Evolution of liquid-drop aerosol cloud during deposition in a high-temperature environment

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Abstract. Physical mathematical model of the evolution of a liquid-drop aerosol cloud in the atmosphere during fire extinguishing with the help of aviation is presented. Some results of calculations of the motion, heating and evaporation of polydisperse water droplets during refrigerant medium discharge from the aircraft board are given.

1. Introduction

One of the effective ways to extinguish large fires, especially in hard-to-reach areas, is to discharge the refrigerant medium into the hearth of fire from an airplane or helicopter. As a refrigerant medium, water mist is usually used. When water mist affects the flame, the mechanism of a volume-surface interaction is realized. The water mist cools the combustion zone and at the same time, due to evaporation, it blocks the access of oxygen to burning elements by steam. The effective use of this method is based on the patterns of deposition of a liquid-droplet cloud and its interaction with the medium near the fire center. These patterns are the fundamental basis for the development of optimal regimes for the use of aviation to extinguish fires, taking into account real conditions.

The main volume of publications on fire extinguishing issues with the use of aviation relates to the technical aspects of the implementation of the process of refrigerant medium discharge into the fire center [1, 2]. To increase the fire extinguishing efficiency, it is necessary to carry out physical and mathematical modeling of dispersion processes of the macrovolume of a liquid refrigerant medium during discharge from the aircraft board [3, 4], the evolution of an aerosol cloud during its gravitational deposition [5, 6] and the interaction of sprayed droplets with a flame [7, 8].

In this paper, we consider mathematical model of the evolution of an aerosol cloud formed after fragmentation of the macrovolume of a liquid refrigerant medium. Some results of numerical modeling of the motion, heating, and evaporation of polydisperse water droplets entering into the fire center are presented.
2. Mathematical formulation of the problem

The formation of the primary liquid-droplet cloud occurs during discharge of refrigerant of mass $M$ into the atmosphere due to the aerodynamic crushing of the macrovolume of the liquid into fragments in the form of polydisperse spherical droplets of different initial radius $r_{s0}$ [5, 6]. The fragmentation of the liquid macrovolume is implemented at a given height $H$. Dynamics of a liquid-droplet cloud is considered as gravitational sedimentation of droplets of each size, taking into account the speed and direction of the wind, as well as the rate of rise of heated air from the center of fire. In the process of evolution of the liquid-droplet cloud, the heat exchange of the droplets with the environment and the change in their size due to evaporation are taken into account. During deposition, the processes of droplets crushing are taken into account. Within these provisions, the dynamics and heat and mass transfer of the liquid-droplet cloud in the Cartesian coordinate system \{x, y, z\} (0z axis is directed vertically downwards, 0x axis is in the direction of movement of the aircraft) is described by the following system of equations:

\[
\begin{align*}
\frac{du_s}{dt} & = \varphi(u-u_s), \\
\frac{dv_s}{dt} & = \varphi(v-v_s), \\
\frac{dw_s}{dt} & = \varphi(w-w_s) + g, \\
\frac{dT_s}{dt} & = \frac{3\lambda}{2r_s^2\rho_sc_p} Nu(T-T_s) - \frac{q_{vap}m_{vap}}{m_sc_p}, \\
\frac{dr_s}{dt} & = -k\frac{\rho_0}{\rho_s} p_0 \left( p-p_0 \right). 
\end{align*}
\]

System (1) is complemented by the kinematic relations:

\[
\frac{dx}{dt} = u_s, \quad \frac{dy}{dt} = v_s, \quad \frac{dz}{dt} = w_s.
\]

In equations (1), (2), $U(u, v, w)$, $U_s(u_s, v_s, w_s)$ is the vector of air speed and droplets; $t$ is the time; $\varphi = 3\rho C_D[U-U_s]/(8\rho r_s)$; $\rho$, $\rho_s$ is the density of air and liquid; $r_s$ is the droplet radius; $C_D$ is the drag coefficient; $g$ is the gravitational acceleration; $T$, $T_s$ are the air and droplet temperatures (averaged over the droplet volume); $\lambda$ is the coefficient of air thermal conductivity; $c_p$ is the specific heat of the liquid; $Nu$ is the Nusselt number; $q_{vap}$ is the specific heat of evaporation of a liquid; $m_{vap}$ is the mass of the evaporated liquid; $m_s$ is the droplet mass; $k$ is the mass transfer coefficient; and $p$, $p_0$ is the ambient pressure and vapor partial pressure.

Under the assumption of a spherical droplet shape, the values of the aerodynamic drag coefficient $C_D$ and the Nusselt number $Nu$ were determined depending on the flow regimes according to the formulas [9]:

– Stokes regime ($Re \leq 1$):

\[
C_D = \frac{24}{Re}, \quad Nu = 2;
\]

– transient mode ($1 < Re < 10^3$):

\[
C_D = \frac{24}{Re} + \frac{4}{\sqrt{Re}}, \quad Nu = 2 + 0.6Re^{1/2}Pr^{1/3},
\]

where $Pr$ is the Prandtl number;

– turbulent regime ($Re > 10^3$):

\[
C_D = 0.44 = \text{const}, \quad Nu = \frac{0.37Re^{-0.8}Pr}{1 + 2.443Re^{-0.1}(Pr^{2/3}-1)}.
\]
Reynolds number was calculated by the relative movement of the droplet
\[ Re = \frac{2\rho |U - U_s| r_s}{\mu}, \]
where \( \mu \) is the air coefficient of dynamic viscosity.

The dependence of the coefficient of dynamic viscosity on temperature was determined by the Sutherland formula:
\[ \mu = 0.68 \cdot 10^{-2} \left( \frac{T}{T + 122} \right)^{3/2}. \]

The critical value of the Bond number
\[ Bo_s = \left( \frac{4 \rho_s \sigma}{\rho r_s^2} \right) = 90 \] (\( \sigma \) is the acceleration of mass forces and \( \sigma \) is the surface tension) was taken as a criterion for crushing drops due to the Rayleigh–Taylor instability, and due to the Kelvin–Helmholtz instability – the critical value of the Weber number
\[ We_s = 2\rho |U - U_s| r_s / \sigma = 17. \] It was assumed that when the critical values of the Bond number or the Weber number are reached, the drop crushes into two spherical drops of equal mass [9].

The mass transfer coefficient \( k \) in the model (1) was calculated by the formula [10]:
\[ k = \frac{c_f D_f M_f}{2 r_s} \left[ 2 + 0.6 \left( \frac{2 r_s |U - U_s| \rho_s}{\mu_f} \right)^{1/2} \left( \frac{\mu_f}{\rho_f D_f} \right)^{1/3} \right], \]
where \( D_f, c_f, M_f, \mu_f \) are the binary diffusion coefficient, the total (air and liquid vapors) volume molar concentration, the molecular mass of the droplet substance and the air coefficient of dynamic viscosity at film temperature \( T_f = 0.5(T_s + T) \).

The binary diffusion coefficient was determined on the basis of the empirical relation, which in general is [10]:
\[ D_f = \frac{T^{1.75} \left( \left( M_A + M_B \right) / M_A M_B \right)^{0.5}}{p \left( \Sigma V_A \right)^{1/3} + \left( \Sigma V_B \right)^{1/3}} \]
where \( M_A, M_B \) are the molecular masses of components \( A \) (liquid) and \( B \) (air); \( \Sigma V_A, \Sigma V_B \) are diffusion volumes of molecules of components \( A \) and \( B \).

Values of diffusion volumes of molecules for different substances are given in [11]. Based on the relation (3), the formula for determining the diffusion coefficient of water droplets in the air is obtained:
\[ D_f = \frac{C \left( T_f / 273 \right)^{1.25}}{p}, \]
where \( C \) is a constant.

The system of differential equations (1) was solved numerically by splitting method on physical processes [12].

A primary cloud of liquid droplets is formed as a result of spontaneous crushing of individual unstable fragments when a macrovolume of a liquid refrigerant is emitted into the atmosphere. The differential function of the countable distribution of droplets on size in the primary cloud is close to exponential. In the numerical modeling, the distribution function of the number of liquid droplets on sizes was adopted [12]:
\[ f(r) = a \exp(-3.12r), \]  

(4)

where \( a = 1.575 \text{ mm}^{-1} \) is the normalizing multiplier; \( r \) is the current radius of droplets, mm.

When making calculations, taking into account the distribution (4), six fractions of droplets of the same radius \( r_{si} \) were considered. The values of counting \( C_{ni} \) and mass \( C_{mi} \) proportion of the droplets of each fraction are given in table 1.

Table 1. Proportions of each fraction in the primary cloud of refrigerant.

| Fraction | \( r_{si} \) (mm) | \( C_{ni} \) (%) | \( C_{mi} \) (%) |
|----------|-------------------|------------------|------------------|
| 1        | 0.5               | 54.7             | 1.2              |
| 2        | 1.0               | 25.0             | 9.5              |
| 3        | 1.5               | 11.5             | 19.7             |
| 4        | 2.0               | 5.3              | 24.9             |
| 5        | 2.5               | 2.4              | 24.3             |
| 6        | 3.0               | 1.1              | 20.4             |

3. Numerical modeling results

Numerical modeling of the evolution of a liquid-droplet aerosol cloud during deposition in a high-temperature environment was carried out for different initial sizes of water droplets (Table 1). It was assumed that the fragmentation of the macrovolume of the liquid refrigerant is realized at a height of \( H = 300 \text{ m} \) from the surface of the earth. The ambient temperature was 20 °C, and the wind speed was 6 m/s. It was assumed in the calculations that the speed of the upward air flow from the fire source decreased linearly from 0.5 m/s (on the earth surface) to zero at a height of 50 m. The air temperature decreased linearly from 370 °C (on the earth surface) to 20 °C at the height of 200 m [12]. The given initial data correspond to refrigerant (water) discharge during fire extinguishing with the help of the VSU – 5 water drain device located on the helicopter board [1].

Figure 1 shows the dependences of the temperature of water droplets of different initial sizes \( r_{s0} \) on the distance to the surface of the earth \( h = H - z \) (\( h = 0 \) corresponds to the surface of the earth).

![Figure 1](image-url)

Figure 1. Dependences of the temperature of droplets of different initial radius on the distance to the surface of the earth: 1, 2, 3 – \( r_{s0} = (3; 2; 1) \text{ mm} \); 4 – temperature of the upward air flow.

Analysis of the obtained results has shown that droplets with an initial radius of \( r_{s0} = (1 \div 2) \text{ mm} \) heat up, starting at \( h = 200 \text{ m} \), and evaporate completely at \( h = (60 \div 130) \text{ m} \). Droplets with an initial radius of \( r_{s0} \sim 3 \text{ mm} \) at \( h = 0 \) are heated to a temperature of \( \sim 100 \text{ °C} \).
Figure 2 shows the dependences of changes in the current radius of droplets of different initial sizes $r_{s0}$ due to evaporation when moving in a heated upward air flow. From the given dependences, it follows that the radius of droplets with $r_{s0} \sim 3$ mm decreases to $\sim 2$ mm during deposition in a heated air flow. Droplets with an initial radius of $r_{s0} = (1; 2)$ mm completely evaporate.

The dependences of evaporation rate of water droplets of different initial radii from the distance to the surface of the earth is shown in Figure 3.

Analysis of the obtained results has shown that evaporation rate of droplets increases exponentially during their deposition in an upward flow of heated air. The process of evaporation of larger droplets is less intense due to greater thermal inertia and a higher speed of passage of heated air by them.

4. Conclusions
The developed physical-mathematical model of the evolution of a cloud of a liquid-droplet aerosol during deposition in a high-temperature environment allows estimating heating, evaporation, and the dynamics of gravitational sedimentation of polydisperse droplets during discharge of refrigerant from the aircraft. The results of numerical modeling can serve as a basis for choosing the height of the refrigerant discharge for effective fire extinguishing by means of aviation, taking into account real meteorological conditions.

One of the main parameters for the implementation of the proposed model is the distance $H$, at which the macrovolume of the liquid refrigerant is fragmented to form a cloud of polydisperse droplets. Currently there are no mathematical models to determine $H$. A reliable estimate of the dynamics of the destruction of the macrovolume of a liquid can be obtained using criterial dependencies based on the results of experimental studies [4].

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