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A Fast Optimization Method of Water-Dropping Scheme for Fixed-Wing Firefighting Aircraft

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ABSTRACT The water-dropping scheme plays an important role in the aerial firefighting mission. When a wildfire occurs, the main problem faced by the aircrew is how to choose the appropriate water-dropping scheme (speed, height and trajectory) to achieve the optimal firefighting effect. However, so far, the crew members can only rely on the existing experience to generate the scheme, which lacks the corresponding theory method support. To solve above problem, this paper proposes a fast optimization method of water-dropping scheme for fixed-wing firefighting aircraft. Through the feature extraction of grid distribution, the agent model between aircraft water-dropping scheme and water distribution polygon is built taking advantage of neural network. Meanwhile, the corresponding extinguishing efficiency evaluation model is established with discrete points of fire area. Based on these researches, the combined genetic algorithm is used for searching the optimal water-dropping scheme. Finally, the feasibility and rapidity of the method are demonstrated through the application of examples. It is also shown that the method can optimize the water-dropping scheme quickly instead of aircrew experience and play a role of auxiliary decision support for the firefighting mission of fixed-wing firefighting aircraft.

INDEX TERMS Aerial firefighting, agent water-dropping model, fixed-wing firefighting aircraft, genetic algorithms, water-dropping scheme, neural networks, aerospace simulation.

I. INTRODUCTION

As a hazard that threatens public safety and social development, wildfire occurs every year all over the world. Due to the complex situation on the ground, it is difficult for ground firefighting operations. At the same time, considering that rapid fire extinguishing actions in the early stage of a wildfire can better control the fire and reduce the loss [1], [2], a quick and efficient firefighting method is needed. The advantages of strong mobility, ability to quickly travel to the mission area and being less restricted by terrain and ground features make aerial firefighting a highly efficient and fast method widely used in the world [3]–[6]. In particular, compared with firefighting helicopters, fixed-wing firefighting aircraft (FWFA), with its unique advantages of heavy load and fast speed, can play a greater role in firefighting missions [7]. Among the firefighting mission of FWFA, the water-dropping stage directly determines whether the water can effectively cover the target fire area to achieve good firefighting efficiency. Different from helicopters, which can drop water at low speed or in hover, FWFA need to determine appropriate speed, height and trajectory to perform the mission of dropping water, so as to ensure a better fire extinguishing effect.

There have been a lot of achievements in the study of water-dropping. Since the middle and early 20th century, studies on dropping water of firefighting aircraft have been carried out in occident. There are some typical related experiments conducted by United States Department of Agriculture-Forest Service. A spray model is developed based on the geometric size of the fire extinguishing tank, the opening speed of the tank, the height and the speed of the aircraft in 1968 according to MacPherson's work [8]. Numerous experiments conducted in subsequent years are used to refine the spray model from the work of George *et al.* [9] and Blakely [10]. On this basis, Swanson *et al.* [11] use the PATSIM program to prepare the first user's guide for aircraft spraying fire extinguishing for several types of aircraft aiming at the actual flow of

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fire retardant. This guide lists various spraying conditions, device performance, and charts to help the aircrew better formulate the firefighting scheme to improve fire extinguishing. In recent years, with the rapid development of computational resources and speed, the use of numerical calculation to simulate water-dropping has been further developed. Satoh *et al.* [12] compare CFD with real experiments, and provide data to run simulation and research for the formulation of water-dropping scheme. Amorim [13]–[15] has made a very detailed numerical study on the water-dropping model, especially discussing the mechanism of droplet rupture and the influence of tree canopy on gas-liquid flow. Furthermore, Legendre *et al.* [16] combine the multi-type experimental data and theories to fit the formula of water-dropping distribution and verify it with the experimental data from Giroud *et al.* [17]. Under considering the breakdown and dispersion of droplets, Qureshi and Altman [18] improve the distribution model. In China, Yongliang [19] proposes the water-dropping algorithm in combination with the bomb dropping algorithm. Then Han *et al.* [20] apply the simplified water model to VR simulation and the numerical water-dropping studies of an amphibious aircraft- AG600 are also carried out from the work of Zhao *et al.* [21] and Yu [22]. The existing research on water-dropping has been very detailed, and it is basically to build the relationship between water-dropping distribution and water-dropping scheme, including flight speed, height and trajectory. In actual execution mission, the aircrew needs to quickly optimize the above water-dropping scheme according to the situation of the fire area and environment to achieve a better fire extinguishing effect. However, the current research and application have the following two problems. Firstly, all the above-mentioned studies on the formulation of the water-dropping scheme still require the aircrew to artificially combine the water-dropping distribution and the fire area, which means that it still needs to rely on the experience and professional knowledge of the aircrew to judge how to cover the fire area. Even the research from Zohdi [23] has used the digital twin framework to optimize the aircraft water-dropping scheme, but there is a lack of consideration of firefighting efficiency corresponding to different zones of fire area. Secondly, the complexity of the model is still very high, and the CFD method based on such model cannot quickly optimize the water-dropping scheme in the limited computational resources. So, it is difficult to meet the needs of rapid emergency response and lacks the ability of auxiliary decision support.

Aiming at the problems existing in the current research, this paper proposes a fast optimization method of water-dropping scheme for FWFA. Based on the integration of the existing water-dropping model, the discrete points of fire area are introduced and the corresponding evaluation model of firefighting efficiency is established. At the same time, the ground distribution of the numerical water-dropping model (NWM) is represented by the polygonal descriptive water-dropping model (DWM). Furthermore, build agent water-dropping model (AWM) between the water-dropping scheme of aircraft and water distribution polygon by using neural network. Finally, AWM is used to optimize the firefighting efficiency by the combined genetic algorithm to determine the current FWFA at what height, what speed, what angle and what trajectory point to carry out water-dropping operation. This is a very important auxiliary decision support method for the firefighting crew. It is helpful for the crew to respond to the fire situation more quickly, which improves the firefighting efficiency in the water-dropping stage and enhances the aviation emergency rescue capability of FWFA for firefighting.

II. METHODS

In the face of such problems as water-dropping scheme optimization, there are heuristic algorithms including particle swarm optimization (PSO) [24] algorithm, genetic algorithm (GA) [25], which are suitable for solving such mission optimization problems. The studies of applying PSO to determine the maritime search and rescue area [26] and multi-UAV task allocation using the GA with double-chromosome encoding [27] have been carried out. This kind of optimization algorithm needs to be iteratively optimized based on a certain population to get the optimal solution.

The optimization problem needs to determine the optimization parameters and optimization objectives. In this paper, the general framework of this method is shown in Fig. 1. According to above requirements, five water-dropping scheme variables, namely, flight height H, flight speed V, initial trajectory point x, y, and initial azimuth angle θ, are set as optimization parameters. These five parameters are used by NWM to calculate the ground distribution of water. Then DWM is built by extracting the key water-dropping zones and using polygons to represent these zones. Based on this, the samples are generated and AWM is trained by neural network to build the relationship between the five parameters and the water distribution polygon of water-dropping. The process of generating AWM is an offline calculation. The front of fire line is used as the input parameter to get the fire area through the fire area model, and the Poisson's dish sampling is used to represent the fire area with discrete points. Furthermore, on the basis of the water-dropping model and discrete points of fire, evaluation model is used to calculate the optimization objectives. Finally, the optimized water-dropping scheme can be obtained through the combined GA for online optimization.

In order to realize the above optimization method, the first section introduces the water-dropping model as the core modeling part of this study. The fire area model is introduced and discretized in the second section. After these two, the evaluation model is established to complete the determination of optimization objectives. Then, the fourth section introduces the combined GA to realize scheme optimization. In the end, the optimization method is summarized in the fifth section.

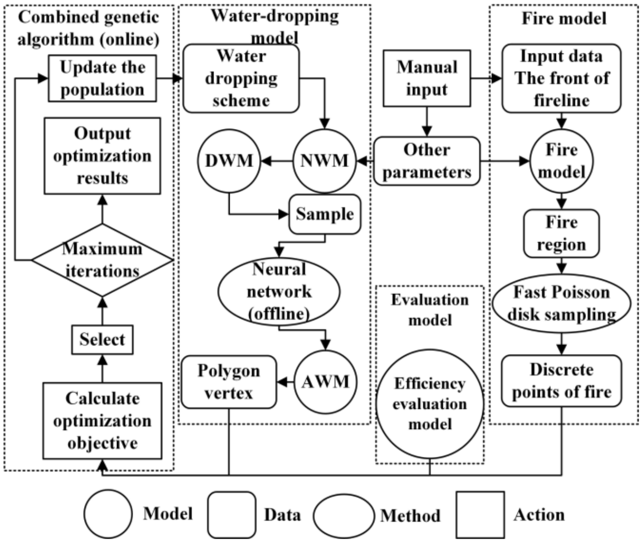

FIGURE 1. Unified method framework.

A. WATER-DROPPING MODEL

Water-dropping model is the core content of the optimization method about water-dropping scheme. It is necessary to build the relationship between the parameters of water-dropping scheme and ground water-dropping distribution. On the basis of this model, a new model should be established to reduce the calculation amount of the simulation and optimization. So NWM, DWM and AWM are introduced accordingly.

1) NUMERICAL WATER-DROPPING MODEL

According to the research, the water-dropping model can be divided into three aspects: initial stage of water-dropping, rupture movement and diffusion distribution. In this paper, it is necessary to establish the relationship among the water-dropping scheme, the other water-dropping parameters and the final ground distribution. And initial stage of water-dropping and rupture movement should be considered as the intermediate links.

a. In the initial stage of water-dropping, the relationship among the water tank parameters, the water-dropping outlet velocity and water-dropping time is established according to the conservation law of mechanical energy. It is suitable for the constant pressure system and constant flow system respectively. Among them, the free water-dropping system could also be seen as a constant pressure system, and the corresponding differential pressure is 0.

The outlet velocity component in the z direction u_z of the constant pressure system varies with time as follows referring to the modeling method of Han *et al.* [20]:

$$u_z = -\left(\sqrt{2h_0 g + \frac{2P}{\rho_L}} - \frac{S_0}{S} g t\right) \tag{1}$$

where, h_0 is the height of the water tank, g is gravitational acceleration, P is the pressure potential energy per unit volume (0 for the free water-dropping system), ρ_L is the water density, S_0 is the outlet section area, and S is the horizontal section area of the water tank. The outlet velocity components in the x, y direction u_x, u_y are derived from the flight speed.

The water-dropping time t_{drop} can be solved by the following formula under the certain total water Q:

$$Q = \int_0^{t_{drop}} u S_0 dt \tag{2}$$

The outlet velocity of the constant flow system is a constant value, and the corresponding water-dropping time is easy to obtain, so it is not listed.

b. In the stage of rupture movement, the relationship between the flight trajectory of the aircraft and the ground center trajectory of water should be introduced. Studies have shown that after dropping the water, ligament flow and large liquid drops will be formed by rupture at first. And then the interaction between fluids will cause the second rupture to form small droplets, which will produce fog-like water at macro level and diffuse downwards. Meanwhile, the shape of the outlet can be simplified to an equivalent circular nozzle. In this way, the equivalent radius of outlet and the hypothesis of circular jet can be obtained. It is assumed that the two ruptures of water body are instantaneous.

The first rupture radius r_{fir} of water body according to the study of Amorim [15], Reitz [28] and Reitz and Diwakar [29] is:

$$r_{fir} = 5.5R_e \frac{(1 + 0.45Oh_L^{0.5})(1 + 0.4Ta^{0.7})}{(1 + 0.87We_G^{1.67})^{0.6}} \tag{3}$$

where, R_e is the equivalent radius of outlet, Oh_L is the Ohnesorge number of liquid, Ta is Taylor number, and We_G is the Weber number of gas.

The second rupture radius of water body $r_{\sec}$ according to the study of Amorim [15], Reitz [28] and Reitz and Diwakar [29] is:

$$r_{\sec} = 1.8 \cdot r_{fir} \cdot Oh_L^{0.2} / We_{G,\text{ mod}}^{0.25} \tag{4}$$

where, $We_{G,\text{ mod}}$ is the modified Weber number of gas for the high viscosity liquid.

After the rupture radius of water body is obtained, it can be considered as a small droplet, and then the volume and mass can be calculated. Based on it, the dynamic equation of the droplet is given in the ground coordinate system in Fig 2. And the influence of wind field $\vec{U}_W(U_{Wx}, U_{Wy}, U_{Wz})$ on droplets is also considered according to Lei *et al.* [30] and Farley and Orville [31]:

$$m_L \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \vec{i} \\ \vec{j} \\ \vec{w} \end{bmatrix} \left[\vec{G} + \vec{D} + \vec{B} + \vec{C}\right] \tag{5}$$

where, m_L is the quality of the droplet, a_x, a_y, a_z are the acceleration components of the droplet, $\vec{G}$ is universal gravitation, $\vec{D}$ is air drag, $\vec{B}$ is air buoyancy, and $\vec{C}$ is Coriolis force. The

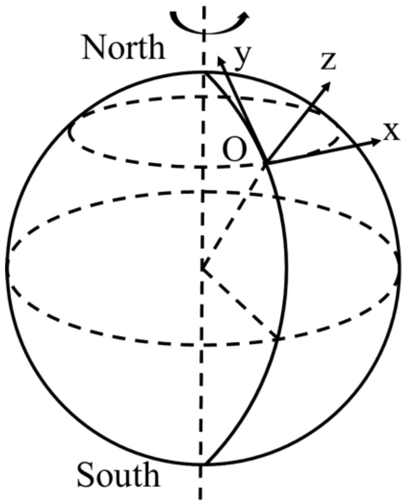

FIGURE 2. Ground coordinate system.

calculation of air drag $\vec{D}$ needs to use the relative velocity $\vec{U}_R(U_{Rx}, U_{Ry}, U_{Rz})$ of the aircraft relative to the wind field. The relative velocity could be calculated as:

$$\vec{U}_R = \vec{U}_A - \vec{U}_W \tag{6}$$

where, $\vec{U}_A$ is the absolute velocity of FWFA to the ground. Corresponding to x, y, z coordinate axis, it can be expressed as:

$$\vec{U}_A = \dot{x}\vec{i} + \dot{y}\vec{j} + \dot{z}\vec{w} \tag{7}$$

The time when the water starts to drop is $t = 0$, and the water body dropped in the period from t to $t + \Delta t$ is regarded as a whole. Without considering the volume and diffusion deformation of this water body, based on the above dynamic model, the central landing point of each water body can be obtained. And then the central trajectory of ground distribution can be gotten.

c. In the diffusion distribution stage, the relationship among the water-dropping scheme, the above parameters, the diffusion radius and ground distribution of water body needs to be built. Combined with the jet theory from Albertson *et al.* [32] and the experimental fitting model of Legendre *et al.* [16], it can be seen that after reaching a certain height, the evaporation and dissipation of the droplet will stop the expansion of the diffusion radius. Therefore, the entire diffusion radius of the water body will expand in accordance with the law of jet flow first. After reaching a certain diffusion radius, it will fall at the same radius. Then, the diffusion radius R_{diff} can be expressed as:

$$R_{diff} = \min(0.25H, 0.5\sqrt{S_0}f_c q^{0.2}) \tag{8}$$

where, f_c is the correction coefficient, and q is the momentum ratio.

According to the fitting result from Legendre *et al.* [16], the horizontal water density η of the water body could be set as:

$$\eta(y) = \eta_{\max}\exp(-9y^2/4\ln(2)\lambda_0^2) \tag{9}$$

where, $\eta_{\max}$ is the maximum coverage level, y is the lateral position, and λ_0 is the correction coefficient of diffusion radius.

Based on the above central trajectory of ground distribution, the central point of each grid is used to find the nearest center trajectory coordinate. Then (9) is used to calculate the water density, and the distribution of the whole water can be obtained.

NWM can be completed based on the above three contents. It is suitable for constant flow system and constant pressure system.

The construction of the model is based on a two-dimensional ground grid. As the length and width of water-dropping distribution vary greatly, the grid scale should be controlled at 1 m in order to achieve ideal accuracy for the division of square grids. Therefore, it is necessary to simplify the NWM.

2) DESCRIPTIVE WATER-DROPPING MODEL

Through numerical calculation, under the trajectory of straight flight, the ground distribution of the constant flow system presents a rectangular distribution, and the longitudinal water distribution of the water belt is the same. Therefore, if the ground distribution at both ends is ignored, the rectangle of edge zone can be used to represent the periphery of water distribution. Further, because the water distribution is concentrated in the middle and sparse at the edges, the water distribution could be divided into effective fire extinguishing zone and cooling and humidifying zone by referring to coverage factor of evaluation index of aerial suppression drops from Plucinski and Pastor [33]. Among them, the effective fire extinguishing zone is the area where precipitation reaches the minimum fire extinguishing demand. Its boundary is obtained by calculating the water per unit area of the grid and comparing it with the minimum fire extinguishing demand η_{eff}.

The principle of fire extinguishing by water is mechanical action and cooling action. In actual firefighting mission, the falling water body has a huge impact force through acceleration and could cool down by gasification. It is an effective way to put out fires by dropping large water droplets on burning combustible materials. For the typical Chinese vegetation, Chen *et al.* [34] points out that the minimum fire extinguishing demand is $1-2.5kg/m^2$. It should be noted that this value can be selected according to different vegetation conditions, and the area of the fire extinguishing zone will change accordingly. The value in this paper is determined to be $1.2kg/m^2$.

The effective fire extinguishing zone also ignores the semicircular water distribution at the head and tail and could be set as a rectangle. The cooling and humidifying zone can only achieve the function of cooling and humidifying due to less precipitation, and it is the part that does not coincide with the rectangle of the edge zone and the effective firefighting zone. To determine the rectangle, five parameters are required: center point coordinates (two parameters corresponding to the coordinate axes), angle (the angle between the center point and the midpoint of the wide side), length and width.

According to NWM, it is easy to know that, for the cooling and humidifying zone, length of the edge zone rectangle is the flight length of FWFA in the water-dropping process, and the angle of this rectangle corresponds to the flight angle of the aircraft. The width corresponds to the diffusion radius. Only the width of the effective fire extinguishing zone rectangle is different, which can be given by the effective radius R_{eff} corresponding to $\eta = \eta_{eff}$ from (9). The five parameters of the two rectangles can be calculated as follows:

$$rect_{bor} \text{ or } rect_{eff} \begin{cases} L = V \cdot t_{th} \\ W = 2R_{diff} \text{ or } R_{eff} \\ x\_center = x + 0.5L \cdot \cos(ang\_) \\ y\_center = y + 0.5L \cdot \cos(ang\_) \\ ang\_ = \theta \end{cases} \quad (10)$$

In the same way, for the constant pressure system, since its ground distribution is fusiform belt, it cannot be represented by a simple rectangle. The polygon combined with trapezoid and triangle is considered to represent the water belt. Because the density of water is gradual with the central trajectory, use dichotomy method to quickly find the water body corresponding to $\eta_{\max} = \eta_{eff}$ as the end water body. According to the flight distance corresponding to the end water body, the total length from the beginning of water-dropping could be divided into three equal parts, and the water body corresponding to each third of the total length is used to calculate the diffusion radius R_{diff} and the effective radius R_{eff}. In the current tripartite case, two trapezoids and a triangle are formed. The length of the top and bottom of the trapezoid is 2 times of the corresponding radius, and the height is the flight distance of the corresponding water body. The vertex of the triangle corresponds to the central trajectory coordinates of the above end water body. Since there are common points, a total of seven points can represent the corresponding zone. Of course, the accuracy of the description of effective fire extinguishing zone and cooling and humidifying zone could be improved by more delineation, but the time and computational cost would be increased accordingly.

Finally, DWM can be completed by forming the polygon of the edge zone and the effective fire extinguishing zone by seven points. DWM is used to complete the transformation from grid ground distribution to water distribution polygon. Here, the water distribution rectangle applied to the constant flow system is the special case of the water distribution polygon.

After constructing the relationship between the water-dropping scheme and the water distribution polygon, the calculation still needs to solve the partial differential equations in the dynamics part, which still brings calculation pressure to the optimization.

3) AGENT WATER-DROPPING MODEL

In the face of the above problem, this paper uses neural network to seek a simplified agent model to describe the relationship between the two, so as to further reduce the computational effort. The principle and application steps of neural network can be found from the work of Zhao *et al.* [35] in great detail.

Firstly, the samples should be provided for the training of neural network. The training samples consist of input data sets and output data sets. What needs to be noted here is that it takes time for the generation of the samples and the training of the neural network. In practical application, the agent model should be trained in advance and then applied in emergency events. Since the wind field can be considered unchanged at the time of water-dropping, and it is impossible to predict the wind direction during training, so wind field information should also be used as training input. Input parameter X is determined as:

$$X = (H, V, x, y, ang, U_{Wx}, U_{Wy}, U_{Wz}) \quad (11)$$

Input data sets consist of input parameters.

Next, the boundary of input parameter X shall be determined accordingly. The range of input parameters is discussed below. For FWFA, too slow speed will lead to aircraft stall, and too fast speed will aggravate water atomization, which will lead to firefighting efficiency decline. For the flight height, a too low height will easily lead to the danger of entering smoke or the ground, a too high one will also increase the vaporization of water body and lead to the decrease of firefighting efficiency. Referencing the research of Yongliang [19], the constraint is set as $H \in [40, 70]$ and $V \in [60, 80]$.

Under normal circumstances, the fire extinguishing crew always drives to the fire target directly ahead. At the same time, in order to ensure a relatively sufficient exploration area, the fire area should be located with a peripheral boundary 75m from the left and an 80-110m boundary from the bottom. Here, the position of the lower boundary corresponds to the different water-dropping system, which needs to be corrected according to the advance distance of the first water body. As the fire line is relatively thin, the left and right boundary range is mainly between 0-150m. Then the constraint can be set as $x \in [50, 100]$, $y \in [50, 100]$ and $\theta \in [45, 135]$, so as to ensure that the aircraft has enough exploration area. In the wind field, it is not suitable for the violent wind field to drop water, and the airflow in the vertical direction should not be too large. Through the investigation of flight crew, the wind field constraint is set as $U_{Wx} \in [-3, 3]$, $U_{Wy} \in [-3, 3]$ and $U_{Wz} \in [-0.3, 0.3]$. This range ensures the safety of firefighting missions, which is basically within force 3 wind.

Input data sets are randomly generated within the above range. Then output data sets could to be generated by DWM, which are the sets of point coordinates of the corresponding zone. Considering the time and training requirements, 10,000 data sets are respectively created for constant flow and constant pressure systems. According to previous studies of

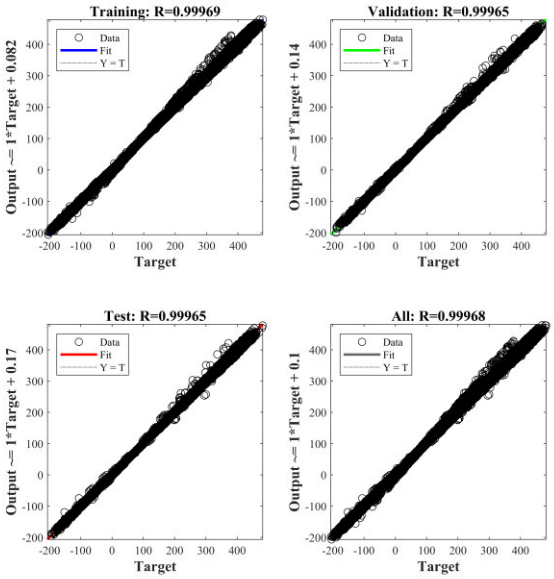

FIGURE 3. Regression of constant pressure system training.

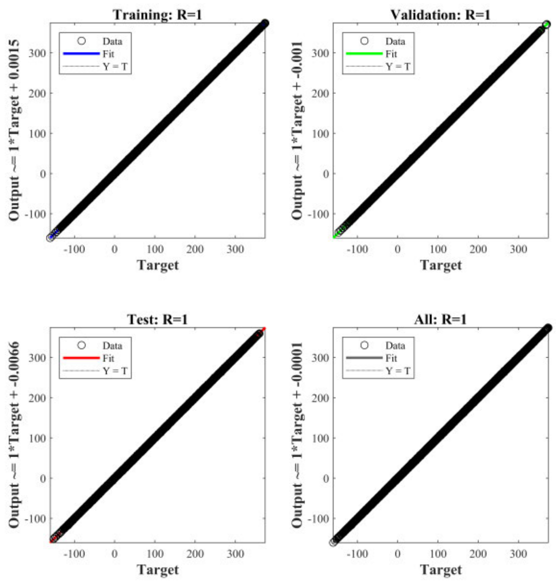

FIGURE 4. Regression of constant flow system training.

Zhou and Kang [36], the hidden layer of the neural network is set as 2 in this paper, and the number of nodes is 10 and 8 respectively. It can be seen that the correlation coefficients R for both systems are ideal (The closer the correlation coefficient is to 1, the better the fitting effect is), which means the fitting effect is good from Fig 3 and Fig 4. The construction of AWM is completed.

4) SUMMARY

In this way, NWM, DWM and AWM jointly completed the establishment of the water-dropping model. The relationship of three models is shown in Fig 5. The input parameters

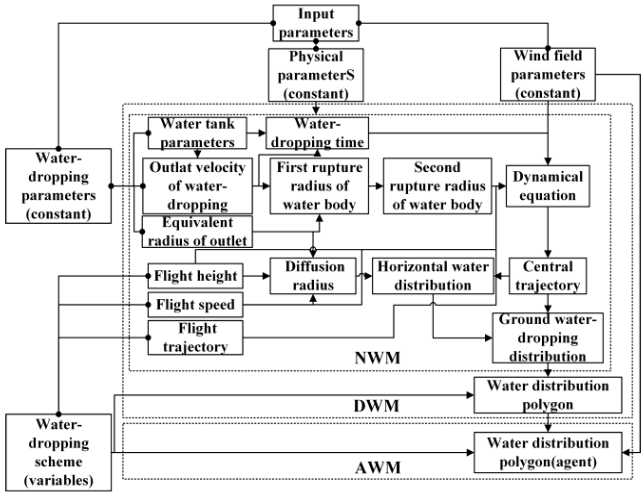

FIGURE 5. Water-dropping model framework.

required by the water-dropping model are divided into four parts, namely, water-dropping parameters, physical parameters, wind field parameters and water-dropping scheme. The first three are manual input parameters. Among them, the water-dropping parameters include the length, width and height of the water tank, the outlet velocity of water-dropping (relative to the aircraft), and the equivalent radius of outlet, which are constant parameters for the aircraft of a determined type. Physical parameters including gravitational acceleration, water viscosity coefficient, etc., can be considered constant. Because the water-dropping time is short, the wind field is assumed to be fixed for simplification. In this way, only the change of water-dropping scheme affects the ground distribution of water. It builds a relationship between the two. In the study of this paper, the scheme includes flight height (relative to the ground), flight speed and flight trajectory. Due to the water-dropping time is short and the safety of the mission, assume that the flight height and speed don't change during the period of dropping water and the trajectory is a straight line. Under these assumptions, flight trajectory corresponding to the initial trajectory point and initial azimuth angle can be obtained. And the relationship between the water-dropping scheme and the grid ground distribution could be built in NWM. DWM is got on the basis of NWM by using the distribution polygon to represent the grid distribution, and AWM is obtained by training in the samples of DWM. AWM is used for subsequent optimization. It should be noted that this study only focuses on flat terrain, and complex terrain with slope will be carried out in the follow-up study.

Further comparisons are made between the water-dropping distributions obtained by NWM, DWM and AWM. It can be seen that DWM can accurately describe the water-dropping distribution characteristics in Fig 6. While AWM has certain errors. but the characteristics of water edge zone and effective fire extinguishing zone are also described roughly. It can be used for subsequent optimization work.

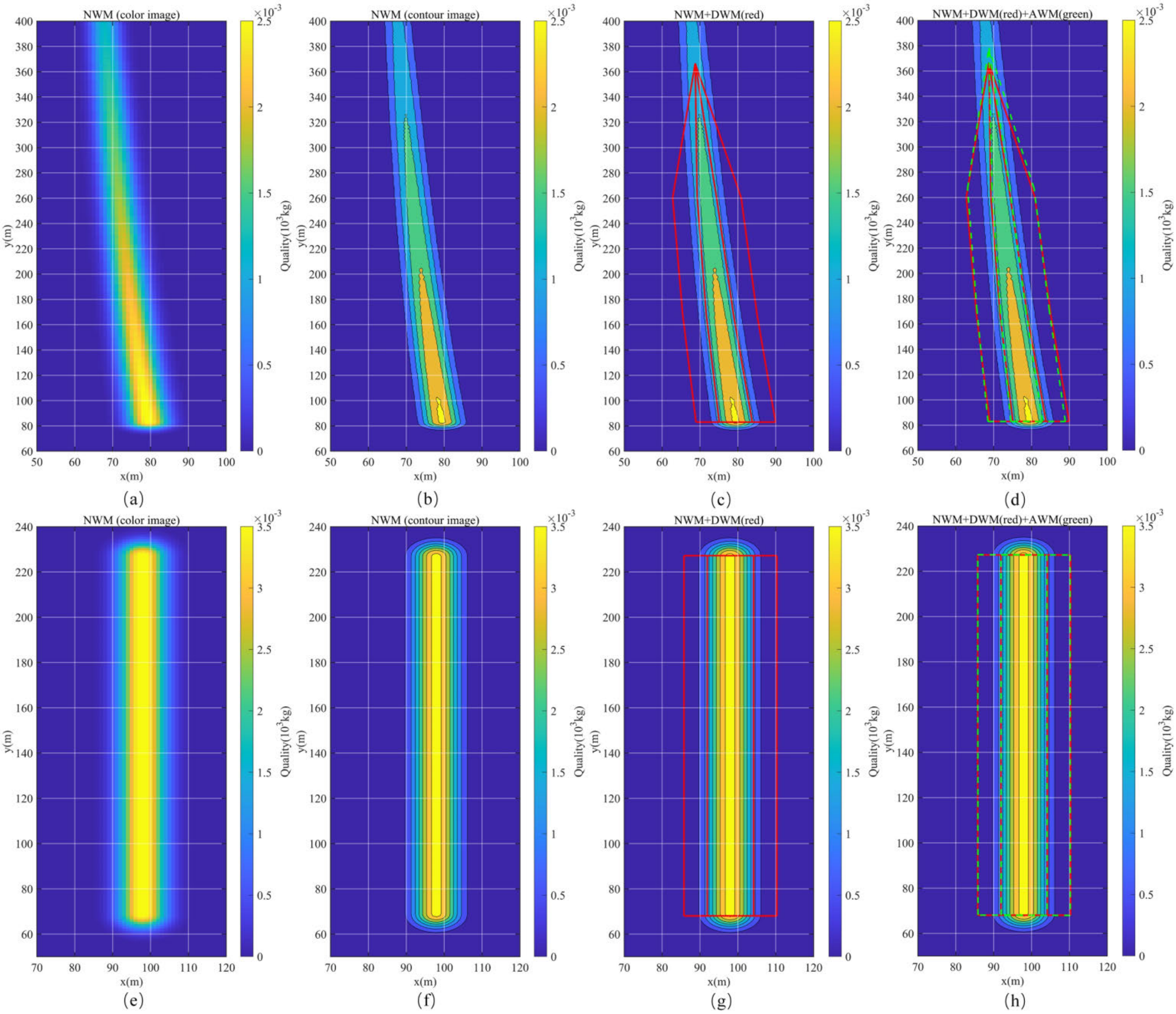

FIGURE 6. **Simulation results of water-dropping model, (a)-(d) constant pressure system, (e)-(h) constant flow system.**

B. FIRE AREA MODEL

A great number of researches have been done on fire area model, which could be taken as the target to be covered by water body. Aerial firefighting is commonly used for wildfires. By vegetation type, wildfires can be classified as forest fires, bush fires and cover plant fires. Furthermore, fire spread is affected by many factors like terrain, weather, vegetation type and other according to Angle *et al.* [37]. Because this paper is not focused on the fire model, but the optimization method. In this section, we mainly explain how to discretize the continuous fire area into points, so as to achieve the matching and optimization of the corresponding water distribution polygon.

At the same time, we provide a fast method to calculate the fire area with the input of the predicted fire line according to the actual demand in southwest China. The method takes into account fixed wind fields and vegetation types. The predicted fire line can be detected by infrared detection equipment mounted on satellites or drones from study of Ollero and Merin [38].

1) CALCULATION OF FIRE AREA

The spread speed of fire line F_0 is defined by the study of Rothermel [39]:

$$F_0 = \frac{I_r \xi}{\rho_b \varepsilon Q_{pr}} \times 0.3048 \tag{12}$$

where, I_r is reaction intensity, ξ is propagating flux ratio ρ_b is ovendry bulk density, ε is effective heating number and Q_{pr} is heat of preignition. The values of these variables vary with different vegetation types.

By using revised wind direction model of Mao [40], the fire spread speed under wind field F is:

$$F = F_0 e^{0.1783 W_{map}} \tag{13}$$

where, W_{map} is the mapping of wind speed in the direction of spread. Since the water-dropping model is suitable for the flat terrain, only the flat terrain is considered for the fire spread, and the terrain correction coefficient from the work of Wang [41] could be ignored.

The complete combustion model obtained by Liu *et al.* [42] and Collin *et al.* [43] is as follows:

$$\begin{cases} \rho(C_s + H_\mu C_l)\dfrac{dT}{dt} = h_{tran}(T_a - T) + \rho\dfrac{dH_\mu}{dt}L_{ev}\delta_{T=T_{ev}} + p_r \\ \dfrac{d\rho}{dt} = -\rho\alpha\exp(-\dfrac{E}{R_G T})T \geq T_{\text{ig}} \text{ and } \rho \geq \rho_{ext} \end{cases} \tag{14}$$

where, T_a, T_{ev}, and T_{ig} represent the ambient, evaporation, and ignition threshold temperature, C_s is the heat capacity of fuel, C_l is the heat capacity of water, h_{tran} represents the heat transfer coefficient, L_{ev} is the evaporation latent heat of water, p_r is the density of total radiation power ρ_{ext} is residual ash density, α is the prefactor, R_G the ideal gas constant, E the activation energy and the δ is the Dirac symbol. For the sake of simplicity, in the short time to drop water, the above variables are assumed to be constant values and the way to calculate them is to refer to Liu *et al.* [42]. And density ρ, relative fuel moisture H_μ and temperature T could change over time.

Based on the complete combustion model, the whole fire area can be divided into 7 stages corresponding to the changes of three variable, including density, relative fuel moisture and temperature. And the corresponding time t_{stage} of each stage could be calculated.

Then, the corresponding length L_{stage} of each stage can be calculated by the following formula according to Rothermel [39]:

$$L_{stage} = F t_{stage} \tag{15}$$

In the simulation, the normal direction of the connection between each two nodes is the spreading direction of the fire line. Calculating the length of each stage in this direction can be extended from the fire line to the construction of the fire area. The arc between the two fire lines is negligible.

What needs to be emphasized in particular is that the transmission of fire line under real conditions is unstable due to the radian and other factors. But for the moment of water-dropping, the fire area can be considered to be constant and stable transmission. If conditions permit, more accurate predictions of fire areas can be obtained by other means. According to the subsequent optimization time, it is recommended to predict the fire line input in about four minutes.

2) DISCRETIZATION OF FIRE MODEL

If the obtained fire area is successively retrieved and evaluated through the grid, the resources occupied by the calculation optimization will be very large and cannot meet the requirements of rapidity. Inspired by the solution to planning the maritime search and rescue area of Chen *et al.* [26], this paper uses the fast Poisson dish sampling algorithm of Bridson [44] to realize the characterization of the fire area with discrete points.

Based on the above fire area model, according to the relevant parameters of the fire area and the wind field data, the fire spread speed could be calculated. Meanwhile, the corresponding time of each stage of the fire area could also be obtained according to the complete combustion model. The length of each stage of the fire area is got by the speed and time, and combine the input data of the predicted front fire line to create the range of the fire area. In this study, the fire model does not need very detailed research, therefore, some stages of the fire area will be integrated. It goes to infinity in stage 1 and stage 7, so only the stage from 2 to 6 need to be considered. According to the boundary of fire area, the five stages are divided into burning zone 5, burned out zone 6 and unburned zone 2-4. By selecting a reasonable distance of sampling points, the characterization of the three zones of the fire area can be realized. Considering that the fire line is a long and thin strip, the minimum distance should be representative in the width of each area. According to the domestic firefighting example, the long fire line will be generally put out in sections, and the length of sections will be controlled below 300m. So, the total length of the fire line is also suggested to be around 200-300m. Considering the amount of calculation, 30%-50% of the area length is suggested to determine the minimum distance for control in this paper, which can control the total number of discrete points around 1500-2000.

The discretization of the fire area by applying this method is shown from (a) to (b) of Fig 7.

C. EVALUATION MODEL

In this section, the firefighting efficiency evaluation model will be set up as the optimization objective. The ultimate goal of this study is whether the water body can effectively cover the fire area to extinguish the fire. Therefore, the main optimization objective is the firefighting efficiency of water body. In this paper, the effective utilization rate of water body A is used as the corresponding evaluation index. The points in the different fire zone will drop in effective fire extinguishing zone or cooling and humidifying zone, resulting in six situations. Considering the cooling effect and humidification effect of water, this paper uses analytic hierarchy process (AHP) introduced by Guo *et al.* [45] to calculate the weight of different situations for every single point. Then, calculate the number of different points in different zones and take the weighted sum as the final effective utilization rate.

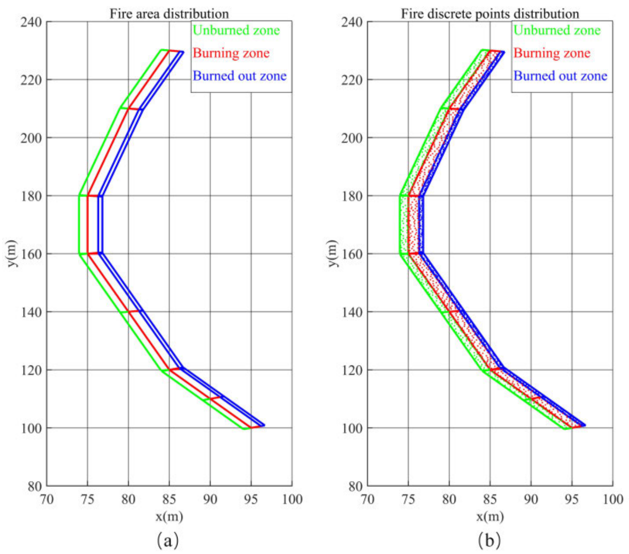

FIGURE 7. Simulation results of fire area model.

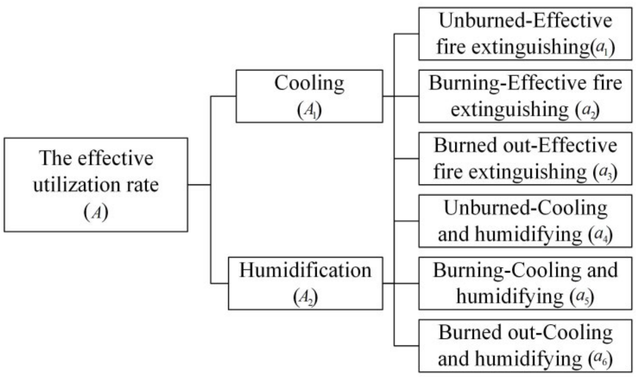

FIGURE 8. Hierarchical structure of index *A*.

Here, the hierarchical structure corresponding to index A is established in Fig 8.

According to the three zones corresponding to the fire area, when the water drops in burning zone, it can directly play the fire extinguishing effect. And it will suppress reignition on the burned out zone and plays a role in cooling and humidifying on the unburned zone. So, different weights need to be calculated for different situations. With the help of pilots and experts, the AHP analysis is used to form the judgment matrixes and take consistency test, and the final weights are shown in Table 1:

The formula for index A is as follows:

$$A = \sum_{i=1}^{6} n_i(w_1 a_i(A_1) + w_2 a_i(A_2)) \tag{16}$$

where, n_i is the number of discrete points in the case i.

Furthermore, considering the special case that the water quantity will not match the fire area, the optimization based on the index A alone will have numerous optimal solutions. This includes excessive water-dropping area covering all the fire area within the effective firefighting zone. Therefore, four indexes, height safety index B, speed safety index C, trajectory point efficiency index D and trajectory angle efficiency index E, are introduced as the minor objectives considering the factors of flight safety and admission efficiency. In this way, all the water-dropping schemes have the optimization direction under the same index A. The solution is guaranteed to have strong convergence.

TABLE 1. Weight table of index *A*.

Type ($j = 1, 2$)	A_1	A_2
Weigh (w_j)	0.6667	0.3333
$a_1(A_j)$	0.1658	0.1513
$a_2(A_j)$	0.5529	0.5470
$a_3(A_j)$	0.1125	0.1189
$a_4(A_j)$	0.0781	0.0855
$a_5(A_j)$	0.0319	0.0342
$a_6(A_j)$	0.0588	0.0630

The formulas of index B and index C under flight safety consideration are as follows:

$$\begin{aligned} B &= |H - H_{ideal}| \\ C &= |V - V_{ideal}| \end{aligned} \tag{17}$$

The formulas of index D and index E under the consideration of admission efficiency are as follows:

$$\begin{aligned} D &= \sqrt{(x - x_{ideal})^2 + \left(y - y_{ideal}\right)^2} \\ E &= |\theta - \theta_{ideal}| \end{aligned} \tag{18}$$

For index B, C, D and E, ideal safe height H_{ideal}, ideal safe speed V_{ideal}, ideal entry point x_{ideal}, y_{ideal} and ideal entry angle θ_{ideal} should be specified before optimization. Considering the safety of the aircraft, the pilot wants to drop water at a faster speed and a higher height, so the ideal height and speed are the maximum values in the range $H_{ideal} = 70$ and $V_{ideal} = 80$. For the entry point and direction, it is desirable to enter as parallel as possible to one side of the fire line in order to better prepare for the water-dropping mission. Therefore, within the search area, the value is set to $x_{ideal} = 50$, $y_{ideal} = 0$ and $\theta_{ideal} = 90$. Of course, these values can be modified to meet other requirements, but the goal is to make the optimal solution convergent.

D. COMBINED GENETIC ALGORITHM

Based on the above evaluation model, in which index A is taken as the main optimization objective, and when A is the same, the multi-objective optimization of index $B - E$ is considered. Because the tradeoff between different indexes is more difficult. Therefore, the multi-objective optimization

GA based on non-dominated sorting is used to realize the optimization. As the number of multi-objective optimization parameters is 4, the combination between the single main objective optimization and nondominated genetic sorting algorithm III (NSGA III) proposed by Deb and Jain [46] is adopt. The independent variables of optimization are the parameters of water-dropping scheme, the value range of the five variables is the same as the neural network training sample above, which is expressed as follows:

$$WS = (H, V, x, y, \theta) \tag{19}$$

Based on the above five parameters and AWM, the water distribution polygon can be obtained, and then the calculated discrete points of fire area can be used to evaluate. The optimization problem can be expressed as:

$$\begin{aligned} & main \min \left(1 - A/A_{ideal}\right) \\ & minor \ \min[B, C, D, E]^T \\ & s.t.\ H \in [40, 70], \quad V \in [60, 80], \quad x \in [50, 100] \\ & \quad y \in [50, 100], \quad ang \in [45, 135] \end{aligned} \tag{20}$$

Here, the effective utilization rate of water body is transformed into the minimum optimization problem, and A_{ideal} is the effective utilization rate when all the fire area points drop in effective fire extinguishing zone. In the optimization process, the selection of each iteration is based on the main objective. When the values of the main objective are the same, the non-dominated method and the reference point selection method of NSGA III are used for selection based on minor objectives. Then an iteration update will be completed.

In NSGA III, reference point selection is involved. In this study, the structured method is used to generate hyperplane reference points from the work of Das and Dennis [47]. Since there are four sub-targets to be optimized, considering the amount of calculation, each target is selected to be divided into 8 equal parts, and there should be 495 reference points. Use the simulated binary crossover (SBX) operator and polynomial mutation to update the population. The crossover parameter and mutation parameter are set as $\eta_m = \eta_c = 20$ according to the classical nondominated genetic sorting algorithm II (NSGA II) proposed by Deb *et al.* [48], and the mutation probability and crossover probability are set as $p_m = 0.1, p_c = 0.9$, which is the same value from the application of Bodenhofer [49].

The detailed processes are shown as follows:

Step1: generate the reference points and first generation population P_1, including optimization variables *data* and the main optimization objective cost $= A(data)$. The number of populations is N;

Step2: for each generation t, population P_t is sorted by main objective, which can be divided into sets $(O_1, O_2, \cdots)$. Then population P_t is sorted by other minor objectives, which can be divided into sets $(F_1, F_2, \cdots)$;

Step3: get a reconstruction of population P_t^{rec} based on the main objective sets $P_t^{rec} = P_t^{rec} \cup O_k$. In the case of the same main objective, selection is according to the sets of minor objectives $P_t^{rec} = P_t^{rec} \cup F_i(K)$. The number of members to be selected K is decided by minimum value between the size of current minor objective set F_i and the gap to generate the new reconstruction population;

Step4: generate the new population P_t^{new} using crossover and mutation;

Step5: combine the two populations to get the next generation population $P_{t+1} = P_t^{new} \cup P_t^{rec}$.

After optimization, the result with the minimum main objective is selected as the final result, which will output the corresponding five optimize variables of water-dropping scheme. In this paper, the algorithm pseudocode and flowchart of the combined GA is shown in Fig 9.

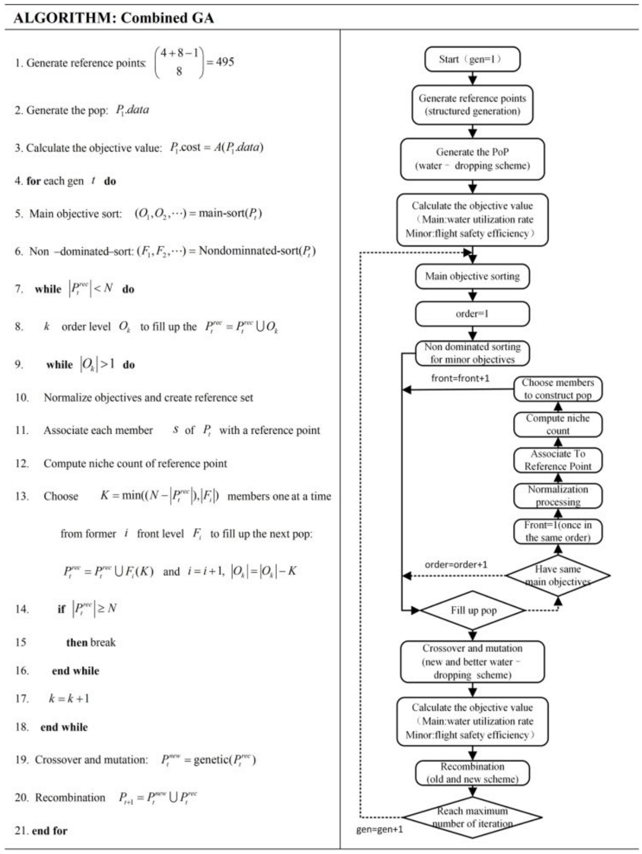

FIGURE 9. The flowchart and pseudocode of combined GA.

E. SUMMARY

The application diagram of optimization method is shown in Fig 10. The relationship between water-dropping scheme and ground distribution is built through the three water-dropping models in the first section. The water ground distribution could be divided into effective fire extinguishing zone and cooling and humidifying zone. The fire area model in the second section is used to represent the three zones of the fire area with discrete points. Based on the position of the distribution polygon calculated by AWM and the discrete

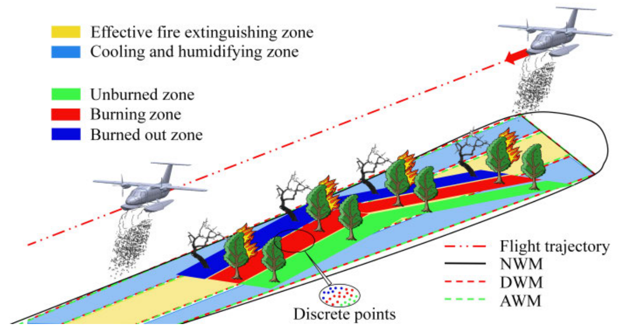

FIGURE 10. The application of optimization method.

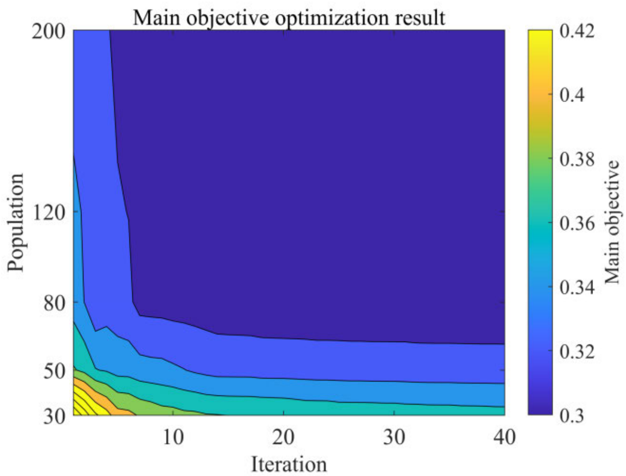

FIGURE 11. The variation of main objective value with the change of population and iteration number.

points, the main optimization objective can be obtained using the evaluation model in the third section. Finally, considering the minor objectives, use the combined GA to realize the rapid optimization of water-dropping scheme.

III. SIMULATION EXPERIMENT

The following simulations were performed on a personal computer with Intel Core i7-9700KF CPU, 16 gigabytes RAM, GTX 2060 m GPU and running on Windows 10 64-bit OS.

A. OPTIMIZATION PARAMETER SELECTION AND FEASIBILITY ANALYSIS

The two important parameters that need to be determined in the use of the combined GA are population number and iteration number, which directly affect the stability of the results and the speed of the method. So, the reasonable population number and iteration number are determined from the stability and time as constraints.

Because the constant pressure system has a large amount of calculation, different population numbers are set as the test objects for the simulation of this water-dropping system. The relationship between the operation times and the main

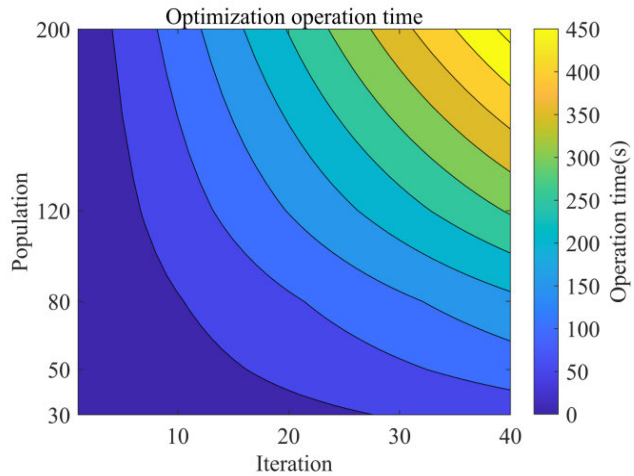

FIGURE 12. The variation of operation time with the change of population and iteration number.

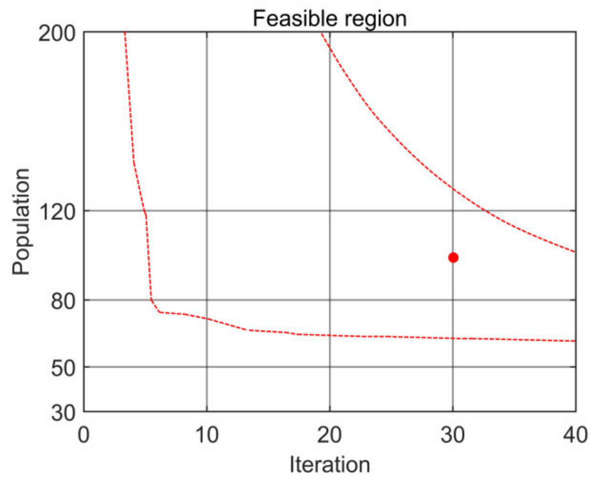

FIGURE 13. The feasible region of iteration and population number.

objective values as the number of iterations changes are obtained. Each population number is simulated for 50 times and the average value is taken to make contour chart with the change of iteration number and population number.

When the population size is too small, the global optimization ability is lacking and the stability of the solution is poor from Fig 11. Similarly, when the iteration number is too small, the optimization is incomplete. With the increase of population number and iteration number, the main objective of the algorithm becomes smaller and tends to be stable.

It can be seen that, as the number of populations and iterations increases, the operation time will increase accordingly in Fig 12.

Here, in order to ensure timeliness and accuracy, the main objective value of 0.32 and the operation time of 200s are selected as the boundary to obtain the corresponding feasible region in Fig 13. In this feasible region, good convergence and stability can be achieved and the requirements of solution

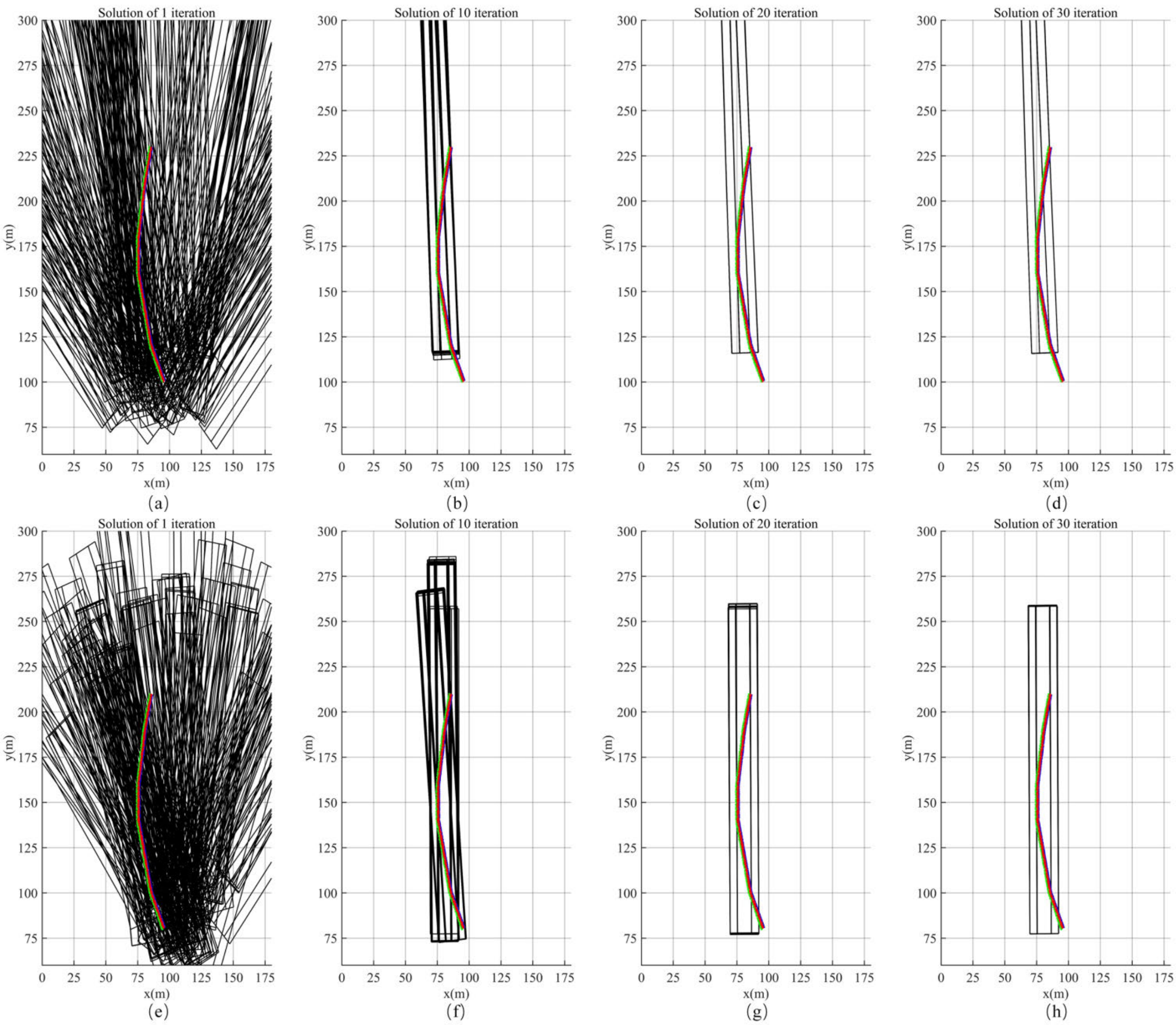

FIGURE 14. Optimization process, (a)-(d) constant pressure system, (e)-(h) constant flow system.

time can be met. The subsequent simulation in this paper adopts 100 population number and 30 iteration number. It's within the planning feasible range.

Meanwhile, corresponding to the above input of the fire line, constant pressure system (free water-dropping) and constant flow system are respectively used for optimization and the changes in the process are recorded in Fig 14.

As can be seen, with the increase of iteration number, the water-dropping polygon converges towards the fire line, which is the result of the main objective playing a major role in optimization. After the completion of the final iteration, the optimal solution converges uniquely. It can be seen that the effective fire extinguishing zone covers the current fire line to a large extent, and the cooling and humidifying zone has also been better used. The above simulation results demonstrate the feasibility of this research method.

It should be noted that in the face of different water-dropping systems, the lower boundary needs to be changed to ensure that the exploration area is relatively abundant. The intuitive expression is that in the first iteration, the randomly generated water-dropping polygons are well arranged around the fire area, so that the solution can better explore the optimal solution to cover the fire area.

B. RAPIDITY ANALYSIS

The water-dropping model and the fire area model are the basic models. In this study, more attention is paid to the water-dropping model and its relationship with the water-dropping scheme. As mentioned above, due to the pressure of

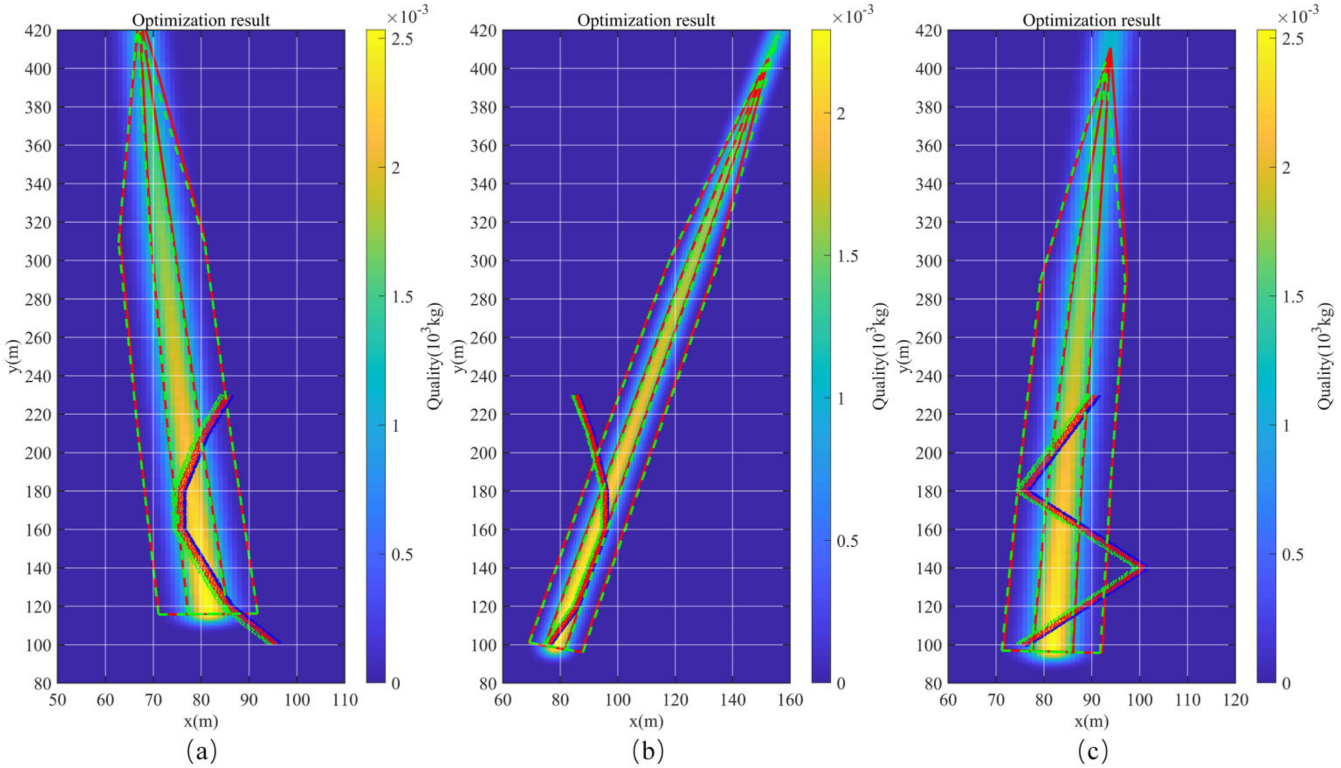

FIGURE 15. Comparison of images and main objective values between AWM (green) and DWM (red), (a) 0.2899(AWM) 0.2939(DWM), (b) 0.2991(AWM) 0.2928(DWM), (c) 0.4606(AWM) 0.4607(DWM).

calculation, NWM was simplified to DWM, and AWM was further trained by neural network. The following examples illustrate the advantages of AWM applications.

Three kinds of fire line input are simulated. These three inputs respectively consider the situations of convex, concave and combined fire line. After the optimized results are obtained by AWM, the corresponding water-dropping scheme is substituted as the input back to NWM and DWM to calculate the water-dropping distribution and the corresponding water-dropping polygon. On this basis, combined with the firefighting efficiency evaluation model, the different main objectives are calculated in Fig 15. It can be seen that the results of AWM are similar to the results of DWM under the same water-dropping scheme input, with main objective error of less than 5%, which verifies the effectiveness of AWM.

Furthermore, corresponding to the above three fire line inputs, AWM and DWM are used for optimization simulation under the same population number, each model was simulated for 100 times, and the comparison results of average main objective value and average operation time are obtained.

As can be seen in Fig 16, the optimization results of the AWM and DWM are close to each other, which echo the above results and further confirm the effectiveness of AWM. The operation time of AWM is basically less than half of the time of DWM in Fig 17, which can greatly improve

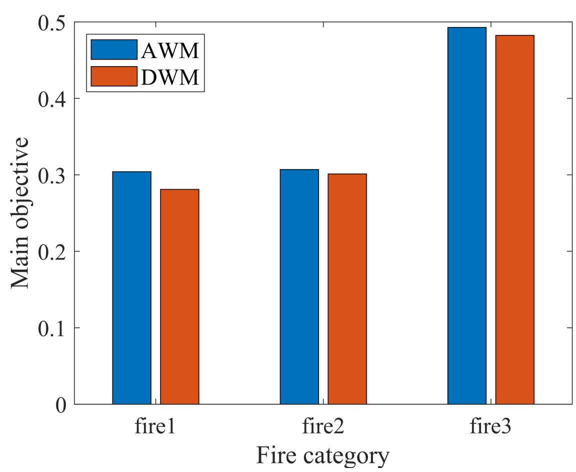

FIGURE 16. Comparison of main objective values.

the optimization efficiency and the rapid response ability of scheme optimization. It shows that AWM based on DWM in this method has the advantage of rapidity.

C. INFLUENCE OF WATER-DROPPING SCHEME PARAMETERS

Based on one of the above optimal solution, the influence of changing the parameters of the water-dropping scheme on

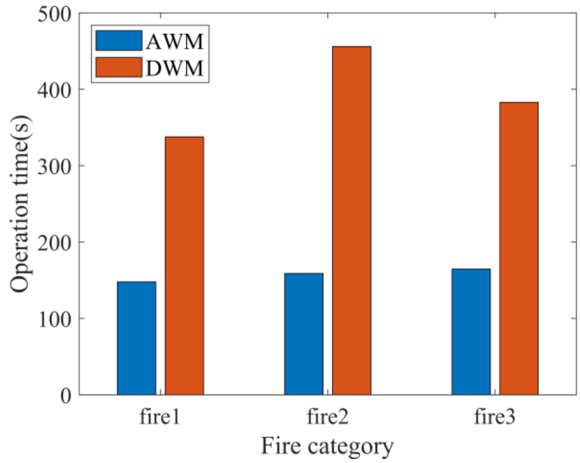

FIGURE 17. Comparison of operation times.

the water-dropping distribution is qualitatively analyzed by changing these parameters and making NWM diagram.

Firstly, change initial trajectory point in the water-dropping scheme. Since the wind field is constant, it can be predicted that the whole distribution has no change in shape, but only shifts with the change of trajectory point. Due to space constraints, graphic description is not shown.

Change the azimuth angle of water-dropping, and the corresponding results are shown in (a)-(d) of Fig 18. It can be seen that the whole water-dropping distribution will rotate with the rotation of water azimuth angle. Meanwhile, in this example, the water body is affected by the rightward wind field, and the distribution is basically on the right side of the trajectory of aircraft. If the angle is also to the right, the velocity component on the right will push the distribution of water further to the right.

It can be seen that with the increase of the height in Fig 18, (a) and (e)-(h), it will take longer time for the water body to drop on the ground, and the corresponding movement distance in the air will become longer, which is shown as the trajectory shifts to the right. Besides, at a higher height, the diffusion radius is approximately unchanged. When the height gets lower, the water will not have enough diffusion, which will make the diffusion radius become smaller and the water-dropping distribution becomes more concentrated, which is manifested as the increase of water distribution in every grid.

Change the speed in the water-dropping scheme. As it is shown in (a) and (i)-(l) of Fig 18. The flight trajectory of water-dropping will become longer with the increase of speed. And the corresponding diffusion radius will become smaller with the increase of unit water body's length. Therefore, the increase of speed will increase the length of the water-dropping distribution and therefore decrease the width of the distribution.

It can also be seen from the above discussion that initial trajectory point and initial azimuth angle have a great influence on the water-dropping distribution.

D. ADAPTABILITY TO SPECIAL FIRE AREAS

All the above-mentioned fire areas have long length, and it is difficult to completely cover the fire area with the effective fire extinguishing zone of water. In this section, special ignition sources or small fire areas are considered, in which the effective fire extinguishing zone of water body can completely cover the fire area. In this case, if the minimize transformation of the effective utilization rate is used as a single optimization objective, the situation with numerous optimal solutions will occur. So, the comparison between the single objective GA and the combined GA in this paper is made. Each method is simulated for 100 times. The population number is set as 100 and the number of iterations is 30. The result is calculated in Fig 19. It can be seen that the combined GA has good convergence characteristics and can complete the convergence before the 10th generation.

Moreover, the optimal solution of the main objective is 0, maximizing the utilization rate of water body, which is a correct result in accordance with common sense. However, single objective GA will slow down the solution convergence rate due to too many optimization directions, and even after 30 iterations, the water utilization rate still cannot reach the ideal minimum. It can be seen that the time spent on the combined GA is similar to that of the single objective GA from Fig 20, which indicates that the combined algorithm can be applied to solve the scheme optimization problem of the small fire area input without significantly increasing the operation time. It is proved that this method has the adaptability to special fire areas.

E. DISCUSSION

Through the above simulations, it is noted that the solutions of the same population are not the same in different optimizations, which indicates that the solutions may not the global optimal. On the one hand, the global optimization of the algorithm itself should be further improved, and on the other hand, the model and method should be improved to improve the non-convexity of the optimization problem.

This optimization method is currently applicable to the optimization of water-dropping scheme in flat terrain. Due to the limitation of data sources, the simulation uses a variety of assumptions, including the parameters of the aircraft water tank and the setting of the fire area. However, the overall optimization method can be applied to the problem of how to better cover the target zone by executing the optimized scheme. In other words, the target zone is discretized as points, and the weight of points in different water-dropping zones is different, so as to optimize the watering scheme corresponding to the better water distribution polygon.

In addition, the influence of the scheme parameters on the effect of water-dropping is discussed in the above example. At the same time, it should be noted that the consideration of environmental field in this paper is not perfect. Terrain factors will affect the flight safety of aircraft, the distribution of water and the spread speed of fire line will be also affected to a

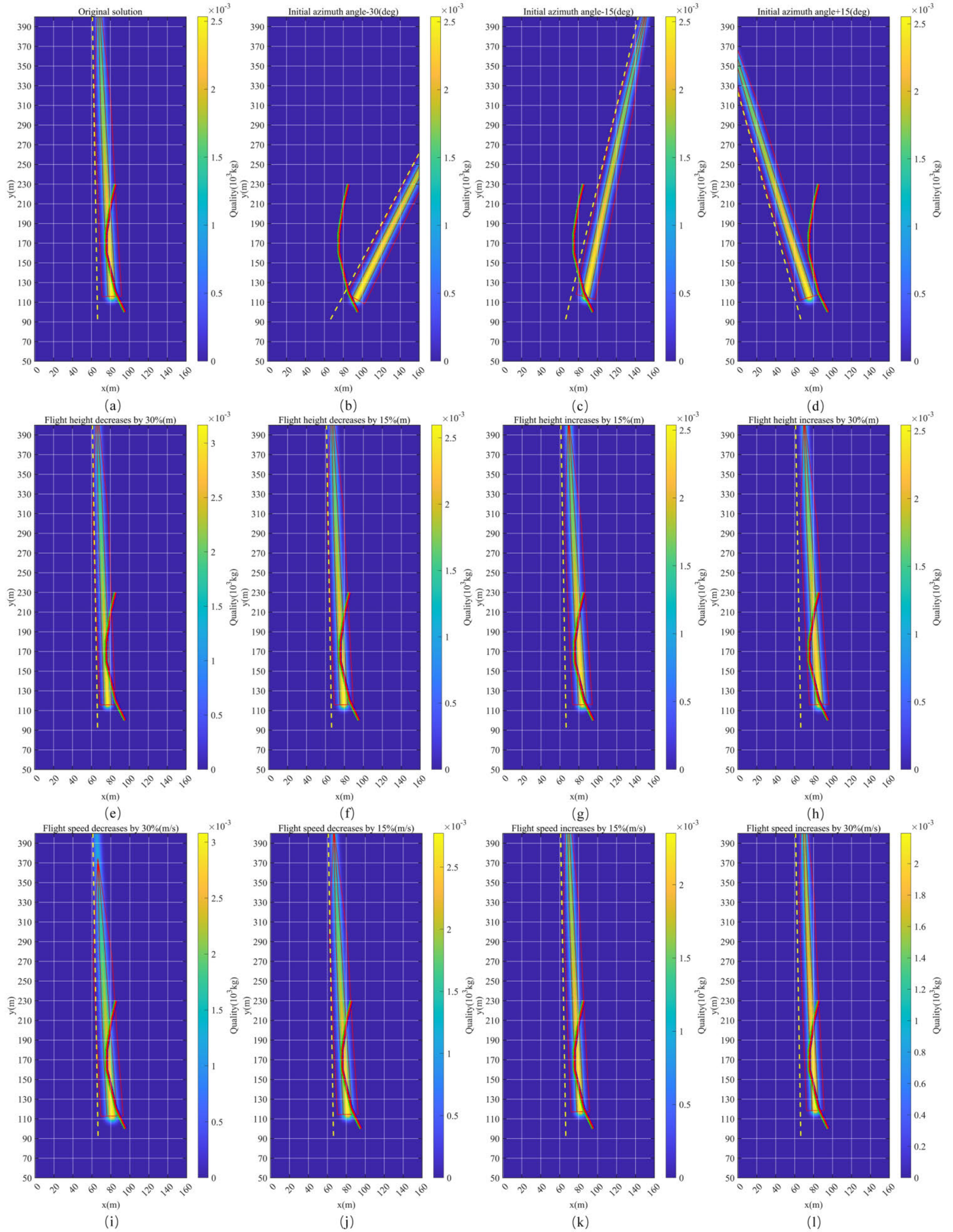

FIGURE 18. The influence of water-dropping scheme parameters to water-dropping distribution.

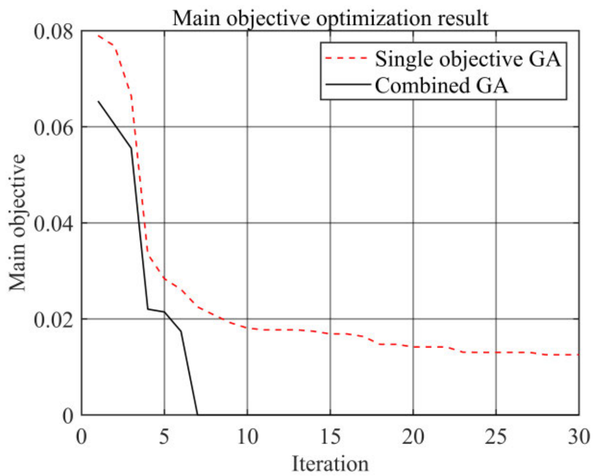

FIGURE 19. The variation of main objective value between two algorithms.

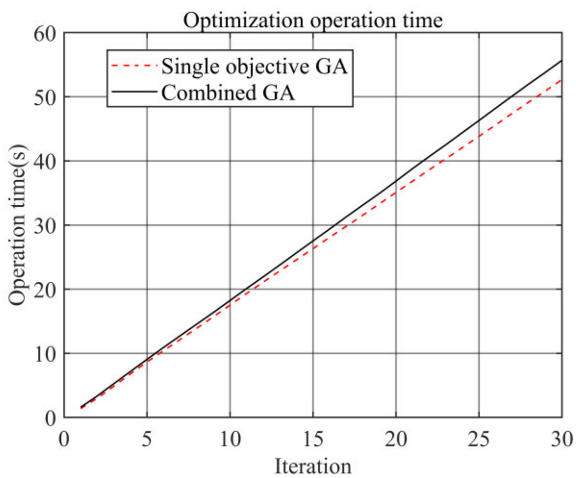

FIGURE 20. The variation of operation time between two algorithms.

certain extent. At the same time, the existence of smoke field will affect the flight safety of aircraft. Under the assumption that the wind field remains unchanged, the smoke diffusion will be affected by the wind, and the water-dropping will also be affected in the same direction. Therefore, the aircraft always drops water in the upstream direction of the smoke field, which is the research scope of this paper. However, if the wind field is unstable and different from each other, the smoke field will have complex diffusion and distribution, so it is necessary to conduct the research of smoke field avoidance. The above work will be carried out in the follow-up research.

IV. CONCLUSION

Aiming at the problem that the aircrew of FWFA rely on the existing experience to make the water-dropping scheme to extinguish the fire and lack the corresponding theory method support, this paper puts forward a fast optimization method of water-dropping scheme for FWFA. The water-dropping model, fire area model and efficiency evaluation model are established accordingly, and the combined GA is realized by combining the multi-objective optimization and single-objective optimization of GA. It can complete the rapid optimization of the water-dropping scheme of FWFA. This optimization method is suitable for the flat terrain and fixed wind field.

The water-dropping model is divided into three aspects: initial stage of water-dropping, rupture movement and diffusion distribution. On this basis, NWM with numerical precision calculation, DWM with shape parameter description and AWM with water-dropping model based on neural network training are established. The relationship between water-dropping scheme and water distribution of FWFA is built. The water-dropping model is suitable for flat terrain.

Under the study of complete combustion model, different stages are integrated. The fast Poisson's dish sampling algorithm is used to discretize the continuous fire area to discrete points. So, it can be matched with the water distribution polygon to optimize the scheme.

The firefighting efficiency evaluation model is constructed. The main objective is set as the minimize transformation of the effective utilization rate, and the weights of it are calculated by AHP. The safety index of height, speed and the efficiency index of trajectory point, trajectory angle are taken as minor objectives. It helps the algorithm have the fast convergence for both long and small fire areas.

Application examples show that the scheme optimization method proposed in this paper can optimize the water-dropping scheme for both constant flow system and constant pressure water-dropping system. It has feasibility, rapidity and adaptability to special points or small fire areas.

This method is not only applicable to the firefighting mission of fixed-wing aircraft, but also can be used in the scheme optimization of other emergency situations, including sprinkling flame retardant and offshore oil spill treatment, which are all the problems of how to better cover the target zone by executing the optimized scheme. This method will be further improved and applied to the scheme planning system of FWFA, and to a certain extent, it will be used as auxiliary decision support for actual aerial firefighting mission.

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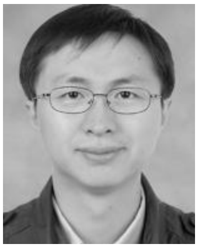

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