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Research on the Optimization of Operating Parameters of Steam Injection Pipe Network

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ABSTRACT

Scientifically optimizing the design of the steam injection pipe network is an important way to improve economic benefits, enhance oil production efficiency, and reduce energy consumption. In the study of the optimal layout of the steam injection pipe network, the operating parameters and operation schemes of the oilfield steam injection system were optimized, and a mathematical model of wet steam flow in dendritic pipelines was established. The genetic algorithm code was written in MATLAB for optimization, and the results were compared with the current steam network layout. The reliability has been proven and can be used as a reference for future pipe network layout studies. Taking the minimum energy consumption loss in the steam injection process as the objective function, an appropriate genetic optimization algorithm was selected to solve the mathematical model for three well parameters. Corresponding constraints and optimization principles were established with the main purpose of reducing energy consumption and improving efficiency. The relevant steam injection parameters were optimized and calculated, and the site of the steam injection station was determined.

KEYWORDS

Pipe Network Optimization; Genetic Algorithm; Written in MATLAB.

1. INTRODUCTION

Currently, the main method for developing heavy oil in China is the hot oil extraction by injecting steam. The design of the steam injection system generally involves designing the position of the steam injection station and the diameter and insulation thickness of the steam injection pipeline under the given well positions and wellhead parameters (wellhead steam injection pressure, temperature, and dryness) of the steam injection wells in a certain area[1], thus determining the position of the steam injection station. In the case where the station site is not determined, the problem is to connect the layout of the steam injection pipeline and the branched pipe network.

The first step in optimizing the pipe network layout is to determine the branched pipe network, the ring pipe network, the radial pipe network, and the combined pipe network that combines these topological structures. These pipe networks are all topological structures and are a common type in the pipe network. The establishment of these types of pipe network topological structures establishes an interconnection relationship between wells and stations in the gathering and transportation system. However, the positions of these wells and stations may not be the optimal positions, which requires the establishment of a model to determine the optimal positions of wells and stations. The established models are generally nonlinear models, and appropriate solution methods need to be selected to solve these models to achieve the optimal well-station relationship and the position of the station[2].

2. TIMIZATION MODEL ESTABLISHMENT

Optimization theory occupies a very practical position in the field of applied mathematics and is also called mathematical planning. It plays a core role in operations research. The core of optimization theory is to discuss how to formulate an optimal strategy under specific constraints to achieve a preset goal. This article aims to introduce the optimization application for oil and gas pipeline technology based on the evolution and importance of optimization theory.

In the optimization operation, the location allocation and optimization of the steam injection station are regarded as two independent but continuous stages. Next, we will comprehensively review and adjust the layout of the steam injection station, and improve the quality of model establishment through the reconfiguration and optimization of well groups. In this process, the optimization configuration of well groups is to explore the most efficient connection strategy between a single oil well and a specified injection treatment station after determining the ideal position of the injection station. This study is based on the hydraulic and thermodynamic models of the pipe network, and establishes the objective function by minimizing the energy loss in the steam injection process with the parameters such as the steam injection volume at the wellhead, the dryness of the steam, and the injection pressure as limiting conditions, according to economic theory. In addition, the optimization design scheme of the pipe network constructs its objective function amework around the enthalpy evaluation.

2.1. Objective Function Establishment

This model is for the overall optimization design of the steam injection pipe network for optimizing the site of the steam injection station. Given the temperature T and pressure P of the steam, calculate the specific enthalpy h”(T, P) of the steam according to formula (1):

$$h''(T,P)=\tau\left(\sum_{i=1}^{9}n_i^0 J_i^0 \tau^{J_i^0-1}+\sum_{i=1}^{43}n_i \pi^{Ii} J_i\left(\tau-0.5\right)^{J_i-1}\right)RT \tag{1}$$

Where: h”(T, P) - The energy contained in a unit mass of steam at a certain temperature and pressure, that is, the sum of the internal energy u of a unit mass of steam and the pressure potential energy pυ;

τ - The reduced temperature, dimensionless, τ = T*/T, T* = 540 K;

n_1^0 - The i-th n^0 coefficien;

ni - The i-th n coefficient;

π - The reduced pressure, dimensionless, π = P/P*, P* = 1 MPa;

Ii - The i-th I coefficient and I index;

Ji - The i-th J coefficient and index;

τ - The inverse reduced temperature, dimensionless, τ = T*/T, T* = 540 K.

2.2. Constraint Conditions Establishment

In the design process, the design variables need to follow specific constraint conditions, involving the optimization treatment of theoretical boundary conditions. Taking the steam injection system as an example, the following standards need to be met.

Condition 1: The Unique Relationship between Well Site and Station Site.

The well-station affiliation and station-site affiliation relationships are determined and unique for a pipe network system with a determined topological structure. That is:

$$\sum_{j \in S_i} \beta_{ijk} = 1 \tag{2}$$

Where: $\beta_{ijk} = \begin{cases} 1 \textit{If there is an association between } k \textit{ and } j. \\ 0 \textit{If there is no association between } k \textit{ and } j. \end{cases}$

Condition 2: Geometric Constraints of the Pipe Network System.The pipelines and station sites of the pipe network need to satisfy their geometric constraints.

$$U \in \Omega \tag{3}$$

Where: $U = \{Ui,\ i = 1,2,\ldots,N\}$;

Ω — The feasible region of U;

U — Represents the position of the water injection station.

Condition 3: Pipeline Hydraulic Constraints

$$i = \lambda \frac{1}{d} \frac{w^2}{2g} \tag{4}$$

Where: i - The hydraulic gradient;

λ - The friction coefficient;

d - The calculated inner diameter of the pipeline, m;

w - The average water flow velocity, m/s.

Condition 4: Ensure that the outer surface temperature of the steam injection pipe does not exceed 50 °C. Given that the steam injection pipe is responsible for transmitting high-temperature and high-pressure steam, the purpose of adding an insulation layer is to reduce heat loss and avoid scald accidents. Therefore, the thickness design of the insulation layer must meet this requirement, and its expression is as follows:

$$T_W - 50 \leq 0 \tag{5}$$

Where: T_W - The temperature of the outer wall of the pipe;

$50°C$ - The temperature specified in the national standard.

Condition 5: Ensure that the parameters at the outlet of the steam injection boiler do not exceed the set values. Specifically, the steam after the optimized design of the hydraulic and thermodynamic calculations such as the outlet pressure, temperature, and dryness should not be higher than the calibrated boiler parameters. This requirement is to ensure the stable operation of the steam injection boiler, and its mathematical expression is as follows:

$$\begin{cases} P - P_R \le 0 \\ X - X_R \le 0 \end{cases} \tag{6}$$

Where: X, P - The dryness and pressure of the steam at the outlet;

X_R, P_R - The rated dryness and pressure of the steam injection boiler.

Condition 6: According to the design requirements of the steam injection pipeline, its pressure drop and heat loss must be less than the maximum values specified in the norms. Therefore, it needs to satisfy the following expression:

$$\begin{cases} q_l - q_{\max} \le 0 \\ \Delta P - \Delta P_{\max} \le 0 \end{cases} \tag{7}$$

Where: q_l - Unit length heat loss, W/m;

ΔP - Unit length pressure drop, Pa/m;

q_{max} - Maximal heat loss, W/m;

ΔP_{max} - Maximal pressure drop in the norms.

3. SOLVING THE MODEL BASED ON GENETIC ALGORITHM

There are many methods for solving nonlinear programming models, such as simulated annealing algorithm, neural network algorithm, etc. The theory of simulated annealing algorithm is not perfect, reducing the calculation efficiency, and the application of artificial neural network requires solid computer knowledge and is difficult to use. Therefore, compared with various algorithms, genetic algorithm has its simple and universal, robust, suitable for parallel processing and wide application range and other significant characteristics[3].

Given that the nonlinear constraint conditions built into the optimization model in this study are difficult to convert into linear forms, and the objective function does not have the possibility of directly solving the first-order partial derivatives, this significantly restricts the choice range of model solving strategies. In such cases, genetic algorithm shows its unique advantages, especially good at dealing with unconstrained nonlinear optimization problems. The advantages are: wide search space, higher ability to explore the global optimal solution, fewer constraints, stronger adaptability and more robust problem-solving efficiency. Further, when genetic algorithm is combined with other heuristic search techniques, it can not only effectively enhance the exploration precision in the local area, but also make significant progress in the overall optimization quality and search efficiency.

For genetic algorithm, an intelligent optimization algorithm, it can simulate evolution according to biological diversity. It is closely combined with computer science, with simple, universal, strong, suitable for parallel processing and wide application as significant characteristics, establishing its position as one of the key intelligent computations in the 21st century, a new algorithm for global optimization search. Therefore, genetic algorithm provides a new means and method for solving the optimization design problem of the steam injection pipe network[4].

3.1. Optimization Design

3.1.1. Chromosome Coding and Population Setting

When the parameter value range is limited from a to b, using a binary string of length L for coding can generate 2^L unique coding sequences. Thus, the coding resolution ability shown by this binary coding system can be expressed as:

$$\delta = \frac{b-a}{2^L - 1} \tag{8}$$

Population setting: The difference between biological individuals is a measure. For a specific set of characters G, different $(|G|+1)^L$ forms will be covered when the length of an individual reaches L. Assuming that the population consists of M individuals, if a pattern can match the patterns of more individuals in the population, then the individual difference degree of this population is more significant. Here, d represents the frequency of an individual's repeated appearance in M individuals. This indicates that under the premise of binary coding, as long as the number of the population is set to L, parallelism can be satisfied.

This indicates that as long as the number of the population is set to L, comparison can be satisfied, provided that it is binary code. This indicates that under the binary premise, the setting of numbers is necessary to satisfy its arrangement. $2^{\frac{L}{2}}$ This number is relatively large, so generally in practice, the range of values for the number of groups is taken from tens to hundreds.

3.1.2. Fitness Function

The greater the degree of adaptation and the more excellent an individual in the genetic algorithm, the greater the probability of selecting genes, and the better it is. A function that measures the degree of individual adaptation is called a fitness function. However, the value of the target function has positive and negative values, so a transformation between the target function and the fitness function is needed during the optimization process[2].

In the initial stage of the genetic algorithm, occasionally outstanding individuals are observed. Because they have extraordinary competitiveness, they may induce the algorithm to prematurely tend to an immature equilibrium state. To prevent such problems, by reducing the value of the corresponding fitness function, the competitiveness of some abnormal excellent individuals can be minimized. In addition, to ensure the effectiveness of the fitness function, to avoid blind random drift that may be caused by a decrease in human competition in the later evolution process, the designer must simultaneously pay attention to the diversity of the population and the balance of the selection pressure it endures.

In practical applications, there are many ways to design the fitness function, covering strategies such as exponential transformation basis, linear approximation techniques, and dynamic regulation. For example, to significantly enhance the optimization precision, convergence speed, and convergence probability of the algorithm, an exponential transformation of the fitness function can be used. The design of the fitness function needs to be integrated with a specific optimization problem, such as setting weight coefficients in a multi-objective optimization problem and constructing a fitness function for a course scheduling problem. However, the value of the target function has positive and negative values, so a transformation between the target function and the fitness function is needed during the optimization process[5].

For the optimization problem of the block pipe network, the core goal is to minimize the energy consumption loss in the steam injection process, and the fitness function must be able to accurately reflect the competitive advantage of an individual in the genetic algorithm. It is recommended that the reciprocal of the target function can be used as a fitness function, given that the output of the target function is always positive. Through this transformation, it can be ensured that the higher the value of the fitness function, the more outstanding the individual, and thus more genetic selection opportunities are obtained.

3.2. Optimization Principles of the Steam Injection Pipe Network

The oilfield ground steam injection pipe network constitutes a complex system, and its optimization arrangement and parameter configuration cannot be directly extracted from the given steam injection well data and mining plan. The optimization design model faces the challenge that the objective function combines continuous and discrete variables, which greatly increases the difficulty of solving the problem. When the scale of the studied steam injection network expands, resulting in a surge in the calculation task, and even approaching an insurmountable limit, the practical feasibility of the solution will highly depend on the scale of the pipe network and the interconnection characteristics between its nodes.

To relieve the complexity of the solution and reduce the computational burden, this study adopts genetic algorithm to deal with the problem of solving the mathematical model, and pre-excludes obviously inapplicable combinations. In practice, most of the steam injection pipe network systems are built on a two-level structure, covering the main steam injection trunk and branches. When facing multi-objective optimization challenges, each goal may not reach the optimal solution in an absolute sense, but tends to find a series of 'non-dominated' effective solutions, which are also vividly described as compromise solutions, non-dominated solutions or acceptable solutions, and one of their characteristics is the non-uniqueness of the solution. In the framework of the mathematical model constructed in this paper, setting the number of nodes of each sub-network M as a design variable effectively expands the solution space, bringing more practical feasibility options for practice, and thus introducing more flexibility into the decision-making process. Conventionally, the steam injection station is regarded as the starting point, the intersecting steam injection pipelines are defined as nodes, and the steam injection pipelines between nodes are defined as branches.

The optimization of the steam injection trunk is an efficiency improvement operation carried out within the established steam injection branch framework. Its prerequisites involve the path planning of the steam injection trunk, the location selection of the steam injection station, and the choice of the diameter of each pipeline section. Regarding the determination of the layout of the steam injection network, from an economic perspective, there is an ideal node, that is, the ideal location of the intersection of the main and branch steam injection lines should minimize the investment cost of the pipeline. From a process level, in the normal practice, when the injection volumes of each gas injection well are similar, it is more reasonable to choose the midpoint of the branch as the intersection point, which is beneficial for the convenience of pressure regulation in daily operations, ensuring that the flow and pressure on both sides of the intersection are balanced, avoiding significant differences, and thus fulfilling the requirements of the process flow. Therefore, placing the main line intersection point near the midpoint of the branch as the first principle of the optimization strategy is a key consideration for satisfying the efficient operation of the whole system.

The injection wells in oilfields are generally irregularly distributed and uneven. On the whole, some injection wells are relatively concentrated, and some injection wells are relatively scattered. There is also an optimization problem economically, that is, how to choose the main trunk line direction, pipe diameter and the site of the steam injection station. The main line direction is a broken line to meet the process requirements. In the case of uneven distribution of injection wells, the intersection of the main line and the branch line is set near the midpoint of the branch line. It is obvious that the broken line is longer than the straight line. Moreover, under certain diameter conditions, the investment in the main line will be more than that in the straight line state. At the same time, the resistance along the broken line is greater than that of the straight line, resulting in an increase in power consumption and operating costs. In addition, it is not conducive to pipeline construction.

Selecting an efficient steam injection pump is a crucial step in the optimization process of pipe network layout - it is necessary to meet the process requirements and obtain the optimal pipe diameter with the minimum energy consumption - the most power-saving layout scheme for the oilfield steam injection system. In terms of pipe network optimization, optimize the pipe network and station sites by optimizing methods such as one station and one network and multi-purpose of one station, determine the main line direction and determine the intersection of the main line and branch line.

Generally, due to the limitation of the types of steam injection pumps, the frictional resistance of the steam injection pipe network along the road should be controlled within the range of 15-30 kg/cm^2 in the planning scheme. Otherwise, the surplus part will be consumed by throttling. Under the determined pipe network, the actual problem of improving the efficiency of the entire system is how to make full use of this part of energy, especially the gas injection wells closer to the gas filling station. The principle of optimizing the main direction of steam injection is that the intersection of the main line and the branch line is near the midpoint of the branch line and meets the process requirements (that is, the branch line that meets the flow distribution and the branch line that meets the pressure distribution).

After determining the main line direction, the automobile pipe network is formed by itself. But there is also a best point, that is, where is the automobile station set. When a certain flow velocity is reached, since the pipe diameter D is a function of the flow Q, that is, D = f(Q), it is similar to the preferred intersection of the main and branch lines, so it changes with the location of the steam injection station. Generally speaking, the steam injection station needs to be set in a relatively middle position of the oil field to make the flow on both sides of the pipeline reach a relatively balanced state to meet the distribution of flow and pressure in the process.

4. EXAMPLE OF STATION SITE OPTIMIZATION

Considering the arrangement process of three well injection stations, its parameters are fixed as export pressure of 17.2 MPa, injection speed of 360 t/d, injection temperature of 360°C, and injection dryness of 90%.

Example: The parameters of the gas injection wells shown in Table 1 have three wells.

Table 1. Injection well parameter information

Parameter	Coordinate	Steam injection pressure	Steam injection speed	Steam injection temperature	Steam injection dryness
Well location 1	(0,0)	11.0MPa	237t/d	280°C	50%
Well location 2	(800,0)	12.0MPa	225t/d	290°C	45%
Well location 3	(500,900)	13.0MPa	235t/d	275°C	40%

After 1000 iterations of calculation, the location and enthalpy of the steam injection station are obtained. The optimal location coordinates of the calculation result are (500, 250), and the optimal steam specific enthalpy at the boiler inlet is 7666.88 kJ/kg, and the maximum calculated enthalpy value is 7702.01 kJ/kg. The optimal location saves 2342.18 kW·h of electricity, and the saving ratio is 4.56%.

5. CONCLUSION

(1) By introducing the characteristics and principles of optimization methods and the optimized design of pipe networks, mainly considering technical, energy-saving and economic aspects. Because the mathematical model established for the optimized design of steam injection pipe networks is a nonlinear constraint function, therefore, the mathematical model established in this paper is selected from many optimization methods by genetic algorithms. Its characteristic is that traditional optimization methods are difficult to solve. Mainly considering technical, energy-saving and economic aspects, by establishing an appropriate objective function and selecting an appropriate optimization algorithm, a combination that meets pipeline parameters and operating capabilities is calculated.

(2) For the optimization of operation parameters of the oilfield steam injection system and the optimization of the operation scheme of the steam injection system, a mathematical model for the flow of wet steam in the pipeline is established. Taking the minimum energy consumption loss in the steam injection process as the objective function, corresponding constraint conditions and optimization principles are established. A suitable genetic optimization algorithm is selected to solve the mathematical model. For the parameters of three oil wells, the site of the steam injection station is determined, and the optimal steam specific enthalpy at the boiler inlet and the optimized saving ratio are obtained. In order to achieve the purpose of improving steam injection efficiency and reducing steam injection energy consumption, relevant steam injection parameters are optimized and calculated.

(3) At the same time, there are also deficiencies. According to the actual distribution of the pipe network, it is necessary to further improve the relevant mathematical model and develop corresponding calculation software to optimize the entire oilfield station area. By combining different optimization algorithms, the shortcomings of other algorithms such as slow convergence speed and large amount of calculation can be compensated for each other. And for the steam injection process of branched pipelines, a ring-shaped pipe network layout can be adopted later to further balance the energy of the pipe network and optimize the steam injection efficiency.

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