Optimal allocation strategy for temperature and humidity based on improved glowworm swarm optimization algorithm

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Abstract. Aiming at the problems that the factors such as strong temperature and humidity coupling, nonlinear time delay and other factors of flower vending machine which affects the optimal matching of the power of the machine. This paper proposed a temperature and humidity optimization allocation strategy based on a variable-step adaptive glowworm swarm optimization algorithm. By studying flower storage constraints, temperature and humidity coupling characteristics and analyzing the influence of temperature and humidity coupling coefficient on the operation cost of flower vending machine. This paper established a temperature and humidity power optimization matching model of the machine with the goal of the optimal economy, and used fuzzy control and improved glowworm swarm optimization algorithm to adjust compensation parameters and optimize the objective function respectively. Simulation results showed that the optimized allocation strategy proposed in this paper effectively reduced the energy consumption of the equipment and improved the economic efficiency of the whole machine.

1. Introduction
Temperature and humidity are two crucial factors in the growth and storage of flowers. The average optimal temperature and humidity for flower storage are 7 °C and 60%, respectively[1]. The traditional vending machine only has an automatic sales function which cannot realize constant temperature and humidity storage of flowers, potted plants, fresh products and the like. Therefore, it is urgent to develop a flower vending machine to achieve high-precision temperature and humidity control of the cabinet, increase the fresh-keeping time of the flowers for sale, and improve the economy of the whole machine.

Huaxia Yan[2] developed the capacity controller of three-evaporator air conditioning system to achieve energy-saving control of indoor temperature and humidity. Li Shujiang[3] decoupled the temperature and humidity of the environmental test cabin by using the predictive decoupling method to achieve rapid and accurate control of the system. The existing literature only studies the temperature and humidity control methods, and the research on the optimal configuration of the temperature and humidity coupling system is relatively less.

Tian Mengchu[4] applied the improved glowworm algorithm to the particle filtering process and reduced the number of particles required for state value prediction and improving the quality and prediction accuracy of the particle group. Magdalene Marinaki[5] organically integrated the combined neighborhood topology glowworm swarm algorithm and variable neighborhood search algorithm with path re-linking algorithm to successfully solve the problems of capacity vehicle routing and vehicle routing with stochastic demand. At present, there is little research on the application of the GSO algorithm to the temperature and humidity coupling optimization configuration of the flower.
Therefore, this paper proposed a step adaptive glowworm swarm optimization algorithm (LLGSO), and applied the improved optimization algorithm to the regulation and optimized configuration of temperature and humidity coupling system. The analysis results showed that the LLGSO algorithm had the advantages of fast convergence, good stability, small output deviation, and low proneness to localization. It could meet the needs of different operating conditions of flower vending machines and realize the optimal configuration of the whole machine with the lowest energy consumption and economical optimization of the temperature and humidity coupling system.

2. Temperature and humidity control system model

Storage temperature is the key factor affecting the fresh-keeping time of flowers. The control model of the flower vending machine needs to accurately control the temperature and ensure that its storage conditions are controlled within a suitable range to achieve long-term low-temperature preservation of flowers.

The flower vending machine uses air conditioning (cooling/heating) to adjust temperature. It is known from the first law of thermodynamics that the heat variation inside the flower vending cabinet in a certain time scale is the calorific value of the air conditioning cooling/heating:

\[
Q = m\gamma \Delta T = m\gamma(T_{in} - T_{Set})
\]

Where: \( Q \) is the heat transferred in the air conditioning work; \( m \) is the air quality in the cabinet; \( \gamma \) is the specific heat capacity coefficient of air; \( \Delta T \) is the temperature difference inside the cabinet in a time period; \( T_{Set} \) is the initial temperature in the cabinet; \( T_{Set} \) is the temperature inside the cabinet after the time period of \( \Delta t \); \( \lambda \) is the energy efficiency ratio of the air conditioner; \( P_{in} \) is the rated power of the air conditioner.

Similarly, the humidity of the air in the cabinet is balanced by a humidifier/dehumidifier, and new air is introduced during the humidification/dehumidification process, thereby affecting the temperature fluctuation of the air inside the cabinet.

As shown in Fig. 1, the temperature and humidity in the flower vending cabinet restricts each other, with strong coupling and heavy hysteresis. In order to ensure the relatively stable balance of humidity in the flower vending cabinet, it is necessary to accurately adjust the humidity in the cabinet through the humidifier/dehumidifier. According to the psychrometric chart,[6] the humidified and dehumidified air amount in the cabinet are respectively:

\[
W_{JS} = V_{JS} \cdot \rho \cdot (d_{in} - d_{set})
\]

\[
W_{CS} = V_{CS} \cdot \rho \cdot (d_{in} - d_{set})
\]

Where: \( W_{JS} \) is the humidified air amount of the humidifier; \( d_{in} \) is the moisture content of the air in the cabinet; \( d_{set} \) is the set moisture content in the cabinet space; \( W_{CS} \) is the dehumidified air amount of the dehumidifier.

The air moisture content in the flower vending cabinet is determined by the temperature and relative humidity in the cabinet:

\[
W_{CS} = V_{CS} \cdot \rho \cdot (d_{in} - d_{set})
\]

Where: \( H_{in} \) is the relative humidity of the air in the cabinet; \( P_{in} \) is the pressure of the saturated water vapor at the real-time temperature in the cabinet; \( P_0 \) is the total pressure of the air, set to a standard atmospheric pressure of 101.3 kPa.

According to the Antoine equation, the pressure of the saturated water vapor can be described by
three simple parameters, as shown in equation (5), where the values of parameters A, B, and C are $A = 18.5616$, $B = 3991.11$, and $C = 233.84$, respectively.

$$\ln P_n = A - \frac{B}{T_n + C}$$

(5)

Equation (5) is substituted into equation (4):

$$d_m = \frac{0.622 \cdot H_m}{101.3 \cdot \exp \left( \frac{3991.11}{T_n + 233.84} - 18.5916 \right) - H_n}$$

(6)

According to the humidification amount and the dehumidification amount, the working power of the humidifier and the dehumidifier can be respectively obtained:

$$P_{in} = \frac{P_{Jin}}{W_{Je}} ; P_{in} = \frac{P_{Cin}}{W_{Ce}}$$

(7)

Where: $P_{Jin}$ is the input power of the humidifier; $P_{Cin}$ is the input power of the dehumidifier; $W_{Je}$ is the rated humidification amount of the humidifier; $W_{Ce}$ is the rated humidification amount of the dehumidifier.

3. Regulation strategy and optimization configuration model of vending machine

3.1 Temperature and humidity regulation strategy of vending machine

In order to prolong the survival life of flowers, reduce the energy consumption of vending machines, and improve system economy, it is necessary to accurately control the temperature and humidity in the cabinet. In this paper, fuzzy control was used to correct the temperature and humidity of the flower vending machine, and the decoupling coefficient was introduced to dynamically decouple the temperature and humidity coupling system. The flow chart of temperature and humidity control system is shown in Fig. 2.

The difference between the set temperature (humidity) and the real-time temperature (humidity) in the cabinet and the change rate of the difference serve as the input of the temperature (humidity) controller and the compensation values of temperature, respectively. The compensation value of temperature and humidity is obtained by fuzzy decoupling, and the temperature and humidity output value of the system after fuzzy correction is obtained:

$$T_B = K_1 \cdot T_{act} + T_f ; H_B = K_2 \cdot H_{act} + H_f$$

(8)

Where: $T_B$ is the output temperature after systematic correction; $T_{act}$ is the set temperature value; $T_f$ is the compensation value of temperature; $K_1$ is the accuracy coefficient of the temperature controller; $H_B$ is the output humidity after systematic correction; $H_{act}$ is the set humidity value; $H_f$ is the compensation value of humidity; $K_2$ is the accuracy coefficient of the humidity controller.

Through the decoupling regulation of temperature and humidity decoupling coefficient, the output temperature and humidity of the air conditioner and the humidifier/dehumidifier in the flower vending machine are respectively:

$$T_m = \frac{T_B}{K_1} \cdot K_1 + \frac{H_B}{K_1} \cdot (1 - K_1)$$

(9)
\[ H_{in} = \lambda_{H} \left( \frac{T_{H}}{\lambda_{T}} \cdot (1 - K_{H}) + \frac{H_{H}}{\lambda_{H}} \cdot K_{H} \right) \]  \tag{10} 

Where: \( K_{T} \) is the temperature decoupling coefficient; \( K_{H} \) is the humidity decoupling coefficient; \( \lambda_{T} \) is the temperature normalization coefficient; \( \lambda_{H} \) is the humidity normalization coefficient. Thereinto, \( \lambda_{T} \) is the maximum value of \( T_{H} \), \( \lambda_{H} \) is the maximum value of \( H_{H} \), and the values of \( K_{T} \) and \( K_{H} \) are in \([0, 1]\).

In fuzzy control, the domain of input values \( T_{E} \) and \( T_{EC} \) is \([-3, 3]\). The domain of input values \( H_{E} \) and \( H_{EC} \) is \([-6, 6]\). The domain of output value \( T_{\phi} \) is \([-3, 3]\). The domain of the output value \( H_{\phi} \) is \([-6, 6]\), and the fuzzy subset of the input and output control variables are \{NB, NM, NS, ZO, PS, PM, PB\}.

3.2 Optimized operation economic model of flower vending machine

The performance of the flower vending machine not only needs to ensure the preservation and storage time of flowers, but also requires considering the maintenance and operation cost of the equipment. Different control schemes of temperature and humidity matching will lead to different fresh-keeping cycles of flowers. If the storage time is too long, the operation cost of the equipment will be higher than the cost of the flowers themselves, which directly affects the overall economy of the flower vending machine. In order to solve this problem, this paper establishes an economic evaluation model for flower vending machines.

The electric equipment of the flower vending machine includes an air conditioner, humidifier, dehumidifier, motor, and other devices. The power consumption per hour of the whole machine can be calculated by equation (11):

\[ q_{t} = (P_{t} + P_{S} + P_{CS} + P_{os}) \times 1 \]  \tag{11} 

Where: \( P_{t} \) is the power consumption of the air conditioner at time \( t \); \( P_{JS} \) is the working power of the humidifier; \( P_{CS} \) is the working power of the dehumidifier; \( P_{os} \) is the working power of other equipment such as motor and illumination lamp.

Taking the storage temperature and humidity of flowers as the constraint conditions, the single-day working electricity price of the flower vending machine is the final optimization goal, and the optimized operation economic model of flower vending machine is established.

\[
\begin{align*}
\min f &= \sum_{i=1}^{n} H_{i} \cdot q_{i} \\
T_{low} &< T_{in} < T_{up} ; \\
H_{low} &< H_{in} < H_{up}
\end{align*}
\]  \tag{12} 

Where: \( f \) is the electricity fee for a 24-hour flower vending machine; \( \mu_{i} \) is one hourly electricity price of the city; \( q_{i} \) is the total power consumption of a flower vending machine for one hour; \( T_{up}, T_{low}, H_{up} \) and \( H_{low} \) are the upper and lower limits of the temperature and humidity of the flowers vending machine cabinet, respectively.

4. Improved glowworm swarm optimization algorithm and performance analysis

Glowworm optimization algorithm is the new heuristic optimization algorithm based on bionics mechanism\([7]\), widely used in different engineering fields such as multimodal function optimization, circuit analysis, dispatching management, economic operation, path planning, etc.\([8,9]\). This paper utilizes GSO algorithm to find out the optimal solution of equation (12).

The traditional GSO algorithm has the problems of slow convergence speed, low solution precision and large randomness, and falls into the local optimal solution. The exponential factor and the logarithmic factor was introduced to change the step change rate, so that the glowworm algorithm can adopt a larger step in the initial stage to quickly search for the global optimal neighborhood and avoid falling into local optimum; In the later stage, the small step is used to accurately search in the optimal neighborhood to improve the search accuracy and reduce the occurrence of oscillation. The improved algorithm can greatly improve the convergence speed and enhance the stability of the system. The formula of the step to update is shown as equation (13):
\[ s = \frac{(T_{\text{max}} - t)^{1.3}}{T_{\text{max}}} \times s_{\text{start}} + \log_{T_{\text{max}}}^{t} \times s_{\text{end}} \quad (13) \]

Where: \( T_{\text{max}} \) is the maximum number of iterations; \( t \) is the current number of iterations; \( s_{\text{start}} \) is the initial moving step value of the glowworms; and \( s_{\text{end}} \) is the terminal moving step value of the glowworms.

In order to further verify the effectiveness and superiority of LLGSO, two standard test functions were used to compare and test the performance of the original glowworm algorithm (GSO), the linear optimization glowworm algorithm (LGSO), and LLGSO. The standard test function is as follows:

\[ f_{1} = 0.5 \times \frac{\sin^{2} \sqrt{x_{1}^{2} + x_{2}^{2}} - 0.5}{[1.0 + 0.001(x_{1}^{2} + x_{2}^{2})]^{0.5}} \quad (14) \]

Where \( x_{1} \in [-5,10], x_{2} \in [0,15] \), the global optimal value of the function is 0.

\[ f_{2} = x_{1}^{2} + x_{2}^{2} + 25(\sin^{2} x_{1} + \sin^{2} x_{2}) \quad (15) \]

Where \( x_{1} \in [-2\pi, 2\pi], x_{2} \in [-2\pi, 2\pi] \), the global optimal value of the function is 0.

In order to avoid individual specificity in the results of the single experiment, each test function was run 100 times by GSO, LGSO, and LLGSO respectively. The results are shown in Table 1. The convergence curves of the two test functions are displayed in Fig. 3. Taking the test function \( f_{1} \) as an example, the glowworms moving trajectory is presented in Fig. 4.
It can be seen from Fig. 4 that LLGSO has the best optimization effect, and the glowworms are concentrated on the global optimal position. Some of the glowworms in Fig. 4(a) and (b) are scattered far away from the optimal value, indicating that the improved LLGSO effectively improves the solution performance of the algorithm and optimizes the best results.

| Function | Algorithm | Optimal value | Worst value | Average value | Standard deviation | Bad rate |
|----------|-----------|---------------|-------------|---------------|-------------------|----------|
| $f_1$    | GSO       | 0.000 015 909 9 | 0.009 727 431 6 | 0.009 716 102 0 | 0.000 001 475 0 | 0        |
|          | LGSO      | 0.000 015 901 6 | 0.009 715 658 0 | 0.009 392 229 0 | 0.001 743 075 3 | 0        |
|          | LLGSO     | 0.000 000 017 8 | 0.000 020 265 9 | 0.000 000 983 7 | 0.000 000 557 5 | 0        |
| $f_2$    | GSO       | 0.009 715 909 8 | 0.037 224 075 1 | 0.010 632 848 7 | 0.000 000 000 011 | 0.033   |
|          | LGSO      | 0.009 715 904 7 | 0.009 715 918 7 | 0.009 715 910 2 | 0.000 000 000 003 | 0        |
|          | LLGSO     | 0.000 050 740 1 | 0.000 095 308 2 | 0.000 059 904 9 | 0.000 000 000 003 | 0        |

As can be seen from the data, there is the large deviation between the optimal value of the $f_1$ calculated by the GSO and LGSO and the global optimal value of the function. The optimal value obtained by the LLGSO is closest to the global maximum of the function, and the standard deviation of LLGSO is the smallest, indicating that LLGSO has the best stability, and the deviation of multiple optimization results is the smallest, with the optimal overall performance; The optimal value found by the function $f_2$ through the three algorithms and the global optimal value have large deviation, but the LLGSO is closest to the global optimal value of the function, and the worst value obtained by the LLGSO is also relatively close to the global optimal value, with smallest standard deviation and without bad value appearing. The data shows that the performance of the LLGSO is superior, and the function is not easy to fall into the local optimal solution, with better stability.

The results of simulation running and test function verification demonstrate that LLGSO proposed in this paper has better stability, stronger optimization ability and faster convergence speed than the original glowworm algorithm and the improved glowworm algorithm proposed in the literature\[10\], and the comprehensive performance of LLGSO is superior.

5. Application of LLGSO in temperature and humidity optimization configuration

In order to verify the effectiveness of the temperature and humidity optimal configuration strategy for flower vending machines, this paper selects different flower varieties for simulation solution, analyzes the influence of temperature and humidity decoupling coefficient on the economy of the cabinet, and explores the best temperature and humidity configuration for flower vending machines. Table 2 shows the optimum temperature and humidity values of different varieties of flowers and the set temperature and humidity values controlled by the cabinet. The parameters of the flower vending machine are as follows:

$m=0.986 \text{ kg}, \gamma=1.012 \text{ kJ/(kg}^\circ\text{C})^{-1}, \lambda=1.8, P_{Ju}=1 \text{ (kw·h}^{-1}), P_{Cu}=1.2 \text{ (kw·h}^{-1}), W_J=18 \text{ (kg·h}^{-1}), W_{Ce}=22 \text{ (kg·h}^{-1}), \rho=1.25 \text{ (kg·m}^{-3}), d_{ac}=1.8$.

| Flower variety | Optimum temperature | Optimum humidity | Setting temperature | Setting humidity |
|----------------|---------------------|------------------|---------------------|-----------------|
| Geranium       | 4–7 °C              | 65%–80%          | 5.5 °C             | 72.5%           |
| Zingiberaceae  | 12–18 °C            | 75%–85%          | 15 °C              | 80%             |
| Oriental lily  | 12–18 °C            | 70%–80%          | 15 °C              | 75%             |
| Primula vulgaris | 15–25 °C           | 45%–55%          | 20 °C              | 50%             |

Taking geranium as an example, the temperature and humidity output values of the flower vending machine in the three cases of no correction without decoupling (S1), fuzzy compensation without decoupling (S2), optimization algorithm decoupling & fuzzy compensation (S3), are comparatively analyzed, as shown in Fig. 5.
In Fig. 5(a), when the system is under the disturbance effect of the external environment, S1 has the largest fluctuation; S2 also reduces the influence of external fluctuation on the cabinet temperature to a certain extent, but the reduction is small; S3 has the smallest temperature fluctuation, which is the most suitable for the storage temperature requirement of geranium. In Figure 5 (b), S3 can effectively reduce the maximum humidity of the cabinet environment compared with the other two modes. The maximum humidity is less than 80%, which meets the requirements of geranium for the highest humidity, but when the humidity disturbance is at a lower value, the correction ability of S3 and S2 is evenly matched.

Fig. 6 is the comparison diagram of temperature and humidity compensation range of geranium under three different modes: S1, S2 and S3.

As shown in Fig. 6(a), S3 does not need to compensate when the temperature is lower than the optimum minimum temperature of geranium, which effectively reduces the temperature compensation range, decreases the start-stop number of the air conditioner, and improves the economy of the whole machine; In Fig. 6 (b), when the humidity is lower than the optimum minimum humidity of geranium, the compensation effects of S2 and S3 are the same. When the humidity is greater than the optimum maximum humidity of geranium, S3 drops the compensation range, decreases the working frequency of the dehumidifiers, and reduces the energy consumption of the whole machine.

Table 3. Power consumption of three control modes of different kinds of flowers

| Flower variety   | S1       | S2       | S3       | Decoupling coefficient $K_r$ | Decoupling coefficient $K_u$ |
|------------------|----------|----------|----------|-------------------------------|-------------------------------|
| Geranium         | 20.679   | 16.602   | 11.038   | 0.22                          | 0.8                           |
| Zingiberaceae    | 22.112   | 16.560   | 13.952   | 0.58                          | 1                             |
| Oriental lily    | 19.200   | 15.112   | 9.453    | 0.58                          | 0.8                           |
| Primula vulgaris | 20.425   | 17.921   | 12.069   | 0                             | 0.78                          |

Aiming at different types of flowers, the simulation analysis is carried out for the daily power consumption of the system after compensation by the three methods, and the calculation results are shown in Table 3.

It can be seen from Table 3 that for the types of flowers with requirements of different temperature and humidity, the daily power consumption by the direct control method is the highest; The daily power consumption through fuzzy control is slightly reduced, and the system economy is improved; The fuzzy control mode corrected by the optimized algorithm decoupling has the lowest daily power consumption. The system daily power consumption of the four types of flowers is reduced by 46.6%,
36.9%, 50.8%, and 40.9%, respectively, compared with that of the direct control method. At the same time, it can be seen from the table that when the optimum temperature and humidity required by the plant change, the decoupling coefficient of the system also changes.

6. Conclusions
For the purpose to reduce the daily energy consumption of flower vending machines, the influence of the time-delay nonlinear coupling factor of the temperature and humidity in the cabinet on the system economy is reduced. An optimization configuration model of temperature and humidity power for flower vending machines is established. The fuzzy control algorithm is utilized to correct the compensation and based on the proposed improved variable-step adaptive glowworm optimization algorithm, the objective function optimization is performed. The simulation results demonstrate the correctness and effectiveness of the proposed variable-step adaptive glowworm algorithm applied to the temperature and humidity optimization configuration strategy, which can greatly reduce the energy consumption of the flower vending machine and improve the economy of the system.

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