Simultaneous Optimization of Pump Configuration and Operation Parameters in Multi-source Water Injection System

Jianjun YANG [a], Qingtang LI [b], Zhiyuan ZHANG [c]

School of Mechanical Engineering, Qingdao Technological University, Qingdao, 266520, China

[a]email: yjjdem@163.com, [b]email: 476347505@qq.com, [c]email: 925771904@qq.com

Keywords: Water Injection System; Pump Configuration; Operation Parameter; Simultaneous Optimization; Genetic Algorithm

Abstract. The pump operation condition and configuration are closely related in water injection system, but the existing operation optimization is carried out in the given pump configuration. In order to optimize the operation condition of the new-built system, the pump configuration and operation parameters are optimized simultaneously. In the objective function, the investment and operating cost are considered, and the displacement is identified as design variable, the determination method of pump type is given. In applications of the genetic algorithm, the coding method and crossover and mutation methods that adapted to the optimize problem are designed, and the processing method of constraint conditions are proposed, the fitness function is adjusted. An example shows the efficiency of the simultaneous optimization algorithm.

Introduction

Water injection system is an important power consumer in oilfield production, the operation optimization of water injection system is an important method for the energy consumption reduction. At present, there are two kinds of operation optimization, operation parameter optimization [1] [2] and start up scheme optimization [3] [4] [5] [6]. But the two kinds of operation optimization is carried out in the given pump configuration, and only applicable to the optimization of existing system. To the new or reconstructed water injection system, the existing method is that the pump configuration was fixed firstly based on the experience, and carrying out operation optimization after the completion of the system. But the different pump configurations corresponding to the different optimal running status, so the running status and the pump configuration are closely related. In order to achieve the best running status of the water injection system, it is necessary to optimize the pump configuration and operating parameters simultaneously.

The Optimal Mathematical Model

In order to reflect the impact of pump configuration and operation parameters to the system, in the optimization objective function, the investment cost of pump and drive motor, and the system operation cost in the investment recovery period are considered. The specific form of expression is:

$$\min \quad f^{'} = \sum_{i=1}^{N_{\mathrm{p}}} \left(C_i + \omega T C_{\mathrm{d}} \gamma \frac{H_i Q_i}{\eta_{\mathrm{p}i} \eta_{\mathrm{m}i}} \right) \tag{1}$$

In the type: $f^{'}$ is the weighted sum of the investment cost and the operation cost of pump; N_{p} is the total number of the pump; C_i is the investment cost of pump *i* and its drive motor; ω is the adjustment coefficient between the investment cost and the operation cost; T is the investment recovery period; C_{d} is unit price of power; γ is unit conversion factor; H_i is the head of pump *i*; Q_i is the flowrate of pump *i*; $\eta_{\mathrm{p}i}$ is the efficiency of pump *i*; $\eta_{\mathrm{m}i}$ is the efficiency of drive motor for pump *i*, and the efficiency of drive motor has little change, can be regard as constant[7].

At the same time, the following constraints should be considered.

The first constraint is water balance constraint. The total flowrate of all pumps is a fixed value, equal to the total water demand of the system.

$$\sum_{i=1}^{N_{\mathrm{p}}} Q_i = Q_{\mathrm{All}} \tag{2}$$

In the type: Q_{All} is total water demand of the system.

The second set of constraints is hydraulic equilibrium constraint. When the system is running, the equilibrium equation must be met between the flowrate and pressure for each junction node, the equation can be written as follows [4]:

$$u_i - u_i^{'} - \sum_{j \in I_i} s_{ij} \operatorname{sgn}\left(p_i - p_j\right) \left|p_i - p_j\right|^{1/\alpha} = 0 \tag{3}$$

$$\operatorname{sgn}(A) = \begin{cases} 1, & A \geq 0 \\ -1, & A < 0 \end{cases} \tag{4}$$

In the type: u_i, $u_i^{'}$ are output and input flowrate of node *i*, respectively; s_{ij} is the pipeline resistance coefficient between nodes *i* and *j*; p_i, p_j are the pressure of nodes *i* and *j*, respectively; I_i is the set of all the nodes connected to node *i*; α a constant coefficient; sgn is the sign function.

When the system is simulated, the pipe network layout, demand flow of nodes and press of the reference node are all known, through iterative computation, the pressure heads of all other nodes can be obtained, and the hydraulic equilibrium constraints are satisfied automatically in the process of simulation. But the node pressure values are relative values that relative to the reference node, all of the node pressure values increase or decrease a unified value, the equilibrium equations still are met.

The third set of constraints is node press constraint. The node pressure value should be greater than or equal to the minimum working pressure at each consumption node.

The fourth set of constraints is pump flowrate constraint. In order to make the pump running in high efficiency area, and reduce the search range of the algorithm, the pump flowrates are limited within a certain range.

$$Q_{i\min} \leq Q_i \leq Q_{i\max}, \quad i = 1, \cdots, N_{\mathrm{p}} \tag{5}$$

In the type: $Q_{i\min}$, $Q_{i\max}$ are minimum and maximum flowrate of pump *i* respectively.

The fifth set of constraint is pump working pressure constraint. In order to make the pump running normal, the outlet pressure of pump should be greater than the node pressure of water injection station.

$$p_{\mathrm{o}i} - \Delta p_i = p_{\mathrm{e}i} + H_i - \Delta p_i \geq p_s^i, \quad i = 1, \cdots, N_{\mathrm{p}} \tag{6}$$

In the type: $p_{\mathrm{o}i}$、$p_{\mathrm{e}i}$ are outlet and inlet pressure of pump *i* respectively; Δp_i is the friction loss from outlet of pump *i* to the outlet of water injection station; p_s^i is the node pressure of water injection station *s*.

The pressure differential between the outlet pressure of pump and the node pressure of water injection station is pump–pipe pressure differential, the minimum value of pump–pipe pressure differential is equal to friction loss, if there is throttle loss, the value will be bigger.

Through the designs of coding operation methods, constraints of pump flowrate and water balance are satisfied automatically. After a set of pump flowrates are given, using the equilibrium equation, a set of node pressure values that relative to the reference node can be obtained. After the unified adjustment of the node pressure values, we can obtain a set of minimum pressure values, and the node press constraint is satisfied, with the minimum energy consumption of the system. Finally, the pump working pressure constraint can't be satisfied directly, so penalty function is used to convert the original objective function and the remaining constraint to final objective function, that is

$$f = f' + M\sum_{i=1}^{N_p}\max\left\{p_s^i - \left(p_{ei} + H_i - \Delta p_i\right), 0\right\} \tag{7}$$

In the type: M is the penalty parameter.

The Main Solution Steps of Genetic Algorithm

Determining the Optimization Variable and Pump Type. In the objective function, the investment cost is related to pump type, so the head of pump, flowrate, the efficiency, and pump type all need to be optimized. But when a flowrate of pump is given, and the pump type is determined, the head and efficiency of pump can be obtained through corresponding characteristic curve. So after the flowrate and type of pump are determined, the objective function value can be computed. In order to reduce the infeasible solutions and improve the search efficiency of the algorithm, when a flowrate is given, the pump type can't be determined randomly, but can be determined according to the following methods: 1) if the flowrate only in one flowrate constraint range of pump type, then select the pump type. 2) if the flowrate belongs to several flowrate constraint ranges of pump type, then we can compute the pressure values based on the flowrate, and compute the objective function value of the pump according to the equation 5, select the pump type corresponding to the minimum value. Through the above analysis, only the flowrates of the entire pump are selected as direct optimization variables finally.

Fitness Function. The final objective of the optimization problem is the minimum cost, but the optimization direction of the genetic algorithm is the maximum, so we need to convert the objective function into fitness function, and the fitness function value is a nonnegative number. In order to overcome the premature convergence in the initial phase and stagnation state in final phase, the minimization problem is converted into an equivalent maximization problem by the following transformation:

$$F_i = k_n f_{\max} - f_i \tag{8}$$

$$k_n = 0.99^{n-1} k_0 \tag{9}$$

In the type: F_i is the fitness function corresponding to the objective function; $f_{\max}$ is the maximum objective function value in the population; k_n is adjustment coefficient; n is the iteration number.

In order to ensure the fitness function value is nonnegative and not zero, k_n should always is greater than 1, because the maximum iteration number is 200 in this study, so the value of k_0 is 8.

Coding Design and Generation of Initial Population. The flowrate is a real number, in order to achieve the accurate expressing, real number coding is adopted. When a flowrate in an initial solution is generated, pump type is selected randomly, and a real number is generated randomly in the flowrate constraint range of the pump type. After all the flowrates are generated, we check the satisfiability of the water balance constraint. If the constraint is not satisfied, the flowrate is adjusted, and ensure that the flowrate belongs to one flowrate constraint range of pump, until the water balance constraint is satisfied.

Crossover operation. The arithmetic crossover method that suits the real number coding is adopted. For example, we randomly select （$x_1, \cdots, x_i, \cdots, x_{N_p}$） and （$y_1, \cdots, y_i, \cdots, y_{N_p}$） as two parent individuals, the calculation method is:

$$\begin{cases} x_i' = \lambda x_i + (1-\lambda) y_i \\ y_i' = \lambda y_i + (1-\lambda) x_i \end{cases} \tag{10}$$

In the type: λ is a random decimal between 0 and 1.

After the crossover by using this method, the offspring can meet the water balance constraint automatically. When two flowrate values belong to different types participate in crossover, a flowrate value that not belong to any flowrate constraint range of the pump type will probably generated, when this happens, re-crossover or random adjustment is needed, and the flowrate constraint is satisfied.

After the crossover, the flowrate and running status of the system are changed, the pump types need to be determined again.

Mutation Operation. In order to reduce the infeasible solutions, one parent individual is selected randomly, and two genes x_i and x_j are selected randomly, one gene vale is increased or decreased a small value randomly, and another gene value is decreased or increased the same value, each flowrate constraint is satisfied at the same time. That is:

$$\begin{cases} x_i'' = x_i \pm \Delta \\ x_j'' = x_j \mp \Delta \end{cases} \tag{11}$$

In the type: Δ is a smaller disturbance quantity.

Through the mutation method, the water balance constraint is satisfied automatically. But the flowrate values of the two pumps are changed, and the pump types need to be determined again.

Optimization Example

To validate the algorithm proposed above, we optimize a water injection system. In the system, there are 8 pumps, the total water injection is 2503 m^3/h, the existing pump configuration and operation parameters are shown in table 1. The pump configuration and operation parameters are optimized simultaneously by using the method. In the optimization, the adjustment coefficient ω=0.01, the investment recovery period T=5, the unit price of power C_d=0.6 Yuan/kW·h. The objective function values of before and after optimization are 8.28×10^6 and 8.10×10^6 respectively. The detailed results of after optimization are shown in table 1.

Table 1 Comparison of operation parameters before and after optimization

Pump number	Operation situation				After optimization			
	Pump type	Q/$m^3 \cdot h^{-1}$	η/%	P/kW	Pump type	Q/$m^3 \cdot h^{-1}$	η/%	P/kW
1	D400-150×11	339	80.53	2075	D300-150*11	329	81.09	1980
2	D155-175×10	225	77.34	1360	D155-175*10	208	76.02	1309
3	D300-150×11	322	80.72	1954	D280-160A	276	74.69	1765
4	D300-150×11	294	78.94	1874	D400-150*11	375	81.79	2160
5	D400-150×11	386	82.28	2166	D300-150*11	337	81.29	2003
6	D280-160A	265	73.87	1730	D300-150*11	316	80.05	1950
7	D400-150×11	352	81.15	2127	D400-150*11	371	81.56	2166
8	D400-150×11	320	79.96	1995	D280-160A	291	76.10	1820

After optimization, the investment cost of pump and drive motor from 4.264 million Yuan reduced to 4.086 million Yuan, reduced by 4.17%. The total input power from 15281 kW reduced to 15153 kW, reduced by 0.84%. The optimized effect is better.

Conclusion

To the new or reconstructed water injection system, in order to achieve the best running status of the system, the simultaneous optimization of the pump configuration and operating parameters is proposed, the optimization objective function considering the investment cost and operation cost is established.

The pump flowrates are determined as optimization variables by analyzing the relationship between the variables, and the determining method of pump type is given.

The solution procedures of the genetic algorithm include coding, crossover and mutation are designed, and some constraints are satisfied automatically, the number of the infeasible solutions is reduced.

Acknowledgement

In this paper, the research was sponsored by the Project of Shandong Province Higher Educational Science and Technology Program (Project No. J13LB13).

References

[1] Yang Jianjun, Liu Yang, Wei Lixin, et a1. Optimization of operation parameters of waterflooding system considering variable frequency speed regulation[J]. China Petroleum Machinery,2005,33(9):16-20.

[2] Yang Jianjun, Liu Yang, Zhan Hong. Operation optimization of complex water-injection system with variable frequency speed-regulation pump[J]. Acta Petrolei Sinica, 2007,28 (2):124-128.

[3] Wang Yuxue, Zhang Haiyan, Liu Ying. Study on operational optimization for oilfield water injection system by using artificial fish algorithm [J]. Oil-gasfield Surface Engineering,2010,29(4):38-40.

[4] Yang Jianjun, Liu Yang, Wei Lixin, et a1. Dual coding hybrid genetic algorithm for optimal schedule of pumping stations in multi-sources water injection system[J]. Acta Automatica Sinica, 2006,32(1):154-160.

[5] Vieira J, Cunha M C, Nunes L, et al. Optimization of the operation of large-scale multisource water-supply systems[J]. Journal of Water Resources Planning and Management, 2011, 137(2): 150-161.

[6] Yuan Yixing，Zhong Dan，Gao Jinliang． Optimization operation of water distribution system based on macroscopic model[J]. China Water＆Wastewater，2010,26(5):55.59.

[7] Cheng Jilin, Zhang Lihua, Zhang Rentian, et al. Optimal methodology of Single-un it variable speed operation in pumping station[J]. Transactions of the Chinese Society for Agricultural Machinery, 2010,41(3):72-76.