Mathematical Modeling and Simulation of Helicopter Fire Extinguishing with Water

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Abstract. In view of the landing point and landing forms of water during the helicopter dropping water and extinguishing fire, a mathematical calculation method is proposed, which considers the factors such as helicopter flying height, helicopter sailing speed, wind speed and so on. Through the study of the helicopter's water-dropping algorithm, the position of the water-dropping point and the area of sprinkler fire-extinguishing under various conditions are obtained, which provides an effective place for the helicopter's water-dropping research and theoretical support for the formulation of the technical parameters of the helicopter's water-dropping and fire-extinguishing.

1. Introduction
The forest fire extinguishing in our country is mainly carried out by artificial, which is in poor safety and has low efficiency, and can't meet the requirements of forest fire extinguishing nowadays. At present, most of the forest fire extinguishments are based on the principle of "fighting early and fighting small". If the forest fire is not effectively warned or is not effectively contained in the initial stage of occurrence, the fire will quickly develop into disaster. Due to the fierce fire and the large space of flame combustion distribution, the conventional fire extinguishing methods can’t effectively contain it [1-3]. As for the fire situation at home and abroad at this stage, because the fire truck is affected by geographical factors, it is impossible to control the fire quickly, resulting in serious loss of forest resources, and the personal safety of fire-fighters cannot be guaranteed, so the forest fires after the disaster mainly rely on forest aviation fire-fighting. Because chemical fire extinguishing agents pollute the environment, and water has an infiltration effect on firewood, it is the best choice to use water to extinguish forest fires. Water is the development direction of forest fire extinguishing agent when it pays attention to the harmonious development of ecological environment and human beings [4]. In order to solve the problem that the airport is generally far away from the fire scene, helicopters are often used as forest aviation fire-fighting helicopter, and simple helicopter airports are arranged near the forest. The water tanks and buckets are filled with water in advance before the disaster occurs, and the water tanks can be replaced directly when the helicopter returns from fire-fighting.

At present, the application of fire extinguishing in forest helicopter buckets and belly tanks in China is still in the initial stage and exploration. The water-dropping and fire-extinguishing mainly depends on the experience and technical level of the flight personnel. The theoretical research on aviation fire-fighting methods is still a research gap, and there is no mathematical model or guidance method that can guide the dropping water at high altitude. Therefore, it is of great significance to establish a sprinkler model of a fixed target point in helicopter flight, to study the technical scheme and numerical simulation of multi-machine cooperative fire-fighting based on the conditions of
helicopter safety flight speed and altitude, and to improve the actual combat training level of the army and enhance the actual combat capability of fire-fighting.

Affected by geographical environment factors, forest fires are mainly put out by aircraft. This paper is based on the research background of high-altitude and high-speed aircraft dropping water for fire fighting, taking the belly type and bucket type water tank dropping water as the research object under high-altitude and high-speed conditions, considering the influence of wind speed, wind direction and other factors on the dropping water effect, using the research methods of mathematical modeling and numerical simulation, the mathematical model in the dropping water landing process is established, and the parameters such as dropping water landing speed, landing position and distribution form are obtained, providing technical support for the formulation of flight height, landing speed and discharging time of aircraft fire fighting.

2. Helicopter dropping water model

Suppose the pilot controls the helicopter from point O to aim at the ignition point M along the OX axis at airspeed $V_0$. The helicopter arrives at the launch point O after time T, the pilot opens the sprinkler nozzle to aim at the target and launches water at the initial velocity $u_0$. Because of the effect of horizontal initial velocity and wind speed $U$, water moves parabolically in the air after throwing, and after a period of time the water body covers the fire area. In the case of ensuring the thickness of the water within the unit area to meet the requirements of fire suppression, fire-fighting is carried out in the fire area. The principle of helicopter flooding water and fire extinguishing is shown in Figure 1. The helicopter heading coordinate system is OXYZ, the origin O is the helicopter position, the OX axis follows the helicopter heading, the OZ axis follows the vertical downward, and the OY axis is determined by the right-hand rule.

![Figure 1. Plane's water-dropping aiming map.](image)

The altitude of the helicopter from the ground is H, the time of landing of the water body is T, the windless range OC0 of the water body is A, C is the hit point, $\epsilon$ is the heading angle of the wind, the horizontal distance from O’ to target M is D, and the azimuth angle of the target to the helicopter heading is $\varphi$.

Set the hit point position of the water body on the ground at that time, compare the hit point position with the position of the helicopter relative to the target, and be responsible When the coordinates of the mid-point position coincide with the coordinates of the target position, it means that the helicopter reaches the drop point, at which time it can drop water to hit the fire area to achieve the purpose of extinguishing fire, namely[5]:

$$
\begin{align*}
V_0t &= D \cos \varphi - U(t + T) \cos \epsilon - A \\
U(t + T) &= D \sin \varphi / \sin \epsilon 
\end{align*}
$$

Without considering the air resistance, the analysis of a certain part of the water drop shows that:

$$
H = u_0t + \frac{1}{2}gt^2
$$

So, the time of water stagnation is:
When there is no wind, the range is:

\[ A = V_0 T \] (4)

The aiming time \( t \) can be obtained by substituting the expressions (3) and (4) into the expressions (1), and the airplane keeps its current state from OJ point to make a uniform linear motion \( t \) can reach the location of the drop point to drop water.

According to the principle of circular free turbulent jet, the semi-expanded thickness \( b \) of the jet can be expressed as a function of the following variables.

\[ b = f(M_0, \rho, x) \]

Using dimensional analysis, there is \( b = C_0 x \).

Where, \( M_0 \) is the momentum of water at the spout, \( \rho \) is the density of water, \( x \) is the vertical height of the drop point, and the constant \( C_0 \) is determined by experiment.

Due to the different analysis methods and experimental materials used by different researchers, the results will be slightly different. For each characteristic half thickness of the jet, an approximate value is taken, and it is suggested that semi-expanded thickness \( b \) of jet be

\[ b \approx 0.246x \] (5)

The sprinkling area of the water process is formed by superposing \( n \) circular areas. The amount of water falling to the ground per unit area is:

\[ m = \frac{\rho V}{s} \] (6)

Where \( \rho \) is the density of water.

3. Model solution and simulation

Suppose that the aircraft is throwing water in the horizontal direction at the speed of \( V_0 \), the water storage of the aircraft is \( V \), there are four circular outlets with the diameter of \( d \), and the water is ejected vertically from the outlet at the initial speed of \( u_0 \). Only the water is thrown in the crosswind, assuming that the wind speed and direction remain unchanged, and the wind speed is \( U \). According to the above analysis, the principle formula of the water injection algorithm can be obtained as follows[5]:

\[ S \approx 2bL_\alpha = 0.5(V_0 + U \cos \varepsilon)T_0H \] (7)

the formula (8) is the calculation formula of fire extinguishing area and landing water quantity.

Let \( \varphi = \cos \varphi \), and because \( \varphi \in [0, 90^\circ] \), According to the alternative elimination method, the formula (1) can be changed to:

\[ C(t + T)^2 - D^2 = 0 \] (8)

Where, \( C = V_0^2 + 2V_0U \cos \varepsilon + U^2 \).

Thus, the solution of equation is

\[ \begin{cases} t = \frac{D}{\sqrt{C}} - T \\ \varphi = \arcsin \left( \frac{U}{\sqrt{C}} \sin \varepsilon \right) \end{cases} \] (9)

4. Simulation results and analysis

Assume that a large fire-fighting helicopter has a water carrying capacity of 10 tons, the speed of flight is 20 m/s when sprinkling, the heading angle of the wind is 30 degrees, the helicopter is 1 km away from the fire point when it starts to aim.

At the same time, the Flunt simulation platform was used to simulate the helicopter's aerial water injection. The simulation process are shown from Figure 2 to Figure 6, and the simulation results are
basically consistent with the numerical calculation results.

Figure 2. Helicopter position model initialization

Figure 3. Initialization of water injection model

Figure 4. Grid Division of Water Projection Ground

The content of the phase in Figures 5 and 6 is that blue represents water and red represents air.

Figure 5. Start throwing water
Substituting the above parameters into the principle equation of the water injection algorithm can obtain the water injection position parameters and sprinkling data as shown in the table 1.

Table 1. Position parameters and sprinkling effect of helicopter dropping water.

| Sprinkling height(m) | Wind speed(m/s) | Aiming time(s) | Sprinkling area(m²) | Floor water volume(g/m²) | Horizontal distance from the starting point x(m) |
|----------------------|-----------------|----------------|--------------------|---------------------------|-----------------------------------------------|
| 80                   | 3               | 12.09          | 650                | 3150                      | 230                                           |
| 80                   | 3               | 12.17          | 678                | 2900                      | 238                                           |
| 100                  | 3               | 15.09          | 976                | 1100                      | 317                                           |
| 100                  | 3               | 15.17          | 1020               | 930                       | 325                                           |
| 150                  | 3               | 20.56          | 1170               | 520                       | 471                                           |
| 150                  | 3               | 20.65          | 1220               | 590                       | 488                                           |

From the calculation results, as the sprinkling height and wind speed increase, the helicopter aiming time gradually decreases, and as the wind speed increases, the helicopter yaw angle increases. Under the breeze conditions, the watering effect of 100m height is the best, the water stagnation time is the shortest, and the ground is humid. With the increase of sprinkling height, the sprinkling area increases, but the amount of landing water is small, the drift is increased, and the accuracy is reduced. With the increase of wind speed, the accuracy and effect of sprinkling are obviously weakened. For general fires, the applicable fire extinguishing capacity is 0.4~1.63 kg/m². Therefore, under normal circumstances, the sprinkler height should be kept at 100~150m.

5. Conclusions
In this paper, a model of helicopter water delivery is established, and the delivery point, sprinkler area and landing water volume of helicopter under different conditions are calculated. When the helicopter keeps flying at a speed of 20~300 km/h, the wind speed is low, and the sprinkler height is kept at 100~150m, the fire extinguishing efficiency is better. Moreover, because of its large water carrying capacity, it reduces the number of helicopter sprinkling times, saves the fire extinguishing time, further improves the fire extinguishing efficiency and meets the fire extinguishing requirements. This algorithm provides an effective method for the research of helicopter water-dropping and fire-extinguishing.
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