a model of a blanket with toroidal ducts), convection plays a potentially beneficial role creating turbulence and, thus, serving as a tool for efficient heat transfer.

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INSTABILITY OF THE TAYLOR VORTICES: TRANSITION TO THE WAVY-VORTEX FLOW

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The stationary wave instability of the axisymmetric laminar flow of a viscous conducting liquid in an infinitely long circular cylinder, arising under the influence of a coaxially rotating magnetic field raised by one pair of poles, has been investigated. The first approximation equations for small disturbances of velocity and pressure allow a periodic solution with respect to φ and z:

$$f = f(r)\exp(\sigma t + in\varphi + iaz),$$

where a is the real dimensionless wave number, and n is the integer number.

Usually a special case of rotary symmetry $n = 0$ is considered, in which a primary flow is independent of φ, but perturbations of velocity u_r, u_φ, u_z and pressure p are not zero. This problem has been investigated in detail, in particular, for small values of relative frequency $\overline{\omega} = \mu_0 \sigma \omega R_0^2$ [1, 2]. Calculations have shown that the secondary flow is realised in the form of a system of periodic meridional vortices along a vessel's axis – so-called Taylor's vortices. For a wide range of process parameters, the curve of neutral stability has been obtained, separating the area of one-dimensional azimuthal flow from that of three-dimensional laminar-vortical flow. It has been shown that for small $\overline{\omega}$ the stability is characterised by two independent criteria Re_ω and Ha_{ac} ($\mathrm{Re}_\omega = \omega R_0^2/\nu$, $Ha_{ac} = B_0 R_0 \sqrt{\sigma/2\eta}$). Calculations reveal a one-vortical (in radial direction) pattern of Taylor vortices.

The case $n \neq 0$ directly corresponds to wave instability. The solution is obtained by using Galerkin method. The arising secondary flow can be characterised as a wavy-vortex flow, i.e. the new flow represents the wave surfaces distributed along the azimuth. Calculations generate curves of neutral stability for various values of n. At small values of Hartmann number the values of the critical parameters corresponding to the wave type of instability are somewhat above the values corresponding to occurrence of Taylor instability $(n = 0)$. In other words, at such Hartmann numbers the loss of stability of the primary azimuthal flow leads to the appearance of precisely this Taylor's structures of vortices. Calculations have shown that the further transition to wave instability with $n \neq 0$ occurs in rather interesting fashion. At $Ha_{ac} \sim 5.35$, $\mathrm{Re}_\omega \sim 422.4$ curves of neutral stability for $n = 0$ and $n = 1$ are crossed. Upon the increase in Hartmann number the instability at $n = 1$ will appear at smaller value Re_ω, than that at $n = 0$. Thus, it can be treated as the loss of stability of Taylor's vortices and transition to wavy-vortex flow. The wave number a thus changes jump-like from value 8.46 to 8.53. Because this leads to a qualitative restructuring of a secondary flow, it is possible to consider point $Ha_{ac} \sim 5.35$, $\mathrm{Re}_\omega \sim 422.4$ as a point of bifurcation. At the increase in Hartmann number we observe a cascade of bifurcations: at $Ha_{ac} \sim 9.04$, $\mathrm{Re}_\omega \sim 469.1$ a mode of a flow with $n = 1$ is replaced by a flow with $n = 2$, wave number changes jump-like from 10.79 to 11.06; at $Ha_{ac} \sim 13.71$, $\mathrm{Re}_\omega \sim 605.1$ a mode with $n = 2$ is replaced with that of $n = 3$, and a jumps from 13.57 to 14.13, and so on. Notably such transitions between the modes of wavy-vortex flows with the increase of n are accompanied by jump-like transitions to smaller-scale vortices each time.

The completed research expands our understanding of the primary one-dimensional laminar azimuthal flow transition to a three-dimensional laminar wavy-vortex flow.

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EFFECT OF INTERACTION BETWEEN FERROPARTICLES ON PRODUCED MAGNETIC HYPERTHERMIA

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Magnetic hyperthermia (MH) attracts considerable interest of researchers because it is perspective for many biomedical applications (see refs. [1–4]). Recent developments indicate that this highly specific and targetable method of localized remote heating can be successfully used in clinical practice in the treatment of cancer and other tumors, either as an adjunct to radiotherapy and chemotherapy. This method could be promising to treat small or deep-seated tumors.

The main idea of the MH usage for the tumor therapy is to heat up the tumor cells by using magnetic nanoparticles (MNPs) placed in an alternating magnetic field. Magnetic nanoparticles can be injected either directly into the tumor or intravenously in a colloidal suspension [1]. This method can be used to target the cancerous cells specifically rather than the general area of the tumor in a manner that is less invasive than interstitial arrays or thermo seeds. Once the magnetic nanoparticles are situated in the tumor region, an alternating magnetic field of high frequency is applied to this region. Under the action of this field the particles can be heated up to the temperature 42–46 ºC; that leads to destruction of the ill cells. Analysis shows that magnetic nanoparticles are more efficient for that than the larger ones, because there are a number of independent heating mechanisms which can act simultaneously. Some of these mechanisms are significantly stronger for particles in a low size range.

A key point in the theory of dynamics of a suspension of magnetic nanoparticles is the macroscopic equation for macroscopical magnetization, which should be derived by analyzing the Brownian rotation of a particle in a viscous host fluid. To the best of our knowledge, the theoretical works on the hyperthermia effect deal with the very dilute systems of non interacting magnetic particles. The obvious way to increase the heating effect is to increase the particles concentration. However in the concentrated systems interaction between the particles can be quite pronounced and significant.

In the present work we study the effect of magnetic interaction between single-domain ferromagnetic particles on magnetic hyperthermia. This hyperthermia is produced by the particles subjected to an alternating magnetic field. Analysis is restricted to the internally homogeneous (without any heterogeneous aggregates) systems. Our results show that the interparticle interaction increases the rate of temperature rise (hyperthermia effect) when the field frequency is relatively small and decreases the rate for high frequencies.

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MAGNETORHEOLOGICAL SUSPENSIONS UNDER SHEAR RATE OSCILLATIONS

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This work deals with theoretical study of rheological properties of the suspension of micron-sized magnetizable not Brownian particles. We suppose that these particles under the action of an applied magnetic field form the linear chain-like aggregates.

For typical Newtonian fluid the Navier-Stokes equations are used. This equation does not apply to the magnetorheological suspensions [1]. Firstly, the stress in these suspensions is nonlinearly dependent on the shear rate. Secondly, in a magnetic field, these suspensions are anisotropic, for example, by the formation of chains, consisting of particles. In this case, the relationship between the stress and shear rate are not fixed and suspensions exhibit the effects of viscoelasticity, which are studied in the present work.

We consider a plane gap filled with magnetorheological suspension. Let us introduce a Cartesian coordinate system *x*, *y*, *z* with the axis *Oz* perpendicular to the gap. One of the plates oscillates in the direction of the axis *Ox*. The magnetic field vector **H** is perpendicular to the axis *Oy*; the angle of deflection of the magnetic field vector from the axis *Oz* is ψ. Shear γ is related to time *t* by the following equation $\gamma = \gamma_0 \sin(\omega t)$. The aim of the work is to determine the stress σ vs shear γ relationship.

The viscoelastic properties of magnetorheological suspensions are due to two mechanisms: the change of orientation of the chains in the space and the process of growth-destroying chains. Our attention focused on the study of orientation of the chains. Similar to [2], we model the *n* – particle chain by ellipsoid of revolution with the minor and major axes equal to *d* and *nd*, respectively. It is of principal importance that the volume of this ellipsoid equals to the total volume $v = \pi n d^3/6$ of all particles in the chain. Thus, the volume concentration of ellipsoids is the same as concentration of the particles in the ferrofluid. We assume that the length of all chains is the same and determined by the average value of the shear rate according to the theory in [3].

Using the results of statistical hydromechanics of suspensions of nonspherical particles [4], one can represent the macroscopical viscous stress tensor as follows:

$$\sigma(t) = \sigma_a(t) + \sigma_s(t), \quad \sigma_a(t) = \frac{\varphi \Gamma_m(t)}{2nv},$$

$$\sigma_s(t) = \eta_0 \dot{\gamma} + \eta_0 \varphi \dot{\gamma} \left[\alpha_n + \frac{\zeta_n + \beta_n \lambda_n}{2} + \frac{\beta_n \cos[2\theta(t)]}{2} + \frac{(\chi_n - 2\beta_n \lambda_n) \sin^2[2\theta(t)]}{4} \right] - \frac{\eta_0 \varphi \beta_n}{2} \frac{d}{dt} [\sin[2\theta(t)]], \quad (1)$$

$$\Gamma_m(t) = \frac{9 \mu_0 H^2 v (n-1) \sin[2[\theta(t) - \psi]]}{8}, \quad \dot{\gamma} = \frac{d\gamma}{dt}.$$

Here σ_α is the antisymmetric part of the shear stress; σ_s is the symmetric part of the shear stress; φ is the volume concentration of micron-sized particles; Γ_m is the magnetic torque, which tends to align the chain axis with the field direction; η_0 is the viscosity of the carrier liquid; $\dot{\gamma}$ is the shear rate; θ is the angle of an *n* – particle chain deviation from the axis *Oz*.

According to the mechanism of change of chain orientations in the space the results of calculations shows a stress vs shear ellipsoid. The axes of this ellipsoid deviated from the Cartesian axes. For a Newtonian fluid the calculations also yield a stress vs shear ellipsoid, however, the axes of this ellipsoid coincide with the Cartesian axes. The stress σ decreases with increasing angle ψ, and this stress reaches its maximum value when the angle ψ is equal zero.

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COMBINED FOKKER-PLANCK-BROWN AND YVON APPROACH FOR DESCRIBING THE DYNAMIC MAGNETIC RESPONSE OF INTERACTING FERROPARTICLES IN MAGNETIC FLUIDS

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Extensive experimental studies evidence the Debye type of the frequency spectrum of the ferrofluid dynamic magnetic susceptibility. But in many cases the ferroparticle polydispersity results in broadening of the spectrum due to the dependence of both the Neel and the Brown relaxation times on particle size. That is why, the experimental data processing fails in identification of the part of interparticle correlations in dynamic magnetic response of concentrated ferrofluids. Theoretical description of the ferrofluid dynamic magnetic properties is commonly based on the Fokker-Planck-Brown (FPB) equation [1, 2] for the probability density of the randomly chosen particle magnetic moment to be oriented in some direction under the action of applied alternating magnetic field. The point is that FPB equation is primordially the one-particle approach; and only few attempts are known [3–6] incorporating the interparticle interactions with the help of various methods.

On the other hand, the static (equilibrium) magnetic properties of ferrofluids are well explained theoretically under the condition when the interparticle magnetic dipole interaction is taken into account. One of the models here, known as the modified mean-field model [7], is based on the equilibrium Yvon link between the one-particle distribution function and the pair correlation function of the ferroparticle magnetic moments in the orientation space. It is worth mentioning that the equilibrium one-particle distribution function has the same meaning as the static solution of FPB equation for the orientation probability density.

Here we suggest the combined approach incorporating the mentioned Yvon link to FPB kinetic equation. The obtained nonlinear equation becomes explicitly dependent on ferroparticle concentration and the intensity of the interparticle magnetic dipole interaction.

We consider the simplest case of weakly interacting ferroparticle fluid with the Brownian relaxation mechanism under the action of vanishingly weak probing harmonic magnetic field. The interparticle interaction is taken into account within the thermodynamic perturbation method. Linearizing the obtained non-linear equation over the small Langevin parameter, we get the solution for the initial dynamic magnetic susceptibility in the Debye form. The calculated collective relaxation time appears to be concentration dependent. In the lowest order of the thermodynamic perturbation approach over the intensity of magnetic dipole interaction, our result for the collective relaxation time coincides with that by Zubarev [3].

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