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EVOLUTION OF 1,1-DMH DROPS IN THE CLOUD THAT AROSE DUE TO EXPLOSION OF CARRIER ROCKET

The model investigation has shown that irrespective of altitude of explosion of a carrier rocket the significant expanding of a cloud and the appropriate dimethyl hydrazine (1,1-DMH) "dilution" up to safe concentration happens in the range 40-55 km, and these phenomena in a small degree depend on the sizes of drops. The main reason of these phenomena is the presence of a maximum of temperature of the atmosphere at the altitude about 50 km. This maximum of temperature is as a "shield" defending low layers of atmosphere and the earth surface against penetration of 1,1-DMH clouds with dangerous concentration.

1. Introduction

The complex of physical phenomena, which accompany explosion of a rocket, initial process of formation and evolution of a toxic cloud, sequentially, is considered [1]. When the cloud goes down to the height of about 50 km, the temperature of the atmosphere increases to 260?K, which is higher than the melting point of 1,1-DMH - 215?K. It means that the crystals should thaw, and further it is necessary to consider the evolution and movement of drops of the liquid. Speed of evaporation of 1,1-DMH drops in the atmosphere is determined by formula [2,3]

$$\frac{dm}{dt} = -4\pi Dr\left(\rho_v - \rho_a\right)F_v F_{kn}, \qquad (1)$$

D is the diffusion factor of 1,1-DMH molecules air.; ρ_v is the density of saturated vapor of 1,1-DMH; ρ_a is the density vapor of 1,1-DMH in air. When Alexandrov [1] considered falling of separate drop, he supposed that there are no vapors of 1,1-DMH in the atmosphere; thus in (1) ρ_a=0. As a result, in conformity with (1) the mode of the fastest evaporation of a drop was provided. At the same time during falling of drops of one size their speeds of falling will be equal. During falling, the drops of the bottom border of a cloud will evaporate, and "generate" vapor, through which will fly the subsequent drops. Thus, it is impossible to assume ρ_a=0 for the subsequent drops. As a result, according to (1), process of evaporation of the drops should be slowed down substantially in the cloud. The purpose of the work is the estimation of pollution of the ambient space as a result of "collective" falling of drops.

1. Process of evaporation of drops

First of all, we shall consider the process of evaporation of 1,1-DMH drops of the greatest size 2-2.4 mm [1,2]. These drops have the greatest weight, and will move to the ground with the greatest speed. Besides they have about a quarter of volume of all liquid of a cloud. We shall assume that the drops, irrespective of their size, are uniformly distributed in the volume of a cloud. During calculations we assumed, that the cloud looks like a sphere. It is obvious, that this assumption will be valid only in cases when the sizes of a cloud are less than height of a homogeneous atmosphere. Otherwise quantitative estimations will be unfair, and qualitative conclusions are possible only. The cloud will "lose" vapor during its movement because the speed of falling drops will be much greater than speed of falling vapor. When falling, a cloud will leave vapor trace in the form of a cylinder. So the vapor loss by the cloud during time dt can be estimated by expression $m_{loss} = \rho_V \pi r^2 Vdt$, where r is radius of a cloud. Then the background density of vapor in a cloud for this situation will be equal to

$$\rho_a = \frac{\rho_V\left(\frac{4}{3}r - Vdt\right)}{\frac{4}{3}r} . \qquad (2)$$

The experimental data on the value of diffusion factor of 1,1-DMH molecules in air are not available in literature. Therefore, we use the expression for diffusion factor, which was derived from the kinetic theory of gases [3]: $D = \frac{1}{3}ul$ where $u = \left(\frac{8RT}{\pi M}\right)^{1/2}$ is average arithmetic speed of thermal movement of molecules, R is the universal gas constant, M=60.24 – molecular weight of 1,1-DMH, $\rho_V = \frac{0.9643}{T}\exp\left(\frac{16.78T - 3445}{T - 52.27}\right)$, kg/m^2 [4].

To describe the temperature dependence on time, we use equation [3]:

$$mc_s\frac{dT}{dt} = -4\pi\left[\lambda(T - T_a) + HD\rho_V\right] F_V F_{kn} , \qquad (3)$$

where H =586 кДж/kg is heat of evaporation of 1,1-DMH.

During transformation of the liquid into vapor, it will create pressure inside a cloud and will lead to its further expansion. We write down the law of preservation of quantity of movement for this case as

$$\frac{d\left[(M_a + M_t)*v\right]}{dt} = s(p_v - P_a) , \qquad (4)$$

where $M_a = \frac{4}{3}\pi\rho\ r^3$ is mass of air entrained in the movement; $M_t = \frac{4}{3}\pi\rho_t\ r_0^3$ is total weight of drops of the considered size, ρ_t – density of propellant; $s = 4\pi r^2$ is area of surface of a cloud ; p_v – pressure in a cloud caused by vapor of evaporating propellant. Let's determine this pressure by formula [4] $p_v = \exp\left(23.663 - \frac{4075.6}{T}\right)$ Pa; p_a is pressure of atmosphere on a given height.

It is possible to assume that the pressure in the cloud was equal to atmospheric from the moment of freezing drops to the moment of the beginning of their evaporation, and cloud sizes did not change. During falling in the atmosphere the crystals will be heating and melting. We shall calculate trajectories of their falling on the basis of formulas

$$\frac{dV_z}{dt} = 0.5\frac{\rho(t)}{m}c_x S(t)V^2(t)\cos\theta_z - g , \qquad (5)$$

$$\frac{dV_x}{dt} = -0.5\frac{\rho(t)}{m}c_x S(t)V^2(t)\cos\theta_x , \qquad (6)$$

$$\frac{dV_y}{dt} = -0.5\frac{\rho(t)}{m}c_x S(t)V^2(t)\cos\theta_y , \qquad (7)$$

where: x-axis is direction to the East, z-axis is direction to the upward, and y- axis is direction to the North; $\cos\theta_z = V_z(t)/V(t)$, $\cos\theta_x = V_x(t)/V(t)$, $\cos\theta_y = V_y(t)/V(t)$. The origin of coordinates is taken to be the point of explosion of the rocket, so that

$$z(t) = \int V_z dt\quad x(t) = \int (V_x + W_x)dt ,\ y(t) = \int (V_y + W_y)dt , \qquad (8)$$

where W_x and W_y – zonal and meridional components of wind, respectively; V is absolute speed of movement of drops relative to the atmosphere; ρ – density of the atmosphere; c_x – dimensionless coefficient depending on a Reynold's number $\mathrm{Re} = \frac{2r\rho V}{\eta}$; S is area of the greatest section of a drop; r is radius of a drop, η is viscosity of the atmosphere; t is time from the moment of explosion. The dependence c_x(Re) is determined experimentally for

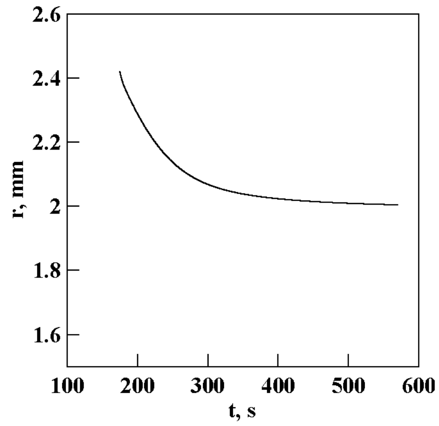


Fig. 1. Change of drop radius with time

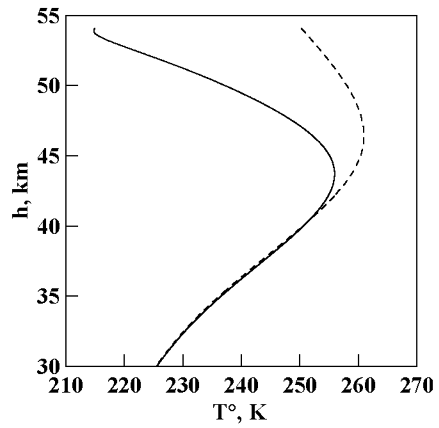


Fig. 2. Change of temperature of a drop during its falling (solid line) and a profile of temperature of the atmosphere (dotted line)

liquid and gaseous mediums. This dependence is well described by a curve irrespective of a medium. Equations (1-8) were solved numerically. Fig. 1 shows the calculation results of drop radius reduction because of evaporation from the moment when the crystal was completely melted (the case of the explosion at the height of 93 km [1]). We can see that in the beginning the drop quickly loses the sizes, and then this process is slowed down. It is related to saturation of a cloud by vapor. As a result the evaporation of a liquid becomes less intensive. The plot of change of temperature of a drop during its falling is given in Fig. 2 for the same conditions. The temperature of the atmosphere profile is also shown in this plot.

The temperature of a drop at the initial stage is essentially lower than that of the atmosphere, and then tends to it and practically repeats its course. The plot of speed of drop movement for a considered part of the trajectory is shown in Fig. 3. Change of vapor pressure in the cloud with height is represented

increasing up to a few tons and more below 100 km. Obviously, realization of such explosions is unreasonable. Then in practice, it may be an explosion of low energy during emergency. It will cause the formation of a cloud with small sizes and increased

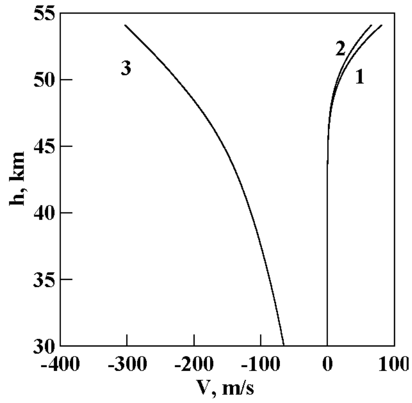


Fig. 3 - Dependence of speed components of drop movement on height: 1 – V_x, 2 – V_y, 3 – V_z

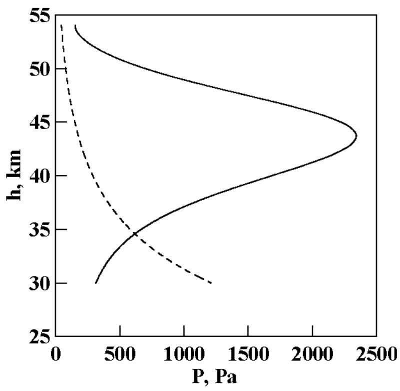


Fig. 4. The change with height: atmospheric pressure - dotted line, vapor pressure - solid line

in Fig. 4. The maximum of pressure in the cloud corresponds to the height of temperature maximum in the cloud. The pressure in the cloud gets balanced by pressure of the atmosphere at the height about 35 km, because of balance the cloud expansion comes to the end.

3. Estimation of pollution of the ambient space

The developed model allows to calculate minimum explosion power, due to which the formed cloud will have concentration of toxic propellant of the below than the maximum allowable norm (MAN) at once after explosion. Let's assume that all remaining propellant of second and third stage of the launcher "«Proton" will simultaneously be ejected into the atmosphere during the explosion; and we will neglect combustion of propellant for calculation of the greatest possible contamination of the atmosphere. The result of this calculation is presented in Fig. 5. We can see that at altitudes higher than 100 km the yield of an explosion practically equals zero.

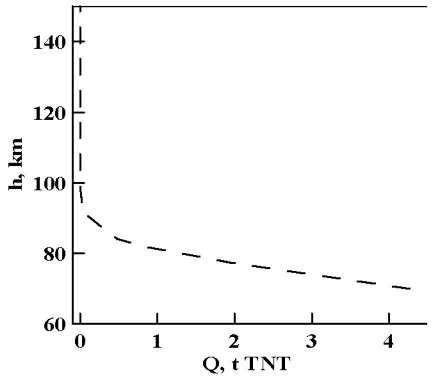
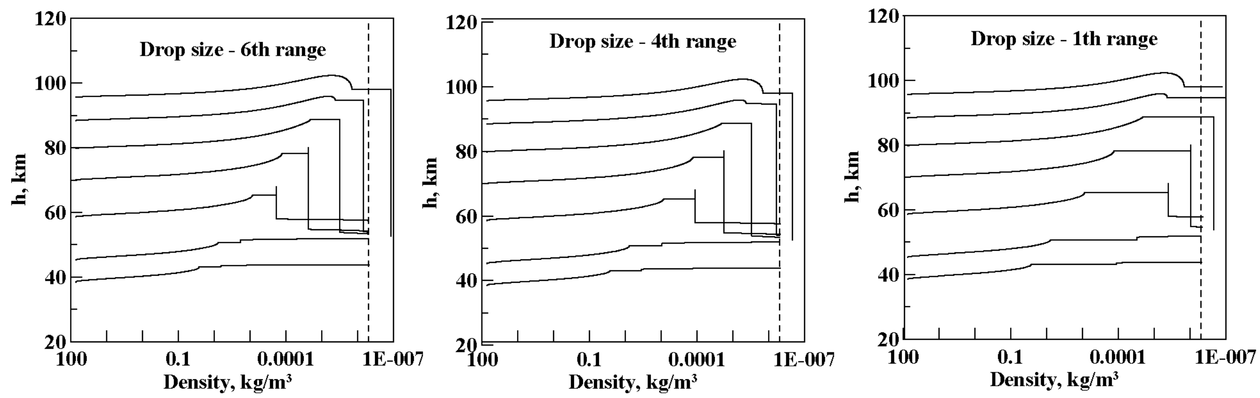


Fig. 5. Dependence on altitude of yield of an explosion necessary for spraying 1,1-DMH in the space with concentration lower than the maximum allowable norm

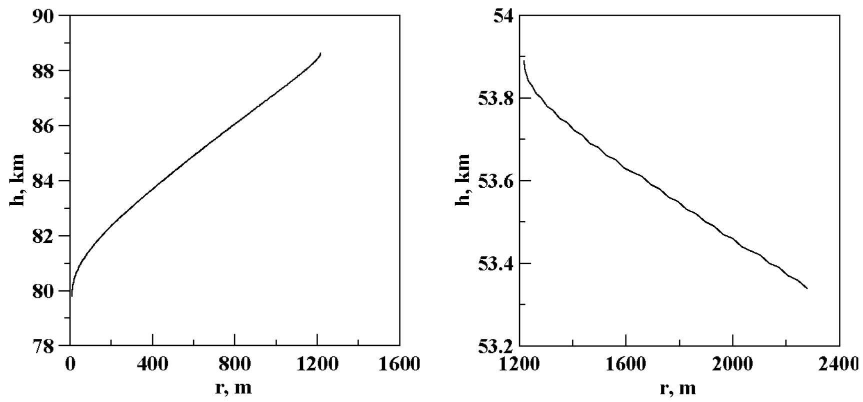
Thus, only pressure of vapor of evaporating fluid is enough to increase the sizes of an extending cloud up to volume, when the concentration of propellant becomes lower than the MAN (it is supposed, that pressure and propellant are uniformly distributed in the cloud). Altitude of undocking of the second stage of the launcher "«Proton" equals 139 km, and altitude of undocking of the third stage is 201 km. Thus, to ensure the spraying of propellant in near-earth space of a worked-out second and third stage of the launcher up to safe concentration, it is enough to include in the design of the launcher a small charge ensuring destruction of propellant tanks. We can also see in Fig.5, that the power of the charge is sharply concentration of 1,1-DMH. Further we shall consider this unfavorable situation, and for calculations we shall take the explosion power to be equal to 1kg TNT. Such energy, apparently, will be enough for destruction of tanks of a rocket and ejection of propellant into the atmosphere. Calculations of change of the propellant concentration in the cloud depending on height for explosions at various heights and for the different initial sizes of drops for three ranges: 0–0.4 mm (first range), 1.2-1.6 mm (4[th] range) and 2-2.4 (6[th] range) - are given on Fig. 6. First of all, we consider qualitatively the course of processes. For an example we choose an explosion of CR at a height of 80 km (Fig. 6a). The cloud of 1,1-DMH originally also arises at the height of 80 km, and calculation of concentration of 1,1-DMH is started with 80 km. After explosion the cloud starts to move due to inertia upwards (due to an impulse transferred by movement of a rocket) and simultaneously the vapor expands under action of explosion and pressure. The dependence of radius of the cloud on height for this part of the trajectory is plotted in Fig. 7a. The radius of the cloud has increased hundreds times.

Simultaneously with expansion of the cloud and splitting of the liquid into drops the decrease of cloud temperature up to the temperature of freezing of drops take place[1]. By the end of action of explosion the cloud will consist of vapor and crystals of various sizes. The process of evaporation terminates, and pressure in a cloud is leveling up to atmospheric. Because the speed of falling of crystals depends on their size, there is a stratification of a cloud: crystals of the greater size with the big speed fall down.



a b c

Fig. 6. Concentration of 1,1-DMH in a cloud depending on height for explosions at different heights and for the different initial sizes of drops (dotted line is the level of 1,1-DMH concentration of maximum allowable norm)



a b

Fig. 7. Expansion of the cloud at the stage of explosion (a) and at the stage of drop evaporation after melting of crystals (b).

Accordingly, the weight of the sprayed propellant may be distributed between the clouds, each of which contains crystals of identical sizes. Since this moment it is necessary to consider processes in a cloud depending on the size of crystals in it. Figure 6a describes behaviors of processes for crystals of the maximal size. Jump of density from 2.07 10^{-5} up to 3.2 10^{-6} kg / m^3 at height of 88.6 km indicates the transition from a cloud, containing all propellant, to a cloud containing part of propellant in drops of the maximal size. It is possible to neglect by evaporation of propellant, and accordingly by vapor pressure in the cloud during falling of crystals. As a result the cloud conserves the size and the density of propellant in it till the moment of melting of crystals. This part of the trajectory in Fig. 6 is described by vertical jump of height from 88.6 up to 53.9 km under constant density - 3.2 10^{-6} kg/m^3. At the height of 53.9 km crystals thaw and evaporation of drops begins, resulting in the further expansion of the cloud. The plot of expansion of the cloud at this stage is given in Fig. 7b. Calculations are carried out till the moment when concentration of 1,1-DMH in the cloud became lower than the maximum permissible norm. The sizes of the cloud at this stage have increased approximately twice at the distance of 0.7 km. It characterizes the intensity of evaporation and the efficiency of the given mechanism of the expansion of a cloud. We can see in Fig.6 that irrespective of height of explosion of CR the reduction of concentration of 1,1-DMH up to MAN occurs in the range of heights 40-55 km, and in a small degree depends on the sizes of drops. The main reason of this phenomenon is the presence of a maximum of temperature of the atmosphere at the height of 47 km (Fig. 2). This maximum of temperature is as a "shield", which protects the bottom layers of the atmosphere and the ground from penetration of clouds of 1,1-DMH with dangerous concentration. The value of this maximum in a strong degree depends on a season. In winter the value of the maximum of temperature is less, and therefore it is possible to expect smaller evaporation of drops for a winter season. To analyze the phenomena, we have carried out the calculations of concentration of 1,1-DMH in a cloud for the winter profile. However the change of the temperature profile did not greatly affect the pattern of the phenomena: the concentration of 1,1-DMH decreased to safe norm in a range of heights of 40-55 km.

4. Conclusion

The investigation has shown that "collective" falling of drops "actuates" the effective mechanism of expansion of a cloud: due to vapor pressure. Irrespective of height of explosion of CR the reduction of concentration of 1,1-DMH up to safe amounts occurs in the range of heights of 40-55 km, and in a small degree depends on the sizes of drops. The main reason of this phenomenon is presence of a maximum of temperature of the atmosphere at height of 50 km. This maximum of temperature is as a "shield", which protects the bottom layers of the atmosphere and the ground from penetration of clouds of 1,1-DMH with dangerous concentration. As a result, it is possible to suppose expansion of a cloud due to this mechanism till the big horizontal sizes. "Collective" falling of drops leads to saturation of a cloud by vapor. As a result, the process of their evaporation is slowed down. Thus, it is possible to suppose that the drops in a cloud can exist a long time. This conclusion is confirmed by the observation of a cloud of rocket fuel in April, 18, 1997 over California, which the experts of NASA connect with carrier rocket "Soyuz", which was started up from cosmodrome "Baikonur" on April 6, 1997 [5]. Only pressure of vapor of evaporating fluid is enough to increase the sizes of an extending cloud up to volume, when the concentration of propellant becomes lower than MAN. Altitude of undocking of the second stage of the launcher "«Proton" equals 139 km, and altitude of undocking of the third stage is 201 km. Thus to ensure the spraying of propellant in near-earth space of the worked-out second and third stage of the launcher up to safe concentration it is enough to include in the design of the launcher a small charge ensuring destruction of fuel tanks.

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Резюме

Зымырантасығыштың жарылысы салдарынан пайда болған бұлттағы зымыран жанармайының эволюциясы қарастырылған.

Резюме

Рассмотрена эволюция капель ракетного топлива в облаке, возникшем из-за взрыва ракеты-носителя.

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