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Physical research of microgravity influence on physical phenomenon in cryogenic liquids and general-purpose onboard cryogenic facility for realization of this research aboard International Space Station

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The united research plan named «Boiling» is created on the basis of several cryogenic research projects developed by experts in Russia and Ukraine for International Space Station. The «Boiling» plan includes 8 first experiments aimed at investigating the influence of microgravity on boiling processes, heat transfer and hydrodynamics in liquid helium being either under normal or superfluid conditions. The experiments are supposed to be carried out with individual cells collected inside a single cryogenic onboard experimental facility. The international research program experiments are characterized by the following features: utilization of several artificially simulated microgravity levels, owing to rotation of the experimental helium cryostat; visualization of the processes that occur in liquid helium; research of boiling and hydrodynamics both in a large volume of stationary liquid, and in a liquid flow running through a channel. Upon completion of the «Boiling» research plan, the cryogenic onboard facility created for International Space Station would be able to find its application in further scientific and experimental researches with helium.

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Introduction

The history of evolution of the research program for investigations of microgravity influence on boiling of liquid helium is another proof of beneficial character of Chernogolovka conferences, whereby conceptually new ideas are not only a subject to reports and disputes by the International scientific society, yet acquire another impetus to further development in the complemented contents form. After a long way forward and milestone events like publications by ukrainian [1–5] and russian [6–8] scientists, this initial idea has been transformed into a joint international russian and ukrainian project on investigations of liquid helium aboard the russian segment of the International Space Station (ISS).

The joint project program has incorporated a collection of decent experience gained by five research institutions in both countries, reflecting their scientific interests and goals. Now, thanks to the complex study of the problem and to the novel approaches hereto, this joint project program holds promise to give a sufficient boost to comprehending the mechanisms of microgravity (MG) influence on processes of heat transfer and hydrodynamics at boiling of normal and superflow liquids.

Onboard cryogenic facility

The international joint project program is based on integration of two initial technical concepts. On one hand, the idea is to employ, at investigations aboard the ISS, a universal helium cryostat, whereby several experimental cells will be lodged, and whereas some innovative scientific research possibilities would be provided by arrangement of several controlled MG levels (due to rotation of the cryostat), along with a possibility of visualizing the liquid He-related processes (Fig. 1).

On the other hand, there is an idea to organize a universal cryogenic workplace aboard the ISS (for details, see [7]), where, in particular, with purpose to increase a number of spaceborne experiments, there would be provided an additional cryostat with liquid helium intended to refill the research cryostats. This project would be implemented by Central Research Institute of Mashine Building (CRIM) force.

Inside the rotating research cryostat there would be lodged 3 to 5 experimental cells (Fig.2) (to arrange a step by step sequence of spaceborne experiments), alongside with a video recording system.

Both cryostats would be connected together through a pipeline intended to feed the research cryostat with a pumped up flow of normal or superfluid helium from the standby cryostat. In this manner two problems are expected to be solved for realization of a spaceborne experiment on heat transfer, hydrodynamics under forcible supply of liquid helium and planned refilling of the research cryostat.

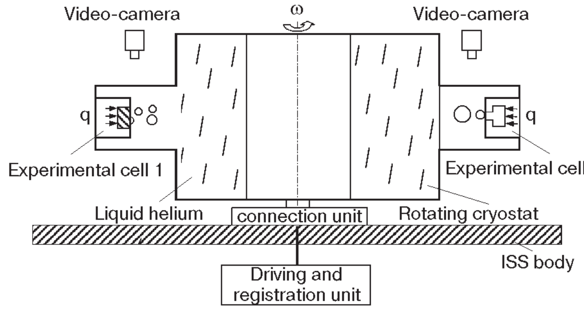

Fig. 1. Schema of the helium cryostat with experimental cells.

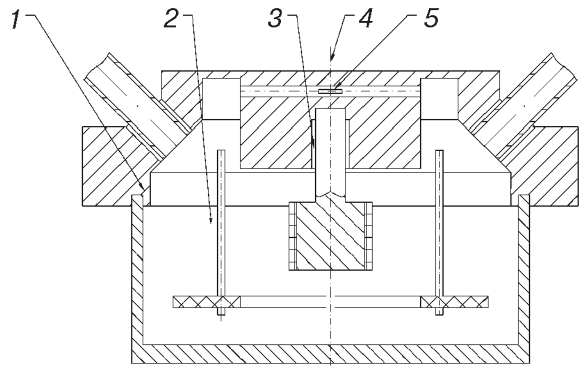

Fig. 2. Experimental cell for the «Bubble» experiment: heater body (*1*); vacuum insulation (*2*); heating unit (*3*); center of boiling (*4*); temperature sensor (*5*).

The concept of all the spaceborne experiments includes the following functions: supply of thermal power to experimental cell heaters, due to a preset program, registration of pursuant temperature change readings, registration of pressure drop, identification of boiling phenomena, like origination and propagation of vapor bubbles or vapor films rearrangement of two-phase flow structure.

The spaceborne experiment project plans

The «Bubble» spaceborne experiment would be implemented by Special Research and Development Bureau for Cryogenic Technologies (SRDB) force

An objective of this spaceborne experiment is obtaining a video record of processes of vapor bubbles growth and departure from a single centre of bubble boiling in normal liquid helium at 4 levels of MG. Result expected is a definition of type of dependence of the departure diameter of bubbles and frequency of the bubble departure in liquid helium on value of microacceleration within range of $\eta = 1$ (based on data of onground experiments) up to $\eta \approx 10^{-5}$.

The «Borbatage» spaceborne experiment would be implemented by SRDB force

An objective of this spaceborne experiment is obtaining a video record of processes of vapor bubbles growth upon and departure from a single centre under influence of excessive pressure in normal state or superfluid helium at 4 levels of MG. Result expected is a definition of type of dependence of the bubble departure diameter and frequency of the bubbles departure from liquid helium on value of microacceleration and excessive vapor pressure.

The «Auto-wave» spaceborne experiment would be implemented by SRDB force

An objective of this spaceborne experiment is obtaining (by means of video recording and temperature registrations) of experimental data on direction and speed of propagation (upon boiling surface) of the boundary between areas of bubble and film boiling regimes for normal state liquid helium at 4 levels of MG. Initially, the boiling surface would be heated uniformly and boiling phenomenon would occur on it in bubble regime. A local thermal disturbance (i.e., an additional heat up) would create a source of film regime which differs from the bubble boiling process both in physical appearance and temperature. The newly borne source of phenomenon may either collapse or outstretch over the entire boiling surface, depending on whether is the disturbance rate below or above the critical level, correspondingly. As a result, it is expected to identify the type of dependence of the critical local thermal disturbance value and dynamical characteristics of autowave process at change of boiling regimes for normal state liquid helium on surfaces of different dimensional categories on magnitude of microacceleration.

The «Film» spaceborne experiment would be implemented by Moscow Power Engineering Institute (MPEI) force

An objective of this spaceborne experiment is obtaining (by means of video recording and temperature registrations) of experimental data on conditions of the vapor film birth, dynamics and decay in superfluid liquid helium and heat transfer at 4 levels of MG. If thermal flow density is below critical, the heat transfer will take place in regime of the single-phase convection of superfluid liquid helium. In excess of critical level there appears a vapor film which separates the superfluid liquid helium from the heated surface. With consequent power decrease there occurs a reverse transition which leads to decay of vapor film. Parameters to be measured in the course of this spaceborne experiment are the following: value of thermal power, temperature of the boiling surface and microacceleration. Values to be determined from the video recording are: outside diameter of vapor film, velocity of vapor film extension or collapse variations and frequency of extension/collapse variations. To provide superfluid helium boiling in microgravity it is required to create conditions for confinement of He II in experimental volume containing the heater. We believe that capillary porous medium may be used for

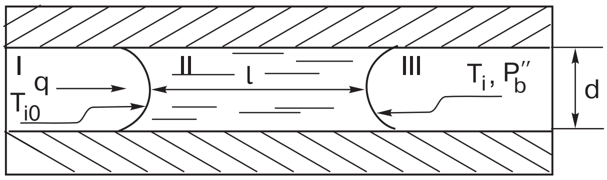

Fig. 3. He II column in the capillary of porous structure: zone I and III occupied by vapour; zone II occupied by He II.

achievement of this purpose. At boiling of He II in porous medium situation represented in Fig. 3 may be occurred.

This problem was solved in paper [8]. In present work the offered in [8] approach is developed for more common statement: the helium II-filled system consisting of two vessels connected by capillary of length l. The heater is placed at the top of left-hand vessel of diameter D_0. This vessel is closed hermetically. Vapor film exists between heater and liquid helium. The left-hand vessel and side surface of a capillary are adiabatically insulated. A heat flux is delivered from the heater to the interface through vapor film. At the right-hand vessel of diameter D vapor pressure P_b'' is maintained constant. It is required to describe behavior of superfluid helium in this system.

From the writing in [8] conservation laws and equation describing heat and mass transfer on the interfaces the following solution of the problem is obtained.

Relationship for He II flow velocity has a form:

$$\overline{V}' = \frac{d^2}{32\eta l} \frac{(q_w/r)\sqrt{2\pi R T_i}}{\left(1 - \frac{\rho''}{\rho' - \rho''}\frac{r}{ST}\right)} \times$$

$$\times \left[0.6 \left(\frac{D_0}{D}\right)^2 + \frac{r}{8RT} + \frac{\rho' g\,(h_1 - h_2)}{(q_w/r)\sqrt{2\pi R T_i}} \right] -$$

$$- \frac{q_w}{\rho' ST}\left(\frac{D_0}{d}\right)^2 ,$$

where h_1, h_2 — altitudes of superfluid helium columns in left-hand and right-hand vessels, respectively; d — diameter of a capillary tube; R — helium ideal gas constant; r — latent heat of evaporation; q_w — heat flux density.

At some altitude difference $\Delta h = h_1 - h_2$ superfluid helium velocity $\overline{V}'$ becomes to equal zero. This altitude difference is determined by formulae:

$$\Delta h = \frac{q_w}{\rho' g}\left[\left(1 - \frac{\rho''}{\rho' - \rho''}\frac{r}{ST}\right) \frac{32\eta l}{\rho' ST d^2} \left(\frac{D_0}{d}\right)^2 - \right.$$

$$- 0.6 \frac{\sqrt{2\pi RT_i}}{r}\left(\frac{D_0}{D}\right)^2 - \frac{\sqrt{\pi}}{4\sqrt{2RT_{i0}}}\Bigg],$$

$$\Delta h = \frac{S\Delta T}{g}\Bigg[1 - \frac{\rho''}{\rho' - \rho''}\frac{r}{ST} -$$

$$- \frac{d^2\rho'\sqrt{2\pi RT}}{32\eta l}\frac{ST}{r}\left(0.6\left(\frac{d}{D}\right)^2 + \frac{r}{8RT}\left(\frac{d}{D_0}\right)^2\right)\Bigg],$$

where ΔT — temperature difference along the capillary length. (As temperature difference in the vessels is much less than temperature drop along capillary it is accepted that temperatures in vessels do not depend on depth.) This formula looks like well-known fountain effect relationship: $\rho' g\Delta h = \rho' S\Delta T$.

Nevertheless, the term

$$\frac{d^2\rho'\sqrt{2\pi RT}}{32\eta l}\frac{ST}{r}\left(0.6\left(\frac{d}{D}\right)^2 + \frac{r}{8RT}\left(\frac{d}{D_0}\right)^2\right)$$

is contained in the this formula. This term exists owing to the viscous of normal flow in capillary and kinetic effects on interfaces in a considered system. If capillary diameter $d \to 0$ and because

$$\frac{\rho''}{\rho' - \rho''}\frac{\mathrm{r}}{ST} << 1$$

formula transforms in the last relationship. Thus, it is apparent that the nature of this phenomenon is similar to the nature of a fountain effect.

Analysis of formulae for determination of Δh shows that Δh is zero at some length which can be denoted as L_{01}:

$$L_{01} = \frac{d^2\rho'\sqrt{2\pi RT_i}}{32\eta\left(1 - \frac{\rho''}{\rho' - \rho''}\frac{r}{ST}\right)}\frac{ST}{r}\left(0.6\left(\frac{d}{D}\right)^2 + \frac{r}{8RT}\left(\frac{d}{D_0}\right)^2\right).$$

Thus, value of the difference between altitudes of superfluid helium columns in vessels $\Delta h = h_1 - h_2$ can be both less and more than zero for general case. However, if vessels diameters are much more than capillary diameter then the following peculiarity takes place. For zero value of the difference between altitudes of superfluid helium columns in vessels «critical length» is very small in comparison with similar length for a single capillary. Therefore, even at a very little capillary length the superfluid helium moves in a vessel with heater, while in the single capillary the He II flows to the heater only at considerable length of column (more than critical length). If column length is smaller than critical length then the column moves from the heater as for case of ordinary liquid.

Result expected is a definition of type of dependence of: the heat transfer coefficient, critical densities of heat flux and vapor film dynamics index in superfluid liquid helium, on value of microacceleration.

The «Impulse» spaceborne experiment, would be implemented by Moscow Institute of Physics and Engineering (MIPE) force

An objective of this spaceborne experiment is obtaining (by means of video recording and temperature registrations) of experimental data on conditions and time of delays in occurrence of bubble and film boiling regimes for normal liquid helium at different modes of «attacking» heat supply to the boiling surface at 4 levels of MG.

Results expected are: definitions of dependences of typical periods of delays in boiling and onset of stationary regimes of liquid helium boiling at «attacking» heat supply, on values of microacceleration and thermal pulse peaks; obtaining a correlation between rapid temperature variations on solid surface, and processes of vapor formation in liquid helium.

The «Pore» spaceborne experiment would be implemented by Institute for High Temperature of Russian Academy of Science (IHT) force

An objective of this spaceborne experiment is obtaining of experimental data on heat transfer and on dimensions of vapor bubbles in normal state liquid helium, which is subjected to boiling on surfaces of different geometrical characteristics of coatings at 4 levels of MG. Result expected is a definition of a type of dependence of heat transfer coefficient, critical density of thermal flow and average departure size of vapor bubbles on value of microacceleration and geometry of porous coatings.

The «CryoManifold-1» and «CryoManifold-2» spaceborne experiments to be implemented by Central Research Institute of Machine Building (CRIMB) force

Both these experiments are similar, only differing in characteristics of liquid helium to be supplied to the experimental cell. The experimental cell is typically a channel which is supplied under excessive pressure with liquid helium from the stand by cryostat.

The «CryoManifold-1» experiment would employ a normal state liquid helium at 4.4 K temperature whereas in «CryoManifold-2» experiment there would be employed the superfluid liquid helium at 1.8 K.

An objective of this spaceborne experiment is obtaining of experimental data on heat transfer, hydraulic resistance and flow regimes for single- and two-phase flows of liquid helium at different mass flow rates and under conditions of intrinsic microacceleration aboard the ISS.

Result expected is a definition of type of dependence of heat transfer coefficients, hydraulic resistance coefficients and flow regimes for single- and two-phase helium flow on value of microacceleration and pressure drop.

Conclusion

In present time the project status is in the following progress: the cryogenic onboard facility and experimental cells are at design stage; a relevant documentation accompanying efforts by cooperation researchers in Russia and Ukraine is being developed and coordinated; shares of contribution hereto by either party are allocated; implementation of joint «Boiling» plan is being pre-arranged by both parties; mock up verions of experimental cells are being investigated; mock-up model testing is carried out, and preliminary on-ground experiments with normal and superfliud LH are being undertaken.

A diverse spectrum of every potentially perspective research in physics and techniques of low temperatures under MG conditions, which would be implemented by aid of the cryogenic onboard facility, is a prerequisite of further evolution of the concept under discussion.

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