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Condensation of combustion products in rocket plume in the upper atmosphere

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ABSTRACT:

The process of water vapor condensation in rocket engine exhaust in the upper atmosphere is considered. Effects of the heating of condensed particles by the latent heat of condensation, radiating heating and energy losses due to radiation are considered. The formed condensate is not in heat balance with gaseous combustion products, and the dominating process responsible for the energy losses of the condensate is their thermal radiation. During condensation process, a thickness of condensed layer on the surface of particles can reach more than 70 Å (0.07mkm).

Keywords: Upper Atmosphere, Rocket Exhaust, Condensation of Water Vapor.

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1. Introduction

One of the most significant mechanisms producing optical phenomena in the upper atmosphere is the sunlight scattering on disperse particles having a natural or man-caused origin. Almost the only reason of artificial gas-dust clouds formation in the upper atmosphere is an ejection of combustion products from rocket engines. This phenomenon connected with the operation of rocket engines in the upper atmosphere, and could be observed in twilight. In reality such kind phenomena have a different duration and geometrical characteristics, depending on the type of engines and modes of operation [1]. The most important factor defining the intensity of such effects is the presence of disperses particles in exhaust [2-4]. Disperse particles can be formed practically only as a result of condensation of water and carbon dioxide vapor in exhausts as result of sharp drop of combustion products temperature at their expansion.

The condensation of water vapor in combustion products of rocket engines was repeatedly considered by different authors [2,3,7]. The estimations of the size of condensed particles yield ~17 Å (0.017 mkm). In these papers, it was supposed that condensation products are in thermal equilibrium with the environment that is rather an exception, than a rule for real conditions. In reality, the latent heat of condensation per one molecule (δW_{con}) more than 10 times exceeds the average kinetic energy of the molecules (δW_{kin}) in the combustion products $\delta W_{con} \approx 20\ \delta W_{kin}$.

During the water vapor condensation, the heating of particles is produced and the presence of an intensive heat-conducting path is necessary to maintain the thermal balance with environment. In cases, when the environment gas density is great enough and the partial pressure of water vapor is low in comparison with the pressure of combustion products, a heat balance is effectively maintained by collisional heating exchange with the environment. However, during operation of rocket engines in which the combustion products consist ~70% (or more) of water vapor, and the speed of condensation can decrease by 10 times because the reduction of the effective factor of the accommodation of water molecules to the surface of particles, the assumption of thermal balance can not be valid.

As in the paper [3] the estimation of the condensed particles size was made for powerful engine Rocketdyne J-2, we will consider the condensation process for the same condition but taking into account the radiation effects. Such a study would demonstrate the importance of radiative processes in the energy balance of the condensed particles. The condensation of water and carbon dioxide vapors in modern engines exhausts with a complex chemical composition of combustion products requires special consideration and will be made in subsequent papers.

2. Results of calculations

In the present paper we consider process of the water vapor condensation by solving the equations of the heat balance of the particles. The change of the sizes of particle is also considered.

The following designations are used in the article: $l(t)$ – distance from a rocket nozzle to condensation region; t – time of motion of the combustion products at a distance l from nozzle; $T_v(t)$ – water vapor temperature in exhausts; T_p – temperature of condensed particles; r – characteristic size (radius) of condensed particles; ρ – particle density; $q(T_p)$ – heat capacity; Q_{con} – latent heat of condensation; α – adaptation factor of water molecular to a condensate surface; $P_S(T_p)$- saturated vapour pressure over particles surface; $P_v(t)$ – partial water vapor pressure in rocket exhaust; $P(t)$ – combustion products pressure in rocket exhaust; k – Boltzmann's constant; σ – Stefan-Boltzmann's constant; $\chi(r,\lambda)$ – water absorption factor; $B(\lambda,T)$ - Planck function; $F_S(\lambda)$ – energy flux of sunlight outside the terrestrial atmosphere; S_N - area of engine nozzle; Q_{col} – factor of heat collisional transmission; μ – water molecule mass.

The dynamics of the change of temperature and size of condensed particles is described by the equations of heat balance and change of the size of particles:

$$dW_p = Q_{con}dm + dW_{Sun} + dW_{Pl} - dW_{rad} - dW_{co}, \quad (1)$$

$$dr = f(P,T,\rho)dt. \quad (2)$$

In these equations [6],

$$dW_p = \frac{4}{3}\pi r^3 q(T_p)dT, \quad (3)$$

is the change of condensed particles energy,

$$Q_{con}dm = 4\pi r^2 Q_{con}\alpha\left[P_v(t) - P_S(T_p)\right]\sqrt{\frac{\mu}{2\pi k T_v}}dt, \quad (4)$$

is the energy of the condensation,

$$dW_{Sun} = \pi r^2 \int \chi(r,\lambda)F_S(\lambda)d\lambda, \quad (5a)$$

$$dW_{Noz} = \pi r^2 \frac{S_N}{2\pi l^2(t)} \int \chi(r,\lambda)B(T_N,\lambda)d\lambda, \quad (5b)$$

are energy of sunlight and energy of nozzle thermal radiation absorbed by the condensed particles, respectively;

$$dW_{rad} = 4\pi r^2 \gamma\sigma T^4, \quad (6)$$

is the loss of energy due to thermal radiation ($\gamma \approx 0.92$ - radiant emittance of water); and

$$dW_{col} = 4\pi r^2 \varepsilon(T_p - T_v)\frac{P(t)}{P_0}, \quad (7)$$

is the loss of energy dew to the heat collisional transmission to environment ($\varepsilon \approx 10500$ W/m^{2}K is a factor of heat transmission of the condensed water vapor at normal pressure $P_0 \approx 10^5$ Pa).

Taking into account the above expressions, the equations of heat balance are represented as following:

$$\frac{4}{3}\pi r^3 \rho q(T_p)dT_p = \left\{4\pi r^2 Q_{con}\alpha[P(t) - P_S(T_P)]\sqrt{\frac{\mu}{2\pi k T_v}} + \pi r^2 \int \chi(r,\lambda)F_S(\lambda)d\lambda + \pi r^2 \frac{S_N}{2\pi l^2(t)}\int \chi(r,\lambda)B(T_N,\lambda)d\lambda - 4\pi r^2 \int \chi(r,\lambda)B(T_P,\lambda)d\lambda - Q_{col}(T_{pv},t)\right\}dt, \quad (8)$$

$$4\pi r^2 \rho dr = -4\pi r^2[P(t) - P_S(T_P)]\sqrt{\frac{\mu}{2\pi k T_v}}dt, \quad (9)$$

A change of temperature and pressure in a rocket plume is defined by stream parameters at nozzle exit section: pressure, temperature, density and speed of exhausts. The physical conditions for the central fluid tube of a rocket plume calculated for the concrete engine (a launcher Saturn IVB, engine Rocketdyne J-2, using liquid hydrogen and oxygen) [3] were used in the calculations. It is obvious that condensation process can occur only under condition $P_v(t) > P_\infty(T_P)$, which starts to be positive at a critical value of the temperature of the combustion products (T_C), that corresponds to the distance lc from an engine nozzle. In Fig. 1, the dependences of the water vapor pressure in a rocket exhaust and the pressure of saturated water vapor upon temperature are presented.

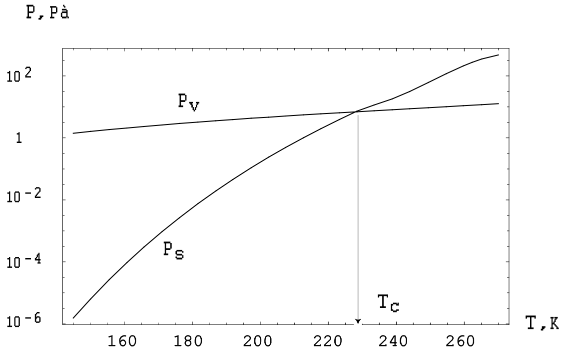

Fig. 1. Dependence of water vapor pressure in rocket exhausts (P_v) and saturated water vapor pressure (P_S) upon temperature (in a logarithmic scale).

It is obvious that the contributions of various mechanisms to the processes of heating and cooling of condensed particles are different. Let us estimate efficiency of the cooling of condensed particles as a result of collisional heat exchange with environment gas in comparison with the heating as result of condensation energy. The relation of condensation energy to the energy lost gives:

$$a_T = \frac{4\pi r^2 \alpha Q \dfrac{P_v - P_S}{\sqrt{T_v}} \sqrt{\dfrac{\mu}{2\pi k}}}{4\pi r^2 \varepsilon \left(T_p - T_v\right) \dfrac{P(t)}{P_0}}. \qquad (10)$$

Assuming that $P_S \ll P_v$, T_v~100 K, and T_v~270 K, ($T_v \cong 270$ K is the maximum temperature at which condensation is possible), it is easy to find: $a_T \sim 20\alpha(P_v/P)$. If the adaptation factor $\alpha \sim 0.9$ [4], and the partial pressure of water vapor in the rocket exhaust is greater than 10% of the common combustion products pressure, the mechanism of collisional heat transmission from condensed particles to environment is inefficient. In the combustion products of the liquid propellant rocket engines the partial pressure of water vapor depending on used fuel varies from ~30% (for heptyl fuel) to ~97% (for hydrogen-oxygen fuel). The content of water vapor in the combustion products in solid propellant engines exhaust is amount to ~8% [8]. Thus, in the exhaust of solid fuel rocket engine it is necessary to consider the lost of energy due to collisional heating exchange with combustion products. For liquid propellant engines, the absence of alternative mechanisms of heat conductivity will lead to the reduction of the effective value of the adaptation factor to values of ~0.05÷0.1. It means that the speed of the condensation will essentially decrease. It is also obvious that, for liquid propellant engines, the assumption about thermal balance between the condensate and combustion products is unreliable. While the mechanism of energy loss, as a result of a thermal radiation of a condensate could be considered there as more effective. We will compare the energy of condensation to the losses on radiation:

$$4\pi r^2 \alpha Q \frac{P_v - P_S}{\sqrt{T_v}} \sqrt{\frac{\mu}{2\pi k}} \div 4\pi r^2 \gamma \sigma T_p^4. \qquad (11)$$

Assuming that value of temperature T_v~100 K, we obtain that radiative losses of energy have been provided the effective cooling of the condensate under the condition $\eta T_v < T_p/300$ (P–Pa, T–K, $\eta \approx 1$ dimensional factor). It is easy to see that this condition can be fulfilled in all regions behind a point of the beginning of condensation. We will show now that heating of particles by solar irradiance and thermal radiation of the nozzle of an engine is of secondary importance in comparison with heating by the latent heat of condensation. For small particles, the absorption factor of radiation is described by the expression [9]:

$$\chi(r,\lambda) = \mathrm{Re}\left[\frac{i8\pi r(m^2-1)}{\lambda(m^2+2)}\right], \qquad (12)$$

where $m = n - ik$ is a complex indicator of a refraction. In the calculations, the dependence of n and k upon wavelength (λ) [10] was used. Radiation of a nozzle of an engine was represented by radiation of a black body with area of ~1 m² that has a temperature of 4000 K (it is evident that these values are overestimated). Ratios of condensation energy to energy of sunlight and thermal radiation energy of a nozzle, absorbed by a particle, can be written respectively:

$$a_S = \frac{4\pi r^2 \alpha Q \dfrac{P_v - P_S}{\sqrt{T_v}} \sqrt{\dfrac{\mu}{2\pi k}}}{\pi \int \chi(r,\lambda) F_S(\lambda)\, d\lambda} \approx \pi r^2 90 r, \qquad (13a)$$

$$a_N = \frac{4\pi r^2 \alpha Q \dfrac{P_v - P_S}{\sqrt{T_v}} \sqrt{\dfrac{\mu}{2\pi k}}}{\pi \int \chi(r,\lambda) B(T_N,\lambda)\, d\lambda} \approx \pi r^2 75 \left(\frac{l_c}{l}\right)^2. \qquad (13b)$$

Assuming, as above that $P_S \ll P_v$, T_v~100 K, α~1 we will get: $a_S \sim 25P/r$ и $a_N \sim 30P/r$ (P-Pa, r-μm). It is obvious that in the region of most intensive condensation for particles with characteristic size of 0.01÷0.1 microns, a_S and a_N are essentially more than 1 and the heating of particles by radiation is weak. It is necessary to note, however, that after the condensation, the heating of particles by sunlight becomes a determining factor in the heat balance of the particles. Simple estimations show that intensity of the thermal radiation of a rocket plume (combustion products), even in the assumption that they radiate as a black body, does not exceed 10% of the radiation intensity of a nozzle, therefore this mechanism of heating can also be neglected in a heat balance of particles. The obtained estimates allow us to conclude that the most significant mechanisms for the heat balance of condensed particles are their heating by the latent energy of the condensation and cooling because of thermal radiation. Using these assumptions, the equations of heat balance and change of particle size become:

$$\frac{dT}{dt}=\frac{3}{r(t)\rho q(T_p)}\left\{\frac{\alpha Q_{con}\left[P_v(t)-P_S(T_p)\right]}{\sqrt{T_v}}\left[\sqrt{\frac{\mu}{2\pi k}}-\beta\sigma T^4\right]\right\}, \tag{14}$$

$$\frac{dr}{dt}=\frac{1}{\rho}\frac{\alpha\left[P_v(t)-P_S(T_p)\right]}{\sqrt{T_v}}\sqrt{\frac{\mu}{2\pi k}}. \tag{15}$$

Numerical solution of these equations for initial conditions $T(t=8\text{мс})=220$ K, $T(t=8\text{мс})=10$ A are presented in Figs. 2.

As the condensation process has a surface character, a speed of increase of the condensation layer thickness, naturally, should not depend on initial size of condensation's kernels, what is proved by calculations at various initial conditions. Calculations performed with various initial values of particles' temperature - T_p have shown that for initial values T_p in a wide enough range (180÷250 K), the temperature of particles almost instantly reaches an equilibrium value that is defined by a balance between heating and cooling (~220 K). Slow enough reduction of the particle temperature in comparison with the temperature of the combustion products means that the condensate is not in a heat balance with the environment. Thus, active process of the condensation in exhausts of a hydrogen-oxygen rocket engine in the upper atmosphere occurs at distances of ~50÷200 m from then engine nozzle. The thickness of the condensed layer does not depend on the initial size of the condensation kernels and is defined, basically, by the value of the water vapor pressure in combustion products and gives ~80 A for the accepted dependence of pressure and temperature in a rocket plume.

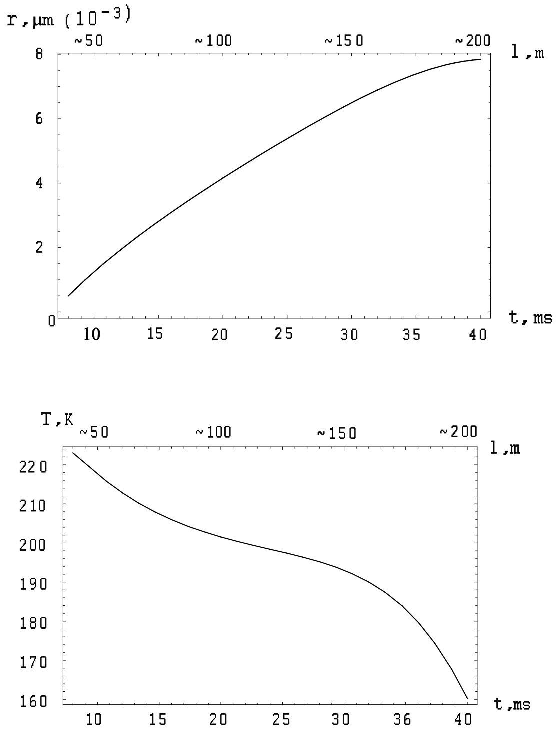

Fig. 2. a) Change of a condensed layer thickness; b) Change of a condensed particle temperature with time (distance from an engine nozzle).

3. Conclusion

The solution of the equations of heat and mass balance of particles condensed from water vapor in rocket engine exhaust in the upper atmosphere allows determining the changes of their size and of the temperature. The formed condensate is not in thermal balance with gaseous combustion products, and dominating process in the energy loss of condensate is their thermal radiation. For other types of engines, the region of the condensation of water vapor in rocket plume and the characteristic sizes of particles can essentially differ from the calculated values.

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