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Preparation for the VIP-CRIT Space Experiment on the ISS: An Analysis of MIR Experiments and Ground-Based Studies of Heat Transfer and Phase Separation in Near-Critical Fluid

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Abstract

We present a review of recent activity of the VIP-CRIT team in analyzing the previous space experiments, developing analytical methods, and carrying out the laboratory and numerical simulations devoted to the study of the effects of microgravity environment on the heat transfer and phase separation in the supercritical and near-critical fluids. The studies complement one another, and the results show that such kind of collective activity is extremely important for both obtaining new basic knowledge and optimizing the future space experiment onboard the ISS.

1. Introduction

The CRIT space experiment is devoted to the comprehensive study of fluid dynamics, heat transfer, and phase separation phenomena in the supercritical (single-phase) and near-critical (two-phase) fluid under the action of background microgravity accelerations (quasi-steady and g-jitter components) and controlled vibration of various types (reciprocation, rocking, and rotation vibration). The project is assumed to contribute to solving a fundamental problem on mastering the microgravity environment on the existing orbital objects including the ISS and to prepare interplanetary expeditions.

A prominent feature of the near-critical fluid – the onset of strong and long-leaved density and temperature inhomogeneities in response to a weak temperature perturbation – makes the near-critical fluid extremely sensitive to the microgravity environment. The study of the behavior of the near-critical and supercritical fluid under microgravity can be considered from two point of view. On the one hand, the study is undertaken in the interests of the use of the near-critical fluid in space, power, and chemical engineering. On the other hand, the near-critical fluid itself is an instrument for the study of microgravity environment which can provide us information that can not be obtained from a standard set of microgravity sensors.

The space experiment is a very expensive, complex, and relatively short-lived undertaking. Thus the ground-based preparation for the space experiment plays the extremely important role. The goal of the studies

presented is to obtain new basic knowledge and ideas on the development of the instrument, clarification of the program, and prediction of some possible flow and heat transfer regimes in the future space experiments on the basis of analyzing previous space experiments and comprehensive ground-based experiments and modeling.

2. Analysis of ALICE-DAKON experiments on the MIR station

We analyzed the results of experiments obtained during the EO-20 expeditionary (1995) with the ALICE-1 instrument and during the EO-27 expeditionary (February-March 1999) when we have managed to carry out a unique space experiment with two instruments, DAKON and ALICE-2, operated jointly¹⁻³.

The convection pickup DAKON has pressure-tight cylindrical chamber filled with air at normal pressure. One of the faces of the cylinder is cooled by the ambient air with a fan. The temperature of the face is about 30°C. The other face is heated electrically, and its temperature is about 80°C. The inertia accelerations cause the buoyancy-driven convection flow of air, which results in the distortion of the temperature field inside the space of the cylinder.

The ALICE-1,2 instruments whose measuring cells can also be considered as convection pickups allowed the study of the effect of microaccelerations on the heat exchange induced by a point heat source in hexafluoride sulfur (SF₆). The fluid inside the cell is maintained near its thermodynamic critical point, which enhances the

sensitivity of the system. The measuring and recording systems of the instruments allow the capturing of video of interference patterns and measurement of temperature. During the space experiments the instruments were affected by the background microaccelerations, by periodic acceleration generated by the electromagnetic vibrator or manually.

The experiments reveal various regimes of heat exchange caused by the onset of thermovibration (Fig. 1 a) and thermoinertia (Fig. 1 c) convection or their combination (Fig. 1 b). The velocity of the spread of the heat front as a function of time is presented in Fig. 2. When the frequency of forced microaccelerations was 0.3 Hz, the convective system responds to each variation of acceleration (Fig. 1c), and the velocity V of the spread of heated domain was proportional to the amplitude of

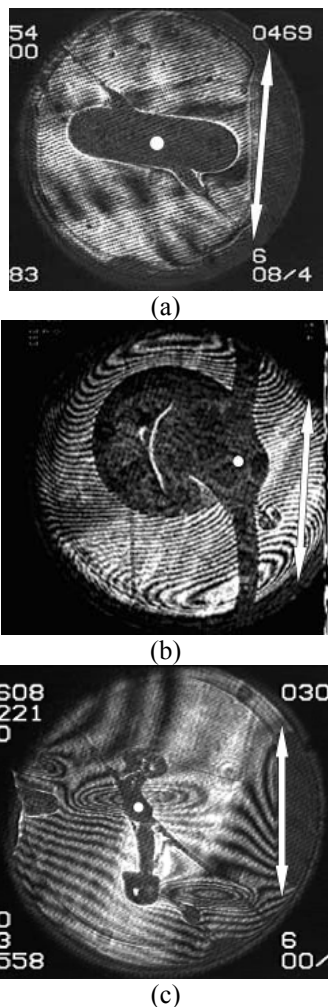


Fig. 1 The structure of heat and mass transfer from a point heater (ALICE-1,2 space experiments). (a) hermovibrational regime, (b) combined regime, and (c) thermoinertial regime. White arrows denote the direction of maximum variation of the microacceleration vector, and white circles denote the location of the heater.

microaccelerations (Fig. 2, curve C). The sensor of the DAKON instrument recorded the oscillation flow of the

same frequency. When the frequency of microaccelerations was 1.6 Hz, a mean convective flow was generated (Fig. 1a) with the intensity depending on the vibration velocity (Fig. 2, curve A). At the same time, the constant component of the signal from the DAKON instrument dropped down to the noise level due to the low sensitivity of the sensor to the mean thermovibration flow. When the vibration acceleration $\omega^2 b$ of the microgravity field was comparable with the level of the quasi-static accelerations⁴, they strongly affect the intensity (Fig. 2, curve B) and the structure (Fig. 1 b) of vibration regimes of heat exchange.

The results obtained suggest that the convective cells can be successfully used for detecting, recording, and measuring the quasi-static and slowly-varying component of inertia microaccelerations up to 1 Hz. At higher frequencies, the convection cells allow determination of the intensity of vibrations. Thus, on the basis of convection pickups the methods of certification of space stations can be developed to assess gravitation sensitivity at the sites of mounting of setups and systems used liquids and/or gases as working fluids.

3. Ground-based simulation of thermo-vibration convection in microgravity

A ground-based simulation of the effect of high frequency and quasi-static components of natural microgravity on the fluid heated from a point source (the joint Russian-French space experiments with ALICE-1,2 instruments, 1995, 1999 and 2000) was carried out with a vibration setup⁵.

The setup has a convective chamber that is made of a horizontal cylinder filled with an incompressible fluid (alcohol) and provided with a ceramic heater or metallic

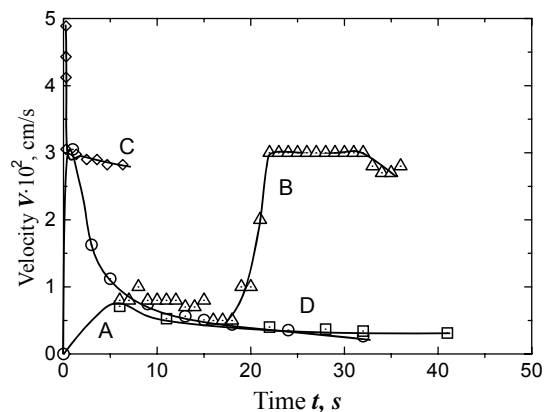


Fig.2 Velocity of the heat front propagation V as a function of time t . (A) Thermovibrational regime, (B) joined regime, (C) thermoinertial regime, and (D) convectionless regime. The sharp bend on curve (B) corresponds to the onset of the action of the high-frequency component of microaccelerations and onset of the regime presented in Fig. 1b

cooler centered inside the cylinder. The chamber was set in vibration with a shaker, and the constant

component of acceleration over the liquid layer was provided by gently sloping of the chamber to the horizon. The geometry and slope of the chamber as well as the parameters of the fluid, heater, and vibrations were chosen to provide domination of the vibration convection and similarity to the space experiments¹⁾.

The results of the experiments show that there is a close similarity between convective modes observed in space (Fig. 1a,b) and on the Earth (Fig. 3a,b). The evolution of the convective structures in a wide range of governing parameters and their spatiotemporal characteristics were studied.

The results of measurements of the dependence of velocity of the convection front on time are presented in Fig. 4.

The mechanisms of passive control of convection by slowly and rapidly varying inertia accelerations were revealed. It was found that the quasi-static component of acceleration strongly affect the convective regimes, which allowed us to use it for control of the process. The mechanisms of the active automatic feedback control were studied with the so called convection loop (or thermo-siphon), a setup composed of two vertical and two horizontal interconnected ducts shaped into, e.g., a rectangle. The setup is heated from bellow and cooled from above to provided nonuniform temperature distribution inside. It is known that the convective processes in such a system well simulate the heat and mass exchange in closed spaces. The convective loop, was affected dynamically by the small variations of the direction of temperature gradient with respect to the direction of gravity acceleration.

The boundary (1) on the map of regimes presented in Fig. 5 separates the A region from the B region. Within the A region the convective flow can not be suppressed and always exists, although with lower intensity. Within B region, the dynamically stable quasi-equilibrium state can be maintained for an infinitely long time (in the experiments, the quasi-equilibrium was maintained for several hours under control).

For rather high values of k the stabilized quasi-equilibrium again becomes unstable, and an oscillation regime is realized in the convection loop (region C). Such a behavior of the system under control is rather surprising since the increase of the intensity of control action is generally expected to result in the increase of the reliability of maintenance of the quasi-equilibrium.

The effect of quasi-static component of microgravity on the structure of fluid flow was clarified, and the results of the ground-based simulation are in good agreement with experimental data obtained in space. Thus we conclude that the quasi-static component of microacceleration, which is always presented in orbital flight, can be used for the suppression of convective flows in fluids or gases

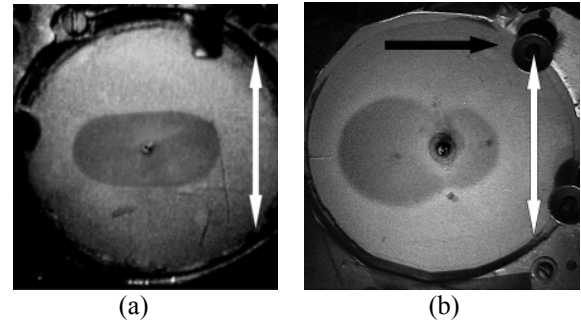


Fig. 3 Effect of vibrations on heat and mass transfer from a point heat source (ground-based experiment). (a) Loss of symmetry of the flow under the action of vibrations, and (b) the intensification of flow by quasi-static acceleration. White arrows denote the direction of vibrations. Black arrows denote quasi-static components

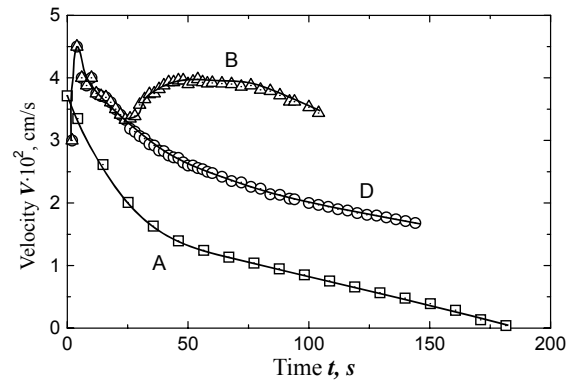


Fig. 4 Convection front velocity as a function of time. (A) Vibration convection regime (see Fig. 3a), (B) vibration convection regime affected by quasi-static component of microaccelerations, and (D) static regime. The sharp bend in the B curve corresponds to the time moment of the onset of high-frequency vibrations on the background of the quasi-static component of vibrations

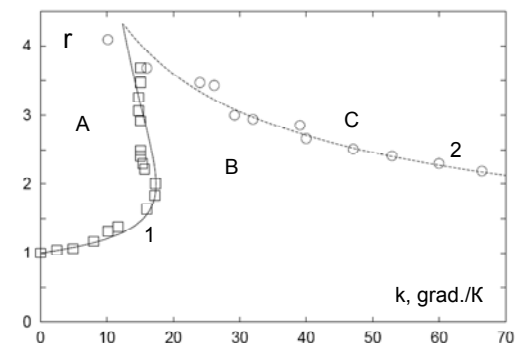


Fig. 5 Map of convection regimes in the r - k coordinates, where r is the relative Rayleigh number and k is the feedback gain. (A) convection, (B) dynamically stabilized equilibrium, and (C) oscillation mode.

with density inhomogeneities, which are used in various devices presented onboard space stations.

4. Laboratory and numerical study of the piston effect and density/temperature relaxation

To study the behavior of some integral characteristics of the heat transfer process near the critical point we carried out a numerical modeling and a specially designed laboratory experiment⁷⁾.

The laboratory experiments were carried out with the ALICE-1 instrument. The temperature inside the experimental cell filled with SF₆ was set to a value that exceeds the critical temperature by $\Delta T = T - T_c = 250$ mK, 450 mK, 4550 mK, 9950 mK, where T_c is the critical temperature. Then the wall temperature changed by a given value ($\delta T = 100$ mK), and the heat transfer process was observed with the interferometer.

Fig. 6 shows the time dependence of fringe deviation proportional to the density variation in the central region of the cell. Each curve reaches a maximum and then drops with time. Qualitatively, the density maximum increases and subsequent density drop slows down as one approach to the critical temperature.

The curves were used for determining two characteristics: maximum density rise in the bulk, $\delta\rho_{\max}$, (a characteristic of the piston effect) and relaxation time, τ_{relax} , (a characteristic of slowed down density relaxation).

The numerical experiments were carried out with a numerical instrument based on the direct solving of 2D Navier-Stokes equations with constant coefficients supplemented by the van der Waals or perfect equation of state. As the parameters, we used the parameters corresponding to SF₆, and each calculation run (like in the experiment) was performed in two stages: first the equilibrium (a vertical density distribution for $g=g_0$ case) was established in the domain corresponding to a given temperature above T_c , and then the boundaries was heated suddenly or gradually by $\delta T = 100$ mK. We performed calculations for the wide range of initial temperatures. **Fig. 7** shows the time dependencies of the relative density variations for various distances from the critical point in the absence of gravity and sudden change of boundary temperature. The initial temperatures for the calculations were the same as they were in the experiments and several values closer and far from the critical temperature (e.g., 50 mK and 50 K as presented in Fig. 7). The run of the calculated curves is qualitatively the same as that of the experimental ones.

From the curves, we again determined two characteristic values of the heat transfer process ($\delta\rho_{\max}/\rho_c$ and τ_{rel}) by a procedure same as it was in the processing of the experimental results. Thus, the parameters, the procedure, and the processing of the results used in the numerical experiments are as close as possible to these realized in the laboratory experiments.

We compare the behavior of density maximum rise and relaxation time as a function of proximity to the critical temperature $\varepsilon = (T-T_c)/T_c$ obtained experimentally and numerically for the van der Waals and perfect gases. Such a comparison for the relaxation time is presented in **Fig. 8** (the maximum density rise demonstrates qualitatively the same behavior). When $\varepsilon > 1$, the data for the van der Waals gas (open circles) and perfect gas (open triangles) are in practice in coincidence. For $\varepsilon \approx 10^{-4} - 1$, the van der Waals values rise and essentially differ from these for the perfect gas. For $\varepsilon < 10^{-4}$, the value is again virtually independent of ε . The inclination of the curves for $g=g_0$ (open squares) is close to that obtained in our experiments (dark squares) and Meyer's experiments (dark triangles)⁸⁾.

We concluded that the method proposed describes both the speeded up temperature/density rise (piston effect) and slowed down temperature/density relaxation. This allows us to hope that the numerical instrument developed is capable to simulate various regimes of heat transfer for more complex geometries and various method of heat supply throughout the heat transfer process.

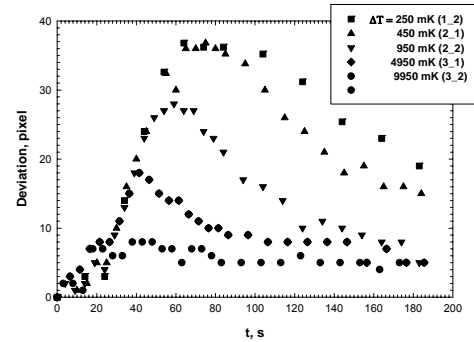


Fig. 6 Time dependence of fringe deviation proportional to the density variation in the central region of the cell for various values of $T_w - T_c$

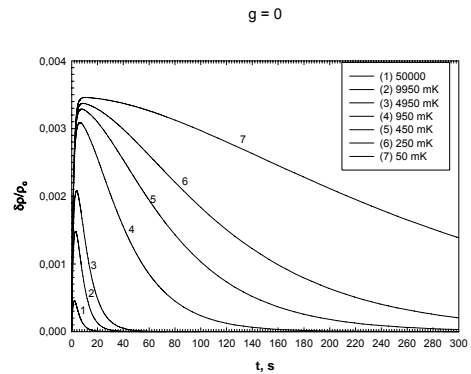


Fig. 7 Time dependence of relative density rise at the center of the calculation domain for various $T-T_c$ values

5. Ground-based simulation of vibration-modified phase separation with H₂ under magnetic gravity compensation

The study have been carried out with H₂ (critical temperature 33K) on ground under magnetic compensation of gravity. The cell containing the fluid is a cylinder (3 mm in diameter) with the horizontal axis perpendicular to the coil axis. It is made of sapphire and is closed by two parallel sapphire windows spaced by 3 mm and sealed with indium rings. The cell is vibrated sinusoidally by means of an electric stepper motor. The phase separation process always very fast, lasting between 0.5 to 15 s.

The results of the experiments are presented in **Fig. 9**. Without vibration, the dynamics of phase transition depends only on the mean distance between liquid or gas domains. When vibrations are presented, the vibration does not affect the domain growth at early times because the domain size is smaller than the viscous boundary layer thickness. When the domain size is larger than the viscous boundary layer the gas and liquid domains acquire different velocities because of inertial effects associated with their different densities.

Our investigation shows that the phase transition of a gas and a liquid can be significantly accelerated by high-frequency vibration. The vibrations initiate velocity differences between the gas-liquid growing domains, whereby the domain size grows larger than the viscous boundary layer. These hydrodynamics phenomena that couple with phase transition reveal intriguing new process⁹⁾.

6. Some new theoretical results

Last years new theoretical results were obtained under the frameworks of the VIP- KRIT project with the use of linearized Navier–Stokes equation and DNS. Unsteady convection regimes with regard to the piston effect were studied¹⁰⁾. A condition of the onset of the Rayleigh-Benard convection in a viscous heat-conducting perfect gas was obtained from the solution of linearized equations¹¹⁾. The Rayleigh number was modified in terms of Jeffrey’s condition. For a van der Waals gas the convection onset criterion was corrected. The analytical formulae obtained indicate that the horizontal convection scale depends on the temperature difference and hydrostatic compressibility. The values of the parameters, for which convection is developed, were confirmed by solving the linearized equations and direct numerical solution of the complete Navier-Stokes equations. The commonly used adiabatic temperature gradient obtained from the Schwarzschild condition is valid for a perfect gas for low temperature differences. For a perfect gas with high temperature differences, the convection onset condition in Jeffrey’s form was obtained. For a van der Waals gas the adiabatic gradient also differs from that obtained from the Schwarzschild condition. In such a case, the

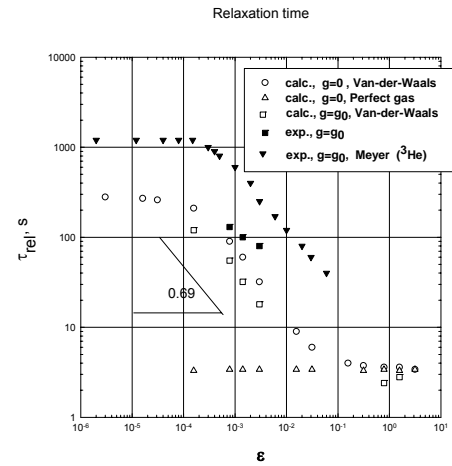


Fig. 8 Relaxation time as a function of the proximity to the critical point $\epsilon = (T-T_c)/T_c$.

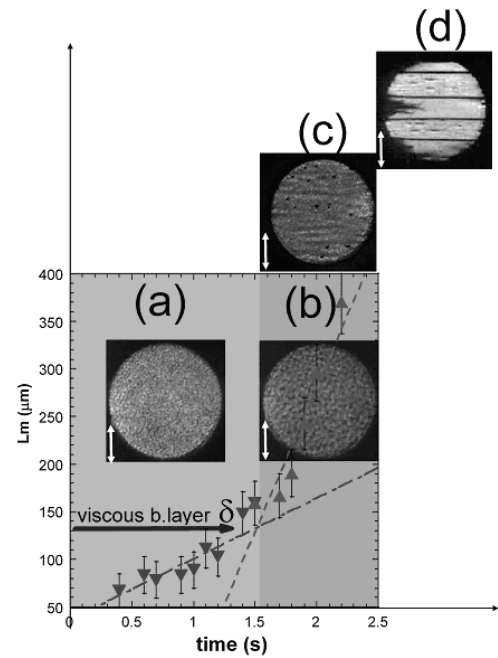


Fig. 9 Evolution of an interconnected pattern of drops and bubbles that is observed when the minority phase (gas here) volume fraction larger than 30%. The double arrow represents the vibration. L_m is the pseudo-period between the domains and δ is the viscous boundary layer, the length of which represents the range of viscous coupling. (a): $L_m < \delta$, no vibration influence. (b): $L_m \approx \delta$, vibration speeds up the evolution and orientates the drop-bubble interfaces perpendicular to vibration (c) till a steady state is obtained in (d). Photos: From (a) to (c): 3 mm diameter, 3 mm thickness H₂ sample under magnetic compensation of gravity and vibration 20.3 Hz frequency and 0.3 mm amplitude, 0.6 mK below the critical point. (d): 10 mm diameter, 10 mm thickness CO₂ sample in a sounding rocket free fall environment (vibration 42 Hz, 0.31 mm, 2 mK below the critical point).

adiabatic gradient depends on both the vertical coordinate and the parameters of isentropic hydrostatic distribution of density associated with a large value of the hydrostatic compressibility. By introducing corrections into the formula for the adiabatic gradient, the convection onset condition in Jeffrey's form was generalized. It was shown that the deterioration of convective heat transfer near the critical point is probably associated with the fact that the adiabatic temperature gradient exceeds a given one. One of the goals of the VIP-KRIT space experiment is to reproduce such regimes in microgravity and to test the above mentioned theoretical conclusions.

7. Conclusions

Last years, the VIP-CRIT project team has showed a high activity in analyzing the MIR experiments¹⁻³⁾, carrying out ground-based and numerical experiments⁴⁻⁹⁾, and developing analytical methods for stability analysis^{10,11)} devoted to the study of the effects of microgravity on the heat transfer and phase separation in the near-critical fluid. It is no doubt that the ground-based simulation of the processes under microgravity and carrying out mutually complementary numerical and laboratory experiments provide us with deficient basic knowledge as well as with new ideas for optimizing the space experiment in order to reduce time and labor consumptions required for carrying out the space experiment. In addition, this allows us to develop an instrument and to make more precise program for the future space experiment on the ISS.

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