Losses are also conditioned by decrease of burning site size d at reaching the concentration limit, as $1/d \sim S/V$, where S is the site surface; V is its volume. Slight decrease of burning temperature results in drop of heat flow from burning site but it is not capable of compensating completely the increasing losses owing to drop of velocity u_n and size d. This tendency, finally, results in the lowest possible temperature $T_b^*(\sigma_\pm)$ and burning rate $u_n^{\min}(T_b^*)=u_n^{\min}(\sigma_\pm)$.

REFERENCES

1. Marshal V. The main hazards of chemical industries: Translation from English. – Moscow: Mir, 1989. – 672 p.
2. Lewis B., Elbe G. Burning, flame and explosions in gases: Translation from English. – Moscow: Mir, 1968. – 592 p.
3. Williams F.A. Theory of burning: Translation from English. – Moscow: Nauka, 1971. – 615 p.
4. Klimov A.M. Laminar flame in turbulent flow // Zhurnal Prikladnoy Mekhaniki i Tekhnicheskoy Fiziki. – 1963. – № 3. – P. 49–58.
5. Zeldovich Ya.B. Chemical physics and hydrodynamics: Izbrannye Trudy. – Moscow: Nauka, 1984. – 347 p.
6. Landau L.D., Livshits E.M. Theoretical physics. V. VI. Hydrodynamics. – Moscow: Nauka, 1986. – 733 p.
7. Netleton M. Detonation in gases: Translation from English. – Moscow: Mir, 1989. – 280 p.

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NUMERICAL MODELING OF THE EVAPORATION PROCESS OF UNSYMMETRIC DIMETHYLHYDRAZINE DROPS IN THE EARTH'S ATMOSPHERE

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The evaporation process of unsymmetric dimethylhydrazine drops at their movement to the Earth's surface after seal failure of fuel tanks of launch rockets at heights up to 50 km has been simulated.

Introduction

The problem of air pollution with unsymmetric dimethylhydrazine (NDMG) being in tanks of liquid engines of launch rockets [1, 2] after first steps work out, is still urgent. It is conditioned to a large scale, by the fact that a concrete mechanism of appearing this pollutant on the Earth's surface is not determined so far. On the one side there are no direct evidences of appearing this substance in soil or phytocoenosis structure. On the other side, in the regions of separation of launch rockets first stage (for example, Gorny Altai [3]) there are examples of abnormal development of some biological systems while there are no other negative influencing factors on these systems. The known results of modeling the processes of «evolution» of liquid NDMG cloud [4, 5] after seal failure of fuel tanks at heights do not allow forming the definite answer to the question of NDGM phase state in atmosphere.

The aim of this work is the numerical simulation of evaporation process of NDMG drop at its motion to the Earth's surface subject to inhomogeneous temperature field of a drop, the conditions of heat exchange with the environment changing in time and resistance force.

Statement of a problem

At problem set the assumption that NDMG drop is not deformed at its motion and remains of spherical form during the whole flying till the evaporation process stop was accepted. The convective heat exchange of NDMG with the environment the parameters of which (temperature, pressure and density) were considered to be variable in height according to distributions introduced in [6] was taken into account. Radiation heat exchange with the environment was not taken into account. Calculating the drop rate of motion υ it was accepted that gravity and resistance forces of gaseous medium influence it. The convective heat exchange αNDMG with air was computed subject to the dependence α on density ρ and rate of motion of NDMG drop υ.

The special feature of the problem is a shift of the drop external boundary because of NDMG evaporation with time variable velocity w. Magnitude w depends on drop surface temperature which changes nonlinearly by its motion to the Earth's surface. The problem in such statement is reduced to solution of the following differential equation system with proper boundary and initial conditions.

Temperature distribution at initial condition $t=0$, $T=T_0$ is described by the equation of heat conductivity for a drop in spherical form:

$$C(T)\cdot\rho(T)\cdot\frac{\partial T}{\partial t}=\lambda(T)\cdot\left(\frac{\partial^2 T}{\partial r^2}+\frac{2}{r}\cdot\frac{\partial T}{\partial r}\right),$$

where $C(T)$, $\rho(T)$, $\lambda(T)$ are the temperature dependences of NDMG for heat capacity, density, heat conductivity; r is the reference radius; T is the temperature of NDMG on radius r; t is the time.

Boundary conditions:

$$r=0,\quad \frac{\partial T}{\partial r}=0;$$

$$r=R,\quad \alpha\cdot(T_B-T)-w_{\text{исп}}\cdot\theta_{\text{исп}}=\lambda(T)\cdot\frac{\partial T}{\partial r},$$

where R is the drop outer radius; α is the heat transfer coefficient; T_B is the air temperature; $w_{\text{исп}}$, $\theta_{\text{исп}}$ are the rate and heat of NDMG evaporation.

The evaporation rate is calculated for current time value by the following formula:

$$w_{\text{исп}}=\frac{\alpha\cdot(T_B-T_S)}{\theta_{\text{исп}}},$$

where T_S is the temperature of NDMG saturation.

For calculation the heat transfer coefficient with the initial conditions $\upsilon=0$, $t=0$ the equation of spherical drop motion:

$$\frac{d\upsilon}{dt}=g-\frac{3\cdot C_D\cdot\rho_B}{8\cdot R\cdot\rho}\cdot(\upsilon-\upsilon_B)^2,$$

where g is the gravity acceleration; C_D is the resistance coefficient; ρ_B, υ_B are the air density and rate, was solved.

The following assumptions were accepted at problem statement. The drop has spherical form and is not deformed when flying. At fixed radius all drop points have one and the same temperature. The heat of NDMG evaporation $\theta_{\text{исп}}$ is taken constant and equal the evaporation heat at initial conditions. Air rate υ_B equals zero. Functions $C(T)$, $\rho(T)$, $\lambda(T)$ are obtained by extrapolation of tabulated values [7]. Air pressure and temperature at a certain height are determined as functions of height obtained by interpolation of standard table data in the latitude of 45° [6]. Possible chemical interactions of NDMG with air and water vapors were not examined.

Results and discussion

The problem is solved for drops of 5 and 1 mm in diameter at their initial temperature 290 K. The change of drop characteristic dimensions, as it follows from the carried analysis, should not influence significantly the NDMG phase state. It is seen how rapidly the drops of 5 mm (Table 1) and 1 mm (Table 2) in diameter evaporate by the obtained dependences of drop evaporation time on initial height.

It was determined that if the seal failure occurs at heights from 50,0 to 40,7 km then NDMG evaporates fully for drops of all sizes. From the height lower than 40,7 km the drops of NDMG move to the Earth's surface without evaporation. The stated regularities are conditioned by thermodynamics of NDMG phase transformations [7] and changes of air temperature and pressure at change of distance to the Earth's surface [6]. The numerical analysis showed that temperature difference between the drop surface and gaseous medium at $d=5$ mm is always higher than the same temperature difference at $d=1$ mm (Table 3), while the motion rate of a drop with a larger diameter exceeds the rate of the drop with smaller diameter (Fig. 3).

Table 1. *Dependence of evaporation time $t_и$ of NDMG on initial height at drop diameter of 5 mm*

Height H, km	Drop evaporation time $t_и$, ms
50,00	10
43,90	20
41,45	29
40,95	40
40,75	50
40,70	70
40,00...0,00	–

Table 2. *Dependence of NDMG evaporation time $t_и$ on the initial height at drop diameter of 1 mm*

Height H, km	Drop evaporation time $t_и$, ms
50,00	0,1
41,60	0,2
40,90	0,3
40,75	0,4
40,70	0,5
40,00... 0,00	–

Table 3. *Dependence of temperature difference between the drop surface and gaseous medium on height, K*

Height H, km	Drop diameter d, mm	
	5	1
39,980	17,9	4,7
39,957	13,9	1,6
39,926	11,1	0,4
39,646	4,7	0,4
30,081...0,106	1,4	0,4

The obtained results may be explained if the dependence of heat exchange coefficient of drops with different diameter on the movement rate is analyzed (Fig. 4). It was established that the heat exchange coefficient for a drop at $d=5$ mm is less than at $d=1$ mm. In the rang of height change $0<H<40$ km subject to the change of rate of drops with different diameter at height (Fig. 3), the dependences of α on movement rate were computed (Fig. 4).

The dependences of temperature difference and movement rate of NDMG drop on height (Table 3 and Fig. 3) confirm the necessity of accounting temperature radius distribution inhomogeneity at the initial movement area. The more the drop the more time is required for its full warming up or cooling down.

It should be noted as well that NDMG drops can not achieve the Earth's surface not only owing to their evaporation but due to air resistance. So, the less the drop diameter, the longer it can move to the Earth's surface (Fig. 5).

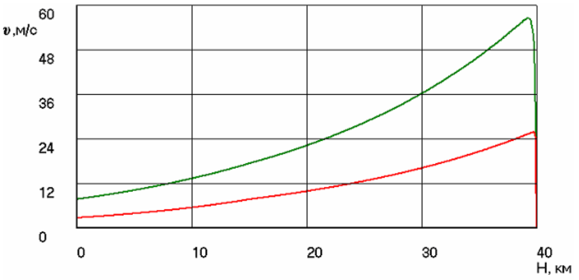

Fig. 3. *Dependence of NDMG drop movement rate on the height at drop diameter, mm: 1) 5; 2) 1*

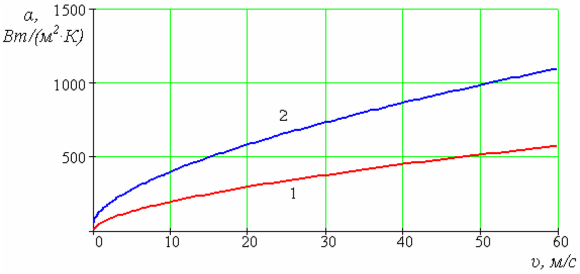

Fig. 4. *Dependences of heat exchange coefficients of drops with different diameter on movement rate at drop diameter, mm: 1) 5; 2) 1*

The stated dependence (Fig. 5) shows that NDMG may be distributed over rather long distances being in liquid state. So, for example, a drop of a starting diameter 1 mm at rather moderate wind velocity at heights 10 m/s may shift to the distance to 50 km from the place of fuel tank seal failure. The drops with smaller diameters stay longer in the air and, therefore, shifted by air mass to the longer distances.

The theoretical results obtained in this work show that the mechanism of NDMG transformations at its motion to the Earth's surface is rather complex. Phase states of this substance depend on many factors and further analysis of the most probabilistic scenarios of physicochemical drop transformation of the liquid NDMG drops at the movement in the air is appropriate. Account of all features of NDMG drop warming up and evaporation may increase considerably the accuracy of prediction of air pollution in the area of separation of the launch rocket first stages.

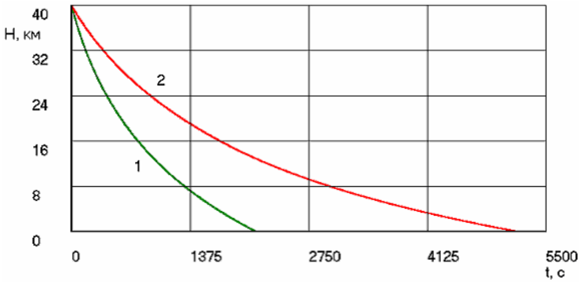

Fig. 5. *Dependence of drop height over the Earth's surface on time at drop diameter, mm: 1) 5; 2) 1*

Conclusion

It was shown that unsymmetric dimethylhydrazine evaporates fully at seal failure of launch rocket fuel tanks at heights from 50,0 to 40,7 km at its initial temperature 290 K. Starting from height about 40 km the NDMG stops evaporating and moves to the Earth's surface in liquid-phase state. NDMG phase state depends to the large extent on seal failure height and initial temperature. Drop evaporation rate depends on its diameter. According to the calculation results the evaporation time for a drop of a diameter 5mm is two orders higher than for a drop of diameter 1mm. The time of achieving the Earth's surface by drops of diameter 1 mm exceeds twice the respective time for drops of diameter 5 mm.

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REFERENCES

1. Ecological problems and risks of the influence of space-rocket equipment on the environment: Reference book / Ed. by V.V. Aldushin, S.I. Kozlov, A.V. Petrov. – Moscow: ANKIL, 2000. – 600 p.
2. Arkhipov V.A., Berezikov A.P., Kozlov E.A. et al. Technogenic pollution modeling at separation of launch rocket stages // Izvestiya Vuzov. Fizika. – 2005. – № 11. – P. 5–9.
3. Streltsova T.A., Ushakova G.V., Cherdantseva O.I. et al. Modeling the NDMG influence on domestic plants // Fundamental problems of environment conservation and ecology of natural territorial complexes in western Siberia: Materials of scientific conference. – Gorno-Altaisk, 2000. – P. 123–125.
4. Arkhipov V.A., Berezikov A.P., Kozlov E.A. et al. Modeling the formation and evolution processes of liquid-drop cloud at seal failure of rocket fuel tanks in atmosphere // Fundamental problems of environment conservation and ecology of natural territorial complexes in western Siberia: Materials of scientific conference. – Gorno-Altaisk. – 2000. – P. 78–79.
5. Nemova T.N., Kuznetsov G.V., Mamontov T.Ya., Bulba E.E. Numerical simulation of dimethylhydrazine drop state at motion from upper air to the Earth's surface // Izvestiya Vuzov. Fizika. – 2006. – № 6. – P. 112–115.
6. GOST 24631-81 State standard of SSR union. Reference atmosphere. Parameters. State standards committee of the USSR. Moscow.
7. Bolshakov G.F. Chemistry and technology of liquid fuel components. – Leningrad: Khimiya, 1983. – 320 p., ill.

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