# Mine Ventilation Optimization Analysis and Airflow Control Based on Harmony Annealing Search

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***Abstract*—The mine ventilation optimization and airflow control are the mine ventilation system's two important aspects, good ventilation optimization design can deliver fresh air to establish good work environment and provide a scientific and reliable basis to prevent disaster. Based on the air distribution request of the mine ventilation network, carries on the optimized computation to the mine ventilation system network, fuses the dynamic perturbation and the simulated annealing to improve the harmony search algorithm, the improved harmony search algorithm enhances the convergent speed, has overcome certain limitations of the traditional ventilation network optimizing control algorithm. In the mine ventilation analysis, the improved harmony search through proper tuning these parameters was presented. The simulation results show that the method outperforms the conventional nonlinear programming approach whether from the viewpoint of the number of iterations required to find the optimum solutions or from the final solutions obtained. Mine fire is a very complex physicochemical process. Once it happens, there are lots of poisonous and harmful gas ingredients. Additionally, the fume caused by the fire will block the vision and decrease the visibility, which will impede human evacuation and fire fighting, moreover, it is easy to cause the gas and coal dust explosion. So it is very important for the evacuation of miners and mining salvation to research the air flow control during mine fire. Airflow control based on harmony search has provided a scientific and reliable basis to develop disaster prevention and processing.**

***Index Terms*—mine ventilation, harmony search, optimization design, airflow control, nonlinear programming**

## I. Introduction

The primary task of the mine ventilation is delivering fresh air to the mine continuously, diluting and discharging noxious gas and dust, adjusts microclimate in coal mine, establishes good work environment, but the most important task of mine ventilation is airflow control while mine fire is happened. The mine ventilation system is a complex network of the high interdependence, in order to satisfy the need of the safety in production, we must distribute air according to need in the pit. How to determine one kind plan of air control, it not only can satisfy the ventilation demand and the working condition limit, conforms to the related laws and regulations, but also can cause the expense which the mine ventilation needs to be least, is the research hot spot and difficulty of the mine ventilation safety engineering for a long time[1-10].

The mine fire is a complex physicochemical process, it will not only cause the massive high temperatures and noxious gas, but also causes the massive loss of coal resources, even destroys the entire mining system [8-10]. In the past long time, many researches have been done for mine fire, which provide scientific foundation for mine fire prevention. Now the research on airflow control scheme during mine fire period is still in the qualitative analysis stage and one of the most famous methods is enclosed loop method. But this method is impossible to get the precise result with qualitative method and the effect of a scheme cannot be assured rather than optimize the scheme. For a complex mine ventilation network, it is difficult for a person to perform qualitative analysis when mine fire changes greatly. Essentially, the ventilation control is a dynamic process during mine fire period. However, it is difficult to describe the change of mine air pressure with the variation of time with a precise mathematic equation. On the other hand, it is impossible to perform continuously and dynamically automatic control under current mine technology. Thus, the airflow status control during mine fire period can only be achieved manually by stages. The ventilation network is considered in balance status at each particular stage. And the control scheme can make the airflow status in this period satisfy the given ventilation requirement. In fact, the derivation of ventilation control scheme in this particular state is a nonlinear programming problem.

By establishing ventilation control model to solve the ventilation control scheme is only a kind of model-aided decision other than a complete decision support system or computer automatic decision. Since it is impossible to establish models for many cases during mine fire period or save them to a database, the wisdom and experiences of commanders are still indispensable. But through model-aided decision, a scientific basis can be provided for commanders to make scientific decisions.

In the ventilation network, the partial air quantity have already been known, the partial air quantity is unknown,


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the air regulation question of the regulated branch and the regulated quantity which all need to be solved, is the most common ventilation network optimization regulation question, in this kind of question, the unknown variable quantity is often more than the constraint equation number, usually may be took as the nonlinear programming problem, traditionally uses the analysis or the numeric repetitive method to solve, its thought is constructing a series of quite simple sub-questions, then solves the optimal solution of the original question finally through the sub-problem's solution[1][3][6]. While the objective function and constraints are simpler, uses the analysis method to solve is effective, may obtain the approximate exact solution. But regarding complex ventilation network optimization question, traditional method exists many limitations, therefore many scholars will start to introduce optimization algorithm to the ventilation network optimization, to solve the mine air quantity optimization adjustment problem[8-10]. This paper uses the harmony search optimization algorithm to carry on solving the mine ventilation network optimization and airflow control questions, has obtained the good optimized result.

## II. Harmony Search Algorithm

The harmony search(HS) algorithm was conceptualized from the musical searching process for a ‘perfect state’ of harmony, namely seeks a best state (fantastic harmony) in the esthetic process through reasonable matching several kinds of musical instrument, just as the optimization algorithm seeks a best state (global optimum) determined by evaluating objective function. Aesthetic estimation is performed by the set of pitches played by each instrument, just as the objective function evaluation is performed by the set of values assigned by each decision variable. The harmony quality is enhanced practice after practice, just as the solution quality is enhanced iteration by iteration.

### *A. The procedure of harmony search*

HS algorithm is shown in figure 1, the steps in the procedure of HS are as follows[14,15]:

Step 1: Initialize the problem and algorithm parameters.

The optimization problem is defined as minimize(or maximize) $f(x)$ where $f(x)$ is the objective function, $x$ is the set of each decision variable, $x_i$ , and $X$ is the set of the possible range of values for each decision variable, that is $x_i^{\min} \le X_i \le x_i^{\max}$ ,where $x_i^{\min}$ and $x_i^{\max}$ are the lower and upper bounds for each decision variable. The HS algorithm parameters are also specified in this step. These are the harmony memory size(HMS),or the number of solution vectors in the harmony memory; harmony memory considering rate(HMCR);pitch adjusting rate(PAR); number of decision variables (N) and the number of improvisations (NI),or stopping criterion.

The harmony memory (HM) is a memory location where all the solution vectors (sets of decision variables are stored). Here, HMCR and PAR are parameters that are used to improve the solution vector. Both are defined in step 3.

Step 2: Initialize the harmony memory.

The HM matrix is filled with as many randomly generated solution vectors as the HMS

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_2^1 & x_2^1 \\ x_1^2 & x_1^2 & \cdots & x_1^2 & x_1^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix}$$

Step 3: Improvise a new harmony.

A new harmony vector, $x' = (x_1', x_2', \cdots, x_N')$ , is generated based on three rules: memory consideration, pitch adjustment and random selection. Generating a new harmony is called ‘improvisation’ [15]. The procedure works as follows:

FOR each $i = [1, N]$ DO

IF $U(0,1) \le HMCR$ THEN /*memory consideration*/

BEGIN

$x_i' = x_{ij}$ , where $j \in \{1,2,\cdots,HMS\}$

IF $U(0,1) \le$ PAR THEN /*pitch adjustment*/

BEGIN

$x_i' = x_i' \pm r \times bw$ , where $r \in U(0,1)$ , $bw$ is an arbitrary distance bandwidth.

END IF

ELSE /*random selection*/

$x_i' = x_i^{\min} + r \times (x_i^{\max} - x_i^{\min})$

ENDIF

DONE

Step 4: Update the harmony memory.

If the new harmony vector, $x' = (x_1', x_2', \cdots, x_N')$ is better than the worst harmony in HM, judged in terms of the objective function value, the new harmony is included in HM and the existing worst harmony is excluded from HM.

Step 5: Check the stopping criterion.

If the stopping criterion (maximum number of improvisations is satisfied, computation is terminated. Otherwise, Steps 3 and 4 are repeated.

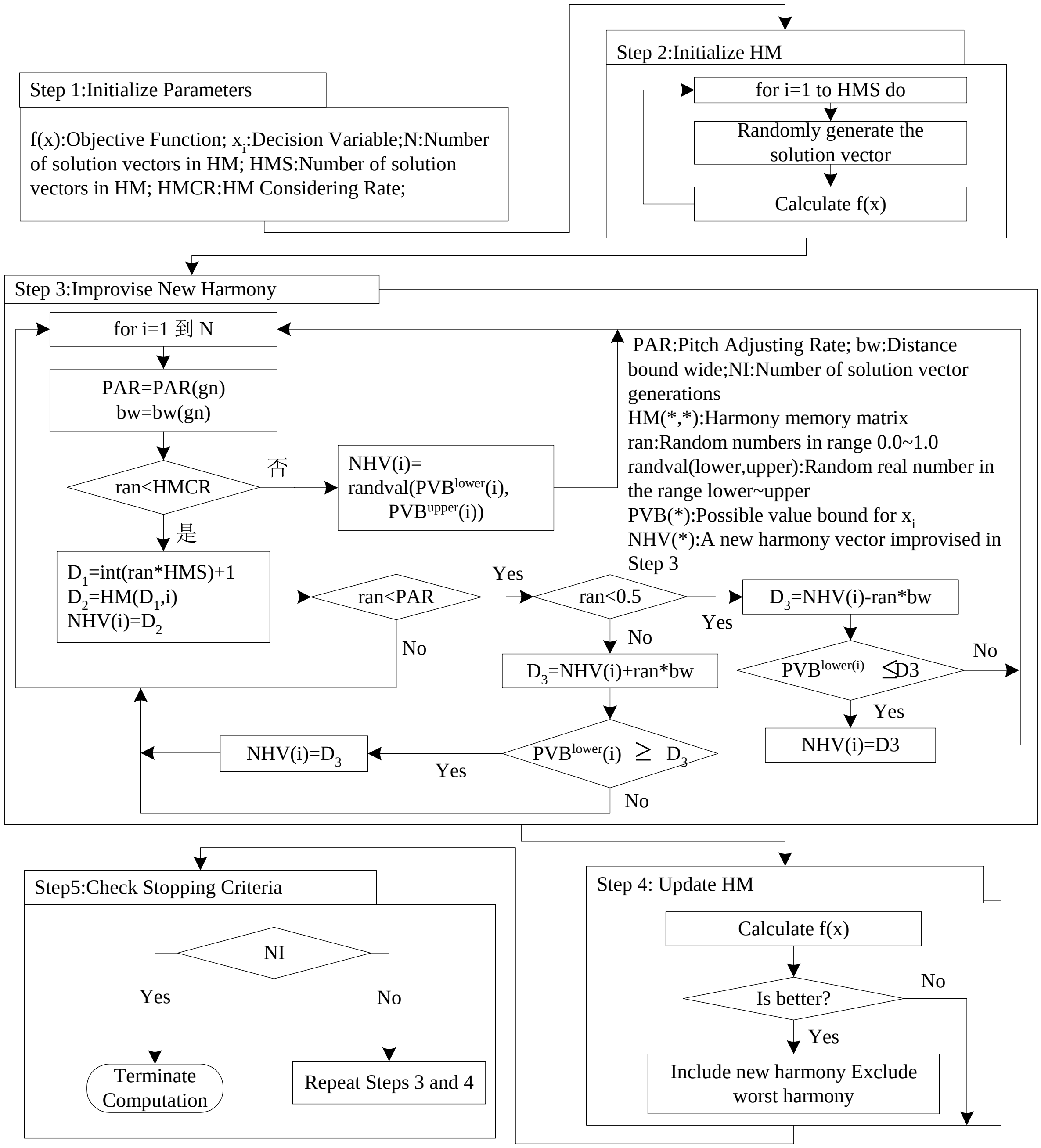


Figure 1. Optimization procedure of the harmony search algorithm

*B. The improved harmony search(IHS)*

In the original harmony search algorithm, new harmony vector carries select randomly by a probability in its value range, carries on pitch adjusting by the fixed $PAR$ value, this will not be good for stability of the algorithm. In order to enhance the algorithm stability, here we improved the original harmony search through two methods. IHS algorithm is shown in figure 2.

At first, $PAR$ is dynamically updated according to the following equation.

$$PAR(t) = PAR_{\min} + \frac{PAR_{\max} - PAR_{\min}}{NI} \times t$$

In the type, $PAR(t)$ is pitch adjusting rate for each generation, $PAR_{\min}$ is minimum pitch adjusting rate, $PAR_{\max}$ is maximum pitch adjusting rate, $NI$ is number of solution vector generations, t is generation number.

Secondly, alters the random selection as executing a simulated annealing algorithm to reduce temperature T.

HAS retained the HS main mechanism in the harmony memory(HM), but use very fast simulated annealing (VFSA) to improve the random selection outside HM. In HS each variable may random select in HM, but in HAS the solution is obtained in HM by the random selection or the partial search by the simulated annealing algorithm.

Here uses VFSA which is more suitable real-valued function optimization question to improve the partial search. And the way of VFSA generating new solution is:

$$m_i' = m_i + y_i(B_i - A_i)$$

$$y_i = T\,\mathrm{sgn}(\mu - 0.5)[1 + 1/T]^{|2\mu-1|} - 1]$$

where $m_i$ is $ith$ variable in the current solution; $u$ is the uniform distribution random number in [0,1]; $m_i$ values range from $[A_i, B_i]$, and $m_i' \in [A_i, B_i]$ after perturbation; $\mathrm{sgn}(\cdot)$ is sign function. The acceptance probability in the Metropolis criterion is

$$P = \exp(-\Delta E/T)$$

Its annealing temperature reduction way is:

$$T(K) = T(K-1)\exp(-CK^{1/N})$$

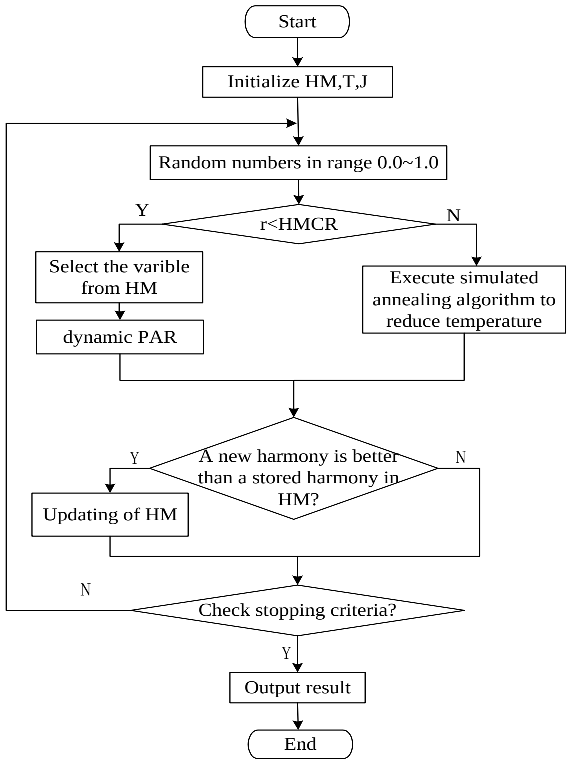


Figure 2. The procedure of improved harmony search

## III. Mine Ventilation Network Optimization Analysis Based on Harmony Search

The ventilation system should be designed such that its output should exactly match the need for ventilation throughout the mine, so as to provide a safe and economic solution.

The objective of any mine ventilation network analysis is to determine the optimal steady state airflow and pressure distribution, given the airway characteristics and network topology. The analysis also indicates the operating points of the fans placed in the network.

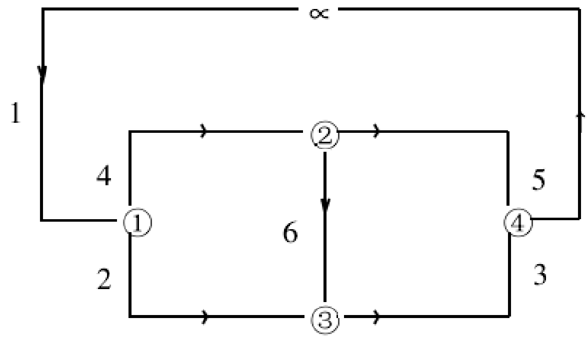


Figure 3. Mine ventilation Analysis Network Based on harmony search

For applying the improved HS to the analysis of mine ventilation systems, a simple mine ventilation network is first simulated to verify the effectiveness of the novel algorithms. Consider the mine ventilation network shown in Figure.3, and determine the natural splitting for every branch. The given data are listed in Table Ⅰ, in which the type of the fan is 4-72-11 No.20, the coefficient of H-Q curve of the fan is: A=1920, B=7.29,C=-0.366.

TABLE I. The Characteristic Parameters of the Example Network

| Branch number | Resistance (N.s2.m3) | Operating discharge of fan (m3.s-1) |
|---|---|---|
| 1 | *0.53* | *45.03* |
| 2 | *0.49* | *45.03* |
| 3 | *0.36* | *45.03* |
| 4 | *0.32* | *45.03* |
| 5 | *0.76* | *45.03* |
| 6 | *1.20* | *45.03* |

This problem is as follows:

$$\min G = \frac{1}{3}\sum_{i=1}^{6} R_i Q_i^3 - (AQ_1 + \frac{1}{2}BQ_1^2 + \frac{1}{3}CQ_1^3)$$

$$s.t.\quad \begin{cases} Q_4 - Q_5 - Q_6 = 0 \\ Q_2 + Q_6 - Q_3 = 0 \\ Q_3 + Q_5 - Q_1 = 0 \end{cases}$$

By using the linear conversion, the above solution is equivalent to the following uncontrolled optimization problem.

$$\min G = \frac{1}{3}(R_1Q_1^3 + R_2Q_2^3 + R_3Q_3^3 + R_4(Q_1 - Q_2)^3)$$
$$+ R_5(Q_1 - Q_3)^3 + R_6(Q_3 - Q_2)^3$$
$$+ (AQ_1 + \frac{1}{2}BQ_1^2 + \frac{1}{3}CQ_1^3)$$

The harmony memory size ( $HMS$ ) is 8, harmony memory considering rate ( $HMCR$ ) is 0.8, the initial value of the pitch adjusting rate ( $PAR$ ) 0.5. Through operating procedure, the computation result is gained after 125 iterative as shown in Table Ⅱ.

TABLE II. THE CALCULATION RESULTS OF THE EXAMPLE NETWORK UNDER THE NATURAL SPLITTING

| Branch number | Discharge* (m3.s-1) | Discharge** (m3.s-1) | Discharge*** (m3.s-1) |
|---|---|---|---|
| *1* | *45.03* | *45.03* | *30.00* |
| *2* | *20.93* | *20.89* | *10.00* |
| *3* | *26.03* | *25.96* | *19.20* |
| *4* | *24.05* | *24.14* | *20.00* |
| *5* | *19.00* | *9.07* | *10.81* |
| *6* | *5.05* | *5.07* | *9.20* |

* by Newton method; ** by genetic Algorithm; *** by harmony search.

As shown in Figure 4 the simulation results of the harmony search(HS)that optimizes the mine ventilation network, after 125 iterations to reach the optimum value, the improved PAR reach the good convergence rate, and it is obviously quicker than other algorithm.

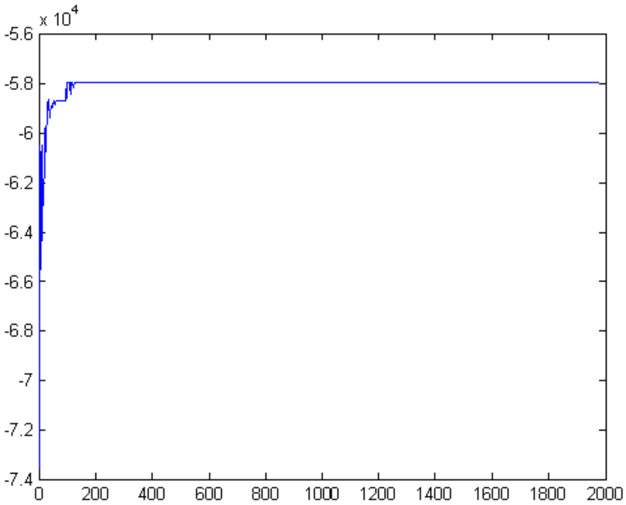


Figure 4. Simulation results for example

## IV. MINE VENTILATION AIRFLOW CONTROL DESIGN

### A. *Mine ventilation network optimization modeling*

In the mine ventilation adjustment, air control should be safe, economical and feasible. The security and feasibility may be reflected on the bound for the air quantity requirement, the air quantity, the adjustment quantity and the branch controllability in generally. Therefore, the objective function of the optimized adjustment question is generally considered from the economic aspect, namely, causes the ventilating total cost to be least.

Because the fan's energy consumption in the ventilation expense occupies great proportion, usually may take the fan power directly as the objective function, namely by making the sum of absolute value of the product of each branch control variable $H_i$ and its air quantity $Q_i$ as optimization objective function and at the same time considering controllability of each branch and lower and upper limit of control variables. According to the above, establishes mathematical model of the mine ventilation network optimization is:

$$\min \quad f = \sum_{i=1}^{N_F} |H_i||Q_i|$$

$$s.t.\ \sum_{j=1}^{N} a_{ij} Q_i = 0,\ \ (i = 1, 2, \cdots, M);$$

$$\sum_{j=1}^{N} b_{ij} H_j - F_i(Q_i) = 0,\ \ (i = 1, 2, \cdots, M);$$

$$Q_{\min} \le Q_j \le Q_{\max};$$

$$H_{\min} \le H_j \le H_{\max};$$

In the type, the objective function $f$ is the ventilation energy consumption, kW; $N_F$ is fan quantity; $N$ is the branch number; $M$ is the loop number, $M = N - J + 1$, $j$ is the node number; $H_j$ is the air pressure of the fan branch $i$, $P_a$; $Q_a$ is airflow quantity through the fan branch $i$, $m^3/s$; $Q_j$ is airflow quantity through a branch $j$, $m^3/s$; $H_j$ is pressure drops of the branch $j$, $P_a$; $F_i(Q_i) = 0$, $i = N_F + 1$, $N_F + 2$, …, $M$; $Q_{\min}$, $Q_{\max}$ is the bound for air regulation separately, $m^3/s$; $H_{\min}$, $H_{\max}$ is the bound for air pressure regulation separately, $P_a$ ;the values of $a_{ij}$ are defined as follows: $a_{ij} = 1$ if branch $j$ is connected to node $i$ and the air flow goes away from node $i$, $a_{ij} = -1$ if branch $j$ is connected to node $i$ and the air flow goes into node $i$, $a_{ij} = 0$ if branch $j$ is not connected to node $i$; the elements of $b_{ij}$ are defined as follows: $b_{ij} = 1$ if branch $j$ is contained in mesh $i$ and has the same direction, $b_{ij} = -1$ if branch $j$ is contained in mesh $i$ and has the opposite direction, $b_{ij} = 0$ if branch $j$ is not contained in mesh $i$.

Uses penalty function method to transfer constraint condition of the optimized model, add the constraint condition to the objective function through penalty form, constitutes penalty function together, obtains the unconfined optimization question, and the objective function becomes:

$$f' = \sum_{i=1}^{N_F} |H_i||Q_i| + \gamma \sum_{i=1}^{M} \sum_{j=1}^{N} \{b_{ij} H_j - P_i - F_i(Q_i)\}$$

$$+ \beta \sum_{j=1}^{N} \left| \min\{0, (Q_{\max} - Q_j)\} + \min\{0, (Q_j - Q_{\min})\} \right|$$

In the type, $\gamma$ and $\beta$ are penalty factor.

### B. Mine ventilation network airflow control

In the mine airflow optimizing control during mine fire period, air control should be safe, economical and feasible. The security and feasibility may be reflected on the bound for the air quantity requirement, the air quantity, the adjustment quantity and the branch controllability in generally. By making the sum of absolute value of the product of each branch control variable $H_i$ and its air quantity $Q_i$ as optimization objective function and at the same time considering the controllability of each branch and the lower and upper limit of control variables.

Now assumed that a fire happens in a certain mining section of a mine, the air flow optimization control during fire period can be solved as follows. The ventilation network in this section is shown in figure 5. There are totally 21 branches, 14 nodes and 8 independent loops. In normal ventilation, the air current direction of each branch is from branch start node to end node, as shown in Table III.

TABLE III. AIRFLOW CONTROL RESULT OF EACH BRANCH BEFORE AND AFTER MINE FIRE

| Branch | Start → end | Resistance ($N*s*m^3$) | Airflow before ($m*s^{-1}$) | Airflow before ($m*s^{-1}$) | Airflow with controls ($m*s^{-1}$) | Branch regulator (Pa) |
|---|---|---|---|---|---|---|
| ***1*** | (1→2) | 0.01816 | 59.959 | 60.332 | 63.057 | 0.00 |
| ***2*** | (10→12) | 81.9610 | 4.005 | 4.047 | 3.051 | 0.00 |
| ***3*** | (2→1) | 1.1265 | 38.494 | 38.005 | 33.861 | 0.00 |
| ***4*** | (14→13) | 1.4616 | 3.867 | -2.513 | 0.205 | 0.00 |
| ***5*** | (14→13) | 0.5156 | 6.511 | -4.231 | 0.345 | 0.00 |
| ***6*** | (2→3) | 0.141 | 21.464 | 22.327 | 29.196 | 0.00 |
| ***7*** | (3→5) | 22.3099 | 1.243 | 1.605 | 1.924 | 0.00 |
| ***8*** | (3→4) | 0.08 | 20.222 | 20.721 | 27.272 | 0.00 |
| ***9*** | (4→5) | 1.0 | 1.325 | 4.810 | 4.805 | 0.00 |
| ***10*** | (4→6) | 0.411 | 18.897 | 15.911 | 22.467 | 0.00 |
| ***11*** | (5→7) | 40.643 | 2.568 | 6.415 | 6.729 | 0.00 |
| ***12*** | (6→7) | 1340.614 | 0.303 | 1.090 | 1.111 | 0.00 |
| ***13*** | (6→8) | 0.093 | 18.594 | 14.822 | 21.355 | 0.00 |
| ***14*** | (7→9) | 0.0012 | 2.870 | 7.505 | 7.841 | 0.00 |
| ***15*** | (8→9) | 5.121 | 4.211 | 17.518 | 17.752 | 0.00 |
| ***16*** | (8→10) | 0.125 | 14.383 | -2.696 | 3.604 | 0.00 |
| ***17*** | (9→11) | 0.0003 | 7.081 | 25.023 | 25.592 | 0.00 |
| ***18*** | (11→12) | 4.1 | 17.459 | 18.279 | 26.143 | Open air door |
| ***19*** | (12→1) | 0.113 | 21.464 | 22.327 | 29.196 | 0.00 |
| ***20*** | (13→11) | 0.2 | 10.378 | -6.743 | 0.550 | |
| ***21*** | (10→14) | 0.2 | 10.378 | -6.743 | 0.550 | 0.00 |

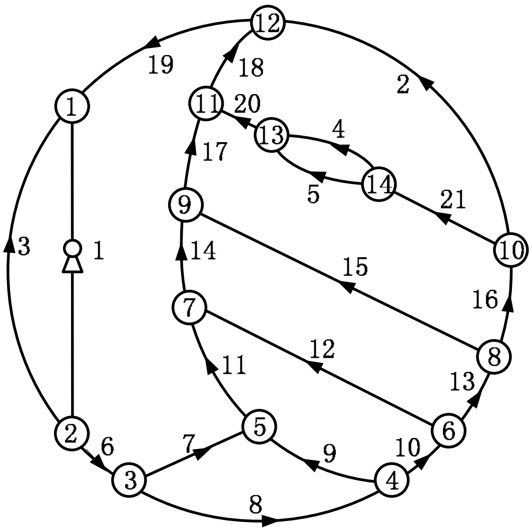


Figure 5. Ventilation network of a mine

Now assumed that a fire happens at branch 17 (9→11, mining section track uphill), if no control measure is adopted, the air currents of branch 4, 5, 20, 21 and 16 will reverse and the fumes will be full of branch 1, 2, 4, 5, 15-21. The areas where fumes spread are illustrated with wide lines as shown in figure 6. Miners in these areas will be greatly threatened by high temperature poisonous gas. Consequently, if no effective air current control measure is adopted, it will be difficult for the workers at working faces 4 and 5 to escape safely.

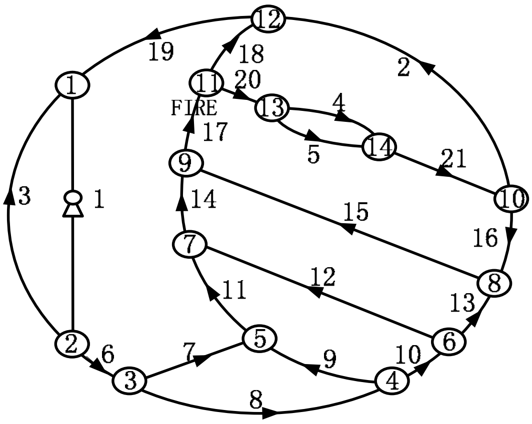


Figure 6. Airflow in a mine fire (without any control measures)

First, by qualitative analysis, for the purpose of safe evacuation of staffs in working face branch 4 and working face branch 5, it is necessary to make the air current directions of the two working areas the same to the air current direction of normal ventilation. And at the same time, fume current should be exhausted along node 11→12→1. Thus the miners in the work face can safely escape along the node 14→10→8→6→4→3→2.

Second, we analyze this ventilation network. This network's 10 tree branch respectively is: 1, 4, 6, 7, 9, 11, 12, 14, 15, 17, 18, 20, 21, and 8 independent loops: Loop 1: 2→18→20→4→21→2, loop 2:3→1→3, loop 3:5→4→5, loop 4:8→9→7→8, loop 5:10→12→11→9, loop 6:13→15→14→11→13, loop 7: 16→21→4→20

→17→15→16, loop8: 19→1→6→7→11→14→17→18→19.

The air quantity balance equations are as following respectively:

Node 1: $Q_1 - Q_3 - Q_{19} = 0$;

Node 2: $-Q_1 + Q_3 + Q_6 = 0$;

Node 3: $-Q_6 + Q_7 + Q_8 = 0$;

Node 4: $-Q_8 + Q_9 + Q_{10} = 0$;

Node 5: $-Q_7 - Q_9 + Q_{11} = 0$;

Node 6: $-Q_{10} + Q_{12} + Q_{13} = 0$;

Node 7: $-Q_{11} - Q_{12} + Q_{14} = 0$;

Node 8: $-Q_{13} + Q_{15} + Q_{16} = 0$;

Node 9: $-Q_{14} - Q_{15} + Q_{17} = 0$;

Node 10: $Q_2 - Q_{16} + Q_{21} = 0$;

Node 11: $-Q_{17} + Q_{18} - Q_{20} = 0$;

Node 12: $-Q_2 - Q_{18} + Q_{19} = 0$;

Node 13: $-Q_4 - Q_5 + Q_{20} = 0$;

Node 14: $Q_4 + Q_5 - Q_{21} = 0$;

The wind pressure balance law can be represented as follows:

Loop 1: $H_2 - H_{18} - H_{20} - H_4 - H_{21} = 0$;

Loop 2: $H_3 + H_1 = 0$;

Loop 3: $H_5 - H_4 = 0$;

Loop 4: $H_8 + H_9 - H_7 = 0$;

Loop 5: $H_{10} + H_{12} - H_{11} - H_9 = 0$;

Loop 6: $H_{13} + H_{15} - H_{14} - H_{12} = 0$;

Loop 7: $H_{16} + H_{21} + H_4 + H_{20} - H_{17} - H_{15} = 0$;

Loop 8: $H_{19} + H_1 + H_6 + H_7 + H_{11} + H_{14} + H_{17} + H_{18} = 0$;

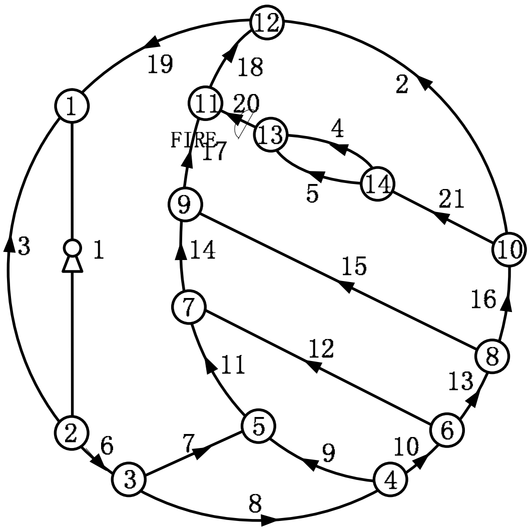


Figure 7. Airflow state after adopting airflow control measures

With the help of the harmony search computer program, the following air current control scheme is obtained: branch 18(11 → 12); Tunnel to increase resistance: branch 20(13→12) and adjusted quantity is 6.655 Pa. The air current flow status is shown in figure 7 after air current control measures are adopted.

## VI. CONCLUSION

Carries on the optimized computation based on the air distribution request of the mine ventilation network, the harmony search algorithm was used to find the global optimal solution of the network. An improved harmony search through proper tuning these parameters was presented. The optimization model of the mine ventilation system network take the fan energy consumption as the objective function, the nonlinear programming mathematical model takes the mine ventilation network node airflow quantity balance equation, the loop pressure balance equation, the branch controllability, the bound for the airflow quantity and the regulated quantity and so on as constraint condition, can satisfied the ventilation demand and the working condition, causes the expense which the mine ventilation needs to be least, thus is suitable in solving each kind of mine ventilation network optimization adjustment question. Applies the improved harmony search to the ventilation network, after the optimization, the ventilation system total energy consumption decreases obviously. Through HS optimized computation, a good operation environment is provided for the calculation of the air current optimization control during mine fire period in the future. It is very important for rescuers to quickly make a correct decision during coal mine fire. Harmony search is not only suitable for mine ventilation optimization design, but also suitable for mine airflow optimizing control when a mine fire is happened.

## ACKNOWLEDGMENT

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