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FREE CONVECTION IN THE INTERNAL PROBLEM: RESULTS AND PROSPECTS

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The fundamental features of free convection, its current classification, mathematical modeling, and software based on a computer laboratory are discussed, and findings of an investigation of the structure of free convection in closed regions, new formulations of problems of free convection in compressible media, and results on the relation of microacceleration measurements and calculations and programs that model free convection are given.

1. Introduction. Free convection is the most important and commonly encountered mechanism of macroscopic motion in heat and mass transfer processes, which is especially vividly illustrated by the scientific program of the Third Minsk International Forum (Belarus), where reports on free convection were delivered at all eleven sections. However, the situation concerning generalization of works devoted to this universal mechanism of motion does not correspond to extensive studies of the latter by specialists. Although a demand for generalization of the results obtained exists, the present investigation of free convection is confined, because it is impossible "to embrace the Universe," to mathematical modeling of convection in the internal problem and mainly to Newtonian media, although much of the experimental work conducted pertains to rheologically complicated fluids.

The subject of this report partially repeats the title of a well-known book by G. A. Ostroumov [1] that is the pioneering work in investigations started in this field in the postwar years, and its results are reflected in a book by L. D. Landau and E. M. Lifshits [2], where for the first time the problem of free convection is rigorously formulated in the educational literature from the positions of mathematics and physics. In the 1960s, a monograph by S. Chandrasekhar on convective stability [3], a survey by S. Ostrach [4], and B. S. Petukhov's monograph on mixed convection [5] were published, while the 1970s and 1980s saw a book by G. Z. Gershuni and E. M. Zhukhovitskii [6] on convective stability, a book by J. Terner [7] on convection in stratified fluids, a book by A. V. Luikov and B. M. Berkovskii on convection and waves [8], a monograph by D. Joseph on convective stability [9], a handbook on free convection by O. G. Martynenko and Ya. A. Sokovishin [10], a collaborative monograph edited by S. Kukac [11], one by V. I. Polezhaev, A. V. Bune, N. A. Verezub, et al. [12] on mathematical modeling of convective heat and mass transfer, the collaborative monograph by B. Gebhart et al. [13], a book by Yu. V. Lapin and M. Kh. Strelets on convective flows of gas mixtures [14], and a monograph by G. Z. Gershuni, E. M. Zhukhovitskii, and A. A. Nepomnyashchii on the stability of convective flows [15]. In the 1990s, books by V. I. Polezhaev, M. S. Bello, N. A. Verezub, et al. [16] on convective processes under weightless conditions, by B. S. Petukhov on heat transfer in a laminar boundary layer [17], and by Yu. K. Bratukhin and S. O. Makarov on interphase convection [18] and a manual by A. M. Kutepov, A. D. Polyanin, Z. D. Zapryanov, et al. on chemical hydrodynamics [19] were published, which reflect some methodological problems and trends in free-convection investigations.

Since investigations of free convection have a rather long history and are being carried out rather extensively, there is a need for consideration of its "territory." The tools of investigation also require further study since in some problem that arise in power engineering, industrial and civil engineering, environmental science, biomedicine, technological processes, and atomic and aerospace technology the adopted models and methods are insufficient. The overwhelming majority of works are carried out using the Oberbeck–Boussinesq model, which

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suffers from important limitations. Moreover, in reference books and textbooks free convection, as a rule, means mainly thermal gravitational convection, although investigations and applications of this kind of motion are more versatile.

Below in Secs. 2–3 the ideas of the survey [20] presented by the author at the First Russian Conference on Heat Transfer, where free convection was the subject of discussion at a separate session, are refined and developed. The fundamental features of free convection as one of the main kinds of macroscopic motion are discussed, and the definition of free convection and its modern classification are clarified.

In Secs. 4–6 some new results obtained mainly in the past 2–3 years using mathematical modeling and software for solving free-convection problems are surveyed; among them the potentialities of a "computer laboratory" and results of investigation of the spatial structure of free convection in closed regions are discussed. Some results of solution of applied problems, formulations of new problems of free convection, the problem of relating measurements to computer programs for analysis, and interpretation and control of free convective flows are discussed in brief.

2. Definition, Modern Classification, and Some Fundamental Features of Free Convection. In the modern scientific literature free convection means flows without a prescribed external velocity that occur under the action of mass or surface forces. They can be classified with respect to the type of acting forces, the kind of working media, and conjunction with other processes. A fundamental difference of free convection from forced lies in the fact that these flows develop as a result of loss of the stability of the equilibrium or as a consequence of the absence of equilibrium. Therefore, they depend strongly on the characteristics of both the motive forces and the medium itself. One of the basic characteristics is the density, which enters the formulation of the force, the equation of continuity, the heat-transfer equation, and the equation of state. This circumstance leads to a variety of formulations of problems in which mathematical models must be formulated in the appropriate way. This is especially distinctly manifested in the case of a convective flow that develops after introducing disturbances if the initial state of the system was that of unsteady equilibrium.

The convective processes most commonly encountered are those under the action of a constant gravitational force or the gravitation force of the centrally symmetric field that occurs in the majority of objects in the Universe. However, the mass force can also be caused by rotation or vibration, which in the absence of a gravitational force, i.e., in the weightless state, is manifested as a nongravitational mechanism of convection. The action of forces of surface tension causes Marangoni convection, which is also of a nongravitational nature. Forces of expansion (compression) caused, for instance, by heating of a compressible medium, which initiates thermoacoustic convection, also are the surface forces. In establishing the equilibrium, non-steady-state flows develop that, although being substantially different from steady-state convection, must be included, nevertheless, in the general classification of free convection.

Depending on the type of "working medium," which can be weakly compressible, homogeneous or heterogeneous, or considerably compressible, as, for instance, in the vicinity of the critical point, convection exhibits significant specific features. In a binary system stratified with respect to density due to temperature and/or concentration inhomogeneities, "double diffusion" occurs, which can manifest itself under the action of both buoyancy forces [7] and forces of surface tension (interaction of thermocapillary and capillary-concentration modes of convection [12, 16] or by analogy with [7] Marangoni "double diffusion"). In conjunction with other processes (a forced flow, a heat-conducting solid mass, a reacting medium, radiation, a phase transition, and/or processes of motion leading to a complicated microgravitational situation [16]) free convection demonstrates significant specific features that give rise to independent classes of problems.

In constructing models of free convection and developing methods for investigating it the role of its sought characteristics is of particular importance. In addition to the traditional characteristics of free convection such as the mean heat transfer, the local heat transfer is of interest, which is not monotonic over the surface since on one part of the surface heat is removed, while on another – it is supplied, i.e., local superheating can occur. In many applications, especially in cryogenic technology, temperature stratification caused by convection plays an important role. In material science more subtle characteristics of convection such as macro- and microinhomogeneities of the impurity distribution, which are difficult to predict, are of interest. In their analysis as well as in interpretation of data from remote probing of convection from artificial satellites the structure of the convection is of particular importance [12, 16]. In this case, some methods can describe mean characteristics rather well but cannot provide sufficiently accurate data on local characteristics and the structure of free convection, which is the concern of special tests (see, e.g., [12, 21-24]).

3. Models of Free Convection. The Oberbeck–Boussinesq model [2, 9] is the one most widely adopted for the description of free convection even now. The achievements of the Twentieth Century could not refute it since in liquids, as a rule, large temperature differences cannot be maintained because of boiling. For various reasons the temperature differences are also not large in the technologies of growth of single crystals and semiconductor structures from melts. This model has been employed in the formulation of the free-convection problems in the case of liquid filtration in permeable porous media when the Newtonian law of friction is replaced by the Darcy law of resistance (see, e.g., [6, 11, 13]). In the Oberbeck–Boussinesq model the change in density is accounted for only in the buoyancy force. Based on this, extended models with allowance for variable transfer coefficients and nonlinear change in density as a function of temperature have found some applications.

In 1968, at the Third All-Union Heat and Mass Transfer Meeting in Minsk (Belarus) convection problem formulation based on the complete Navier–Stokes equations for a compressible gas [25] was a matter of discussion but in those years this model did not yet have applications and only now does it begin to enjoy wide use. This model takes into account the change in density fully and, moreover, in addition to the Grashof and Prandtl numbers it contains such new dimensionless parameters as the hydrostatic compressibility, temperature ratio, and adiabatic exponent. In [2], where the stability of a compressible nonviscous gas is discussed, the stability criterion for a perfect gas is derived in the form of the critical temperature gradient (equal to the adiabatic gradient in the case of a perfect gas). This criterion was first derived by Schwarzschild at the beginning of our century and can be represented as some dimensionless combination that is the ratio of the actual temperature gradient to the adiabatic gradient. This criterion together with the Rayleigh number describes the initiation of convection in a compressible viscous gas [26].

M. Kh. Strelets and his co-workers (and at almost the same time Paolucci [27]) developed an intermediate model of convection (see detailed references in [14]) that has proved to be especially effective in the case of simultaneous action of free convection and a forced flow of a compressible gas. In this model, hydrostatic compressibility, which is insignificant in regions of small dimensions but complicates calculations because of the presence of a small parameter, is filtered out. Since compressibility can be of a temperature or hydrostatic nature and is intrinsically related to the equation of state, it is necessary to formulate different mathematical models that are adequate for the process under consideration. We usually do not face such a need in problems of forced convection, where compressibility manifests itself, as a rule, at large velocities of motion (dynamic compressibility, which is small in problems of free convection). In textbooks and monographs this aspect is elucidated insufficiently.

Works concerned with deviation from the Boussinesq approximation and determination of the conditions of its applicability are still being published. However, determination of these conditions necessitates enormous efforts since it requires investigation of the dependence of the deviation $\varepsilon = \mathrm{Nu} - \mathrm{Nu}_0$ (where Nu_0 is the solution based on the Boussinesq approximation) on the governing parameters, and therefore the volume of work is hugh. Some particular studies are known in which deviations from the Boussinesq approximation are demonstrated in individual problems, but this matter is far from being elucidated completely. It turns out that mixed convection, i.e., the interaction of free and forced modes of convection, can be simulated more effectively in the intermediate models than in the complete model with weak compressibility. However in considering only free convection in a compressible gas, one can model weak compressibility at small values of the parameter of hydrostatic compressibility, thus passing to the limit in the initial equations [25, 26].

Extension of the Oberbeck–Boussinesq model to liquids is related to the so-called model of "an isothermally incompressible liquid" in which the density is variable but independent of the pressure. It is important that in the equation of continuity the density is written in generalized form since the change in density with time, e.g., in the presence of high-frequency vibrations, can be considerable. This model is discussed in [28-30] but it is still developed insufficiently. In cases of a complicated change in the motive force, for instance, in the mass force in the presence of rotation, it is necessary to allow for the Coriolis forces, and in a more complicated case knowledge of

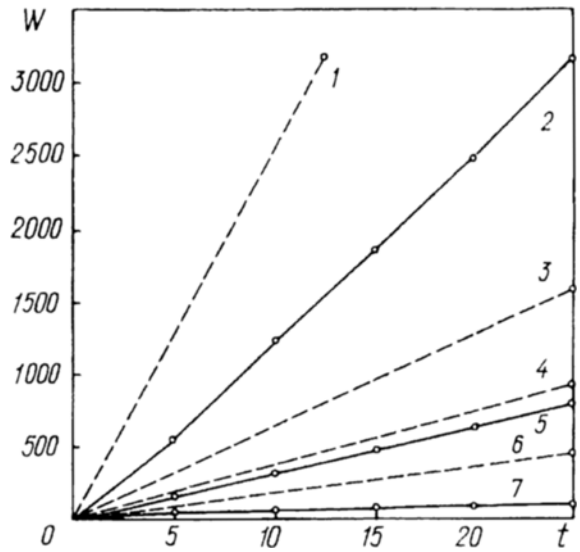

Fig. 1. Comparative characteristics of the efficiency of large-scale computation tools based on microprocessors Intel for modeling convective processes (t, min): 1) 2×i860 (40 MHz), vector regime; 2) i860 (40 MHz), vector regime; 3) 2×i860 (40 MHz), scalar regime; 4) Alpha (275 MHz); 5) i860 (40 MHz), scalar regime; 6) Pentium (133 MHz); 7) main computer IBM-486 (33 MHz).

the law of motion is required [31]. This is important for free-convection studies under conditions of orbital flight [16], where the space-time change in the forces is of a complicated nature and requires adequate consideration in each model mentioned above.

4. Modeling Methods and Software. The Computer Laboratory and Free-Convection Problems. Considerable progress in free-convection studies has been achieved owing to extensive elaboration of the methods of direct numerical solution of nonlinear equations based on the Navier–Stokes equations in the 1960-1980s, which is reflected in the works of the well-known scientific schools guided by Academicians K. I. Babenko, A. A. Samarskii, and N. N. Yanenko. Therefore this trend a good scientific base exists in the CIS (see a more detailed bibliography in [12, 22-24, 32]). Traditionally, methods of stability theory [3, 6, 9, 15] have been a matter of great concern in free-convection studies. At present their role is ever increasing because the results of numerical solution are difficult to understand and because there is a great bulk of insufficiently processed empirical and numerical information, while these methods provide a basis for construction of charts of different regimes and provide approaches to make the information coincise. The close association of these methods is a topic of a number of the books mentioned [6, 15, 16, 24].

Development of convenient tools of mathematical modeling that allow for specificity and variety in formulations of free-convection problems and are suitable for large-scale users, is rather urgent. One of the approaches along this line is made in connection with creation of the "COMGA" ("Convection in Microgravity and Applications) system initially developed for problems of free convection under microgravity conditions [33]. This system is a convenient tool for modeling of free convection by personal computers. Its menu contains all the necessary information for formulation of problems of free convection using the Oberbeck–Boussinesq approximation in regions of the simplest form (relations for sides of a region with prescribed initial and boundary conditions of the first, second, and third kind for the temperature and/or concentration and adhesion conditions and/or conditions on a free surface that include the gradients of surface tension forces, i.e., Marangoni convection, methodological parameters for the calculation, etc.). The mass force is not just the gravitational force but can also be caused by rotation or vibrations of the region. A scheme of possible versions of prescribing the mass forces and versions of the calculation that differ in the mutual position of heat and/or mass flows relative to each other and with respect to the orientation of the mass forces of this system and classification of the problems contained in the system were discussed in earlier works [16, 31, 33] for a simple region in which heat and mass flows are prescribed

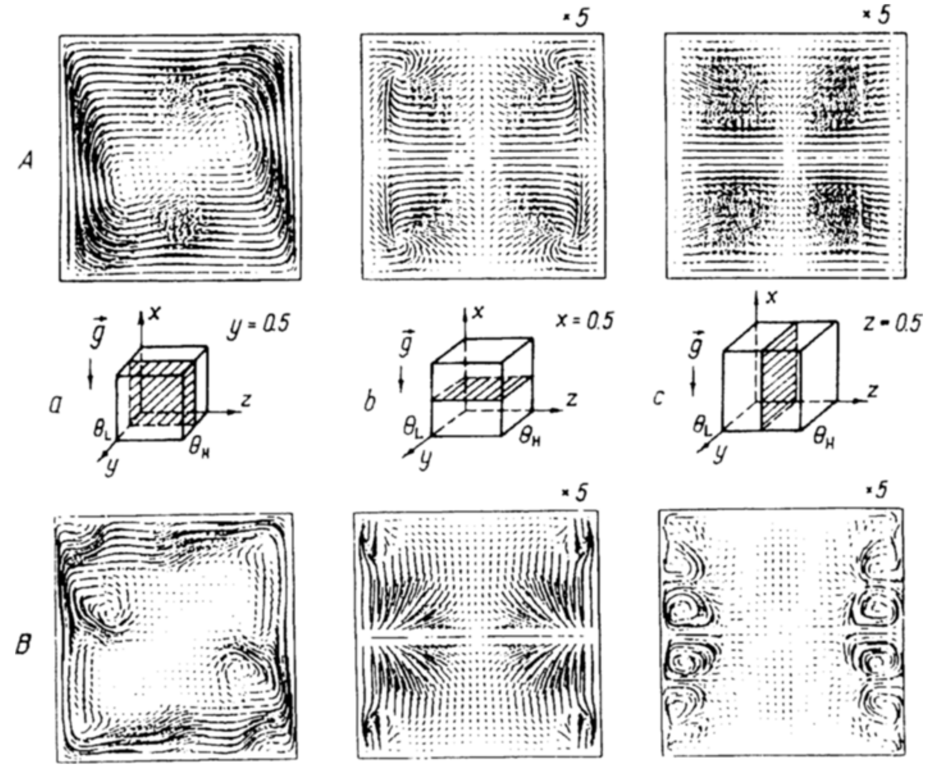

Fig. 2. Spatial structure of thermal gravitational convection in a cubic region exposed to lateral heating (Pr = 0.71; vector lines in central sections a, b, c): A) Ra = 10^5, stationary regime; B) Ra = $8.5 \cdot 10^6$, instantaneous pictures at t = 300 min.

that act in just one direction. Even in such a simple case, the binary system includes ten different possible types of free convection in the presence of "double diffusion" that differ in the mutual direction of the heat and mass flows (salt fingers, a diffusion regime with a parallel direction for these flows or laminated structures with a transverse direction for them).

Thus, in a simplified geometry this system contains the basic elements of the general classification of free-convection problems mentioned above and has already been in operation for several years. There are a variety of examples of problems solved by the authors of this system. However, its application to problems of free convection by researchers inexperienced in solving similar problems is not as simple a matter as had been thought earlier. In [33], the notion of a "computer laboratory" for free-convection problems was introduced that includes previous experience in solving problems of free convection in its basic subdivisions, illustrative examples, characteristics, results of solution of some topical problems that are subdivided into problems potentially contained in the system (*), problems solved earlier and repeated with the aid of this system (**), and new problems solved by this system (***). A detailed description of the computer laboratory with the content of its basic subdivisions of isothermal forced flows (I), free convection due to mass forces (II) and surface forces (III), and applied problems (IV) and a bibliography is given in [33].

For large-scale users, it is important to have convenient and comparatively inexpensive computation tools. Recently, personal computers have been equipped with special processor-accelerators of the Intel i860 type, which can be inserted into the ports of a personal computer. Software for such a multiprocessor computing system has been developed in the laboratory of mathematical and physical simulation in fluid dynamics at the Institute of Problems in Mechanics (Russia). Figure 1 compares on a model example the volume of computational work W performed by computation facilities (PC AT 486, one and 2×i860 processors in the superscalar and vector regimes) available to a large-scale user as well as by new personal computers of the Pentium type.

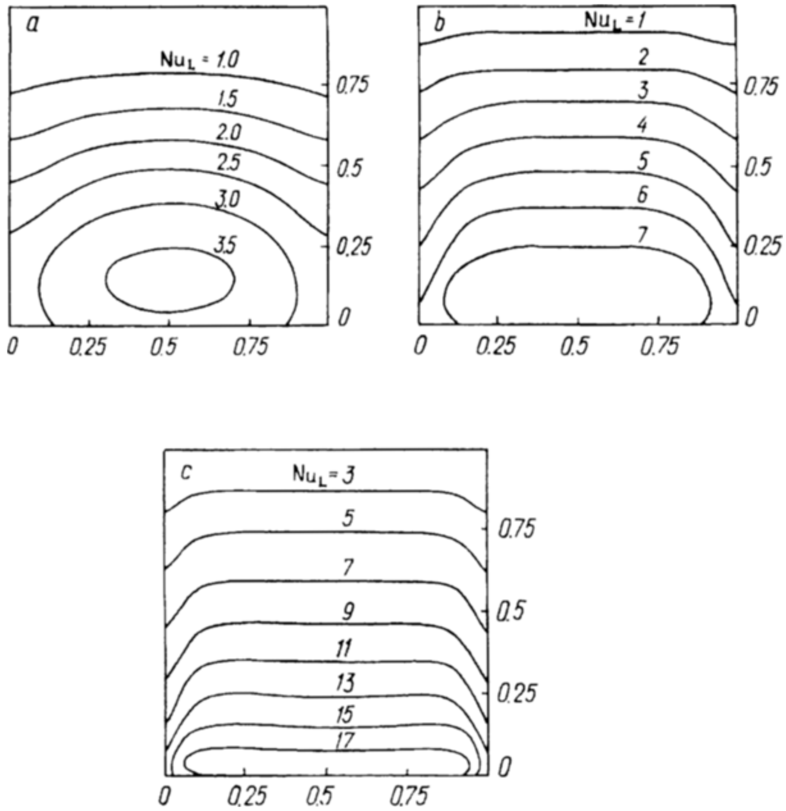

Fig. 3. Isolines of the local Nusselt number on a heated surface with thermal gravitational convection in a cubic region (lateral heating, Pr = 0.71): a, b) Ra = 10^4 and 10^5, stationary regime; c) Ra = $8.5 \cdot 10^6$, instantaneous picture at $\bar{t}$ = 300 min.

5. New Results of Investigations of the Free-Convection Structure in Closed Regions. At present the investigation of two-dimensional free-convection problems has made impressive advances, as seen from the references in the cited monographs. The survey [34] provides additional information on works devoted to the structure of thermal gravitational convection in closed two-dimensional regions which has always been a matter of priority in free-convection studies, opening the ways to various applications. The computer laboratory mentioned above makes it possible to advance this trend and to solve effectively two-dimensional problems without resorting to creating voluminous archives.

Although a number of three-dimensional procedures and programs based on the Oberbeck–Boussinesq approximation (see, e.g., [16, 35-40]), intermediate models [14], and the complete Navier–Stokes equations of a compressible gas [41] are available, investigations in this direction do not make swift advances since, in addition to computational difficulties, there are methodological difficulties in analysis of the three-dimensional structure of free convection, especially in connection with the large scale and diverse intensity of the flow.

Here, as earlier in the two-dimensional case, the test problem of thermal gravitational convection in a closed region with two side walls having different temperatures and with the remaining walls being heat-insulated, by analogy with the problem in [21], which is still insufficiently investigated in the three-dimensional case, is of importance. Systematic consideration of this problem has been started in [36], where the so-called "hybrid" difference scheme is used in the calculations. Test calculations made by O. A. Bessonov in accordance with his procedure [38] are shown in Fig. 2. In depicting the vector structure of the flow, the planes normal to those of the drawing are magnified fivefold since the secondary structures in those planes are very weak but, nevertheless, they can exert an influence on heat and mass transfer characteristics, which is of importance for some engineering and technological applications. At a Rayleigh number of 10^5, stationary secondary structures are formed (Fig. 2A, a).

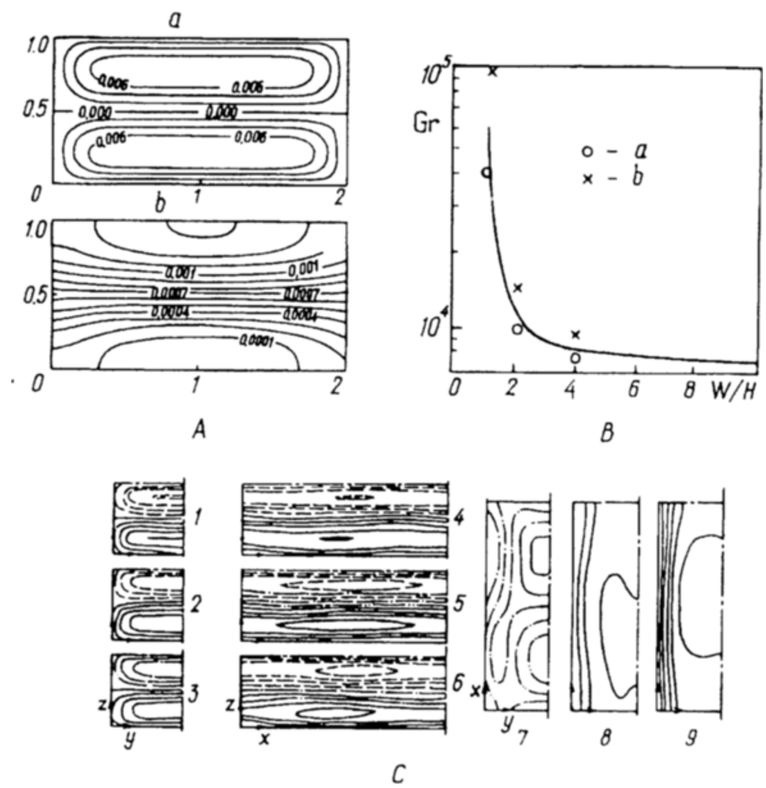

Fig. 4. Stability and spatial structure of thermal gravitational convection in a parallelepiped with lateral heating (Pr = 0): A) main flow at $W/H = 2$ (lines of equal velocity (a) and isotherms (b)); B) critical Grashof number versus width (curve – stability theory; calculation by the finite-difference method; a) main flow; b) secondary flow); C) lines of equal velocity (horizontal component u) in the central part of the parallelepiped: 1) $x = 10$; 2) 10.7; 3) 11.35, vertical section; 4) $y = 0.125$; 5) 0.5; 6) 0.875, vertical section; 7) $z = 0.125$; 8) 0.25; 9) 0.5, horizontal section.

As the Rayleigh number increases, tertiary three-dimensional structures (Fig. 2B, a) as well as three-dimensional structures of the roller type (Fig. 2B, c) appear that are apparently of the same nature as the forced three-dimensional flows, similar to them, in a cavity with a moving boundary [38]. A more detailed investigation of the evolution of these structures requires in understanding of the transition of free convection from laminar to turbulent flow.

One of the most interesting results is the distribution of the local heat flux on a heated or cooled surface first demonstrated, apparently, in [36]. Figure 3 shows plots of constant values of the local Nusselt number for different Ra numbers. In all the cases the local heat flow on some part of the region is larger than in the case of heat transfer by conduction, i.e., local superheating occurs, as has been shown on the basis of two-dimensional models. The three-dimensional model gives zones of local superheating on the xy plane with a characteristic maximum. With increase in the Ra number, the position of this maximum and the shape of the zone with a maximum local heat (mass) flow shift downward, which can be of interest in problems of cooling of devices or in analysis of concentration inhomogeneities. However, in the analysis of pressure rise these effects are not so important and, evidently, two-dimensional (axisymmetric) formulations of problems are sufficient. The mentioned specific features of the local structure of heat transfer are qualitatively consistent with those published in [36], but the mean Nusselt number differs, which is, apparently, a consequence of using a "hybrid" difference scheme in [36].

For horizontally directed crystallization the formulation of problems on thermal gravitational convection in a horizontal parallelepiped with a lateral heat flow is of interest since it allows us to answer the question of at what

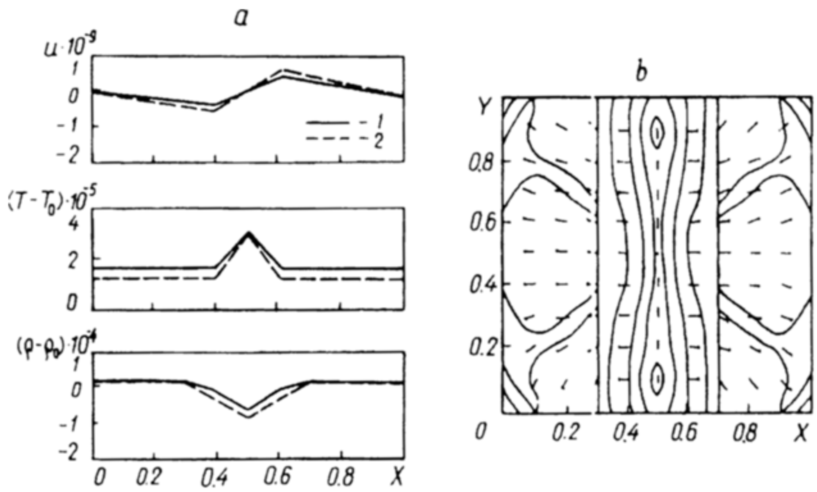

Fig. 5. Structure of thermoacoustic processes in a cavity with carbonic gas near the critical point under zero-gravity conditions at $t = 1.26$ sec after the start of heating by a thermal pulse (modeling based on the Navier–Stokes equations for a compressible gas and the van der Waals equation of state): a) profiles of the velocity and thermodynamic parameters at different moments of time: 1) one-dimensional model, 2) two-dimensional model; b) lines of equal density and field of velocity vectors in the two-dimensional model.

critical Rayleigh number secondary structures arise and how the critical Rayleigh number and the wavelength of the secondary cells depend on the parallelepiped width. In this case, as in that considered above, the methods of stability theory play an important role in analysis of the three-dimensional structure. For a long time stability theory could not answer this question since in the majority of problems a one-dimensional main flow known in the literature as the Birich flow [39] was used. If a generalization of it is used as the main flow, as was done in [40] (see Fig. 4A), then the dependence of the critical Rayleigh number and the scale of the secondary flow on the parallelepiped width can be determined. The occurrence of secondary structures in numerical calculations performed according to the procedure described in [40] is consistent with data of stability theory, which can serve as a test of direct numerical solutions in the case of a slightly supercritical Rayleigh number. Such results are still not numerous (see also [40, 41]). Sections of three-dimensional structures in the form of lines of constant velocity that are obtained by directly solving the three-dimensional nonstationary equations of convection (Fig. 4C) show the specific features of the three-dimensional structure of secondary flows (see details in [40]).

6. Examples of Applied Problems and Some New Formulations of Problems of Free Convection. The Problem of the Relation of Measurements to Computer Programs That Model Convective Processes. In the last 10–15 years multiparametric studies of various applied problems have been conducted, for instance, those on heat transfer and temperature stratification in vessels, convection and heat transfer in porous rock fill of dams, and convection in heat-insulating interlayers of pipelines (see more detailed references in [20]). Solution of complicated conjugate problems has permitted answering many questions. For instance, solution of the problem on convective heat transfer in rotor cavities of turbomachines allows reliable recommendations to be given concerning their starting regimes. Consideration of the convection in a dam body helps in designing protective structures and in determining their longevity. Analysis of the convection in porous isotropic and anisotropic heat-insulating materials makes it possible, on the one hand, to eliminate local superheating of structures (which is very important at high pressures and temperatures) and, on the other hand, to determine mean heat losses, which can be substantial due to the mass character of heat engineering facilities.

At present, use of results of free-convection studies in technological applications, especially in technologies for obtaining such technically valuable materials as single crystals and semiconductor devices, attracts much interest due to the high requirements on the quality of these materials. This is a very complicated area owing to the variety

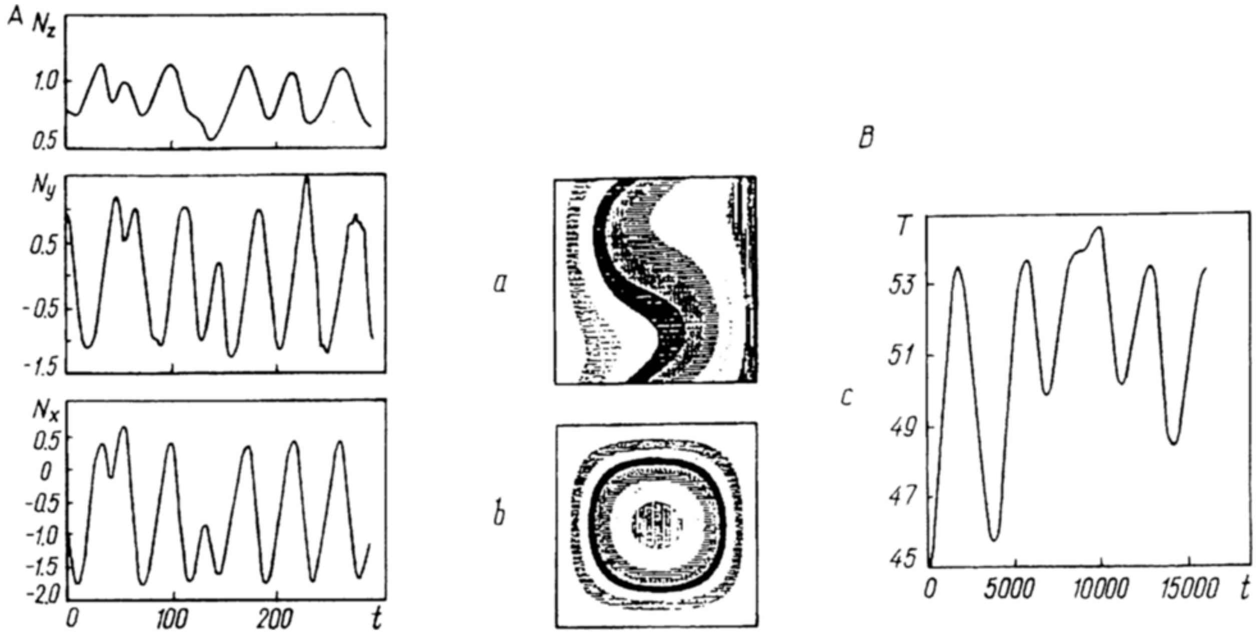

Fig. 6. Illustration of the calculation of the sensitivity of thermal gravitational convection to quasistatic microacceleration components using the "COMGA" system: A) time variation of the quasistatic of microaccelerations component N along the x, y, z axes; t, min; B) calculation results for thermal gravitational convection with allowance for the time variation of the quasistatic microacceleration component along the x, y axes: a) isotherms of the temperature field at one moment of time in the cell with lateral heating and exposure to the quasistatic component; b) stream functions at one moment of time in the cell with lateral heating and exposed to the quasistatic component; c) time variation of the temperature in the cell, Pr = 15, L = 10 cm, ΔT = 50. T, $^{\circ}$C; t, sec.

of different methods for growing crystals (the Czochralski method, the horizontal and vertical Bridgman methods, the noncrucible melting method, etc.) and semiconducting structures (various modifications of liquid epitaxy, the gas transport method). The sought characteristics of three-dimensional single crystals and semiconducting structures vary considerably, and therefore the characteristics of free convection require different descriptions (macro- and microinhomogeneities, geometric inhomogeneities). Here, mathematical and physical models have been developed and a large volume of results has been obtained that underlies "technological fluid dynamics," in which the above-mentioned mechanisms of free convection of the gravitational and nongravitational type play an important role [12, 16].

Convection in compressible media, which contains many new effects as compared to that in the Oberbeck–Boussinesq model and especially with various equations of state, is attracting ever increasing interest owing to insufficient exploration of it and some fundamental scientific problems in astrophysics and the physics of critical phenomena. In compressible media the equation of state can have a complicated form, and the adiabatic gradient may not be a constant, as in the case of a perfect gas [2], but rather an inhomogeneous quantity, in particular, it can contain maxima. In experiments involving interferometric measurements in a near-critical liquid with instantaneous delivery of a small thermal pulse under zero-gravity conditions (g = 0) the problem of suppression of gravitational convection arises [42]. In this case, processes of establishing equilibrium and developing convection of a compressible gas are of interest. In [43, 44], using the van der Waals equation of state these processes are considered based on the one-dimensional Navier–Stokes equations of a compressible gas for the initial stage and the model of [27] for convection. Figure 5a, b shows some results of calculations of the initial stage of establishing equilibrium that illustrate two-dimensional effects in reaching equilibrium in carbonic acid at $(T - T_c)/T_c = 0.001$. The calculations were made by means of a procedure specially developed for this class of problems [45] in a formulation corresponding to [43] with the use of the van der Waals equation of state but on the basis of the two-dimensional equations. In this model a short thermal pulse is delivered not at a point but along the line $X = 0$ (a "thermal knife") for the purpose of a direct comparison of calculation data and results of interferometric measurements [42].

Since the free-convection classification mentioned above is quite branched, with almost every variety of it being multiparametric, and the acting forces and/or disturbances are complicated, it is very important that the computer programs of mathematical modeling of free convection to be related as closely as possible with the equipment in which the physical process is realized, with the purpose of diagnosis of a definite process, analysis and interpretation of full-scale data, and, in the future, control of processes in real time. Therefore it is urgent to relate data on microaccelerations onboard an orbital space station to the "COMGA" computer system. The most detailed data on space-time variation of microaccelerations in an orbital flight are obtained with the aid of the American system "SAMS" (Space Acceleration Measurement System) [46]. At present this system is installed on the "Mir" space station and with its help data on the change in microaccelerations over many days along three axes are obtained that are recorded on a CD ROM that can be used directly, after appropriate processing, with the aid of the mentioned system. For this, a special interface of the computer system "COMGA" has been worked out that allows input of information from the files in which measurement or calculation data are contained. The low-frequency quasistatic components of microacceleration, which cause concentration inhomogeneities, are of greatest interest; however from the viewpoint of so-called "gravitational sensitivity" (see details in [16, 47, 48]) the high-frequency components are also of importance and studies of them are being expanded. Figure 6A illustrates changes in the quasistatic microacceleration components on the "Mir" space station along three axes that were obtained as a result of calculations in [49]. Figure 6B presents results of calculations of thermal convection under microgravity conditions using the microacceleration data from Fig. 6A, which also illustrate the capabilities of a special version of the "COMGA" system that includes input of information and files and output of information on the instantaneous position of the microacceleration vector, instantaneous temperatures and velocities at a fixed point of the volume, and isotherms and stream functions in the region. Results of calculations of the temperature variation with time at a point (Fig. 6B) show, in particular, the rather high sensitivity of the temperature field to variation of the low-frequency microacceleration component. This is a fundamental property of free convection and the topic of studies concerned with the search for alternatives in the control of free convection in a wide range of mass forces and for new means (databases for quantitative investigation of free convection [48], determination of the level of microaccelerations from data on temperature variation [50], etc.) necessary for this.

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REFERENCES

1. G. A. Ostroumov, Free Convection in the Internal Problem [in Russian], Leningrad (1952).
2. L. D. Landau and E. M. Lifshits, Theoretical Physics, Vol. 6. Fluid Dynamics [in Russian], Moscow (1986).
3. S. Chandrasekhar, Hydrodynamic and Hydromagnetic Stability, Oxford Univ. Press (1961).
4. S. Ostrach, "Laminar flows with body forces," in: Theory of Laminar Flows, Oxford Univ. Press, London, Vol. 4 (1964).
5. B. S. Petukhov, Heat Transfer and Resistance in Laminar Liquid Flow in Tubes [in Russian], Moscow (1967).
6. G. Z. Gershuni and E. M. Zhukhovitskii, Convective Stability of an Incompressible Fluid [in Russian], Moscow (1972).
7. J. S. Turner, Buoyancy Effects in Fluids, Cambridge, Univ. Press (1973).
8. A. V. Luikov and B. M. Berkovskii, Convection and Waves [in Russian], Minsk (1975).

9. D. Joseph, Stability of Fluid Motion [Russian translation], Moscow (1981).
10. O. G. Martynenko and Yu. A. Sokovishin, Free-Convective Heat Transfer [in Russian], Handbook, Minsk (1982).
11. S. Kukac, W. Aung, and R. Viskanta, Natural Convection Fundamentals, McGraw-Hill, N. Y. (1985).
12. V. I. Polezhaev, A. V. Bune, N. A. Verezub, et al., Mathematical Simulation of Convective Heat-Mass Transfer Based on the Navier–Stokes Equations [in Russian], Moscow (1987).
13. B. Gebhart, Y. Jaluria, L. L. Mahajaa, and B. Sommakia, Buoyancy-Induced Flows and Transport, Hemisphere, New York (1988).
14. Yu. V. Lapin and M. Kh. Strelets, Internal Flows of Gas Mixtures [in Russian], Moscow (1989).
15. G. Z. Gershuni, E. M. Zhukhovitskii, and A. A. Nepomnyashchii, Stability of Convective Flows [in Russian], Moscow (1989).
16. V. I. Polezhaev, M. S. Bello, N. A. Verezub, et al., Convective Processes under Zero-Gravity Conditions [in Russian], Moscow (1991).
17. B. S. Petukhov, in: Heat Transfer in a Moving One-Phase Medium. Laminar Boundary Layer (ed. A. F. Polyakov) [in Russian], Moscow (1993).
18. Yu. K. Bratukhin and S. O. Makarov, Interphase Convection [in Russian], Perm (1994).
19. A. M. Kutepov, A. D. Polyanin, Z. D. Zapryanov, et al., Chemical Hydrodynamics [in Russian], Reference Book, Moscow (1996).
20. V. I. Polezhaev, in: Proc. of the Russian National Conference on Heat Transfer, Vol. 2. Free Convection, Krasnogorsk (1994), pp. 3-10.
21. De Vahl Davis, Int. J. Numer. Methods Fluids, **3**, 249-264 (1983).
22. V. M. Paskonov, V. I. Polezhaev, and L. A. Chudov, Numerical Simulation of Heat and Mass Transfer Processes [in Russian], Moscow (1984).
23. B. M. Berkovskii and V. K. Polevikov, Computational Experiments in Convection [in Russian], Minsk (1988).
24. E. L. Tarunin, Computational Experiments in Problems of Free Convection [in Russian], Irkutsk (1990).
25. V. I. Polezhaev, in: Heat and Mass Transfer [in Russian], Vol. 1, Minsk (1968), pp. 631-640.
26. V. I. Polezhaev, in: Some Applications of the Grid Method in Gas Dynamics [in Russian], Issue 4, Moscow (1971), pp. 86-180.
27. S. Paolucci, Sandia National Livermore Laboratory, SAND 82-82251 (1982).
28. V. V. Pukhnachev, Izv. Akad. Nauk SSSR, MZhG, No. 5, 76-85 (1994).
29. K. A. Nadolin, Izv. RAN, MZhG, No. 3, 43-49 (1995).
30. G. Z. Gershuni, D. V. Lyubimov, T. P. Lyubimova, and V. Ru, Izv. RAN, MZhG, No. 5, 53-61 (1994).
31. V. I. Polezhaev, Izv. RAN, MZhG, No. 5, 22-36 (1994).
32. A. A. Samarskii and P. N. Vabishevich, Computational Heat Transfer, Vol. 1. Mathematical Modeling, Wiley (1995), p. 406; Vol. 2. The Finite Difference Methods Methodology, Wiley (1995), p. 417.
33. V. I. Polezhaev, M. K. Ermakov, V. L. Griaznov, S. A. Nikitin, et al., 46th Int. Astron. Congress, Oct. 2-6, 1995, Oslo, Norway, IAF-95 – J. 3.11, p. 9.
34. A. K. Sen, in: Encyclopedia of Fluid Mechanics (ed. N. P. Cheremisinoff), Vol. 1 (1986), pp. 896-930.
35. M. Afrid and A. Zebib, Phys. Fluids, **A2**(8), 1318-1327 (1990).
36. J. Fusegi et al., Int. J. Heat Mass Transfer, **34**, 1543-1557 (1991).
37. V. Babu and S. A. Korpela, Computers Fluids, **23**, No. 5, 675-691 (1994).
38. O. Bessonov, V. Brailovskaya, V. Polezhaev, and B. Roux, Lecture Notes in Computer Science, No. 964, 385-399 (1995).
39. R. V. Birikh, Zh. Prikl. Mekh. Tekh. Fiz., No. 3, 67-72 (1966).
40. S. A. Nikitin, D. S. Pavlovskii, and V. I. Polezhaev, Izv. RAN, MZhG, No. 4 (1996).
41. V. A. Andrushchenko and A. A. Gorbunov, Izv. RAN, MZhG, No. 5, 20-26 (1993).
42. D. Beysens, Lecture Notes in Physics, **464**, 3-25 (1996).
43. B. Zappoli and A. Durand-Daubin, Acta Aeronautica, **29**, No. 10/11, 848-859 (1993).
44. B. Zappoli, S. Amiroudine, P. Carles, and J. Ouazzani, Lecture Notes in Physics, **464** (1996), pp. 27-40.

45. A. A. Gorbunov, Izv. RAN, MZhG, No. 5 (1994).
46. M. J. B. Rogers, C. R. Baugher, R. C. Blanchard, et al., Microgravity Sci. Technol., **13**, 207 (1993).
47. J. I. D. Alexander, Microgravity Sci. Technol., **3**, 52 (1990).
48. V. I. Polezhaev, Microgravity Quarterly, **4**, No. 4, 241-246 (1994).
49. V. V. Sazonov, M. M. Komarov, M. Yu. Belyaev, S. G. Zykov, and V. M. Stazhkov, Preprint No. 45, Institute of Applied Mathematics of the Russian Academy of Sciences, Moscow (1995).
50. G. P. Bogatyryov, G. F. Putin, M. K. Ermakov, S. A. Nikitin, et al., The 33rd Aerospace Sciences Meeting and Exhibit, AIAA 95-0890, Jan. 9-12, 1995, Reno, NV.