$y^+ = yv^*/\nu$, dimensionless distance; u, local velocity, m/sec; $u^+ = u/v^*$, dimensionless local velocity; x, distance from pipe entrance, m; B, shift of the logarithmic part of the velocity profile; τ, tangential friction, Pa; $[\eta]$, characteristic viscosity of the solution; M, molecular mass of the polymer; Re, Reynolds number; μ, viscosity of the solution, Pa·sec.

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FEATURES OF THE DEVELOPMENT OF CONVECTIVE PROCESSES UNDER NEARLY WEIGHTLESS CONDITIONS

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Measurements of microaccelerations on board an orbital station are analyzed from the standpoint of the influence (of the state determined by them) on the development of convective processes of a gravitational nature. Two regimes of development of convection are identified, depending on the nature of the variation of the acceleration vector: In one of them the intensity of convective motion is the determining factor, and in the other convection is suppressed and heat conduction (diffusion) is the main transport mechanism.

Features of the development of convective processes (in comparison with analogous processes occurring under terrestrial conditions) in various on-board systems and devices, as well as in technological experiments carried out on board a spacecraft, are the consequence of the special state existing on board a spacecraft, defined as a nearly weightless state. A characteristic of that state is the continuous time variation of the local acceleration vector in magnitude and direction. The variety of laws of time variation of the acceleration vector determines the variety of features in the development of convective processes of a gravitational nature. Systematic investigations of the behavior of a fluid

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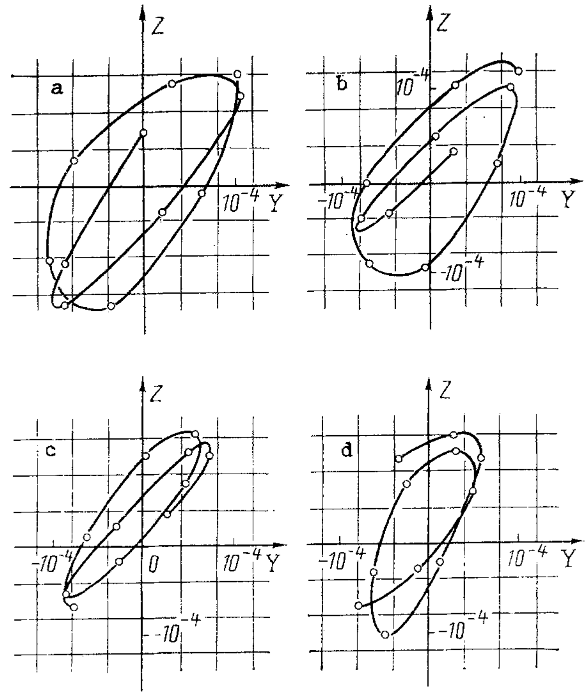

Fig. 1. Curve describing the end of the acceleration vector when an operator is walking on the PTC track at 50 pairs of steps per minute: a) first second; b) second; c) third; d) fourth.

under nearly weightless conditions are needed in order to have a reliable method of predicting features of the development of convection for one or another technological process. From the practical standpoint, the following problems must be solved:

a) coordinate the operating regime of the spacecraft with the law of variation of local acceleration at the point at which the technological experiment is conducted;

b) classify the laws of variation of the acceleration vector with respect to the nature of their influence on the development of convective processes of a gravitational nature;

c) determine, for each class of laws of variation of the acceleration vector, which features will occur and for what values of the determining parameters.

Small accelerations are measured on board a spacecraft using a small-acceleration meter (SAM) [1] along each coordinate axis individually. The purpose of the analysis is to identify the most characteristic laws of variation of the small-acceleration vector, on the basis of which one can classify the nearly weightless states occurring on a spacecraft.

The analysis of small-acceleration measurements on board the Salyut-6 and -7 and the Mir stations has made it possible to identify a number of the most characteristic states. On a passive section of the trajectory, the variation of the local acceleration vector occurs mainly in the plane perpendicular to the station axis. The components of the acceleration vector along the OX- and OY- axes, perpendicular to the OZ station axis, are about an order of magnitude larger than the component along OZ. One can assume, with a high degree of accuracy, that the field of the acceleration vector is uniform in the entire cross section of the station in the XOY-plane. These local accelerations are caused by oscillations of the body of the station from the perturbing action of systems and mechanisms functioning on board and the activity of the crew. Here it can be assumed that the components of the acceleration vector along the coordinate axes vary harmonically with different frequencies and different amplitudes. In some cases in particular, the variation of the acceleration vector is close to rotation at a constant angular velocity of a vector with a constant magnitude. If the station's engines are operating, then a constant component is added to the local acceleration vector. The constant component of the local acceleration vector may turn out to be noticeable even when the engines are turned off, when the station is in a state of gravitational stabilization, and the measurements are carried out at a large distance from the station's center of mass.

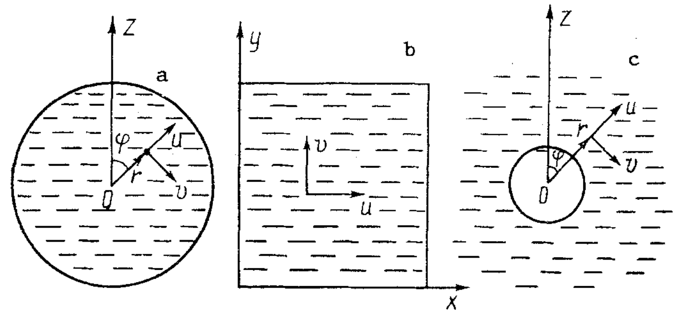

Fig. 2. Calculation schemes: a, b) internal problems; c) external problem.

TABLE 1. Equations for Calculating g* and ω*

N	Law of variation of $\bar{g}$	g^*	ω^*
0	$\bar{g} = \text{const}$	$\lvert\bar{g}\rvert$	0
1	$g_x = g^0 * \sin(\omega * t)$ $g_y = g^0 * \cos(\omega * t)$	g^0	$\omega * R^2/a$
2	$g_x = g^0 * \sin(\omega * t) + g_x'$ $g_y = g^0 * \cos(\omega * t) + g_y'$	g^0	$\dfrac{2 * \omega * R^2 * \text{arcctg}(d)}{\pi * a * \sqrt[4]{1 + d^2}}$
3	$g_x = g_x^0 * \sin(\omega * t)$ $g_y = g_y^0 * \cos(\omega * t)$	$\min(g_x^0, g_y^0)$	$\omega * R^2/a$
4	$g_x = g^0 * \sin(\omega_x * t)$ $g_y = g^0 * \cos(\omega_y * t)$	g^0	$\max(\omega_x, \omega_y) * R^2/a$

In Fig. 1 we show characteristic curves that describe the end of the acceleration vector $\bar{g}$ in successive time periods. The points mark times every 0.1 sec. The measurements were made on the Salyut-6 station while an operator walked on the PTC (physical training complex) track at a frequency of 50 pairs of steps per minute (actions at a frequency 1.7 Hz).

In analyzing measurements of small accelerations, it has been established that for many technological processes occurring on board orbital scientific stations, the period of variation of the acceleration vector and the characteristic hydrodynamic times are of about the same order, so one cannot always use the assumptions adopted in the study of vibrational convection.

The numerical investigation of features of the development of convective processes under nearly weightless conditions was carried out on the basis of model problems. Heat and mass transfer in thermal convection and concentration convection in a closed volume, thermal gravitational convection in an external (to the heat source) region, and convection in a conjugate problem of heat transfer were modeled.

The two-dimensional formulation corresponds to the case in which the cylindrical cuvette, on which the experiment is conducted, is located along the station axis and the acceleration vector varies only in the plane perpendicualr to the station (and cuvette) axis. The numerical investigation is based on the solution of a system of differential transfer equations, in writing which we use the property of incompressibility of the liquid and the independence of the thermophysical properties from temperature, with the exception of the terms characterizing mass forces (the Boussinesq approximation). The formulation of the problem has been given in [2, 3], the calculation schemes are shown in Fig. 2, and features of the finite-difference solution are described in [4].

The determining parameters in the solution of the internal problem with boundary conditions of the first kind include, in addition to the Grashof number (Gr) and the Prandtl number (Pr) (the Grashof number is calculated from some fixed scaling value of the absolute acceleration vector), the law of variation of the acceleration vector, given by the vector function $\bar{g}(t)$.

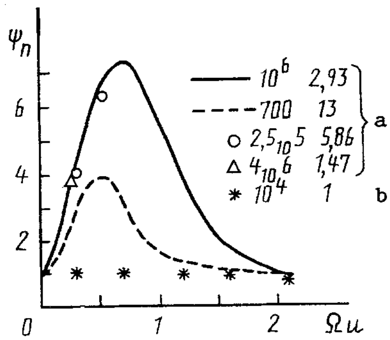

Fig. 3. Relative flow intensity ψ_n as a function of the relative angular velocity Ωu of rotation of the acceleration vector. The results were obtained in a computational experiment: a) in the calculation scheme of Fig. 2a; b) in the calculation scheme of Fig. 2b. Left-hand column: values of Gr; right-hand column: Pr.

The features of the development of thermal gravitational convection are determined by the nature of the variation of the acceleration vector. For typical nearly weightless states one can identify certain general laws and relate them to the determining parameters of the problem. The vector function $\bar{g}(t)$ describes two properties of the acceleration vector: the variations of its length and direction. For regular periodic variation of the acceleration vector, the second property (variation of direction) can be characterized by the rotation period of the vector or some scaling angular velocity. The scaling value of the length of the acceleration vector, which is part of the Grashof number (Gr), corresponds to the first property of the acceleration vector function. In Table 1 we give the equations that should be used to calculate the scaling length of the acceleration vector $\bar{g}$, which appears in the Grashof number

$$\mathrm{Gr} = g^* \beta_T \Delta T R^3/\nu^2,$$

and show the values of the dimensionless scaling angular velocity ω^* used to determine the relative angular velocity from the equation

$$\Omega u = \omega^*/(\mathrm{Pr}\sqrt{\mathrm{Gr}}).$$

The following notation is used in Table 1: g_x and g_y are the components of the vector $\bar{g}$ along the X- and Y-axes; ω_x and ω_y are the circular frequencies of harmonic variation of the projections of the vector $\bar{g}$ onto the X- and Y-axes; g^0, $g_x{}^0$, and $g_y{}^0$ are the respective amplitudes; $g_x{}'$ and $g_y{}'$ are the constant components of the vector $\bar{g}$; $d = |\bar{g}^0|/|\bar{g}'|$.

In row 0 of Table 1 we give the case of a constant acceleration vector, in row 1 a vector of constant absolute value rotates at a constant angular velocity, in row 2 the acceleration vector is comprised of two components, rotating ($\bar{g}^0$) and constant ($\bar{g}'$), and in rows 3 and 4 the projections of the vector vary harmonically with different amplitudes and different frequencies, respectively.

The nearly weightless states used in Table 1 are idealizations of actual states, but sections of an actual law of variation of the acceleration vector at individual times can be replaced by one of those in Table 1 in most cases.

For the calculation scheme in Fig. 2a (convection inside a vessel with the shape of a circular cylinder, with boundary conditions of the first kind), two regimes of development of convection can be identified as a function of the parameter Ωu. The first occurs for $0 < \Omega u < 2$. The intensity of fluid motion in the process pertaining to this regime is of the same order as in the field of a constant acceleration vector. For Grashof numbers in the range from 10^4 to 10^8, corresponding to the development of laminar convective flow in a constant acceleration field, in a variable field characterized by $0 < \Omega u < 2$ the convection will play a decisive role in the process of heat transfer. The intensity of convective motion in a variable acceleration field is sometimes several times that of the analogous process developing in a constant acceleration field. In Fig. 3 we show the dependence of the relative flow intensity

$$\psi_n = \frac{\max\limits_{\mathrm{Fo}} \psi_m^{\omega}(\mathrm{Fo})}{\max\limits_{\mathrm{Fo}} \psi_m(\mathrm{Fo})}$$

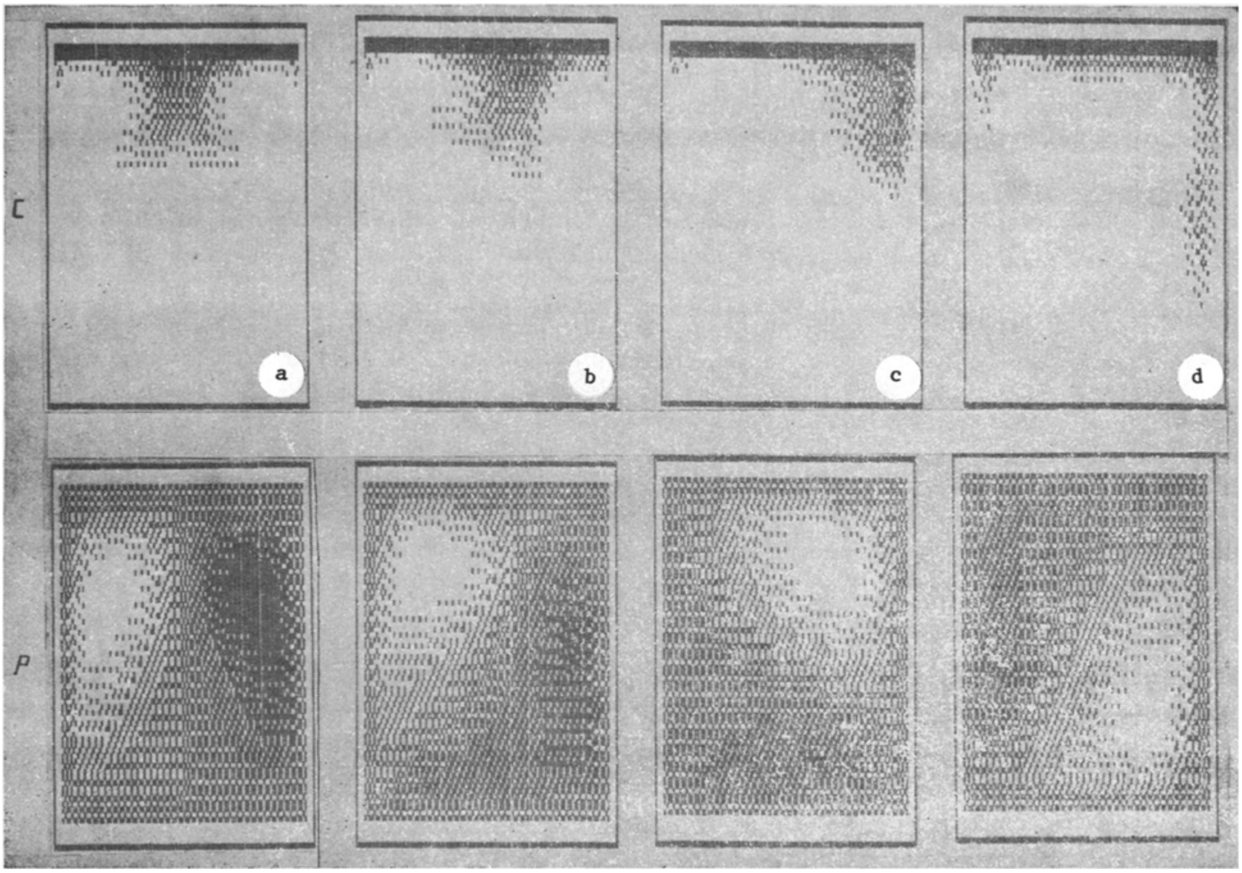

Fig. 4. Fields of concentration (C) and stream function (P) for different Ωu at the time Fo = 0.004 (Gr = 10^6, Gr_C = 0, Pr = 1): a) Ωu = 0; b) 0.157; c) 0.628; d) 1.256.

on Ωu in the case of pure rotation of the acceleration vector for different values of the parameters Gr and Pr. Here $\psi_m{}^\omega(Fo)$ is the time dependence of the maximum value of the stream function in the case of rotation of the acceleration vector; $\psi_m(Fo)$ is the corresponding dependence obtained in a constant acceleration field.

It should be noted that an increase in the intensity of convective flow in comparison with that in a constant acceleration field does not lead to an increase in the rate of rise of the average liquid temperature; the only differences are observed in the temperature distribution.

The second regime occurs for $\Omega u > 2$. If the variation of the acceleration vector is such that there is no constant component, then the primary mechanism of heat transfer is heat conduction, and whereas for values close to 2 (approximately in the range $2 < \Omega u < 5$) the contribution of convective heat transfer is still comparable with that of heat conduction, at larger values the contribution of convection becomes insignificant. The averaged fluid flows and the heat transfer produced by them under these conditions are studied using the assumptions of vibrational convection.

The features of the development of thermal gravitational convection in a variable acceleration field are related to the features of the temperature and velocity distributions. This in turn leads to features of the distribution of other parameters, the concentration of an admixture, in particular. The study of those features is of practical importance. If we assume that a change in the concentration of the admixture does not affect the fluid density (i.e., concentration convection is absent), then mass transfer of the admixture is accomplished by diffusion and by convective flows due to thermal convection. In Fig. 4 we show distributions of the concentration of an admixture (Gr_C = 0) for different velocities of rotation of the acceleration vector. The calculations were carried out by the scheme given in Fig. 2b, the initial fluid temperature was 0, and the temperature of the vessel wall was 1 (boundary conditions of the first kind). The average concentration of the admixture by the time the calculation ended (Fo = 0.004) should be noted, in particular: for

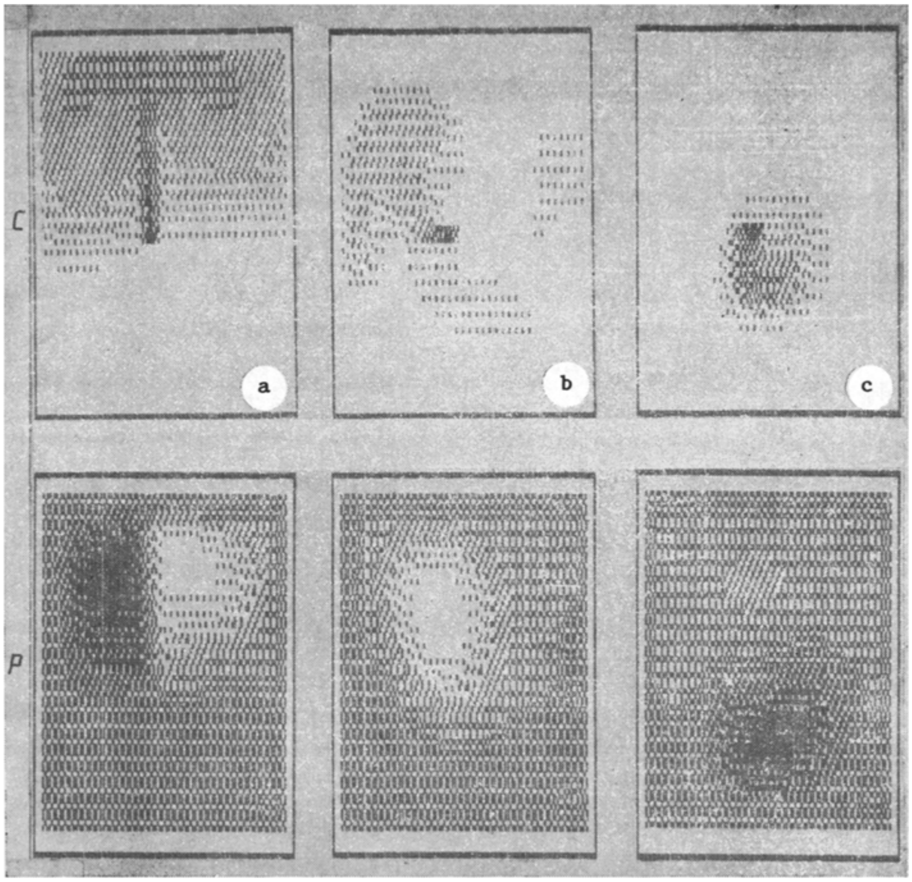

Fig. 5. Fields of concentration (C) and stream function (P) for different Ωu at the time Fo = 0.02 for a point source of temperature and concentration (Gr = 10^6, Pr = 1, Gr_C = 0, Sc = 1): a) Ωu = 0; b) 0.5; c) 2.

Ωu = 0, 0.157, 0.628, and 1.256 the average concentration was C_{av} = 0.10, 0.11, 0.10, and 0.09, respectively.

The intensity of convective motion remains high in all variants (ψ_m ranges from 4270 to 3550); the character of the flow determines the rate of time variation of the average concentration of the admixture in the volume and for Ωu = 1256 it plays the role of a strong moderating factor.

The various combinations of boundary conditions, values of the parameters determining the intensity of thermal and concentration convection, and laws of variation of the acceleration vector determine the variety of slow structures and can result in the most varied quantitative results (such as different values of the integral-mean characteristics: the volume-averaged temperature and concentration). The possibility of controlling the character of the development of flow may make possible more purposeful and economical accomplishment of technological operations under nearly weightless conditions and increase the working safety of astronauts on board the spacecraft. In Fig. 5 we show fields of concentration and stream function obtained from a point source of contamination (burning insulation on a wire, for example) for different laws of variation of the acceleration vector (different station operating regimes). The site of origin of the contamination looks most compact when the time variation of the direction of the acceleration vector is fastest. If necessary, such a state (law of time variation of the acceleration vector) can be created by the astronauts on board.

The problem for which the solution is given in Fig. 5 is an external problem (see Fig. 2c). The quantitative results given in [3] enable one to judge the features of the development of convection near a cylindrical heater from the values of the determining parameters and the law of time variation of the acceleration vector.

NOTATION

OZ, direction of the station axis; OX, OY, directions perpendicular to the station axis; g, acceleration vector; g, absolute value of the acceleration vector; ω, angular velocity of rotation of the acceleration vector; ω^*, scaling angular velocity; g^*, scaling absolute value of the acceleration vector; Gr, Grashof number, $Gr = g^*\beta_t\Delta TR^3/\nu^2$; Pr, Prandtl number, $Pr = \nu/a$; ν, kinematic viscosity coefficient; a, coefficient of thermal diffusivity; T, temperature; β_{th}, thermal expansion coefficient; R, characteristic size, radius of the vessel; Ωu, relative angular velocity; Fo, dimensionless time; ψ_m, maximal value of the stream function; ψ_n, relative flow intensity; Gr_C, concentration Grashof number; C, concentration.

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INFLUENCE OF THE ENERGY SUPPLY ON THE CONDITIONS OF SUPERSONIC FLOW AROUND AN OBSTACLE

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Supersonic flow around an obstacle is calculated in the case of axial nonuniformity of the gasdynamic parameters due to energy supply to the gas in a region upstream from the obstacle. The influence of the distance between the energy-supply region and the obstacle and their relative transverse dimensions on the flow conditions and the lateral-drag coefficient is analyzed.

In practice, it is often necessary to deal with nonuniform supersonic gas flow around a body. Such nonuniformity of the incoming flux may be due to various factors, for example, the formation of a wake behind a body positioned upstream at the pivot of a disk attachment [1], energy and mass supply [2], etc. The character of the nonuniformity depends to a considerable extent on the factors which cause it, and has a significant influence on the flow conditions around an obstacle and the corresponding force and energy interaction.

The flow of nonuniform supersonic flow around an obstacle has recently been studied for the case of energy supply to a local region of the flow [3, 4]. In [3], it was shown that, if a cylindrical body is downstream from a thin thermal layer with reduced density at its axis, approximately threefold reduction in lateral drag is possible, and it was suggested that nonsteady flow conditions are possible here, in principle. The model proposed for the nonuniformity of the incoming flow permits the study of the mechanism of flow restructuring in the shock layer. In practice, however, it is difficult to create a thin thermal layer with constant parameters over its length in a gas, by any known means, since not only radial but also longitudinal nonuniformity of the gasdynamic parameters appears in real conditions. This corresponds to the problem in [4], where supersonic flow around a sphere was calculated in the case of energy input to the flow, with variation in the rate of energy supply and in the distance between the sphere and the region of energy supply. Once again, considerable reduction in the lateral-drag coefficient was found in the calculations.

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