CURRENT RESULTS AND PROPOSED ACTIVITIES IN MICROGRAVITY FLUID DYNAMICS

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ABSTRACT

Overview of the results in microgravity fluid dynamics during last two years with a goal to discuss the problems, which may be of interest for the International cooperation is done.

INTRODUCTION

The Institute for Problems in Mechanics RAS is the main Institute in Mechanics in Russian Academy of Sci. It includes departments of classical mechanics (analytical mechanics, gyroscopes, navigation, optimal control and robots) as well as solid state mechanics (elasticity and deformation, shell's oscillations, lubrication etc.) and fluid mechanics, including combustion, plasma and laser gasdynamics.

Laboratory of the mathematical and physical modelling in fluid mechanics of this Institute develops models, methods and software for analysis of fluid flow, istability analysis, direct numerical modelling and semi empirical models of turbulence as well as experimental research and verification of the models and applications in technological fluid dynamics, microgravity fluid mechanics, geophysics and a number of engineering problems.

This paper presents overview of the results in microgravity fluid dynamics during last two years since 2nd Microgravity Fluid Physics Conference (June,1994, Cleveland) and 1st International Aerospace Congress (August, 1994, Moscow), which enhanced International cooperation in Microgravity in Russia. Nonlinear problems of weekly compressible and compressible fluid flows are discussed. Scientific basis of this research is contained in the books [1,2].

THERMAL/DINAMICAL ACTIONS FOR CONTROL OF CONVECTION DURING CRYSTAL GROWTH

General idea of this work is investigation alternative microgravity possibilities to reduce inhomogeneities in semiconductors that are induced by gravitational or nongravitational types of convection in terrestrial environments [3,4]. Low energetic thermal/dynamical actions for the growth of semiisolating GaAs monocrystals with low density dislocations (thermal waves, steady state and unsteady rotation and/or vibration) are used in modified ground-based Czochralsky techniques with diagnostic of the GaAs monocrystals. Developing of the methods for experimental and theoretical recearch and comparison the results are presented below.

For measurements of temperature distribution during single crystal growth modification of the system for the temperature field dyagnostic was carried out in the Branch of the Institute of Crystallography, Kaluga [5] (Fig.1). The pilot crystal's models manufactured of special ceramics having thermophysical properties similar to those of GaAs were used to make preliminary measurements of temperature distribution in a system investigated. Thermocouples were installed into these pilot models which provided a safe contact between the thermocouples and the object measured. The amplitude-frequency characteristics of thermocouples were determined before-hand which then made it possible to estimate the frequency spectrum of temperature fluctuations in the melt and across the crystal. GaAs single crystals with the diameter of about 80 mm were grown under the same thermal conditions. The growth direction was (001) and the change of the diameter did not exceed 2 mm at pulling rate 2-3 mm/h. Single crystals were grown at constant temperature of the heater.

The experimental investigation was also made concerning the temperature change in subcrystalline region and across the crystal at iso- and counterrotation of the crystal and the crucible with the melt and rotation of the crucible with the melt under acceleration. These actions caused considerable change in the spectrum of temperature fluctuations and were much more sensitive in comparison with the heating control. The described actions and some other ones similar in influencing the process of single crystal growth are classified by as "low energetic" actions because of in that case change in power supplied to the heater was small (not more than 1%) as compared to fixed power.

Mathematical modelling was made,using model of Czochralsky crystal growth which includes hydrodynamics and heat transfer in the crucible on the basis of unsteady Navier-Stokes equations (Boussinesque approach) and a model of a crystal as rotating disc on the melt surface (Fig.2). Special version of PC - based system which is extension of the system "COMGA" was used for this approach. It includes now as a part of Computer laboratory on the basis of this system [6]. Cylindrical crucible radius Rc= 7 cm which filled by GaAs melt to height H=4 cm and crystal radius Rs=3.8 cm was considered. The crucible wall temperature was uniform and in general case can be dependent on time. Temperature on the solid/liquid interface was supply as 1511 K and interface between melt and encapsulant is adiabatic. No-slip conditions for radial velocity and free condition for angular velocity are assumed on the LEC interface. The crucible and crystal rotate with constant angular velocities wc = 16 rpm and ws= -6 rpm. Prandtl number was assumed as Pr= 0.07. Using the scale of length for this problem is the crucible radius Rc,one can obtain nondimensional parameters are Grashof number Gr= 7.8 10^7, crucible Reynolds number Rec= 1.6 10^4 and crystal Reynolds number Res= 6 10^3. The calculations were made on nonuniform grid 75*51 nodes, stretching to crucible walls and solid/liquid interface (minimum space step was equal to 0.2 mm). The computer code was tested for the problem on thermal convection with low Prandtl number fluid (0.015) for Grashof number - 1.6 10^5. Maximum value of stream function was in a good agreement with the results [7] as well as our previous results [1]. The calculation of unsteady problem for constant crucible temperature Tc=1541K including thermal convection and rotations of the crucible and the crystal was made. As it was obtained for such values of parameters in previous works (see [1, 5] the nonregular undamped oscillations of temperature field and motion structure induced by convective instability are observed. Fig 2 illustrates the complex interaction between thermal and force convections (the instantaneous paterns of temperature, rotation moment and stream function are shown). The dependence of the measured (a) and calculated (b) melt temperature in the point near the axis (2 mm below the liquid/solid interface) is given in Fig.3. The oscillations with maximum temperature amplitude till to one degree are good visible. Using described technique the influence of harmonic crucible temperature changing on the amplitude of these oscillations near solid/liquid interface was investigated [5] and analysis of the dynamical actions is in progress.

ANALYSIS OF NEAR CRITICAL PROCESSES ON THE BASIS OF COMPRESSIBLE FLUID MODEL

The goal of this work is study compressible fluid flow and heat transfer near critical point for quantitative analysis of the microgravity experiments and analysis of gravitation sensitivity for certification of the orbital complexes for near critical experiments in microgravity. Special numerical schemes and computer codes for 1D and 2D approaches are developed on the basis of Navier-Stokes equations for compressible fluid with Van der Waals thermodynamics state equation [8]. The results one-dimensional analysis for the problem with rigid wall heating in zero gravity is in well agreement with previous results of B.Zappoli and co-workers, where "piston effect" was calculated on the basis of direct numerical simulation (see [9,10] and cited references).

Fig.4 shows new results for two-dimensional thermoacoustic - dominated regime processes in the earlier stage of "switch on" the heat pulse in zero gravity. Two-dimensional density isolines which will be of interest to registrate in the earlier stage of "switch on" the heat pulse in microgravity in a model of near crytical point instrument (see [10] and cited references) with the goal of benchmark mathematical models and analysis of gravitational sensitivity near-critical fluid processes.

The Institute for Problems in Mechanics have presented a proposal and scientific plan for the use of the French instrument "Alice-1" for cooperative investigation in a framework of the plan for analysis of gravitational sensitivity in liquid/gas systems and convective sensor with the Perm University. Instrument "Alice-1" is exist now in the working state aboard "Mir" station and it is property of RKK "Energiya", but "know-how" of this instrument is a property of CNES. Program realization of the orbital experiment for near critical CO_2 and SF_6 was presented by CNES using ordinary procedure [10]. Experiment was realized 30.09-4.10, 1995 by Russian kosmonavt S.V.Avdeev. Preparation and analysis of the results are in progress. For the use of "Alice-1" instrument as a tool for measurement gravitational sensitivity of compressible liquid/gas systems evolution of the optical pictures to density fields in quantitative form should be done.

CONVECTIVE INSTABILITY AND SPATIAL STRUCTURE OF CONVECTION IN PARALLELEPIPED

A problem of convective instability and convection structure in boat-type configuration related to macro-and microinhomogeneities of crystals grown from the melts has a long-term history [1-4, 11]. A focus of this part of the work is concentrated on the analysis of spatial structure of thermal gravitational convection in a long parallelepiped with differently heated side boundaries, using both stability analysis technique and direct numerical calculation on the basis of three-dimensional Navier-Stokes equations.

Three dimensional unsteady Navier-Stokes equations (Boussinesque approach) are solved in the form of velocity-pressure variables with governing parameters Grashof, Prandtl numbers and two aspect ratios W/H and L/H. An equation for two dimensional basic flow was found, using definition of basic flow in the case of infinite length for a closed flow in rectangle and boundary conditions [12]. It's solution contains Birikh-type basic flow [13] in the limiting case of W>>H. Spatial structure of convection in a parallelepiped including basic flow are shown in Fig 5. Dependency of the critical Grashof number on the W/H using linear stability analysis of the basic flow is correlated with results of direct numerical solution of 3D Navier-Stokes equations for the case of Pr=0, L/H =20, Gr=200000 (Fig.5B). Velocity field structure in supercritical domain near critical line is shown on the Fig.5C. Strong dependency of the crytical Grashof number with reduce of the W/H shows "geometric" possibility for control of gravitational convection.

COMPUTER LABORATORY FOR CONVECTION AND HEAT/MASS TRANSFER IN MICROGRAVITY

Computer laboratory is intellectual shell of the system "COMGA", including help in the statement of the problem, benchmark of computer results and multiparametrical analysis of fundamental and applied problems. was recently. developed and described in [6]. Pc-based system as a core of computer laboratory contains all tools which need for modelling hydrodynamics, heat/mass transfer processes and collected in personal computer. Each of separate version of the this system occupies memory on one disk and presents a flexible and convenient software tool for modelling of forced, gravity-driven and surface tension-driven thermoconcentrational convection on the basis of Navier-Stokes equations in Boussinesque and Boussinesque-Darcy approach (see detailed references in [6]). This version of the system is based on the two-dimensional (plane or axisymmetrical - with three velocity components) unsteady Navier-Stokes equations. Temporal behavior (rotation, vibration) of body force is taken in account.

Contents of computer laboratory includes forced flows of isothermal liquid,.natural gravitational convection, surfac tension-driven convection, interaction between different types of convection and applications.Each task can supports of text books on viscous flows and heat transfer or monographs on buoyancy-induced flows and transport or convective stability and applied problems in microgravity and supplied by additional references on experimental and theoretical researches (see references in [6]). Special sign (*) in the contents of computer laboratory marks problem, solved in previous works, using different kind of methods and software. Other sign

(**) marks problem solved in previous works or renewed using "COMGA" system and sign (***) - new problems solved with a help of this system.

Fig.6A-C shows some results of steady-state and unsteady problems of thermal gravitational and thermocapillary convection (vertical layers with side heating for ordinary and porous media and onset of thermal gravitational convection after suddenly bottom heating and thermocapillar convection and instability in floating zone). Fig.6C shows new result of this computer laboratory-benchmark of the flow/temperature structure and oscillations due to convective instability in dependency on Marangoni number and aspect ratio using HP 735 workstation [14]. It is shown that axisymmetrical mode exists for high Pr number and results correlate with experimental data [15] (see references and discussion in [14]).

Special part of the system uses real microaccelerations data measured by means of an accelerometer or calculated in space flight [16].

Computer laboratory should be used also as a tool for education from initial courses of physics (hydrostatics, hydrodynamics and elementary transport processes) for definition and demonstration buoyancy phenomena (stability of hydrostatic equilibrium), laminar flows, boundary layer etc. (see, mini-plan of Computer Laboratory [17]). For special courses in fluid mechanics and heat transfer computer support of elements boundary layer theory, stability and turbulence can be done. For engineering courses on fundamentals of heat transfer theory of heat conductivity can be demonstrated as well as convective heat transfer across layers with demonstration of structure and heat/mass transfer characteristics. A number of mentioned problems of Computer laboratory may be recommended to use for graduated education in microgravity fluid mechanics [6,17].

CONCLUDING REMARKS

Above mentioned problems as study temperature oscillations in the melts and thermal/dynamical control of crystal growth, analysis of near critical fluid processes, stability and spatial structure of convection in the melts may be potential directions for future projects. Three topics in cooperation of IPMech with other organizations may be add :

1. Microacceleration and gravitational sensitivity analysis on the orbital complexes (with Keldysh Inst. of Applied Math., RKK "Energia ", Inst. for Problems in Mech.) [6, 18]
2. Theoretical and experimental study and flight experiment on Microgravity Sensor, proposed on MIR (ISS). (RKK "Energia", Inst. for Problems in Mech. and Perm State University) [6, 19]
3. Education on Microgravity Fluid Mechanics using computer laboratory (Inst. for Problems in Mech. and Perm State University) [6, 17].

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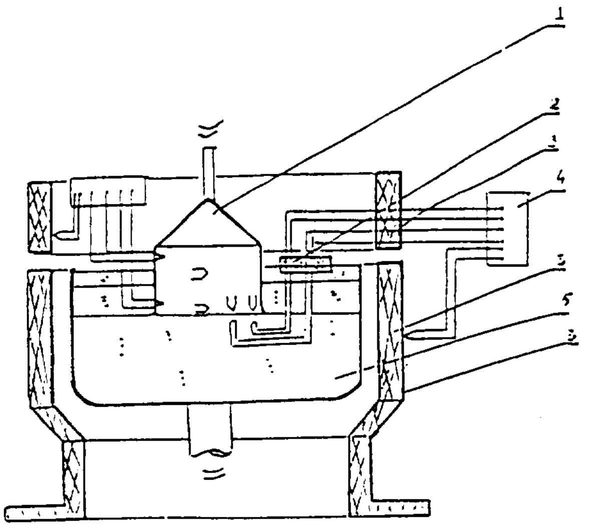


Fig.1 Scheme of the temperature measurements system in a melt and along the crystal
1 - seed, 2 - float with thermocouples, 3 - heater,
4 - system for temperature measurements and registration, 5 - crucible with a melt

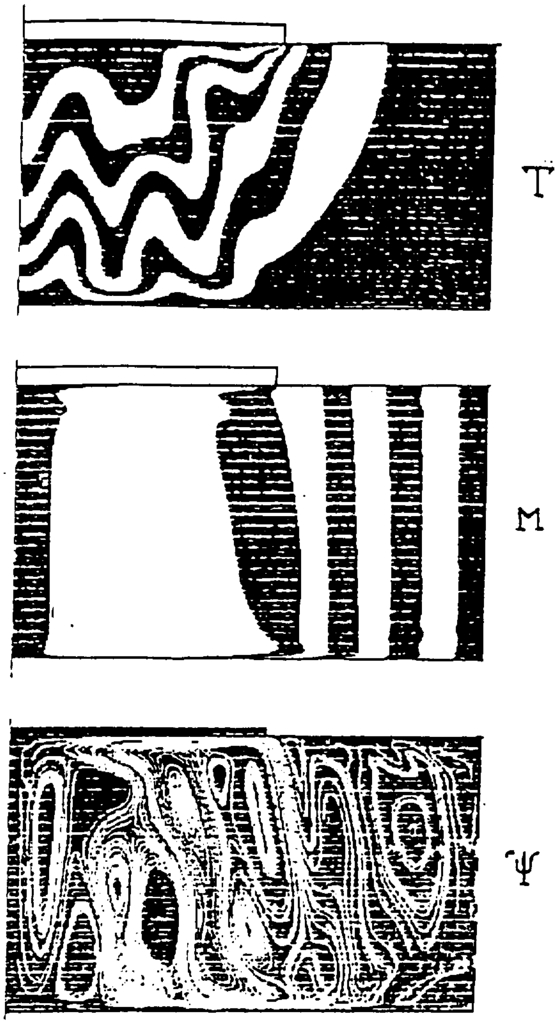


Fig.2 Instantaneous fields of temperature, rotation moment and stream function for thermal convection ($\Delta T=30$ °K) and rotation of crucible ($\omega_c = 16$ rpm) and crystal ($\omega_s = -6$ rpm)

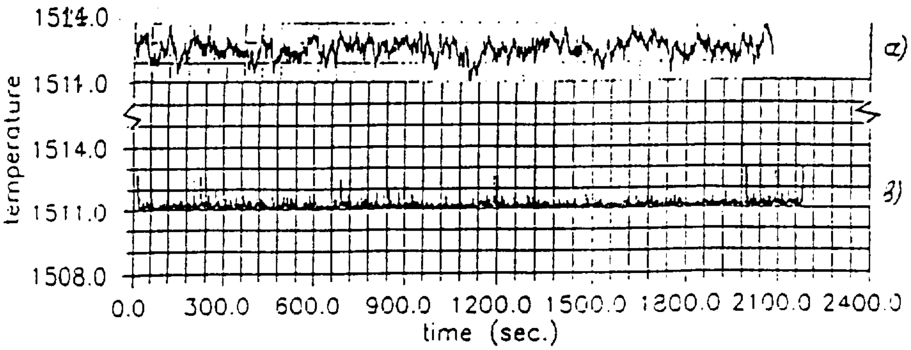
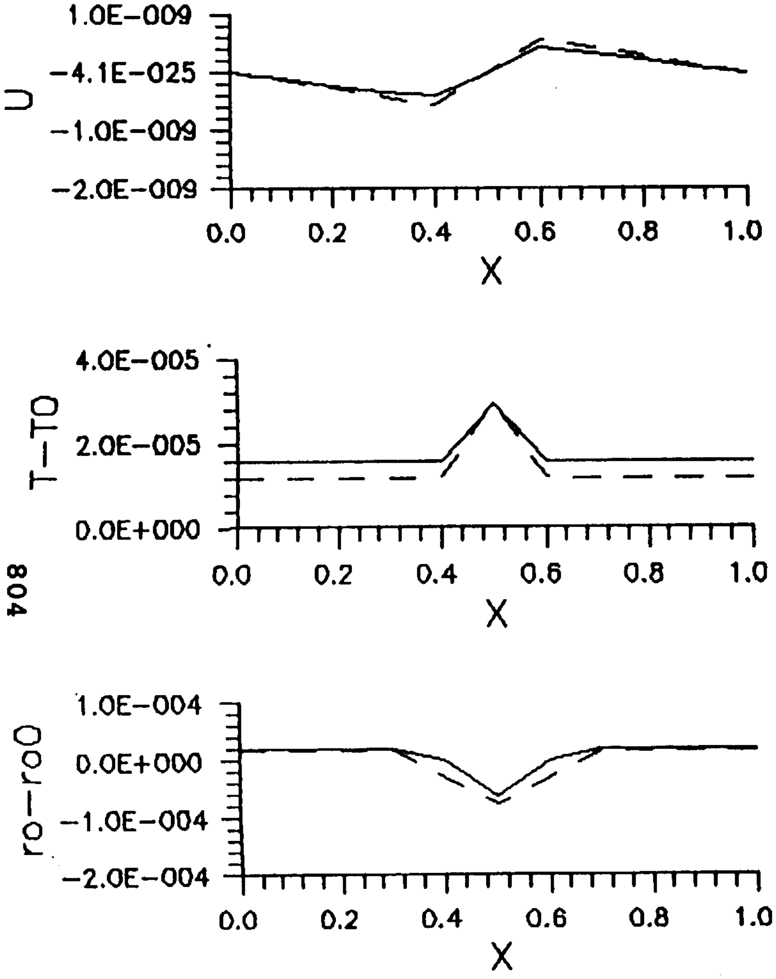
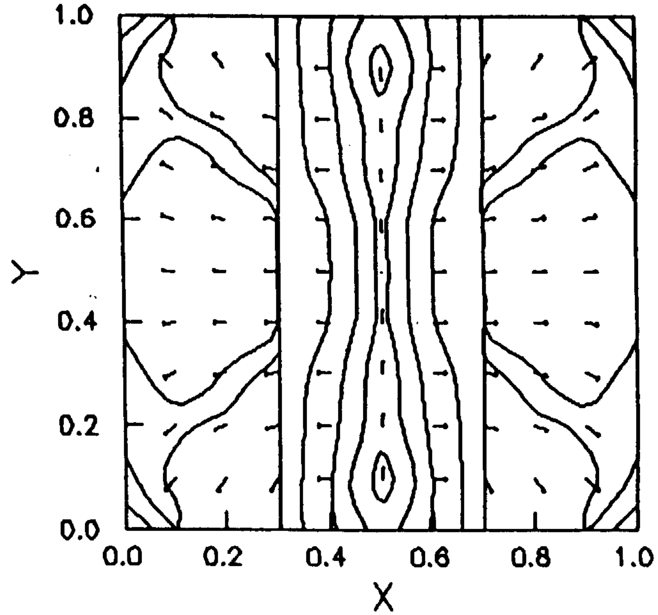


Fig.3 Measurements (a) and calculations (b) of the temperature fluctuations in the melt near axis under constant crucible temperature for a case of thermal convection and rotation of crucible (16 rpm) and crystal (-6 rpm)



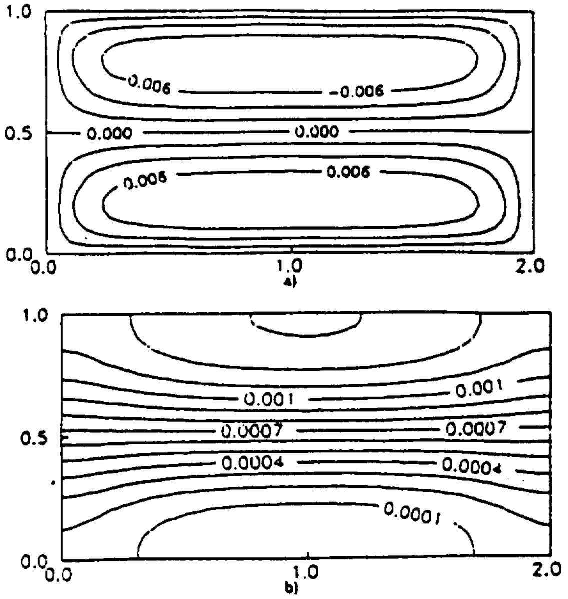
a) Velocity, temperature and density difference profiles in y=0.5 section: - - - - - 1D, ——— 2D



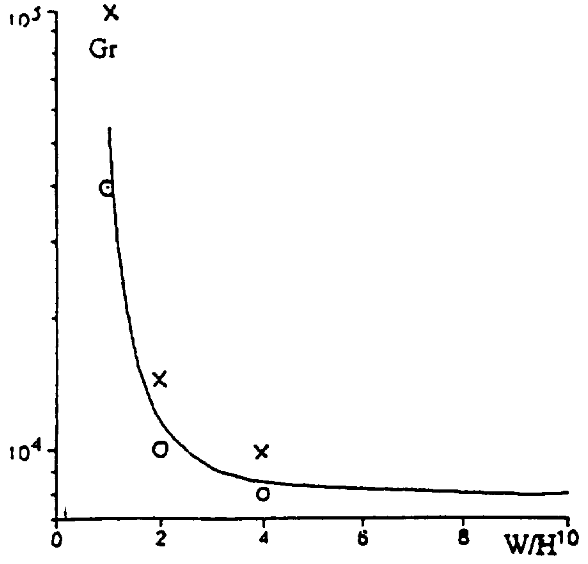
b) Density difference isolines and velocity vector field, 2D model

Fig.4 Thermoacoustic process near critical point after "knife" pulse heating in $x = 0.5$ crossection, (10^{-5} °K during 0.004sec.), $\left(\mu = \frac{T - T_c}{T_c} = 10^{-3}\right)$, CO_2

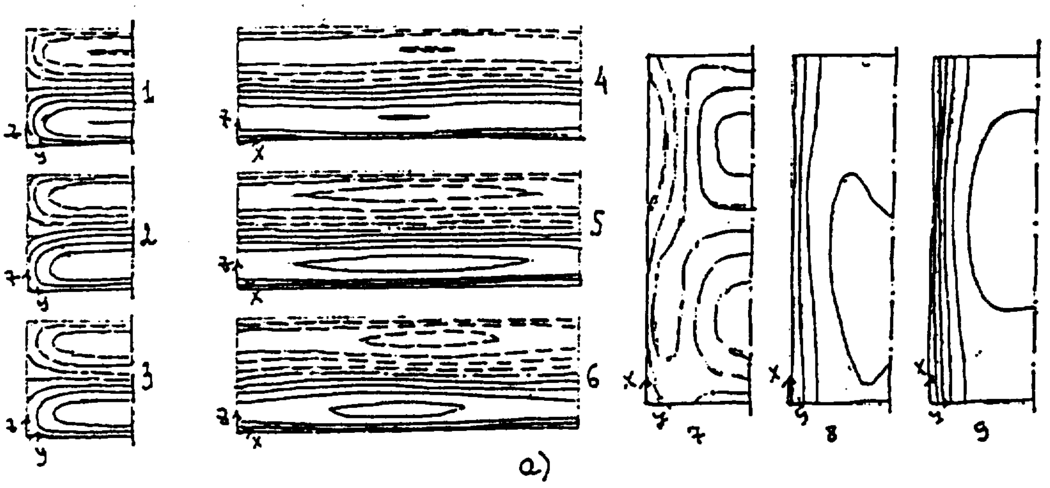
L=1 cm, $t = 1.26$ sec, simulation on the basis of compressible Navier-Stockes equations, Van-der-Waals state equation.



A. Basic flow for W/H=2 :
isolines of velocity (a) and temperature (b)



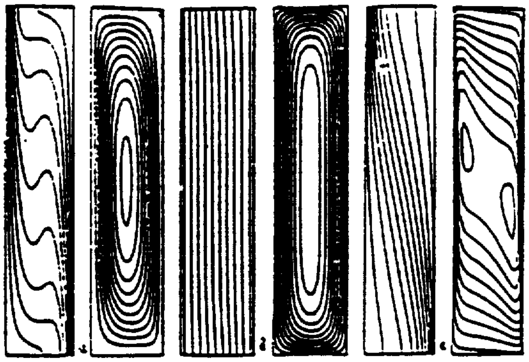
B. Dependency of the critical grashof number on the width
stability analysis: ————
finite difference calculation: o - basic flow,
x - secondary structure



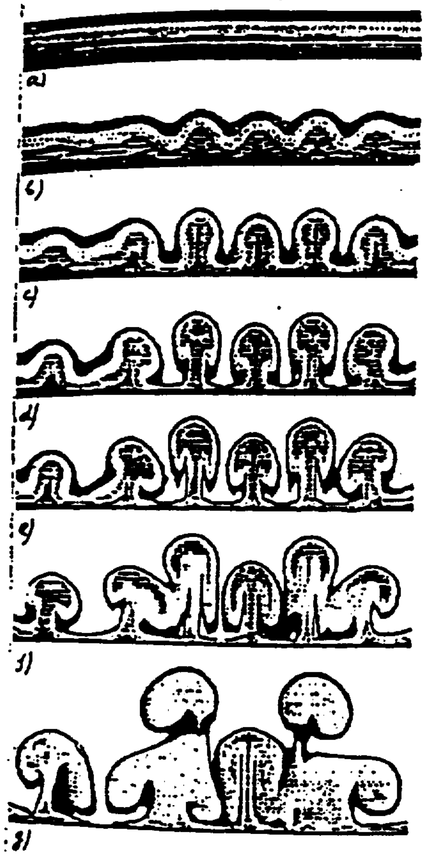
C. Isolines of the velocity component u in the central cell of the layer:

1 - x=10, 2 - x=10,7, 3 - x=11,35 (vertical crossection)
4 - y=0,125, 5 - y=0,5, 6 - y=0,875 (vertical crossection)
7 - z=0,125, 8 - z=0,25, 9 - z=0,5 (horizontal crossection)

Fig.5 Stability and spatial structure of convection in parallelepiped



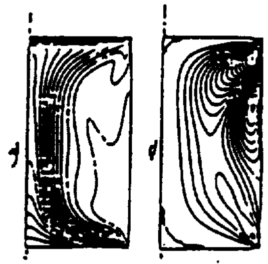
A. Thermal gravity-driven convection in permeable isotropic and anisotropic porous vertical layer with side heating: air, $Gr= 10^5$ (a), isotropic (b) and anisotropic (c) porous media



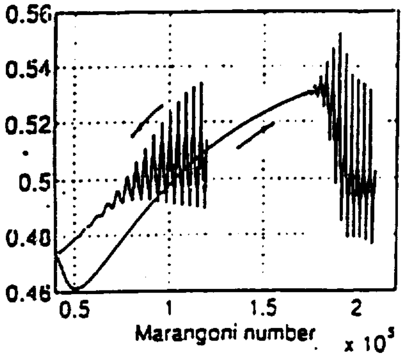
B. Isotherms in the problem of unsteady thermals behavior

$\nu t/\ell^2=0.0135$ (a),

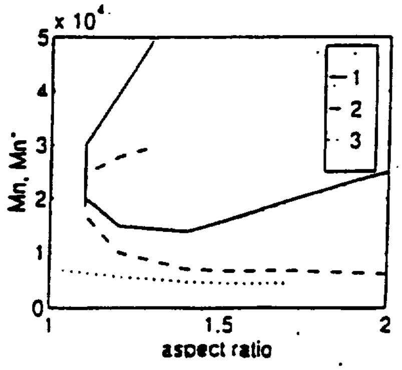
0.0138 (b) ....0.0145 (g).



C. Temperature (a) and stream function (b) for floating zone ($H/R=2$, $Mn=10^5$, $Pr=32$). Oscillation regime



D. Temperature oscillation at $x=0.25$, $y=0.5$ for decreasing and increasing Mn numbers.



E. Critical Marangoni numbers for $Pr=7$

1 - plane A-Mn, 2 - plane A-Mn*, calculations

3 - plane A-Mn*, experiment [15]

Fig.6 Results of calculation on the basis of Computer laboratory: