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The Modeling, Algorithmization, Programming, Animation and Analysis of the Behaviour of Gas Bubble on the Solid Surface under the Acceleration of Gravity Change

M. Shoikhedbrod*
Active Director of Electromagnetic Impulse Inc., 21 Four Winds Drive, Unit 12, North York, Ontario, M3J 1K7, Canada
***Corresponding Author**
Email Id: michaelshoikhedbrod@bell.net; mshoikhedbrod@hotmail.com

ABSTRACT

At present time, accumulated theoretical material of the studies of the equilibrium forms of the gas bubbles, fixed on the surface of solid material in the fluid, under the acceleration of gravity decrease, was conducted either on the basis of the geometric laws of similitude that strongly simplified the essence of the physical processes or on the basis of the theoretical qualitative assessments of the existing hydrostatic equations of the equilibrium of fluid, taking into account the acceleration of gravity decrease, without producing of the numerical solution of these equations. Therefore, for the precise numerical analysis of the gas bubble of wide range of Bond Number values ***β****, fixed on the solid surface, under the acceleration of gravity change, the task of construction of the computer physical model of the behavior of gas bubble in this case and the development of the algorithm of the numerical calculation of this model was set. The paper presents the analysis of results of numerical calculation of the developed model of gas bubble behavior on the solid surface under the acceleration of gravity change, using the modeling, algorithmization, programming and animation, which were experimentally proved during the process of the carried out aircraft's tests on the board of the flying laboratory IL-76K, that permitted to make a conclusion about the energy advantage of microgravity state for the system fluid-gas-solid body and can be used for the simulation of the behavior of real bubbles or drops of fluid with the wide range of values Bond Number* ***β****(both signs) in real state of microgravity, which plays important role in the aerospace chemical-engineering.*

Keywords*: Modeling; Algorithmization; Programming; Simulation; Acceleration of Gravity Change.*

INTRODUCTION

The development of the scientific conception of the physical nature of formation gas bubble in the fluid of three-phase contact (fluid-gas-solid body) was made possible due to the development of the mathematical theory of capillary phenomena. The numerical solution of the equation of bubble (drop) profile was done by F. Bashforth and J. Adams [1] to test of the mathematical theory of capillarity by comparing the calculated and experimentally determined profiles forms of meridional sections drops of mercury various sizes and underlying on the smooth horizontal surface. The results were completed and published in the tables (1883) that became the basis for many of the absolute methods of determination of the forms of drops of fluids (gas bubbles) and of the calculation of the surface tension in the static conditions. It should be noted, as it was shown in [2] "each equilibrium condition of the fluid in any vessel corresponds to another condition: the resulting mirror reflection of the entire system of the equipotential plane with simultaneous replacement of the fluid on the gas and back and contact angles to the additional up to 180º ". Consequently, the case of Bond Number $\beta>0$corresponds to the above fluid air field in the vessel with the cover; $\beta<0$ corresponds to the gas bubble on the solid surface. In [3], these tables were supplemented for the case of $\beta > 0$, and in [4], using the computer, were built the most complete tables, containing more than 400 pages. For ($\beta < 0$), which is of interest, when viewed the various issues related respectively to the electrochemistry of the drop electrode and foam flotation [5,6], the profiles forms of gas bubbles with values β from -0.0125 to -0.25 were calculated. However, it should be noted, that these tables allow building a profile form of certain fluid drops (gas bubbles) with diapason of values β did not precisely matching to the values β of the real drops and bubbles. Therefore, the development of a computer model for calculations of the various real air bubbles, dense drops in various fluids, which is not connected with tables, is an actual important aim. The first scientist, who assigned the task of investigation of the influence of weightlessness on the form of drop of fluid or gas bubble, was Belgian physicist Joseph Plateau [7].

"Weightlessness" Joseph Plateau created, placing certain quantity of oil into the mixture of water and alcohol of the same density. With the complete either almost complete absence of external forces, in particular, the forces of gravity and equivalent forces, the behavior of the fluid masses, partially or wholly limited by free surface, is determined by exceptionally intermolecular interactions. The existing ideas about physics of fluids in these conditions are limited, basically, by "the statics of thin fluid films or by the systems of the small sizes, similar bubbles and drops" [8, 9].

At August 21, 1962, P.R.Popovich reported about the first in the world observations of the behavior of water in the conditions of the orbital flight. Observations showed that the water, which first occupied the flask lower hemisphere, took the form of the entire spherical shell, inside which the air was placed. The section surface between water and air increased 2.52. The theoretical justification of the carried out observations presented by V.V. Shuleykin in [10, 11] dedicated to the behavior of the fluid losing weight.

Theoretical investigation of the form (meniscus) of water change in the glass cylindrical container under the acceleration of gravity change was conducted in [10]. The author showed that in the weightlessness conditions, the work of the forces of surface tension increases free surface water in the container and not only compensates a change of the surface energy, but creates the additional energy, which is converted to the heat. In the case, if there were no friction losses, then with the approach of fluid to the equilibrium form, this additional energy would be converted to the moving kinetic energy of fluid, which would, in turn, forces the water to oscillate near the equilibrium state. However, such oscillations in the time will damp because of the friction and the steady meniscus of the state of equilibrium of fluid will be with the surface of larger, than in the case of Earth conditions. The experiences, carried out by P. R. Popovich, would have been different, if the surface of glass would be covered by the hydrophobic film. Then, there would be no wetting, and the water would be limited outside by a sphere, which would intersect with the underlying surface at the corresponding contact angle. This case was considered in [11].

The number of the work of the modern authors [12-14] is also dedicated to the mathematical description of the forms, taken by fluid, under the acceleration of gravity decrease. However, the collected theoretical material permits to trace the behavior only determined, with the narrow diapason of the values of drops of fluid (gas bubbles) under the acceleration of gravity decrease, as a result of the dependence of the obtained solutions from the used tables. Besides, the analysis of the behavior of the equilibrium forms of fluid under the decrease the acceleration of gravity was conducted either on the basis of the purely geometric principles of similitude that strongly simplify the essence of the on-going physical processes, or on the basis of the theoretical estimations of the existing hydrostatic equations of the equilibrium of fluid, taking into account the decrease of the acceleration of gravity, without producing the numerical solution of these equations. Obviously, for a more precise qualitative and quantitative study of the behavior of drops of fluid (gas bubbles) in conditions of the decrease of the acceleration of gravity, the way of creating the physical computer models that allow numerically, with the high accuracy, to trace the influence of a change of the acceleration of gravity, surface tension and contact wett ability angle on a change of the form, common surface energy of gas bubble (drop of fluid) and equilibrium of forces that retain it on the surface of solid material, is more perspective.

The paper presents the analysis of results of numerical calculation of the developed model of gas bubble behavior on the solid surface under the acceleration of gravity change, using the modeling, algorithmization, programming and animation, which were experimentally proved during the process of the carried out aircraft's tests on the board of the flying laboratory IL-76K, that permitted to make a conclusion about the energy advantage of microgravity state for the system fluid-gas-solid body and can be used for the simulation of the behavior of real bubbles or drops of fluid with the wide range of values Bond Number β (both signs) in real state of microgravity, which plays important role in the aerospace chemical-engineering.

MATERIALS

As materials for developed model were taken above of water surface air in the vessel from organic glass with the water by volumes 2.05, 2.5 cm3. Water density composed 1g/cm3. Water surface tension was equal 70 Dine/cm. Acceleration of gravity change was in the following diapason: from g = 980cm/sec2to g = 0 and from 980 cm/sec2 to g =1960 cm/sec2

METHOD AND DEVELOPED DEVICES

Model formulation

1) The gas bubble (drop) on the solid surface in the fluid is examined in the isothermal, isobaric conditions.
2) The fluid is considered incompressible, *i.e.*, $\frac{\partial\rho}{\partial t} = 0$ ($\rho = \rho_{fl}$ - fluid density) and, therefore, according to the law of the mass conservation, the volume of gas bubble is the constant.
3) The gas bubble is examined under the action of the forces of gravity and of surface tension: external forces are absent.
4) It is considered, that the contact wett ability angle of the gas bubble on the solid surface under the acceleration of gravity change does not change.
5) The acceleration of gravity change leads to a change of the form of gas bubble.

In the present model, the influence of the acceleration of gravity change on the form of gas bubble is considered as follows. With the acceleration of gravity g change, the parameter $\beta = \rho_{fl} g b^2/\sigma_{12}$ change occurs, under changed value of which, the value of one of the coordinates (X or Z) of the profile of the form of gas bubble, which corresponds to the new value of the acceleration of gravity, is determined. Further, in accordance with the law of the mass conservation, the calculation of another coordinate of the profile of the form of gas bubble is produced, thus, that the values of the volumes of gas bubble that correspond to the previous value of the acceleration of gravity and new, coincided. The proposed model permits to study laws, governing of the form, of the common surface energy of gas bubble and resultant force, which retains it on the surface of solid material changes under the acceleration of gravity change. The block - schema of algorithm of the numerical calculation of model on the computer is represented on figure 1.

Calculation was produced as follows:

1) The initial conditions are entered: *MI*- the number of points, $\rho_{fl} = \rho$ - the density of fluid, g - the acceleration of gravity, b - the normalizing factor, *AM* – the value, which determines the contact wett ability angle in the formula $\theta = \pi(1\text{-}1/AM)$, $\sigma_{12} = T$- the coefficient of the surface tension on the border of the phase section of fluid-gas, *A2* - the accuracy of the volume adjustment; *A3* - the step of increment of the parameter β- physical parameter $\beta = \rho flgb^2/\sigma_{12} = B$. The printout of the data input of the program on the computer screen is represented on figure 2.
2) The calculation of the coordinates of the profile of the form of bubble, of its side surface square and forces that retain it on the solid surface under the acceleration of gravity change with a step of, for example, $196\ cm/sec^2$ and retention of the volume of bubble with the accuracy, for example, $A2 = 0.00$ is produced.

This calculation has two cases.

Case 1. The acceleration of gravity decrease, by step $\Delta g = 196\ cm/sec^2$ from $g = 980\ cm/sec^2$ to $g = 196\ cm/sec^2$.

The coordinate: $\frac{b}{\rho}, \frac{X}{b}$, $\frac{Z}{b}$ of the profile of the form of gas bubble that correspond to $\boldsymbol{g = 980\ cm/sec^2}$, are calculated by Kutta-Merson method

The calculated coordinates by multiplication by the normalizing factor $\boldsymbol{b = B1}$ are converted to the real coordinates.

Then the values of the square of the side surface of gas bubble and its volume are calculated, based on the following formulas:

$$\mathbf{S} = \pi\sum_{i=1}^{MI}[X1(i+1) + X1(i)]\sqrt{[Z1(i+1) - Z1(i)]^2 + [X1(i+1) - X1(i)]^2}$$
$$\mathbf{V} = \pi\sum_{i=1}^{MI}[X1(i+1) + X1(i)]^2[Z1(i+1) - Z1(i)] \qquad \mathbf{(1)}$$

1. The value of adhesion force ***F1 = PR3***, of the Archimedes force ***F2 = PR1*** and the force, caused by the surface curvature ***F3 = PR4***, are calculated based on the following formula:

$$PR1 = \rho_{fl}\, gV$$
$$PR3 = 2\pi a\sigma_{12} Sin\theta \qquad \mathbf{(2)}$$
$$PR4 = \pi\sigma_{12}a^2\left(\frac{1}{R1} + \frac{1}{R2}\right)$$

All obtained values are printed. The printout of the results of the work of program on the computer screen for the case of bubble with $\boldsymbol{\beta > 0}$, by the volume $\boldsymbol{2.48326\ cm^3}$, $\boldsymbol{g = 980\ cm/sec^2}$, the contact angle $\boldsymbol{\theta = 1.6053}$ ***radian*** and $\boldsymbol{\sigma_{12} = 70}$ ***Dyne/cm***, is represented on figure 3.

2. After this, the operation of the acceleration of gravity decrease by the step of $\Delta g = 196\ cm/sec^2$, which leads to the decrease of value $\beta = \rho flgb^2/\sigma_{12}$, whose changed value is substituted to the formulas for determination of the coordinates $\frac{X}{b}$ and $\frac{Z}{b}$, is produced.

3. With the accuracy A2, the adjustment of volumes VOL andVOL1, those correspond to g = 980 cm/sec^2 and to the changed value g = 784 cm/sec^2 by increase of the value β and respectively the coordinate Z/b with the step, for example, A3 = 0.001, is produced, as long as the values VOL and VOL1 will not coincide. In this case, the coordinate $\frac{X}{b}$does not change and corresponds to the changed value β for g=784 cm/sec^2. Printout of the results of the adjustment of the volumes VOL and VOL1 by accuracy A2 on the computer screen is represented on figure 4.
4. The values of the coordinates of the profile of the form of gas bubble that correspond to $g = 784$ *cm/sec*^{2} and the volume *VOL = VOL1* are multiplied on the normalizing factor *b =B1* for obtaining real values.
5. The values of the side surface square of gas bubble, of its volume and of the value of adhesion power *F1 = PR3*, of the Archimedes force *F2 = PR1*and of the force, caused by the surface curvature *F3 = PR4*, for the case of$g = 784$ *cm/sec*^{2}, are calculated.

The obtained values will be printed. Described operation is repeated repeatedly, as a result of that, the coordinates of the profile of form, a side surface square, a volume of gas bubble and value of the forces that retain it on the surface of solid material, with the acceleration of gravity decrease from $g = 980$ *cm/sec* ^{2} to $g=196$ *cm/sec* ^{2}, are calculated. The printout of the results of the work of the program on the computerscreen for the case of bubble with $\beta > 0$ and by the volume *2.48326 cm*^{3},$g = 196$ *cm/sec*^{2}, the contact angle $\theta = 1.6053$ *radian* and $\sigma_{12} = 70$ *Dyne/cm* is represented on figure 5.

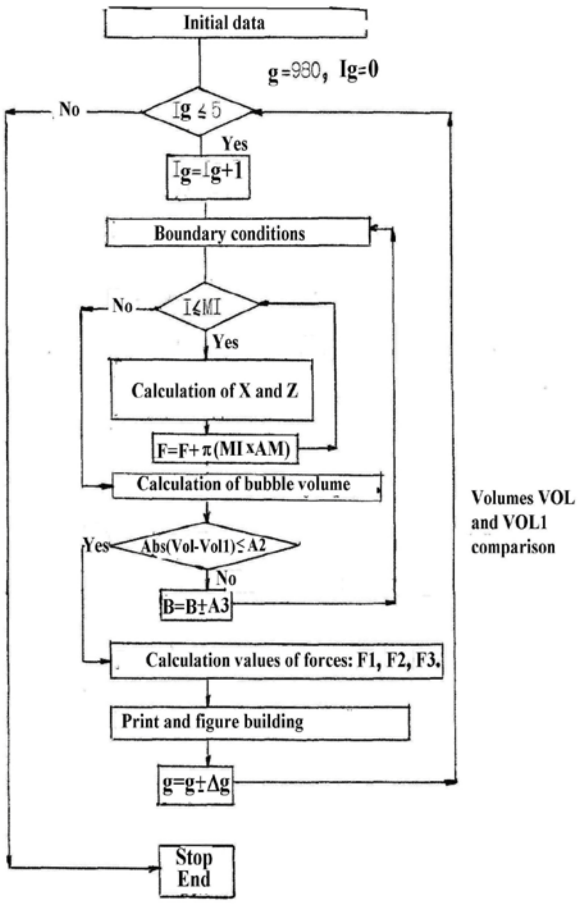
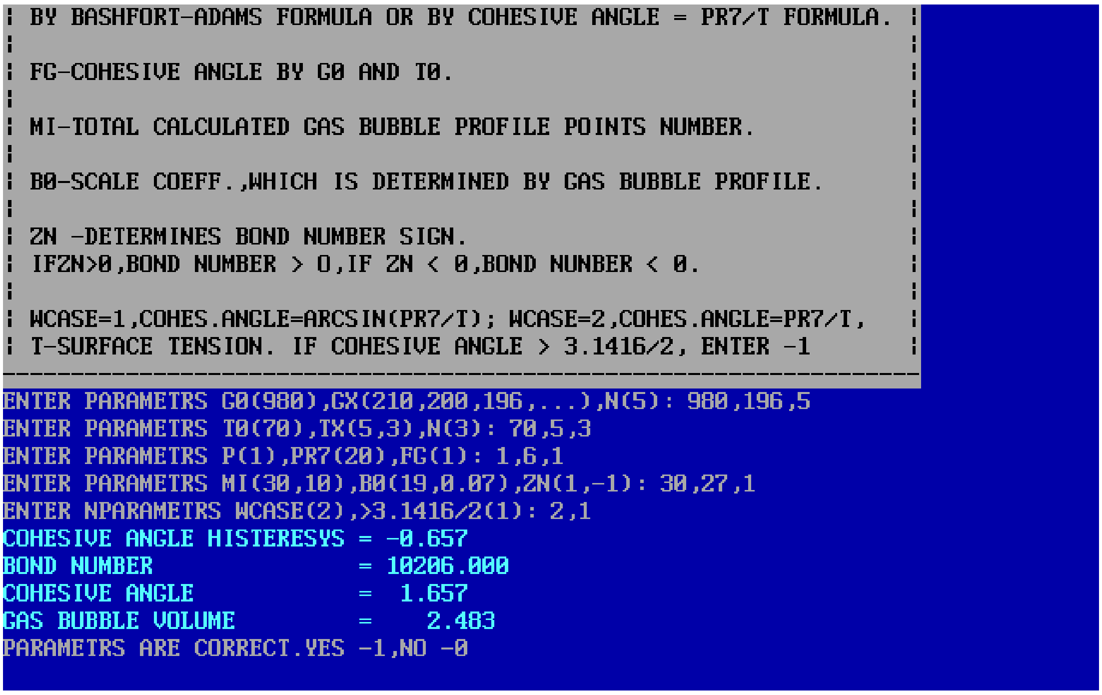


Fig. 1: Block – schema of the algorithm of numerical calculation of the model of the gas bubble on the solid surface under the acceleration of gravity change.



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| BY BASHFORT-ADAMS FORMULA OR BY COHESIVE ANGLE = PR7/T FORMULA. |
|                                                                 |
| FG-COHESIVE ANGLE BY G0 AND T0.                                 |
|                                                                 |
| MI-TOTAL CALCULATED GAS BUBBLE PROFILE POINTS NUMBER.           |
|                                                                 |
| B0-SCALE COEFF.,WHICH IS DETERMINED BY GAS BUBBLE PROFILE.      |
|                                                                 |
| ZN -DETERMINES BOND NUMBER SIGN.                                |
| IFZN>0,BOND NUMBER > 0,IF ZN < 0,BOND NUNBER < 0.               |
|                                                                 |
| WCASE=1,COHES.ANGLE=ARCSIN(PR7/T); WCASE=2,COHES.ANGLE=PR7/T,   |
| T-SURFACE TENSION. IF COHESIVE ANGLE > 3.1416/2, ENTER -1       |
-------------------------------------------------------------------
ENTER PARAMETRS G0(980),GX(210,200,196,...),N(5): 980,196,5
ENTER PARAMETRS T0(70),TX(5,3),N(3): 70,5,3
ENTER PARAMETRS P(1),PR7(20),FG(1): 1,6,1
ENTER PARAMETRS MI(30,10),B0(19,0.07),ZN(1,-1): 30,27,1
ENTER NPARAMETRS WCASE(2),>3.1416/2(1): 2,1
COHESIVE ANGLE HISTERESYS = -0.657
BOND NUMBER               = 10206.000
COHESIVE ANGLE            =  1.657
GAS BUBBLE VOLUME         =    2.483
PARAMETRS ARE CORRECT.YES -1,NO -0
```

Fig.2: Printout of the Data Input of the Program on the Computer Screen.

Case 2. The acceleration of gravity increase with the step of $\Delta g = 196\ cm/sec^2$ from $g = 196\ cm/sec^2$ to $g = 1784\ cm/sec^2$.

1) First of all, analogous to the case 1, the dimensionless and real coordinates of the profile of the form of gas bubble, the value of the side surface square of gas bubble, its volume and the value of adhesion force $F1 = PR3$, the Archimedes force $F2 = PR1$ and the force, caused by the curvature $F3 = PR4$ that correspond to the case of $g = 980\ cm/sec^2$, are calculated.
2) After this, the operation of the acceleration of gravity increase is produced by the step $\Delta g = 196 cm/sec^2$, that leads to the increase the value $\beta = \rho f l g b^2/\sigma 12$, whose changed value, is substituted to the formulas for the determination of the coordinates X/b and Z/b.
3) Further, just as in the case 1, the adjustment of volumes VOL and $VOL1$ that correspond to g = $980\ cm/sec^2$ and to the changed value $g = 1176\ cm/sec^2$ is produced with the accuracy $A2$, by the way of increment of the value β and respectively the coordinate $\frac{Z}{b}$ with the step, for example, $A3 = 0.001$, as long as value VOL and $VOL1$ not will coincide. In this case the coordinate $\frac{X}{b}$ does not change and corresponds to the changed value β for $g = 1176\ cm/sec^2$.
4) The values of the coordinates of the profile of the form of gas bubble that correspond to $g = 1176\ cm/sec^2$ and the volume $VOL = VOL1$ are multiplied on the normalizing factor $b = B1$ for obtaining the real values.
5) The values of the side surface square of gas bubble, its volume and the value of adhesion force F1 = $PR3$, the Archimedes force $F2 = PR1$ and the force, caused by the surface curvature. $F3 = PR4$, are calculated for the case $g = 1176\ cm/sec^2$.

The obtained values printed. Described operation is repeated repeatedly, as a result of which, the coordinates of the profile of form, the side surface square, the volume of gas bubble and the value of the forces that retain it on the surface of solid material with the acceleration of gravity increase from $g = 980\ cm/sec^2$ to $g = 1784\ cm/sec^2$, are calculated. Printout of the results of the work of program on the screen of computer for the case of bubble with ***β* > 0** and by volume ***2.48326cm³,g =1764 cm/sec²***, the contact angle ***θ* = 1.6053 radian** and ***σ_{12}* = 70 Dyne/cm** is represented on figure 6.

GRAVITY	SURFACE TENSION	GAS BUBBLE VOLUME
980	70	2.4833

F	X	Z	P	X/SIN(F)
+0.05121	+0.70380	+0.01401	+5.25332	+13.74941
+0.10242	+0.92616	+0.03272	+2.47838	+9.05859
+0.15363	+1.05024	+0.05133	+1.61381	+6.86312
+0.20484	+1.15015	+0.07351	+1.13538	+5.65436
+0.25605	+1.22245	+0.09548	+0.87559	+4.82683
+0.30726	+1.29443	+0.12450	+0.67085	+4.27985
+0.35847	+1.34861	+0.15308	+0.54427	+3.84394
+0.40968	+1.39079	+0.18116	+0.45846	+3.49169
+0.46089	+1.42419	+0.20868	+0.39659	+3.20226
+0.51210	+1.45077	+0.23556	+0.34997	+2.96072
+0.56331	+1.47187	+0.26175	+0.31366	+2.75638
+0.61452	+1.48840	+0.28719	+0.28464	+2.58150
+0.66573	+1.50105	+0.31180	+0.26097	+2.43033
+0.71694	+1.51034	+0.33553	+0.24135	+2.29856
+0.76815	+1.51668	+0.35832	+0.22487	+2.18288
+0.81936	+1.52041	+0.38011	+0.21086	+2.08073
+0.87057	+1.52182	+0.40086	+0.19884	+1.99010
+0.92178	+1.52116	+0.42050	+0.18846	+1.90938
+0.97299	+1.51864	+0.43901	+0.17943	+1.83727
+1.02420	+1.51445	+0.45633	+0.17154	+1.77275
+1.07541	+1.50878	+0.47242	+0.16461	+1.71495
+1.12662	+1.50179	+0.48726	+0.15851	+1.66318
+1.17783	+1.49363	+0.50082	+0.15313	+1.61688
+1.22904	+1.48444	+0.51306	+0.14838	+1.57557
+1.28025	+1.47437	+0.52398	+0.14419	+1.53887
+1.33146	+1.46354	+0.53355	+0.14049	+1.50648
+1.38267	+1.45208	+0.54177	+0.13724	+1.47816
+1.43388	+1.44012	+0.54863	+0.13440	+1.45372
+1.48509	+1.42776	+0.55413	+0.13193	+1.43302
+1.53630	+1.41514	+0.55828	+0.12980	+1.41598

AT FINISHED BUBBLE PROFLE POINT: F X, Z
+1.53630 +1.41514 +0.55828

SIDE SURFACE
+15.87667

CONTACT SQUARE
+6.29142

GAS BUBBLE VOLUME
+2.48326

CALCULATED GAS BUBBLE VOLUME
+2.48326

ARHIMED FORCE
+2433.591

SURFACE TENSION FORCE
+622.041

LAPLASS FORCE
+3442.120

RESULTED FORCE
-386.487

Fig. 3: Printout of the results of the work of the program on the computer screen for the case of bubble with β > 0, by the volume 2.48326 cm³, g = 980 cm/sec², contact angle θ = 1.6053 radian and σ_{12} = 70 Dyne/cm.

10.77750587463379	2.483256340026855
10.76670074462891	2.483256340026855
10.75590419769287	2.483256340026855
10.7451114654541	2.483256340026855
10.73432540893555	2.483256340026855
10.72354316711426	2.483256340026855
10.7127685546875	2.483256340026855
10.70200157165527	2.483256340026855
10.69123554229736	2.483256340026855
10.68048000335693	2.483256340026855
10.66972732543945	2.483256340026855
10.6589822769165	2.483256340026855
10.64824104309082	2.483256340026855
10.63750648498535	2.483256340026855
10.62677478790283	2.483256340026855
10.61605167388916	2.483256340026855
10.6053352355957	2.483256340026855
10.5946216583252	2.483256340026855
10.58391571044922	2.483256340026855
10.57321548461914	2.483256340026855
10.56252098083496	2.483256340026855
10.55183219909668	2.483256340026855
10.54114818572998	2.483256340026855

Fig. 4. Printout of the Results of the Adjustment of Volumes VOL and VOL1 with the accuracy A2 on the Computer Screen.

	GRAVITY	SURFACE TENSION		GAS BUBBLE VOLUME
	196	70		2.4833
F	X	Z	P	X/SIN(F)
+0.05121	-0.69624	+0.02505	+11.02291	-13.60180
+0.10242	-0.21265	+0.06601	+5.51548	-2.07993
+0.15363	+0.06507	+0.10774	+3.62818	+0.42521
+0.20484	+0.29012	+0.15777	+2.56129	+1.42629
+0.25605	+0.45330	+0.20740	+1.97729	+1.78987
+0.30726	+0.61588	+0.27300	+1.51537	+2.03632
+0.35847	+0.73826	+0.33759	+1.22929	+2.10426
+0.40968	+0.83350	+0.40102	+1.03519	+2.09258
+0.46089	+0.90888	+0.46315	+0.89518	+2.04361
+0.51210	+0.96888	+0.52384	+0.78964	+1.97727
+0.56331	+1.01646	+0.58294	+0.70741	+1.90353
+0.61452	+1.05373	+0.64029	+0.64169	+1.82759
+0.66573	+1.08222	+0.69577	+0.58807	+1.75221
+0.71694	+1.10313	+0.74924	+0.54359	+1.67884
+0.76815	+1.11739	+0.80056	+0.50620	+1.60821
+0.81936	+1.12578	+0.84961	+0.47441	+1.54067
+0.87057	+1.12895	+0.89627	+0.44711	+1.47634
+0.92178	+1.12745	+0.94043	+0.42350	+1.41519
+0.97299	+1.12177	+0.98200	+0.40294	+1.35714
+1.02420	+1.11237	+1.02087	+0.38494	+1.30209
+1.07541	+1.09964	+1.05697	+0.36910	+1.24990
+1.12662	+1.08396	+1.09023	+0.35513	+1.20045

+1.17783	+1.06568	+1.12058	+0.34277	+1.15361
+1.22904	+1.04512	+1.14797	+0.33181	+1.10927
+1.28025	+1.02259	+1.17237	+0.32209	+1.06733
+1.33146	+0.99841	+1.19373	+0.31348	+1.02770
+1.38267	+0.97285	+1.21206	+0.30586	+0.99032
+1.43388	+0.94619	+1.22733	+0.29914	+0.95513
+1.48509	+0.91871	+1.23956	+0.29324	+0.92210
+1.53630	+0.89066	+1.24876	+0.28809	+0.89119

AT FINISHED BUBBLE PROFLE POINT: F X, Z
+1.53630 +0.89066 +1.24876

SIDE SURFACE
+12.01613

CONTACT SQUARE
+2.49217

GAS BUBBLE VOLUME
+2.48326

CALCULATED GAS BUBBLE VOLUME
+2.49225

ARHIMED FORCE
+486.718

SURFACE TENSION FORCE
+391.502

LAPLASS FORCE
+609.978

RESULTED FORCE
+268.242

Fig. 5. Printout of the results of the work of the program on the computer screen for the case of the bubble with $\beta > 0$ and by volume 2.48326 cm^3, $g = 196\ cm/sec^2$, contact angle $\theta = 1.6053$ radian and $\sigma_{12} = 70$ Dyne/cm.

The universal program of numerical calculation of model of the behavior of the gas bubble on the solid surface, taking into account the change of the acceleration of gravity at a constant contact angle and surface tension on the border of the phase section of fluid-gas, carried out on computer language Turbo Basic.The time of the count of the program on the personal computer does not exceed 2 minute. Using the developed model it is possible to perform not only the calculations of the coordinates of the profile of form, of the total surface square, of the volume of the gas bubble on solid surface, and of the forces, which act on it, for any value of the acceleration of gravity, but also using the ***SUBROUTINE GRAPHICS*** of the universal program graphically to build these profiles of forms and to simulate them on the screen of computer. In Figure 7, graphically illustrates the profiles of the forms of gas bubble on the solid surface with $\beta > 0$, the coefficient of the surface tension of 70 Dyne/cm, the contact angle $\theta = 1.6053$ radian and by volume 2.48326 cm^3, taken by them under $g = 980\ cm/sec^2$ (1), $g = 196\ cm/sec^2$ (2) and $g = 1764\ cm/sec^2$ (3). The conducted numerical calculations of the computer model showed (figures 5, 6), that for the bubbles with the parameter $\beta > 0$, laws, governing by the behavior of their form with the acceleration of gravity change consist in the following: with the acceleration of gravity decrease, the height of bubble increase and the perimeter of its fastening on the surface of the solid material decrease, the gas bubble “assembling” on the surface of solid material occurs. With the acceleration of gravity increase, the height of bubble decrease and the perimeter of its fastening on the solid surface increase, the gas bubble “flattening” on the surface of solid material occurs. For the purpose of the experimental test of work of the developed computer model, the modeling of the behavior of gas bubble on solid surface with $\beta > 0$, the coefficient of the surface tension of *70 Dyne/cm*, the contact angle $\theta = 1.6053$ *radian* and by volume *2.05* cm^3, under the acceleration of gravity decrease from $g = 980\ cm/sec^2$ to $g = 196\ cm/sec^2$ and the acceleration of gravity increase from $g = 980\ cm/sec^2$ to $g = 1764\ cm/sec^2$ was conducted. Figure 8 graphically illustrates the profiles of the forms of gas bubble on the solid surface with $\boldsymbol{\beta > 0}$, the coefficient of the surface tension on the border of the phase section of fluid - gas of ***70 Dyne/cm***, the contact angle $\boldsymbol{\theta = 1.6053}$ ***radian*** and by volume ***2.05*** $\boldsymbol{cm^3}$, taken by them under $\boldsymbol{g = 980\ cm/sec^2}$ (1), $\boldsymbol{g = 196\ cm/sec^2}$ (2) and $\boldsymbol{g = 1764\ cm/sec^2}$ (3). For this purpose the program of animation of the behavior of gas bubble on solid surface in the fluid under such conditions on computer screen, carried out on computer language Turbo C, was made.

GRAVITY	SURFACE TENSION		GAS BUBBLE VOLUME	
1764		70		2.4833
F	X	Z	P	X/SIN(F)
+0.05121	+1.10527	+0.01088	+3.94960	+21.59256
+0.10242	+1.27151	+0.02481	+1.84604	+12.43646
+0.15363	+1.36386	+0.03863	+1.20012	+8.91259
+0.20484	+1.43815	+0.05509	+0.84386	+7.07019
+0.25605	+1.49188	+0.07141	+0.65068	+5.89070
+0.30726	+1.54538	+0.09296	+0.49852	+5.10959
+0.35847	+1.58565	+0.11419	+0.40448	+4.51958
+0.40968	+1.61701	+0.13504	+0.34074	+4.05962
+0.46089	+1.64183	+0.15549	+0.29479	+3.69163
+0.51210	+1.66160	+0.17546	+0.26016	+3.39097
+0.56331	+1.67729	+0.19493	+0.23320	+3.14108
+0.61452	+1.68959	+0.21384	+0.21165	+2.93044
+0.66573	+1.69900	+0.23214	+0.19408	+2.75083
+0.71694	+1.70591	+0.24978	+0.17951	+2.59620
+0.76815	+1.71063	+0.26673	+0.16727	+2.46204
+0.81936	+1.71341	+0.28295	+0.15688	+2.34487
+0.87057	+1.71447	+0.29838	+0.14797	+2.24203
+0.92178	+1.71398	+0.31300	+0.14027	+2.15141
+0.97299	+1.71211	+0.32678	+0.13357	+2.07134
+1.02420	+1.70900	+0.33967	+0.12772	+2.00047
+1.07541	+1.70478	+0.35166	+0.12259	+1.93773
+1.12662	+1.69958	+0.36271	+0.11808	+1.88222
+1.17783	+1.69350	+0.37281	+0.11410	+1.83323
+1.22904	+1.68665	+0.38194	+0.11060	+1.79019
+1.28025	+1.67915	+0.39008	+0.10750	+1.75261
+1.33146	+1.67107	+0.39722	+0.10478	+1.72011
+1.38267	+1.66253	+0.40336	+0.10239	+1.69239
+1.43388	+1.65360	+0.40848	+0.10031	+1.66922
+1.48509	+1.64438	+0.41259	+0.09850	+1.65044
+1.53630	+1.63495	+0.41569	+0.09696	+1.63593

AT FINISHED BUBBLE PROFLE POINT: F X, Z
+1.53630 +1.63495 +0.41569

SIDE SURFACE		CONTACT SQUARE
+16.94165		+8.39772
GAS BUBBLE VOLUME		CALCULATED GAS BUBBLE VOLUME
+2.48326		+2.47549
ARHIMED FORCE	SURFACE TENSION FORCE	LAPLASS FORCE
+4380.464	+718.663	+6157.810
RESULTED FORCE		
-1058.682		

Fig. 6. Printout of the results of the work of the program on the computer screen for the case of bubble with $\beta > 0$, by the volume of 2.48326 cm^3, g = 1764 cm/sec^2, contact angle θ = 1.6053 radian and σ_{12}= 70 Dyne/cm.

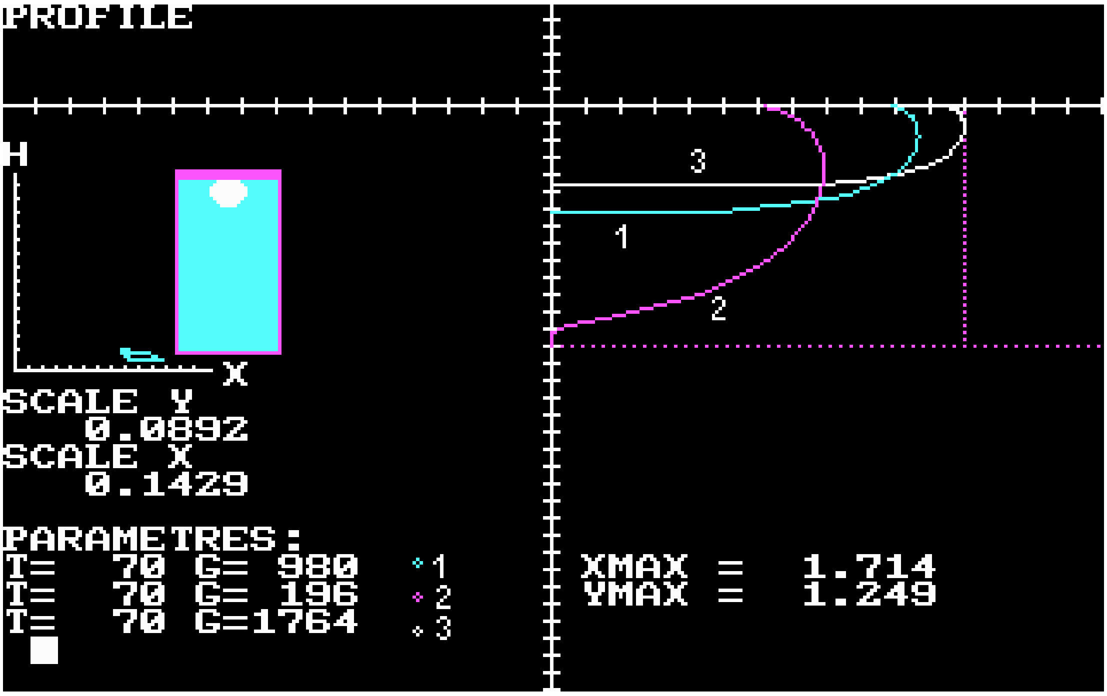

Fig. 7. Graphic illustration of the profiles of the forms of gas bubble on the solid surface with $\beta > 0$, the coefficient of the surface tension 70 Dyne/cm, by the volume 2.48326 cm^3, contact angle θ = 1.6053 radian, taken by them under: 1) - g =980 cm/sec^2; 2) - g =196 cm/sec^2; 3) - g = 1764 cm/sec^2.

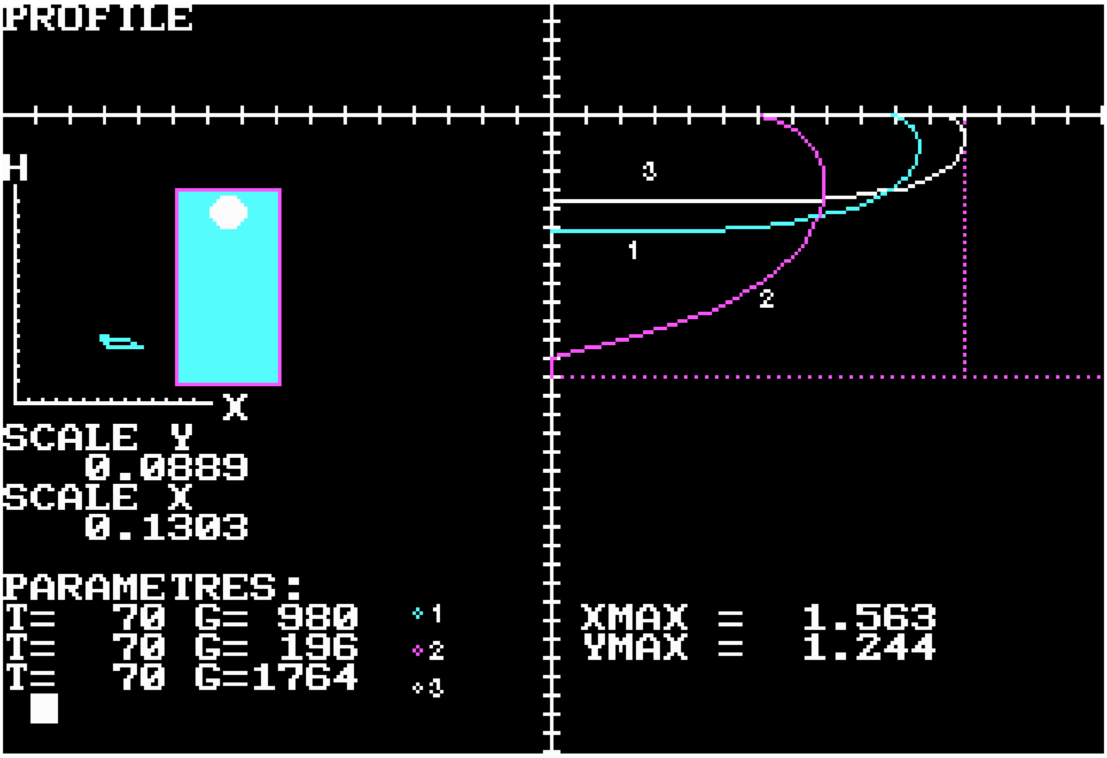

Fig. 8:The computer program graphically illustrates the profiles of the forms of gas bubble on the solid surface, constructed after the conducted computer modeling, with $\beta > 0$, the coefficient of the surface tension on the border of the phase section fluid - gas70 Dyne/cm, the contact angle θ = 1.6053 radian and by volume 2.05 cm^3, taken by them under: 1) - g =980 cm/sec^2; 2) - g =196 cm/sec^2; 3) - g = 1764 cm/sec^2.

To enter data into the animation program, the following block was added to the universal program for recording the total number of points and pairs of all points X and Z of each bubble profile for a fixed surface tension, contact angle, and gas bubble volume at the points of the acceleration of gravity decrease g = 980 cm/sec2,784cm/sec2, 196cm/sec2, 1764cm/sec2 into five separate files ("G1", "G2", "G3", "G5", "G6") into the same folder containing the animation program:

1480 IF IG=2 THEN OPEN "G1" FOR OUTPUT AS #1:PRINT #1,USING "####.##";MI;:PRINT #1,USING "#####.##";G;:PRINT #1,USING "####.##";T;:FOR I=1 TO MI:PRINT #1,USING "####.##";X1(I);:PRINT #1,USING "####.##";Y3(I);:NEXT I:CLOSE #1

1481 IF IG=3 THEN OPEN "G2" FOR OUTPUT AS #1:PRINT #1,USING "####.##";MI;:PRINT #1,USING "#####.##";G;:PRINT #1,USING "####.##";T;:FOR I=1 TO MI:PRINT #1,USING "####.##";X1(I);:PRINT #1,USING "####.##";Y3(I);:NEXT I:CLOSE #1 and so on.

The sequence of starting of universal program, of writing five files into a folder containing an animation program, reading data from five files with this program, and the synchronous animation of the behavior of the under-fluid air region in a vessel with a fluid and of the trajectory of a flying laboratory IL-76K under decreasing and then increasing of the acceleration of gravity on the computer screen on a scale 1: 0.33 was carried out by launching a bubble.bat file with the following contents:

@echo off

wlbubble - universal program

cbubble - animation program

The animation program, written in computer language Turbo C, reading data from five files and the synchronous animating of the behavior of the above-fluid air region in a vessel with a fluid and of the trajectory of a flying laboratory IL-76K under the decrease of acceleration of gravity and then increase of acceleration of gravity on the personal computer screen. On the figure 9 the frames of the work of the developed animating program, which simulates the theoretically calculated profiles of the form of gas bubble with volume 2.05 cm3 and its behavior under the acceleration of gravity decrease from g = 980 cm/sec2 to g = 0 (or with a change of the aircraft overload from n = 1units to n = 0) are demonstrated. On the figure 10 the frames of behavior of drop of water with volume 2.05 cm3, under the acceleration of gravity decrease from g = 980 cm/sec2 to g = 196 cm/sec2 (or with the aircraft overload change from n = 1 units to n = 0) are demonstrated. Represented profiles of the form of gas bubble and its behavior on figure 9, experimentally proved during the tests on the board of the aircraft's flying laboratory IL 76- K, are illustrated by the frames of filming (figure 11), obtained in the process of the conducted flight tests. On figure 12 the theoretically calculated profiles of the forms of gas bubble, of the drops of water, acquired by them with the acceleration of gravity increase fromg = 980 cm/sec2 to g = I784 cm/sec2 (or with a change of the aircraft overload fromn = 1 unit to n = 2 units), are presented. The numerical analysis of the obtained profiles of the forms of gas bubbles showed that with the acceleration of gravity decrease, the square change of the fastening of gas bubble on the surface of solid material decreases, and the side surface square change increases. It is necessary to note, that the square of the fastening of gas bubble change increase, in this case, is considerably more than the square of its side change increase. The produced calculations of the side surface square of gas bubble, of the square of its fastening on the surface of solid material changes, subsequently, were used for calculation of the common surface energy of the bubble change, which appears with the acceleration of gravity decrease. The calculation of the common surface energy change of the gas bubble on the solid surface, which appears under the acceleration of gravity decrease, was produced in accordance with the conclusions, obtained in the work [15] by the formula:

$$\Delta E = \sigma 12\ [\Delta Ss.s. + (\text{Cos}\theta) \cdot \Delta S'] \qquad (3)$$

where ΔSs.s- side surface square change, ΔS' -square of the fastening of gas bubble change; θ - contact wettability angle. The calculated value of the freed common surface energy change of gas bubble was 276.4283Ergs under acceleration of gravity change from 980cm/sec2 to 196 cm/sec2at constant surface tension of 70 Dyne/cm.

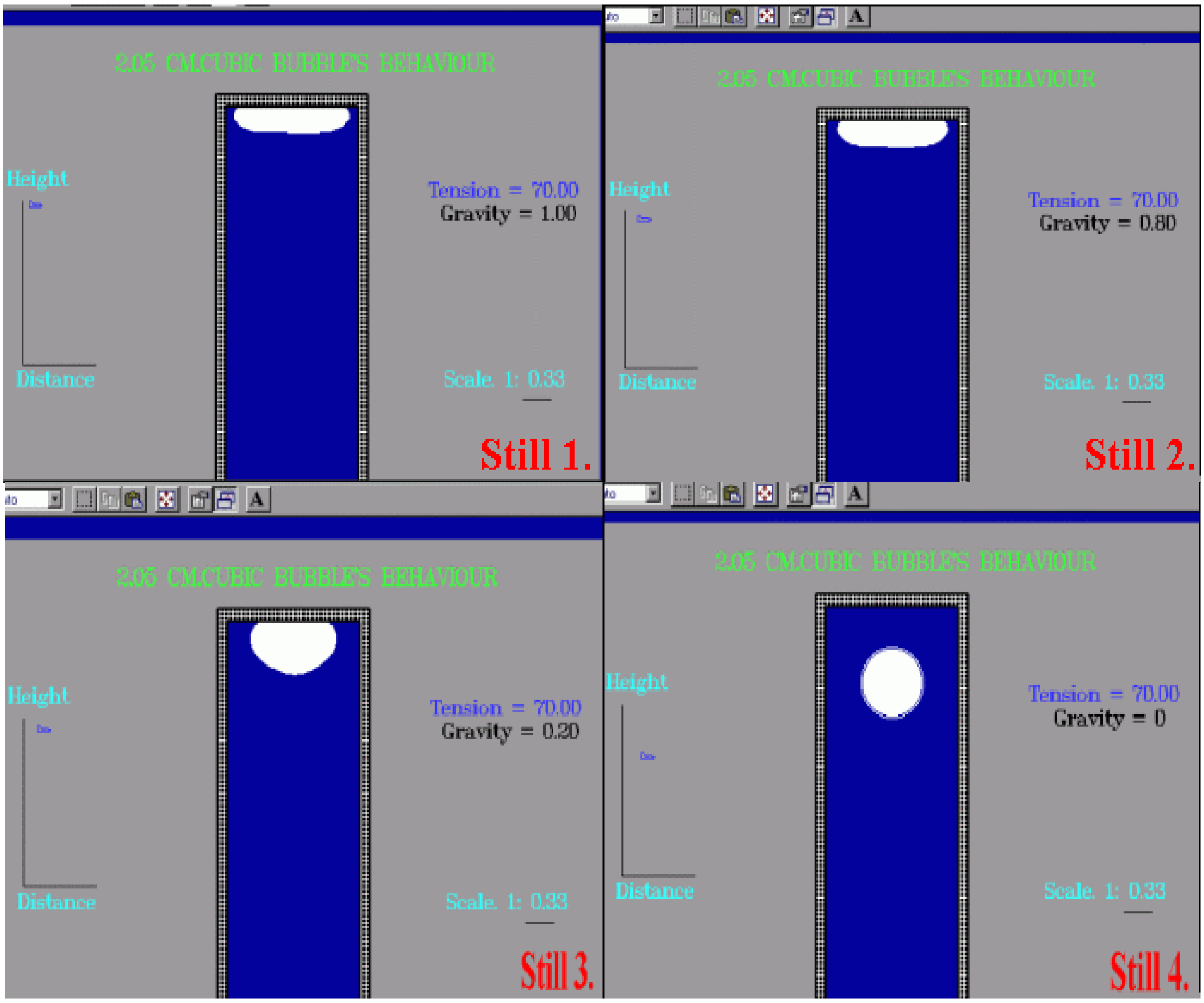

Fig. 9: The frames (stills) of the demonstration of the work of the developed animating program, that simulates the profiles of the form of the gas bubble with the volume 2.05 cm ³ and its behaviour with the acceleration of gravity decrease from g = 980 cm/sec² (or n = 1 unit) to g = 0.

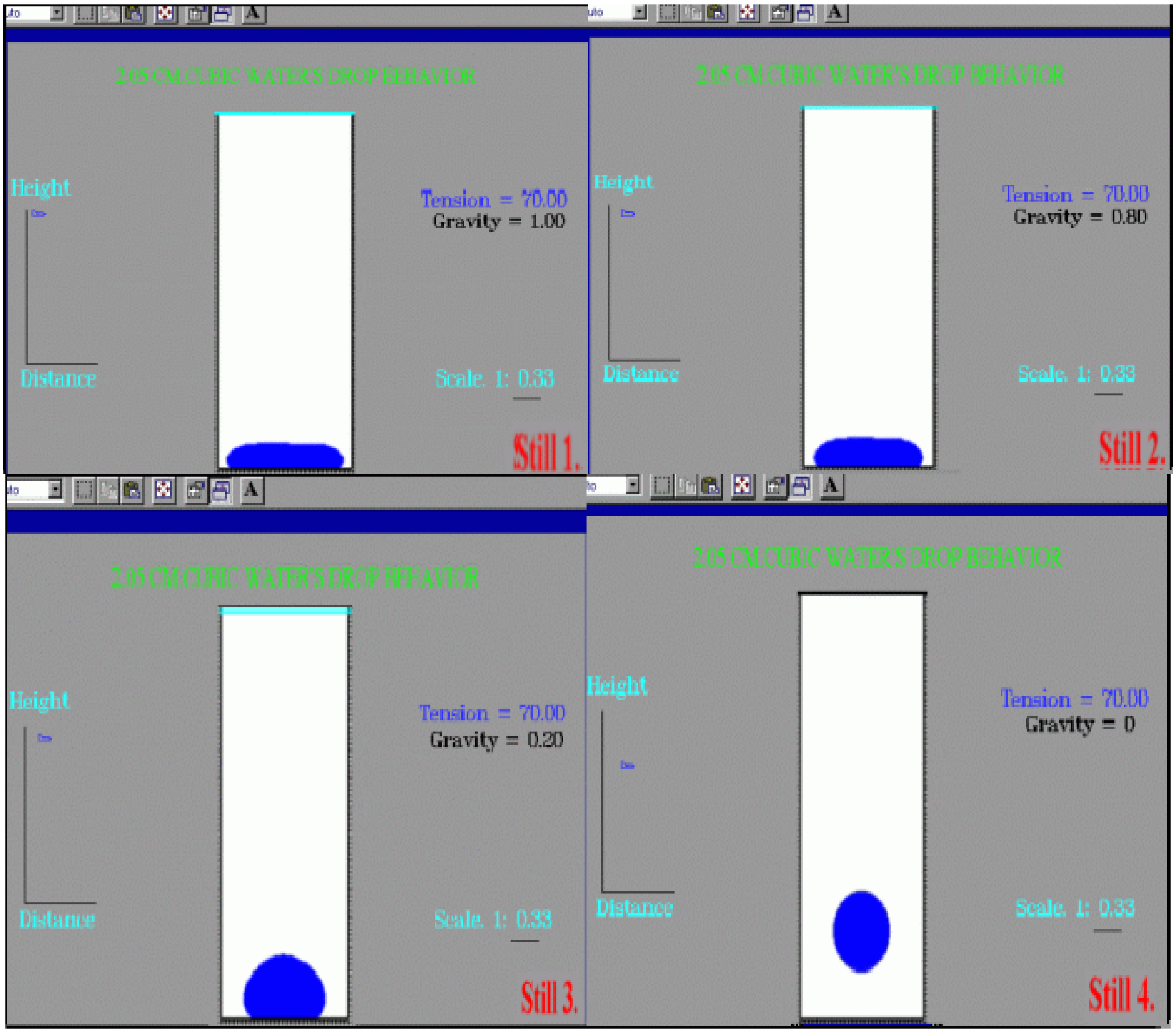

Fig. 10: The frames (stills) of the demonstration of the work of the developed animating program that simulates the profiles of the form of the drop of water with the volume 2.05 cm ³ and its behavior with the acceleration of gravity decrease fromg = 980 cm/sec^2 (or n = 1 unit) to g = 0.

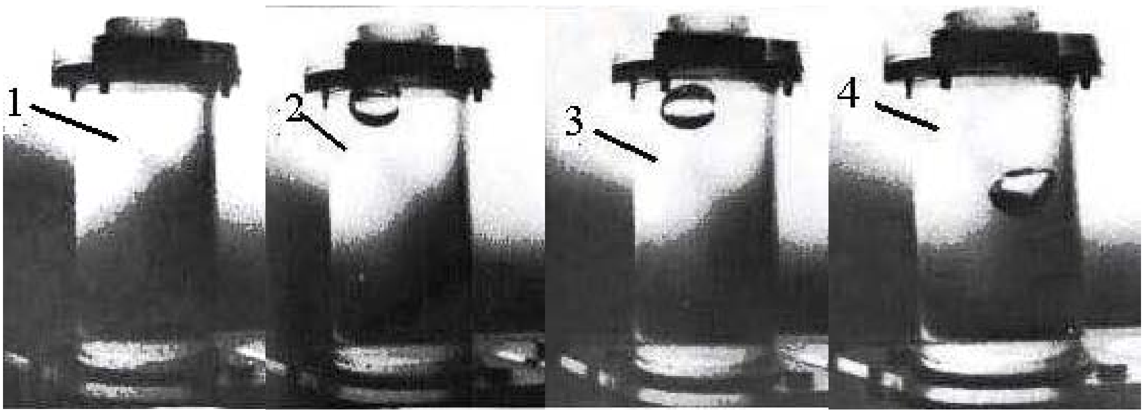

Fig. 11:The frames of filming of the profiles of the form of gas bubble with volume2.05 cm/sec^3 and its behavior with the acceleration of gravity decrease fromg = 980 cm/sec^2 (or 1unit) to g = 0, during of aircraft's flight tests onboard the flying laboratory IL 76 - K. 1. - g = 980 cm/sec^2 (1unit); 2. – g = 196 cm/sec^2 (0.2units); 3 and4 - g = 0.

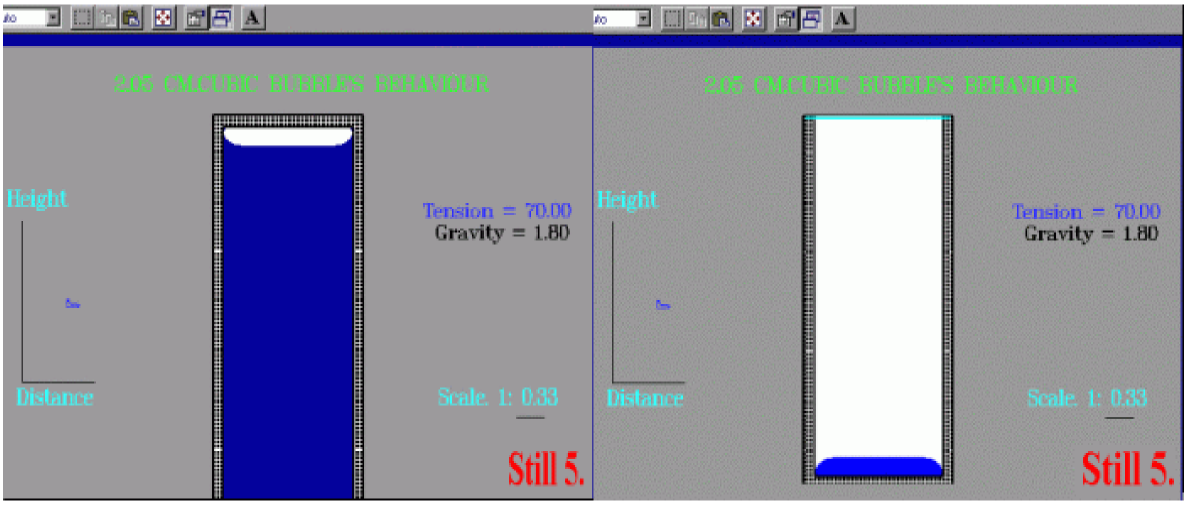

Fig. 12: Profiles of the forms of gas bubble, of the drops of water, acquired by themwith the acceleration of gravity increase from g = 980 cm/sec ² tog = 1764 cm/sec ²(or with a change of the aircraft's overload from n = 1unitton = 1.8 units)

As a result, it was established, that with the acceleration of gravity decrease, the release of the surface energy of gas bubble occurs and its value is the greater, the less the smaller value it reaches ***g***.

The results of the numerical calculation of the common surface energy change increase of the gas bubble on the solid surface with the volume of ***2.05 cm***^{3}, by the contact angle ***θ = 1.6053 radian*** and by the coefficient of the surface tension on the border of the phase section of fluid - gas ***σ_{12}= 70 Dyne/cm*** under the acceleration of gravity change from ***g =980 cm/sec²*** to ***g = 196 cm/sec²*** show that the release of the general surface energy of gas bubble occurs and its value composes***ΔE =276.4283 Ergs***.

Under the acceleration of gravity decrease from ***g=980 cm/sec²***tog = ***196 cm/sec²***, the freed common surface energy change of gas bubble or drop of fluid passes into the kinetic energy of motion of gas bubble or drop of the fluid, when its value exceeds the value of the resultant force, which retains gas bubble on the solid surface or drop of fluid on the solid base layer.

If the value of the freed common surface energy change of gas bubble or drop of fluid less or is equal to the value of the resultant force, which retains gas bubble on the solid surface or drop of fluid on the solid base layer, then in this case, the freed common surface energy change of gas bubble or drop of fluid passes into the vibrational energy of gas bubble or drop of fluid near the equilibrium level, which slowly reduces because of the friction of the fluid or the gas.

The calculation of the resultant force, which retains of the gas bubble on the solid surface, in the computer program was produced in accordance with the equation (9) by formula:

$$\Delta F = F1+F2+F3 = 2\pi a\sigma 12\ Sin\theta + \rho_{fl}\, gV - \pi\sigma 12 a^2 \left(\frac{1}{R_1} + \frac{1}{R_2}\right) \quad (4)$$

For the case of bubbles with Bond number ***β>0***,the calculations of the resultant force are of interest only at extreme points, i.e., with the values of the acceleration of gravity from ***g = 196 cm/sec²*** to ***g = 0***, since in all remaining cases, such above fluid's air bubbles or drops of water recumbent on the base layer are in stable state.

This fact explains by the fact that in this case when the floating force (the force of Archimedes) is directed against the detachment of gas bubble from the upper solid surface or the drop of fluid from the base layer, on which it lies, and this force has a sufficient value.

The calculation of the resultant force at the points of the acceleration of gravity decrease from $g = 196\ cm/sec^2$ to $g = 0$ is of interest, since this calculation gives answer on a question is it sufficient this force for the detachment of above fluid's air bubble from the solid surface or drop of water from the base layer under the acceleration of gravity decrease from $g = 980\ cm/sec^2$ to $g = 196\ cm/sec^2$.

The results of the numerical calculation of the resultant force, which retains the above fluid's gas bubble on the solid surface, with the volume of $2.05\ cm^3$, by the contact angle $\theta = 1.6053$ ***radian*** and by the coefficient of the surface tension on the border of the phase section of fluid - gas $\sigma_{12} = 70$ ***Dyne/cm*** at the acceleration of gravity $g = 196\ cm/sec^2$, show that its value composes $\Delta F = 267.6038$ ***Dynes***.

In the developed universal computer program was introduced estimation of the retention of the gas bubble on the solid surface or drop of fluid on the solid base layer or forward movement of the gas bubble or drop of fluid on the basis, what has been said previously, i.e., on the ratio of the freed common surface energy change and the resultant force, which retains gas bubble on the surface of solid material or drop of fluid on the solid base layer.

In the case of the forward movement of gas bubble or drop of fluid, in the computer program, the distance, on which will move gas bubble or the drop of fluid, was calculated as follows.

The kinetic energy of motion of gas bubble or drop of fluid can be presented in the following form:

$$\frac{mv^2}{2} = \Delta E - (\Delta F \cdot \Delta X_1) \quad (5)$$

Here, v - the speed of the motion of gas bubble or drop of the fluid; m - the mass of gas bubble or drop of the fluid; ΔE - the freed common surface energy; ΔF- the resultant force, which retains gas bubble on the surface of solid material or drop of fluid on the solid base layer; $\Delta X_1 = 1cm$.

If v to represent as $(\frac{\Delta X}{\Delta t})$ and to count $\Delta t = 1\ sec$, then v in (5) can be represented as ΔX - the distance on which will move gas bubble or the drop of fluid for ***1 second***.
The mass of gas bubble can be recorded as $m = \rho_{fl}\, gVol$, where ρ_{fl} - the density of fluid; $g = 980 cm/sec^2$ - the acceleration of gravity and Vol - the volume of gas bubble or drop of fluid.

Substituting the expressed values in (5) and taking into account that$\Delta X_1 = 1cm$, we will obtain the following equation:

$$\frac{\rho g Vol}{2} \cdot (\Delta X)^2 = \Delta E - \Delta F \quad (6)$$

Solving equation (6) relative to ΔX, we will obtain the formula for the determination of distance, on which will move the gas bubble:

$$\Delta X = \frac{\sqrt{2(\Delta E - \Delta F)}}{\rho g Vol} \quad (7)$$

The conducted by the computer program calculations showed that for the gas bubble on the solid surface with the volume of ***2.05 cm³***, by the contact angle ***θ = 1.6053 radian*** and by the coefficient of the surface tension on the border of the phase section of fluid - gas ***σ_{12}= 70 Dyne/cm***,under the acceleration of gravity change from ***g = 980 cm/sec²*** to ***g = 196 cm/sec²*** is freed ***ΔE = 276.4283 Erg***, and the resultant force, which retains above fluid's gas bubble on the surface of solid material at ***g = 196 cm/sec²***, composes ***ΔF = 267.6038 Dyne***. Consequently, we have a condition, when ***ΔE> ΔF***,and, therefore, above fluid's gas bubble with the volume of ***2.05 cm³***, with the contact angle ***θ = 1.6053 radian*** and by the coefficient of the surface tension on the border of the phase section of fluid - gas ***σ_{12}= 70 Dyne/cm*** under the acceleration of gravity change from ***g =980 cm/sec²*** to ***g = 196 cm/sec²*** will be detach from the solid surface and move down in the fluid in the direction to the bottom. The numerical calculations of the computer program, conducted based on formula (7) permitted to calculate the distance, on which gas bubble will move and this distance is equal ***ΔX = 2.933 cm***. Thus, the state of system gas - fluid -solid material in the conditions of small gravity (or weightlessness) is energetically advantageous, since this state is characterized by the release of the surface energy of gas bubble or fluid drop and reaching by them of the minimum of potential energy. Consider the gas bubble with the volume bigger than ***2.05 cm³***. By computer program the profiles of the forms of gas bubble with ***β > 0***, with the coefficient of the surface tension ***70 Dyne/cm***, the volume ***2.48326 cm³*** and the contact angle ***θ = 1.6053 radian***, fixed on the surface of solid material, taken by them, under the accelerations of gravity changefrom ***g =980 cm/sec²*** to ***g =196 cm/sec²***and from ***g =980 cm/sec²*** to***g = 1764 cm/sec²*** were graphically illustrated (figure 7). Using the universal computer program calculate the common surface energy change of gas bubble increase, the resultant force, which retains gas bubble on the surface of solid material, make the estimation of retention of the gas bubble on the surface of solid material or forward motion of gas bubble. Results of the numerical calculation of the common surface energy change of the gas bubble on the solid surface, with the volume of ***2.48326 cm³***, the contact angle ***θ = 1.6053 radian*** and coefficient of the surface tension on the border of the phase section of fluid - gas ***σ_{12}= 70 Dyne/cm*** under the acceleration of gravity change increase from ***g =980 cm/sec²*** to ***g = 196 cm/sec,²*** show that the release of the common surface energy of gas bubble occurs and its value comprises ***ΔE = 247.4691 Ergs***. The results of the numerical calculation of the resultant force, which retains above fluid's gas bubble on the surface of solid material, with the volume ***2.48326 cm³***, the contact angle ***θ = 1.6053 radian*** and the coefficient of the surface tension on the border of the phase section of fluid - gas ***σ_{12}= 70 Dyne/cm*** under the acceleration of gravity ***g = 196 cm/sec²,*** show that its value composes ***ΔF = 268.2419 Dynes***. Thus, the conducted by the universal computer program calculations showed that for the gas bubble on the solid surface, with the volume ***2.48326 cm³***, with the contact angle ***θ = 1.6053 radian*** and the coefficient of the surface tension on the border of the phase section of fluid - gas ***σ_{12}= 70 Dyne/cm*** under the acceleration of gravity decrease from ***g =980 cm/sec²*** to ***g = 196 cm/sec²***,is freed ***ΔE = 247.4691 Erg***, and the resultant force, which retains above fluid's gas bubble on the surface of the solid material, at ***g = 196 cm/sec²***, composes ***ΔF = 268.2419 Dynes***. Consequently, we have a condition, when ***ΔE< ΔF***, and, therefore, the confinement of gas bubble on the solid surface occurs and the freed common surface energy of gas bubble passes into the oscillation energy of gas bubble near the equilibrium level, which gradually reduces because of the friction with the fluid.

RESULTS

The obtained results for two gas bubbles with the volumes, correspondingly, of 2.05 cm³and 2.48326 cm³ were completely experimentally proved in the course of the conducted flight tests on the board of the flying laboratory IL-76K [16]. On the frames of filming (figure 13 (a, b, c, d)), obtained during of aircraft's tests, are fixed the detachment and forward motion of gas bubble by the volume V≈ 2.05 cm^3 along the whole length of the column of fluid and confinement on the surface of the solid material of bubble with the volume of V≈ 2.5 cm^3 under the acceleration of gravity decrease from g = 980 cm/sec² to g = 0 (or under the change of the aircraft's overload from n = 1un. to n = 0).

Thus, the analysis of results of numerical calculation of the developed model of gas bubble behavior on the solid surface under the acceleration of gravity change, using the modeling, algorithmization, programming and animation, which were experimentally proved during the process of the carried out aircraft's tests on the board of the flying laboratory IL-76K, that permitted to make a conclusion about the energy advantage of microgravity state for the system fluid-gas-solid body and can be used for the simulation of the behaviour of real bubbles or drops of fluid with the wide range of values Bond Number β(both signs) in real state of microgravity, which plays important role in the aerospace chemical-engineering.

CONCLUSION

The analysis of results of numerical calculation of the developed model of gas bubble behavior on the solid surface under the acceleration of gravity change, using the modeling, algorithmization, programming and animation, which were experimentally proved during the process of the carried out aircraft's tests on the board of the flying laboratory IL-76K, that permitted to make a conclusion about the energy advantage of microgravity state for the system fluid-gas-solid body and can be used for the simulation of the behavior of real bubbles or drops of fluid with the wide range of values Bond Number β(both signs) in real state of microgravity, which plays important role in the aerospace chemical-engineering.

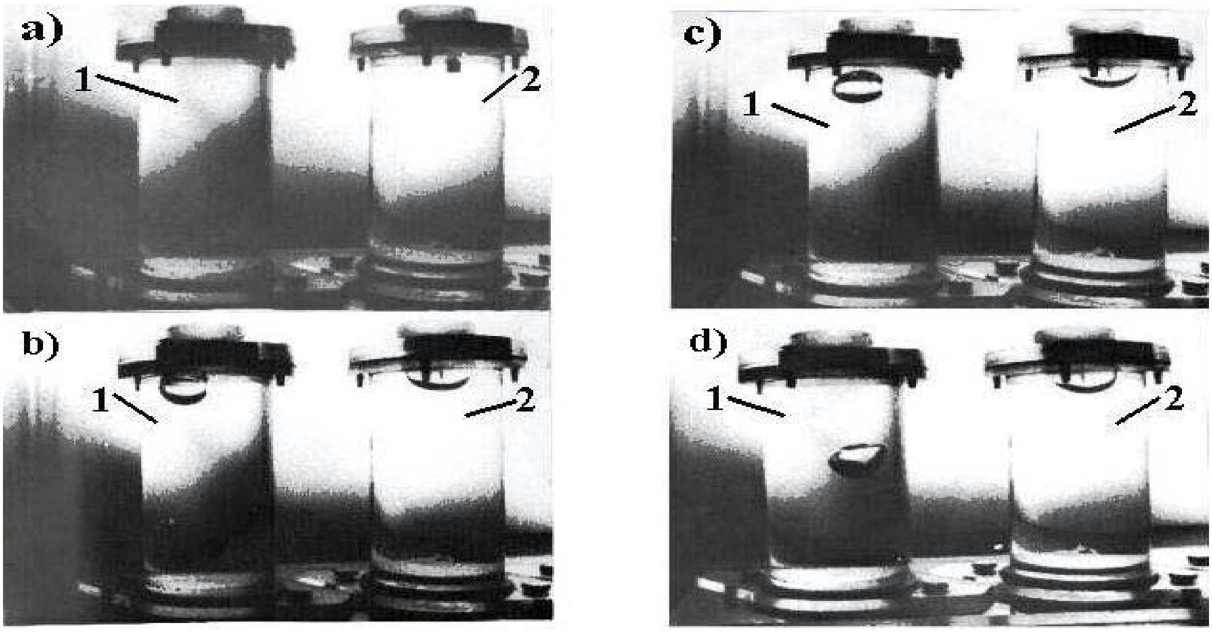

Fig. 13: The frames of the filming of detachment and forward motion of gas bubble by thevolume V ≈ 2 cm³ (1) along the whole length of the column of fluid andconfinement on the surface of the solid material of bubble with the volume ofV ≈ 2.5 cm³ (2) under the acceleration of gravity decrease from g = 980 cm/sec² tog = 0 (or with the overload change from n = 1unit. to n = 0). a)g = 980 cm/sec²; b)g = 196 cm/sec²; c)g = 40 cm/sec²; d) g = 0.

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