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Effect of reduced gravity and weightlessness on vapor bubble dynamics and heat transfer in boiling liquid

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The results on boiling of liquids and gas bubbling under simulated long-term reduced gravity are reported. The possibility of extrapolating these results to the real spacecraft conditions is considered and the program of on-board space experiments is proposed to test the current theory at the relative accelerations 10^{-4}–10^{-6} which are unattainable in a laboratory. Tests in free-fall towers, in aircraft, or in ballistic rockets are inadequate since only prolonged (over one hour) experiments in the Earth's orbit can provide reliable data. The advantage of cryogenic liquids, helium, in particular, in space experiments is discussed.

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Introduction

In the orbit some processes occur in the vapor-liquid and gas-liquid systems, which are related to heat transfer and to the formation and motion of bubbles and drops. The influence of microgravity on the processes in tanks and pipelines with liquid fuel for rocket engines or in various boilers-condensers attracted keen interest in the 1950s and 1960s when practical space exploration advanced quickly [1].

High costs of space experiments, however, called for various methods of simulation of reduced gravity. Many of them (in ballistic rockets, aircraft, free fall towers) were still expensive and permitted only short-term simulation of microgravity. Low-cost methods of long-term laboratory simulation of microgravity for vapor-liquid and gas-liquid systems were developed at the Special Research and Develompent Bureau (Institute of Low Temperatur Physics and Engineering). They are applicable at relative accelerations $\eta = 1$–10^{-2}. One of them involves compensation of weight force that acts on liquid oxygen by a nonuniform magnetic field and the other uses the weight force decomposition in inclined thin containers [2].

Extensive studies of the effect of reduced gravity on heat transfer and boiling in liquids (including liquid oxygen) were performed. The results and conclusions were employed in Soviet space vehicles and partially (but insufficiently) tested in on-board experiments in the beginning of the 1970s. There are still some questions concerning extrapolation of these conclusions to lower relative accelerations ($\eta = 10^{-4}$–10^{-6}). This region is realizable only in long-term orbital flights and cannot be simulated by other methods. Laboratory results should therefore be tested in orbital experiments. Such experiments have never been performed either in the USSR or (as far as we know) in other «space-exploring» countries, despite the advent of numerous on-board cryogenic-cooled instruments (e.g., IR telescopes) and a wide use of cryogenic liquids for experiments in the 1980s and 1990s. Researchers plunged into fundamentals of physics of low-temperature liquids under microgravity. We shall try to show that now, with large liquid-helium cryostats frequently sent into orbit, the time is right to complete the long-standing work and to answer the questions which are still open.

Laboratory results for $\eta = 1$–10^{-2}

The experimental objects were the growth, departure, and motion of vapor or gas bubbles, heat transfer coefficient α under nucleate and film boiling, and critical heat flux densities $q_{\rm cr}$ in liquid oxygen, water, and organic liquids [2]. The true range of η-values was 1–10^{-2} and the highest simulation error was $\pm 10^{-2}$. Oxygen boiled on platinum wires (0.05–0.15 mm in diameter); water and organic liquids also boiled at the edge of a steel tape 0.1 mm wide. Pressure varied in the range 6–700 kPa. The gas (helium or nitrogen) bubbled into liquid through orifices of various sizes. Rapid filming technique (30 000 frames per sec.) was used to investigate the bubble dynamics.

Experimental results were presented as exponential η-functions of corresponding quantities [2]. The bubble departure diameter D was $D(\eta)/D(1) = \eta^k$, where $k = -0.33$ at the atmospheric pressure, and $k = -0.23$ and -0.31 under reduced and elevated pressures, respectively. For the bubble departure frequency at these pressures the k-values were 0.67, 0.57, 0.63, respectively.

The dependence of the velocity of the bubbles is described as $w(\eta)/w(1) = \eta^{0.33}$.

The dependence on η of heat flux density q_{cr}^k corresponding to the nucleate film boiling transition is influenced greatly by pressure; the k values are 0.36, 0.26, and only 0.05 under elevated, atmospheric, and reduced pressures, respectively. During film boiling $\alpha(\eta)/\alpha(1) = \eta^{0.18}$. During nucleate boiling the dependence of the heat transfer on the relative acceleration, in contrast, was weak: $k = -0.05$ at the atmospheric pressure and $k = -0.01$ under lower pressures. Nucleate boiling under elevated pressure deteriorated the heat transfer as α decreased with increasing growing heat flux density q.

Larger scattering and uncertainty are observed in the k values on approaching the lower boundary of the simulated relative acceleration range. This occurs as the «infinite-heater-in-infinite-liquid» condition is violated at small η values when bubble sizes become comparable with the volume of the liquid in the experimental cell and exceed the heater size. Simultaneously, the bubble growth at the heater takes more time and considerably prolongs the characteristic times of the transition process that occurs at the beginning of the experiment. To check the above formulas, we must increase the size of the cell and the heater and the time constant of the experiment at small η values in order to match the bubble size and the growth times. It is obvious that these requirements are even more severe at $\eta = 10^{-4}$–10^{-6}. In boiling water at $\eta = 1$ the bubble diameter is $D = 2.5$ mm; at $\eta = 10^{-6}$ it increases to 250 mm. The characteristic growth time τ increases 10 000-fold.

The advantage of using liquid helium for on-board microgravity experiments

To study boiling at $\eta = 10^{-4}$–10^{-6}, we should choose the liquid with the lowest D and τ under standard conditions, i.e., liquid helium-I with $D = 0.05$–0.1 mm and $\tau \cong 0.003$ s at $\eta = 1$ and atmospheric pressure [3]. Since on-board sources are limited in power, it is important that among cryogenic liquids helium has the lowest characteristic heat flux densities (cf. the standard values $q_{\text{cr}} \cong 10\ 000$ W/m^2 for helium and $q_{\text{cr}} \cong 1\ 000\ 000$ W/m^2 for water). The lowest values of the characteristic times, sizes, and thermal power of helium are due to its low viscosity, surface tension, and latent heat of vaporization.

The ideal capability of liquid helium to wet any solid and the low surface tension ensure the slightest distortion of the free surface of the liquid under microgravity and hence the smallest change in pressure when the amount of the vapor in the liquid increases. The low density of liquid helium (as compared to water) partially counterbalances the cryostat mass (if the volume of the liquid in the on-board experiment is large).

Vaporized helium is safe for the spacecraft crew: it is nontoxic for breathing, noncombustible, and nonexplosive. As a result, on-board experiments do not need special safety systems.

Possible experiments on liquid helium boiling and bubbling under microgravity

The main goal of the experiments proposed is an accurate test of the relations derived for bubble dynamics and heat transfer characteristics during boiling under microgravity simulated in the laboratory with $\eta = 10^{-4}$–10^{-6}. The size (volume) and time scales of the experiment must be held consistent with the expected size of the bubble and the time of its growth under microgravity in order to keep the «infinite-heater-in-infinite-liquid» condition undisturbed.

The research program may include the following on-board experiments:

1. Videorecording of helium gas (vapor) bubbling into liquid through orifices of various diameters at various velocities.
2. Videorecording of active vapor nucleation sites (especially the homogeneous sites) in heated liquid helium; bubble growth, departure and motion during nucleate and film boiling.
3. Temperature measurement in the liquid and of the solid heating surface at various heat flux densities, including stable and transient states of the «liquid-heater» system. It is desirable to use several heating surfaces that differ appreciably in thermal conductivities and roughness since these factors control extensively the bubble nucleation and growth at the heater.
4. Pressure measurement in the liquid to study acoustic waves generated by nucleation and growth of the vapor phase.

The on-board helium cryostat with the experimental cell submerged in liquid helium must be equipped with an optical image output system (through a window or a fiberguide). The electric heater of the cell should have three or four surfaces of boiling with the characteristic size no smaller than 100 mm ($> 10D$ at $\eta = 10^{-6}$). Our estimation of the total heater operation time is 1.5 h. With the mean heat flux of 10^2 W/m^2 ($0.5\, q_{\rm cr}$ at $\eta = 10^{-6}$) the total heat input in the liquid during the experiment is then about 25 kJ and the volume of evaporated liquid helium is about 10 liters.

The total liquid helium volume in the cryostat must be about 100 liters to keep the conditions invariable during the whole experimental period. Liquid helium cryostats of this (and larger) capacity have been developed and used in some experimental projects on-board a space shuttle.

Important elements used to mount the experimental heater in the cryostat include a special suspension damping small vibrations and a high-sensitivity, three-axial accelerometer.

In conslusion, we note that the program proposed will advance our understanding of physics of boiling and will be helpful in solving certain applied problems of on-board experiments. For example, it is known that bubble-generated acoustic waves in the liquid-cooled, high-sensitivity detectors (infra red., magnetic, etc.) carry considerable noise in the signals. Reliable information about the spectrum of boiling under microgravity will permit researchers to filter out the noise.

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