Conjugate Problems of Transport Phenomena under Quasi-steady Microaccelerations in Realistic Spaceflight

V. I. Polezhaev and S. A. Nikitin

Institute for Problems in Mechanics, Russian Academy of Sciences, Moscow, Russia

A new model for spatial convective transport processes conjugated with the measured or calculated realistic quasi-steady microaccelerations is presented. Rotation around the mass center, including accelerated rotation, gravity gradient, and aerodynamical drag are taken into account. New results of the effect on mixing and concentration inhomogeneities of the elementary convective processes are presented. The mixing problem in spacecraft enclosures, concentration inhomogeneities due to convection induced by body forces in realistic spaceflight, and the coupling of this kind of convection with thermocapillary convection on the basis of this model are discussed.

Key words: mathematical modeling; realistic microgravity environment; heat and mass transfer; mixing; stratification

Nomenclature

- \( \rho \): pressure
- \( T \): temperature
- \( U \): velocity
- \( g \): acceleration of gravity
- \( \Delta g_0 \): acceleration of the normal gravity
- \( n \): microacceleration of the body forces in orbital flight
- \( e \): normalized radius vector of the center of mass of the station
- \( \sigma \): surface tension
- \( R \): geocentric radius vector of the center of mass of the station
- \( H \): height of the domain
- \( L \): length of the domain
- \( t \): time
- \( \beta_t \): thermal expansion coefficient
- \( \nu \): kinematic viscosity
- \( \rho \): density
- \( a \): thermal diffusivity
- \( D \): diffusion coefficient
- \( \Omega_a \): mean angular velocity of spacecraft
- \( \omega \): angular velocity of spacecraft
- \( \frac{d\omega}{dt} \): angular acceleration
- \( \Omega_E^2 \): gravitational parameter
- \( \text{Pr} = \nu/a \): Prandtl number
- \( \text{Sc} = \nu/D \): Schmidt number
- \( \text{Gr} = |n|\beta_t (T - T_0)L^3/v^2 \): Grashof number
- \( 4\Omega_a^2L^4/v^2 \): Taylor number
- \( \text{Ra} = \text{GrPr} \): Rayleigh number
- \( \text{Mn} = \sigma T \Delta TH/\rho v^2 \): Marangoni number
- \( \text{Ma} = \text{MnPr} \): Ma number

Introduction

Under spaceflight conditions, the natural mass forces are much weaker than the Earth's gravity force. The specifics of these forces had not been investigated and were underestimated. Moreover, under spaceflight conditions the influence of nongravitational convection (not manifested under terrestrial conditions)
and three-dimensional (3D) effects increase. Up to recently, it was difficult to construct adequate models. This is why although, during this period, the motivation and targets for the practical use of weightlessness conditions onboard space vehicles as an engineering medium changed,\textsuperscript{1–5} the development of the models and methods of mechanics steadily increased.

Spaceflight is characterized by several weak forces of different natures with complicated spatial–temporal behaviors as well as the effect on gravity-related systems. Two main features may occur—stratification and mixing, which usually are difficult to provide simultaneously. New computational fluid dynamics (CFD) possibilities, advances in study of the effect of microgravity on the many gravity-related processes, and new knowledge of the microgravity environment during spaceflight make it possible to improve the analysis and prediction of spaceflight processes. Many experiments on different spacecraft show differences in concentration inhomogeneities in semiconductor crystals grown from the melt. Therefore, gravitational sensitivity is high and detailed analysis is needed.

This report presents a new model of spatial convective transport processes conjugated with the measured or calculated realistic quasi-steady microaccelerations. It continues previous attempts to develop CFD models for microgravity sciences.\textsuperscript{6–9}

A focus of the article is concentrated on 3D conjugate problems of convection in Boussinesq approach. Actual (realistic) information about spaceflight, which contains measured inflight data on rotation of spacecraft, orbit parameters, and design parameters of spacecraft are used. The first concrete problem, which is studied with the use of the new model, is a mixing problem in spaceflight. The next one is the general problem for the material sciences, concerned with the lateral concentration inhomogeneities. Finally some problems in efficient use the new modeling tool and the elementary fluid flows in a microgravity environment are discussed.

\begin{align}
\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla) \mathbf{U} + \sqrt{Ta} (\mathbf{\omega} \times \mathbf{U}) &= \Delta \mathbf{U} - \nabla \rho \\
&+ \mathbf{Gr} \cdot \frac{\mathbf{n}}{n} + \frac{\sqrt{Ta}}{2} \left( \mathbf{r} \times \frac{d \mathbf{\omega}}{dt} \right) \\
\nabla \cdot \mathbf{U} &= 0, \\
\frac{\partial T}{\partial t} + (\mathbf{U} \cdot \nabla) T &= \frac{1}{Pr} \Delta T, \\
\frac{\partial C}{\partial t} + (\mathbf{U} \cdot \nabla) C &= \frac{1}{Sc} \Delta C.
\end{align}

(1)
Here, \( \omega = \Omega / \Omega_a \) is the radius vector of a certain point in the liquid volume, and \( \Omega_a \) is the mean angular velocity of the vehicle. The scales of length, time, velocity, and pressure are, respectively, the characteristic length of the region filled with fluid \( L \), \( L^2 / v \), \( v / L \), and \( \rho v^2 / L^2 \).

System (1) depends on the acceleration \( n \), which can be expressed as

\[
\mathbf{n} = R_0 \times \frac{d\Omega}{dt} + (\Omega \times R_0)
\times \Omega + \Omega^2_e \left[ 3(\mathbf{e} \cdot R_0)\mathbf{e} - R_0 \right] + \mathbf{n}_g,
\]

where \( R_0 \) is the distance from the liquid volume to the center of mass of the vehicle, \( \Omega^2_e \) is the gravitational parameter, and \( \mathbf{e} \) is a unit vector directed from the center of mass of the vehicle toward Earth’s center. The first term of Eq. (2) \([R_0 \times (d\Omega / dt)]\) is the acceleration attributable to the nonuniformity of the vehicle angular velocity; the second term \([(\Omega \times R_0) \times \Omega]\) is the centrifugal acceleration, the third \([\Omega^2_e \left[ 3(\mathbf{e} \cdot R_0)\mathbf{e} - R_0 \right]]\) is the acceleration induced by the gravity gradient, and the last term is the acceleration due to aerodynamic drag.

According to Eq. (1), under spaceflight conditions the fluid motion in the volume is determined by the Coriolis force \( \sqrt{T_a} (\omega \times \mathbf{U}) \), the buoyancy force \( \text{Gr} \times n/|n| \), and the force induced by the angular acceleration \( (\mathbf{r} \times (d\omega / dt))\sqrt{T_a} / 2 \) responsible for so-called isothermal convection. In what follows, we assume that, on all the boundaries of the volume, the no-slip condition is satisfied and the temperature and concentration regime is given.

3D convection problems in this formulation were first solved for a cubic volume and the conditions of motion of the Salyut-6 station in the gravitational stabilization regime.\(^9\) At that stage, the component \((\mathbf{r} \times (d\omega / dt))\) was not taken into account in the calculations. This term was systematically used by several theoretical and experimental works in ground-based conditions.\(^{10–12}\) Also, there has been progress in modeling 3D convection, temperature oscillations, and concentration nonuniformity problems for a parallelepiped.\(^{13}\)

Later, a quasi-steady microacceleration component calculated by taking into account the measured parameters of the station motion was used (see Refs. 14 and 15 with references to previous works in this field). For real space-flight conditions, 3D thermal convection problems with account for the data on the quasi-steady component for Mir station motion were solved in cubic\(^{16}\) and cylindrical\(^{17}\) regions. In Ref. 18, the passive-admixture transport induced by thermal convection in a cylindrical cell was considered in the complete formulation given by Eq. (1) for real Foton vehicle flight conditions.

In Ref. 19, an approach was adopted in which, in contrast to the preceding, attention was focused on a parametric study rather than on taking the real data into account. Also, in the mentioned model formulation there were no flows induced by an angular acceleration.

Progress in computers and numerical methods made it possible to perform direct numerical simulation of transitional and turbulent regimes (for 2D cases, this was first done at the end of the 1980s), which was important for the development of space material engineering. For direct numerical simulation of the 3D equations in the Boussinesq approximation for cylindrical geometry, spectral finite-difference and control volume methods in the “velocity–pressure” formulation were used until the mid-1990s. The next stage was associated with the use of finite-difference schemes. However, many convective processes had not been sufficiently well studied at the 2D level. This was the reason for the development (starting in the 1990s) of a computer laboratory for microgravity conditions.\(^{20}\) This laboratory, which makes it possible to simulate many convective heat/mass transfer processes important for space flight engineering, including the coupling of convection models with a real microacceleration field in space vehicle flight,\(^{21}\) is oriented not only toward research but also toward teaching.
Mixing Due to 3D Convection in Spacecraft Enclosure under Spaceflight Conditions

Model of Mixing in Spacecraft Enclosure

Unsteady heat transfer in a spherical spacecraft enclosure filled by air with normal conditions during orbital flight is studied. Several cubical objects that serve as a heat source inside the enclosure are included. Heat transport from these sources inside the volume during spaceflight is distributed by heat conduction and thermal convection due to buoyancy and convection due to angular acceleration of spacecraft, and outputs by the enclosure boundary.

In the Cartesian coordinate system OXYZ, rigidly fitted to the moving space vehicle, under spaceflight conditions the unsteady 3D system of thermal convection equations and the transport equation in the Boussinesq approximation have used in the form given by Eqs. (1) and (2) for simple motionless ($U = 0$) initial conditions, uniform heated gas ($T = T_0 = 20^\circ \text{C}$).

At $t = 0$ (a start of the orbital flight) according to the flight program, heat is generated by the inner objects and the output across the outer boundary of the spherical enclosure.

The boundary conditions are as follows.

1. On the enclosure boundary: $U = 0$ and $-\lambda \partial T / \partial n = (q_i \cdot n)$, where $q_i$ is prescribed and may be taken as a function of time and coordinate on the enclosure boundary and here $n$ – unit vector normal to boundary. This model does not provide detailed heat exchange across the boundary; for example, it does not take into account heat flux variation due to spacecraft orientation, etc.

2. Boundary conditions on the surfaces of inner objects: $U = 0$ and $-\lambda \partial T / \partial n = (q_i \cdot n)$, where $q_i$ is the heat flux from the unity of $i$th object surface, which is defined by the spaceflight program.

One can see from the preceding model that in spaceflight centrifugal forces of rotations, gravity gradient, and aerodynamical drag, etc., induce buoyancy force $\beta (T - T_0) n$, where $n$ plays a role of efficient microacceleration due to reduced gravity (“low gravity”). A force $(r \times (d\omega / dt))$, taking into account accelerated rotation, is significantly different, because it induces convection, which may be important even in isothermal conditions. Both forces may be a cause of the scalar component nonuniformity or mixing. Material sciences in space flight specifically need to take into account all aspects of the quasi-steady microaccelerations. However, it is important also for a problem of optimization of space flight systems.

Angular Velocities and Microaccelerations Onboard the Spacecraft

Quasi-steady components of microacceleration onboard the orbital spacecraft induced by its motion around the mass center as a rigid body, gravity gradient, and atmospheric drag may be calculated with enough accuracy on the basis of the rotatory motion, using formulation given by Eq. (2). This formulation allows one to calculate realistic quasi-steady microacceleration fields for any times if any kind of information makes it possible to reconstruct actual motion of the spacecraft around its mass center. Such information would contain three component detections of the angular velocity. It is available now in a database with components of microacceleration vector $n$ for different flight regimes of the spacecraft (MIR station, ISS, Foton, space shuttle) during several hours for one flight. These data were presented for the CFD codes by Prof. V.V. Sazonov for different spacecraft in material science problems. Table 1 contains a typical example of the data file, using for the calculation of the microacceleration field $n$ by formulation given by Eq. (2) for the Foton flight.

Isolines of the vector microaccelerations $n$ for recoverable spherical enclosure of Foton in meridional section XZ (see a more detailed discussion in Ref. 22), show minimum $n$ in mass...
TABLE 1. Components of the Angular Velocities, Angular Accelerations, and Aerodynamic Drag for Calculation of Microacceleration Vector for FOTON Spacecraft

| Time (s) | $\omega_x$ (1/s) | $\omega_y$ (1/s) | $\omega_z$ (1/s) | $\langle d\omega / dt \rangle_x$ (1/s/s) | $\langle d\omega / dt \rangle_y$ (1/s/s) | $\langle d\omega / dt \rangle_z$ (1/s/s) | $\mu E / |R|^3$ (1/s) | $\epsilon_x$ (cm/s/s) | $\epsilon_y$ (cm/s/s) | $\epsilon_z$ (cm/s/s) | $a_x$ (cm/s/s) | $a_y$ (cm/s/s) | $a_z$ (cm/s/s) |
|----------|-------------------|-------------------|-------------------|----------------------------------------|----------------------------------------|----------------------------------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| ...      | ...               | ...               | ...               | ...                                    | ...                                    | ...                                    | ...             | ...            | ...            | ...            | ...            | ...            | ...            |
| 252      | 1.49              | -2.23             | -1.20             | 6.19                                   | -1.30                                   | 2.89                                   | 1.31            | -3.92         | -9.03         | -1.75          | -4.00          | 2.10           | -1.14          |
| 256      | 1.49              | -2.28             | -1.08             | 6.14                                   | -1.17                                   | 2.95                                   | 1.31            | -3.89         | -9.13         | -1.21          | -1.30          | 1.44           | -1.14          |
| 260      | 1.50              | -2.32             | -0.96             | 6.03                                   | -1.03                                   | 3.01                                   | 1.31            | -3.86         | -9.2          | -0.67          | -2.10          | 0.78           | -1.14          |
| 264      | 1.50              | -2.36             | -0.84             | 5.88                                   | -0.90                                   | 3.06                                   | 1.31            | -3.83         | -9.24         | -0.12          | -3.00          | 0.14           | -1.13          |
| ...      | ...               | ...               | ...               | ...                                    | ...                                    | ...                                    | ...             | ...            | ...            | ...            | ...            | ...            | ...            |
| 17850    | 1.50              | 1.66              | -1.32             | -1.60                                  | -1.35                                   | -2.03                                  | 1.29            | -2.65         | -5.01         | 8.24           | 86.0           | -9.75          | -0.57          |

Figure 2. Isotherms in a meridional section of the spacecraft enclosure for the realistic microgravity field.
Figure 3. Comparison of the maximal, minimal, and average (straight line for 20°C) temperatures in enclosure for three microaccelerations regimes (bold line, zero gravity; dashed line, low gravity, 10 microg; solid line, realistic microaccelerations).

differences between isotherms here are 2°C, maximal temperature in the enclosure is 47.8°C, and minimal temperature is −6.47°C.

Figure 3 summarizes the maximal and minimal temperature rises in time for the mentioned regimes of microacceleration in comparison with average (straight line for 20°C) temperature in the enclosure. This average temperature is the same for all three cases because the heat output for all these regimes was the same and corresponds to the heat input from the inner sources. The bold lines here correspond to the regime of zero gravity (pure heat conduction). Temperature difference at the end of the heating run here reaches 104°C. The dashed lines are for the regime of constant gravity $g/g_0 = 2 \times 10^{-5}$, and the continuous lines inside are for the realistic accelerations (Table 1). One can see that the temperature difference is reduced till 70°C, and temperature oscillations of $T_{\text{max}}$ for third case correspond to the oscillations of microaccelerations. Temperature difference reduces to 41°C for this case.

As shown in Figure 4, for the low-gravity case the velocity rises to a maximum and reaches a value near 0.2 cm/s, and the velocity for the realistic microgravity case is unsteady and reaches a maximum near 0.8 cm/s, which corresponds to a Reynolds number, defined by the diameter of the sphere, near 2000.

Therefore convection for the realistic case even in regular spaceflight of Foton may be in the transition regime from laminar to turbulent regime, and a significant heat transfer resource exists in realistic case. This result is a new one and may be provided only by the 3D conjugate modeling in realistic spaceflight.

**Temperature and Concentration Inhomogeneities Induced by Different Types of Convection**

We will discuss briefly some results of the use of the new conjugated modeling for a problem of concentration uniformity for material sciences. In contrast to the aforementioned problem of mixing, for material sciences the diffusion regime is important. Under orbital flight conditions, several small but equally important forces determine the resultant flow pattern in
this case. For this reason, the assumption that transport induced by heat conduction and diffusion predominates proved to be incorrect. The study of all these processes necessitates taking all the active factors into account and results in the formulation of coupled problems of hydro- and theoretical mechanics that differ from both the traditional problems of space-flight mechanics and the problems of heat and mass transfer under terrestrial conditions. Because of the multiparametrical nature of this case and the slow motion we will discuss first the results on the basis 2D modeling (see 3D case in Ref. 18).

As shown in Figure 5, one 3D problem corresponds to the three 2D problems with the use microaccelerations on the planes \((z, y), (z, x),\) and \((x, y)\).20,22

**Figure 5.** 2D modeling in a conjugate problem.

### Effect of Elementary Fluid Flows

The distribution of nonuniformity is most important as a goal for the material sciences. We will show some new results deals with body forces and the effect of the surface tension gradient in the realistic spaceflight conditions.

#### Buoyancy-driven Flows

In space material engineering it was believed that under weightlessness conditions in directional crystallization it should be possible to reduce the lateral concentration nonuniformities of a dopant component.3-5 However, in the simplest cases the results of modeling show that this is not always achievable; the dependence of the lateral concentration difference on the Grashof (Rayleigh) number has a maximum. A case of steady-state microaccelerations \(g / g_0 \ll 1\) (“low gravity”) was studied during many years since the 1970s.2,4,6-9

Comprehensive studies of the nonuniformity have been done in previous research (see last historical overview in Ref. 23). Figure 6 shows the dependence of the lateral nondimensional concentration nonuniformity \(\Delta C / C = \Delta C / (C_1 - C_2)\) on the Grashof number for steady-state buoyancy-type flows when the concentration difference is specified along the ampoule. One can see that the temperature field across the ampoule is uniform because of the small Pr number, but the vertical concentration difference passes through a maximum and decreases with increase in the Grashof number.

The physical meaning of the maximum is as follows: in the heat conduction regime, the convective correction to the concentration difference is zero because there is no flow and, for high Grashof numbers (typical terrestrial conditions) this correction tends to zero because of the strong mixing effect. Accordingly, the maximum temperature or concentration stratification is created by weak convection in the intermediate regime. It was established also that all types of convection (gravitational and non-gravitational) possess the property of attaining a maximum with respect to the parameter (Gr, Re, Mn) characterizing the convection rate.9

For lateral action of the gravity force it is possible, knowing the initial concentration nonuniformity (to the left or right of the maximum), to make a qualitative prediction about the value of the nonuniformity with decrease in the gravity force under microgravity conditions (Fig. 6C). It is possible to eliminate nonuniformity of this kind, for example, by slow variation of the layer orientation.9 Thus, the buoyancy forces induced by the quasi-static component of the microaccelerations, together with all the
Figure 6. Dependence of the nondimensional concentration nonuniformity \( \Delta C/C = \Delta C/(C_1 - C_2) \) on the Grashof number \((L/H = 4, \text{Pr} = 0.014, \text{Sc} = 10)\). (A) Stream function, (B) isotherms, and (C) lateral inhomogeneities \([1, \Delta C(\text{Gr}); 2, \Delta C(\text{GrD}); 3, \Delta C(\text{Gr}, \text{GrD}); 4, \text{Re}(\text{Gr})]\).

“internal” phenomena (melt volume variation, capture or expulsion of the admixture on the crystallization front, the viscosity to diffusion ratio, etc.), can be a source of high lateral concentration nonuniformity.

To answer the basic question of when a macrononuniformity attributable to weak convection should be anticipated and when a micrononuniformity induced by convective instability and vibrations is dangerous, a 2D model is insufficient. 3D calculations demonstrate the development of oscillations and the presence of a second concentration nonuniformity maximum much smaller than the first one. The 2D model satisfactorily predicts the lateral concentration nonuniformity induced by the buoyancy but does not describe the oscillation effects accompanied by loss of flow symmetry, which are essentially 3D (see more details in Ref. 13).

Concentration nonuniformities may also result from a convective flow induced by vibration. The magnitude of the nonuniformity may differ depending on whether the vibration is translational or nontranslational and high or low frequency. For a flow subjected to low-frequency translational vibration, the maximum of the dependence of the concentration nonuniformity on the vibration amplitude and frequency was obtained in Refs. 9 and 23 on the basis of 2D models. Lateral concentration nonuniformities were induced by high-frequency translational vibration normal
Figure 7. Flow patterns and concentration nonuniformities in an isothermal semiconductor melt in the presence of an angular acceleration induced by swaying: (A) instantaneous flow patterns, (B) concentration isolines, and (C) concentration variation with time at the center of the two opposite walls.

Nonbuoyancy Effects

The force \( r \times d\omega/dt \) caused by the accelerated rotation may also induce convection and concentration nonuniformity even under isothermal conditions. Both these forces may be the origin of a temperature (concentration) nonuniformity or may be the cause of mixing.

In the formation of concentration nonuniformities attributable to low-frequency nontranslational vibration induced by an angular acceleration, not only the amplitude and the frequency but also the distances from the rotation center are important. This is why, in this case, such general results as those obtained for buoyancy forces are limited. For an example, let us consider the results of a 2D calculation of an isothermal flow and the distribution of an melt component induced by low-frequency vibration (swaying) for distances of the volume from the vibration center \( x = 127 \text{ cm}, y = 6 \text{ cm}, \) and \( z = 3 \text{ cm} \) typical of the Foton sputnik and the same aspect ratio and properties of the melt as in Figure 6, and an oscillation amplitude corresponding to \( g/g_0 \sim 10^{-2} \) at the frequency \( 0.001 \text{ Hz} \). These are greater than the actual flight values\(^{21}\) but considerably smaller than the values to be found in the literature.\(^{10-12}\) In the instantaneous patterns of the stream function and concentration field isolines and the concentration variation on the boundary over one oscillation period, periodically formed secondary structures, typical of this kind of flow, are visible (Fig. 7.) For frequencies of this order, the character of the instantaneous...
concentration nonuniformity depends on the change in flow direction. In this case, the nonuniformity differs significantly from that induced by the buoyancy forces. The lateral nonuniformity may be greater than for the case of buoyancy forces. Depending on the oscillation frequency, there exists a maximum of the transverse concentration nonuniformity corresponding to a superlow oscillation frequency, which in this example is of the order of $10^{-3}$ Hz. For interpreting orbital experiments, in modeling the processes on the crystallization front it is useful to take flows of this kind into account.

Very important in microgravity is another nonbuoyancy—surface tension–driven flow. Concentration nonuniformity by the Marangoni effect in a problem discussed earlier for buoyancy flow ($L/H = 4$, $Pr = 0.014$, $Sc = 10$) shows here, in Figure 8, similar to the behavior as in Figure 6C, but with limiting value $(\Delta C/C)_{\text{max}} \sim 0.25$ for a low Marangoni number about 1.0. This value is very small and may be realized only in special cases.

**Peculiarities of Concentration Inhomogeneities Due to Convection under Realistic Spaceflight Conditions**

To make progress in solving the problems of the material sciences in spaceflight, with many unknown side phenomena, it is useful to compare the concentration nonuniformities onboard different space vehicles with taking into account their real motion, including flight regimes with accelerated rotation. Such a comparison was carried out within the framework of a simplified 2D formulation for convective mass transfer in a closed square cavity with a prescribed concentration on two boundaries in the absence of heat and mass fluxes on the other two boundaries. In this approximation, 2D problems were solved with the use of microaccelerations in the $(z, y)$, $(z, x)$, and $(z, y)$ planes (Fig. 5), and the concentration nonuniformities due to convection induced by all the quasi-static microaccelerations taking into account the specific features of the space vehicle design and flight dynamics. The calculations were performed for four space vehicles (the MIR orbital station, the Foton sputnik, the International Space Station, and the space shuttle). The difference in concentration nonuniformities turned out to be fairly large (Fig. 9) and to increase with increase in the rate of vehicle rotation about the center of mass. This rotation rate is maximal for the uncontrolled motion of the unmanned Foton sputnik and minimal for the manned MIR station.\[14, 21\]

The effect of the $g$-jitter and quasi-steady accelerations on the nonuniformity “reversal” was observable but less well expressed. Moreover, under regular flight conditions the concentration nonuniformities are smaller than those, which could have been obtained by using their maximum values in parametric calculations. 3D calculations for real Foton flight\[18\] performed with account for the quasi-steady component confirm the conclusion that, when real design flight conditions are taken into account, the transverse concentration nonuniformities are smaller than the maximum possible nonuniformities in the 2D case. To clarify the true causes of the nonuniformities under real conditions, it is necessary to carry out parametric analysis.

In this example, the effect of the angular acceleration (which in the cases considered in
Fig. 9 should be greatest for the Foton sputnik) is smaller than the effect of the centrifugal rotation forces. This is because, in regular spaceflight, the amplitude and frequency of the real angular accelerations are small. In real regular Foton flight, the aforementioned concentration calculations can indicate the contribution of each component in each specific case. For example, for the International Space Station the gravity field gradient plays the most important role.

The most probable cause of the anomalously high concentration nonuniformity is the interaction of the “internal factors” (variation of the volume occupied by the melt during motion of the front with concentration variation on the boundary) and the significant influence of microaccelerations under nondesign as opposed to regular flight conditions (“external factors”). For example, in the aforementioned experiment onboard the Soyuz–Apollo, melting took place during the interval of complex dynamics after the docking of the space vehicles. In Ref. 24, an attempt was made to explain this effect on the basis of a more complete model of crystallization, with account for the shape and motion of the front (Stefan problem), but the microaccelerations were assumed to be constant; that is, the real flight conditions were not taken into account.

A typical example is the attempt also to interpret experiments on crucible-free zone melting, in which the surface forces should predominate over the external forces. However, the authors attribute the observed “edge effects” only to “external factors.”25 This is why the results24,25 cannot give a complete explanation of the causes of the anomalous concentration nonuniformities.

**Coupling of the Convection Induced by Quasi-steady Microaccelerations and Thermocapillary Convection**

The complexity of the coupling of the convection induced by quasi-steady microaccelerations and thermocapillary convection may be explained using the result modeling of the
Figure 10. Flow fields of convection, temperature, and concentrations due to coupling of thermal convection under quasi-steady microacceleration with thermocapillary convection in an ampoule with semiconductor melt for different Ma number (see on the left). (In color in Annals online.)

Conjugated problem with microacceleration data on Foton shown from Figure 10. Here the instantaneous (for the same time) flow, temperature, and concentration fields, due to coupling of thermal convection under quasi-steady microacceleration \( \mathrm{Gr}_{\text{max}} \sim 10 \) and thermocapillary convection for the case with surface for different Ma number are shown. A range 0–80 for Ma number in an ampoule with semiconductor melt for the same parameters as in Figures 7 and 8 \((L/H = 4, \Pr = 0.01, \mathrm{Sc} = 10)\), was realized.

Quasi-steady microaccelerations dominate for \( \mathrm{Ma} = 0 \) (the rigid wall case), but thermocapillary convection dominates for Ma more than 10. Therefore, because usually the number of Ma in the semiconductors melt much more than 10, for the case with surface melt and tension gradients the quasi-steady microacceleration for space flight does not matter. However, it should be taken into account that the effect of Marangoni convection mainly near the surface and a problem of the penetration of Marangoni flows inside a bulk exists.

Thus, an analysis of the technological experiments conducted under realistic flight conditions does not rule out the possibility of obtaining highly homogeneous single crystals. However, to achieve this goal both real flight conditions and the “internal factors” need to be taken into account and checked.

Concentration nonuniformities in semiconductor melts is a typical but not the only example of high gravitational sensitivity registered under real spaceflight conditions. In the course of a study of near-critical phenomena performed onboard the MIR station, anomalous heat transfer effects, which can be explained only by the presence of convection, were also registered. All these phenomena clearly show that so-called microgravity requirements on the International Space Station do not have a scientific basis. These circumstances initiated special projects with the title of “global benchmark” and microgravity detector (DAKON) that use the discussed conjugate models of fluid dynamics and mechanics of spaceflight (see more details in Refs. 23 and 27).

Conclusions

The experiments onboard orbital stations that began in the 1970s revealed new, not completely understood, phenomena attributable to gravitational sensitivity. Now, in modeling convection and heat and mass transfer processes the 3D barrier has been overcome. One of the most important points is that 3D conjugate models using realistic information of spaceflight were developed.

Special calculations for the design and flight parameters of the Foton sputnik show the possibility to reduce by about one-half the maximum of the temperature difference inside enclosure from diffusion (zero gravity) regime in realistic flight with angular acceleration. Therefore, a
significant reserve for cooling inside satellites exists in this case.

Using the preceding techniques, comparison of lateral concentration difference in a simplest model with realistic microgravity on MIR, Foton, Space Shuttle, and the International Space Station is done, and in each case the reasons for the inhomogeneity with buoyancy and nonbuoyancy convection are discussed and explained in a simple model of concentration inhomogeneity in the melt. The thermocapillary effect suppresses the effect of quasi-steady microacceleration for concentration inhomogeneity, and one must take all the preceding facts into account as needed.

This work makes it possible to turn the solution of the coupled problems of hydro- and theoretical mechanics into a working tool for the analysis and prediction of results.

However, the elementary convection processes attributable to the specific features of motion under spaceflight conditions, including low-frequency accelerated rotations and the interaction of volume and surface convection mechanisms, are not yet sufficiently well understood for practical purposes. This makes the more detailed theoretical and experimental investigations of these processes under laboratory conditions using high-performance computers all the more pressing.

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Conflicts of Interest

The authors declare no conflicts of interest.

References

component on board the International Space Station. *Cosmic Res.* **42**: 155–164.


