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STUDY ON THE FEASIBLE RANGE OF FLOW RATES OF THE MULTI-BRANCH PIPELINE – A CASE STUDY OF LAYERED WATER INJECTION

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Abstract. *Layered water injection serves as a crucial technical strategy for ensuring long-term stability and high production in oilfield exploration. For addressing the prevailing issues about the feasibility of water distribution schemes when multiple strata are simultaneously activated, and improving water injection success rates, this paper explores the feasible range of flow rates for layered water injection. Initially, the pipeline structure of intelligent layered water injection is elucidated. Grounded on Darcy's law and the flow characteristics of wellhead valve and water distributor nozzles, a mathematical model for the pipeline considering the pressure loss along the path is established. The coupling relationships between steady-state operating points across various strata are examined. Numerical methods are then employed to scrutinize the change patterns of these steady-state operating points in the event of a variation in the nozzle opening of a specific stratum. Subsequently, the particle swarm optimization (PSO) algorithm is employed to confirm the differences in the flow rates corresponding to the same nozzle opening for a specific stratum during separate and simultaneous strata activations. This verification demonstrates that the flow rate relationship when a single stratum is activated separately cannot be used to assess the relationship between the nozzle opening and the flow rate of that stratum when multiple strata are activated simultaneously. Finally, this paper investigates the feasible range of flow rates in the strata, considering the constraint of maximum injection pressure of the strata. The relationship between the nozzle opening of each stratum and the flow rate is derived, providing a theoretical basis for judging the feasibility of the water distribution schemes during the optimization of layered water injection.*

Keywords: Layered water injection, Water distribution schemes, Pipeline structure, Interlayer coupling, Feasible range of flow rates

1. **Introduction.** During the process of oil field exploitation, water injection techniques have become crucial in enhancing oil recovery and subsequently boosting economic gains from oil wells [1-4]. However, conventional generalized water injection techniques often fall short due to a lack of precise management. This imprecision commonly leads to hydraulic breakthroughs and a steep increase in the water-oil ratio, further undermining the economic performance of the oil field. To overcome this challenge, layered water injection techniques have been developed [5,6]. The 4th generation layered water injection technology, developed in recent years, introduces a novel segmented injection process

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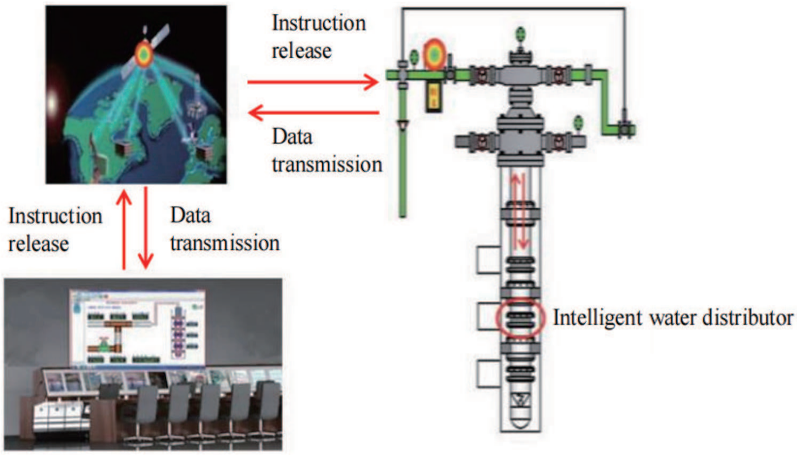

FIGURE 1. Structure of layered water injection

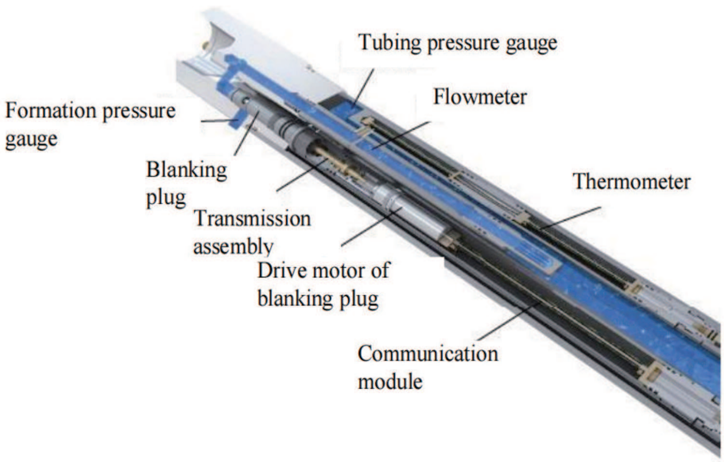

FIGURE 2. Structure of intelligent water distributor

[7,8], consisting of intelligent water distributors, downhole data communication instruments, surface communication equipments, and computer control system [9,10], as shown in Figure 1. The intelligent water distributor is the core tool of the system, integrating a flowmeter, dual pressure gauges, thermometer, communication module, and regulation assembly (consisting of transmission assembly, blanking plug, and drive motor). Through motor-driven adjustments to the blanking plug's nozzles opening, it achieves a closed-loop control of layered water injection flow rates or manual adjustments [11,12]. The structure of the intelligent water distributor is depicted in Figure 2. Downhole data transmission in layered water injection provides crucial support for real-time monitoring of injection data and automatic adjustment of injection flow rate [13]. The technology for downhole data transmission is primarily categorized into wired and wireless types [14]. Specifically, wired transmission predominantly relies on pre-installed cables for real-time parameter monitoring [15]. Wireless transmission uses vibrational, pressure, and flow waves for remote data transmission [16-20]. In 2021, Zhou et al. introduced a layered water injection model based on wireless communication [21]. This model uses historical data to predict and optimize downhole parameters such as pressure and flow rate. The model can accurately forecast the pressure and flow rate of each stratum, offering technical reinforcement for the application of wireless layered water injection systems. In 2023, Yue et al. addressed the issue of wireless code communication technology in intelligent layered water injection

for oil fields [22], proposing an optimal output fusion control method based on MPC-PID. Integrating comprehensive well structure and strata characteristic analysis, this method enhances communication efficiency and has demonstrated, through simulations, superior performance over conventional techniques.

As domestic oil fields increasingly enter a high water-cut phase on a large scale, water injection extraction becomes progressively challenging. Compared to traditional generalized water injection, layered water injection can significantly alleviate interlayer conflicts. However, when the water distribution flow rates do not align with the actual injected flow rates into the strata, it can reduce the layered water injection success rate, preventing optimal reservoir stimulation. Consequently, accurately and swiftly calculating layered water injection flow rates, while ensuring their feasibility, has become pivotal to ensuring efficient water injection in oil fields. Many scholars both domestically and internationally have studied layered water injection. In 2020, Jia et al. introduced a systematic approach combining traditional numerical simulation, data assimilation, and machine learning to achieve detailed water injection design for oil fields [5]. Utilizing automated control technology, this method offers real-time monitoring of data from layered injection and production. Importantly, Jia et al. employed the particle swarm optimization (PSO) algorithm to optimize the water distribution flow rates, ensuring not only more precise water distribution schemes but also a significant enhancement in oil field production efficiency. In 2023, Liu et al. explored downhole monitoring and data transmission techniques for layered water injection in China [23]. They pinpointed the challenges of existing technologies and proposed innovative solutions for monitoring and data transmission. The study underscored the significance of digital communication networks in the digitization of reservoir development. Similarly, in 2023, Wu et al. delved into wireless communication technology for layered water injection [24], with a particular emphasis on its energy efficiency. To mitigate energy consumption, they introduced a multilayer water injection prediction model that is continuously refined using historical data. This model effectively predicts the flow rate and pressure for each stratum. In 2020, Chen et al. introduced a novel optimization algorithm specifically tailored for waterflooding production optimization [25]. This method synergizes global and local surrogate models to enhance the production optimization process. Compared to the conventional one-shot surrogate-based approaches, this technique iteratively selects data points to bolster the accuracy of the surrogate model. In the realm of layered water injection research, scholars both domestically and internationally predominantly focus on several key aspects: 1) the evolution of layered water injection technology; 2) real-time transmission of downhole data; 3) communication techniques for layered water injection; 4) optimization of injection-production processes; 5) strategies to amplify recovery rates; 6) the structural design of layered water injection pipeline. To date, no expert has delved deeply into whether the water distribution schemes in layered water injection are feasible.

In the process of water injection, it is essential to meet the requirements of "injecting enough water, injecting good quality water, injecting water with precision, and injecting water effectively". The key to improving the efficiency of layered water injection lies in reasonably controlling the flow rate of water injected into each stratum and ensuring its success rate [26]. In practical engineering, the change in the blanking plug nozzles opening driven by the motor in the downhole intelligent water distributor is crucial for the control of the strata water injection flow rate. However, when the nozzle opening of a particular stratum is altered to adjust its flow rate, this change can influence the flow rate and pressure of other strata, leading to a shift in their steady-state operating points. Specifically, when the nozzle opening of a stratum is increased, both its flow rate and pressure rise, while the flow rate and pressure of the remaining strata correspondingly decrease. Conversely, when the nozzle opening of a stratum is reduced, its flow rate and pressure decline, but the flow rate and pressure of the remaining strata increase correspondingly. The phenomenon of interlayer interference in the context of water injection control introduces considerable complexity to the assessment of the feasibility of water distribution schemes. A persistently flawed scheme fails to address the water injection demands across various strata, which leads to a decrease in the water injection success rate. The consequent decrease in oil field recovery rates substantially undermines oil production and sends production efficiency into a tailspin [27-29]. The implications grow more dire, with the potential for such circumstances to inflict catastrophic damage on the overall economic viability of the oil field. As production costs escalate dramatically and revenues continue on a downward trajectory, the viability of continuous extraction operations at some oil fields may be brought into question. This places the long-term trajectory of oil field development in a precarious state of jeopardy. Thus, it is crucial to carry out feasibility analyses of water distribution schemes, i.e., a feasible range of flow rates in the strata.

In summary, research into the feasible range of flow rates in the strata is a key research topic in the field of layered water injection technology and holds significant research implications and broad application prospects. This study investigates the feasible range of flow rates in the strata. Firstly, by considering the vertical height of the pipeline, interlayer height, and pressure loss along the path, mathematical models of the pipeline for water injection in a single stratum and multiple strata are established. Subsequently, based on this pipeline model, the PSO algorithm is used to validate that the flow rate corresponding to each nozzle opening when a stratum is independently activated cannot be directly used to determine the flow rate corresponding to each nozzle opening of that stratum when multiple strata are activated simultaneously. This leads to a theoretical exploration of the feasible range of flow rates in the strata. Finally, as a case in point, when three nozzles are simultaneously activated, an analysis is undertaken to observe the changing trends in steady-state operating points of each stratum when the opening of the first, second, or third stratum nozzle alters. Grounded in the theoretical exposition, the feasible range of flow rates is analyzed numerically. The study of a feasible range of flow rates in the strata aids engineers in assessing the feasibility of layered water injection water distribution schemes, bolstering the efficiency of layered water injection techniques. This is poised to become a significant advantage of the fourth-generation layered water injection technology.

2. Mathematical Model of Layered Water Injection Pipeline in Single Stratum.

Firstly, we make some basic assumptions regarding the layered water injection process in oilfields: 1) the fluid flow speed within the pipeline is slow and the fluid flow can be treated as laminar flow; 2) the flow characteristics of the nozzle and wellhead valve group are equivalent to an equal percentage characteristic; 3) the geological characteristics of each stratum remain constant, i.e., the water absorption characteristics of each stratum, the minimum opening pressure, and the maximum injection pressure remain unchanged.

Drawing from field conditions in water injection wells, a pipeline model for a single stratum of layered water injection system is established, as shown in Figure 3. P_0 denotes the pressure before the wellhead valve, treated as a constant supplied by the pump room, and measured in MPa; Q_0 denotes the total pipeline flow rate, measured in m^3/h; P represents the pressure after the wellhead valve, in MPa; C and C_1 are the opening coefficients of the wellhead valve and stratum nozzle, respectively; H_1 represents the distance from the surface to the first stratum, in meters; P_1 and Q_1 represent the pressure and flow rate before the stratum nozzle, respectively, measured in MPa and m^3/h; P_{11} and

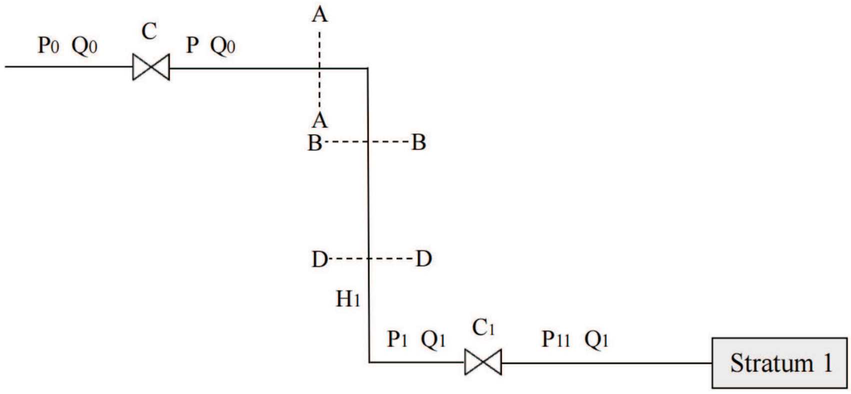

FIGURE 3. Pipeline model of single stratum

Q_1 represent the pressure and flow rate after the stratum nozzle, respectively, measured in MPa and m^3/h. The surface pipeline spans from P_0 to cross-section A-A, while the water injection pipeline extends from cross-section B-B to D-D.

In this section, a water injection pipeline model consisting of a single stratum is established. During the optimization process of layered water injection water distribution schemes, many scholars often neglect the pressure loss along the path due to its insignificance and high computational complexity. However, as the remaining oil amount in the strata continuously decreases and the water cut persistently increases, the requirements for injection pressure accuracy become increasingly stringent. Continuing to overlook the pressure loss along the path could result in misjudgment of interlayer flow rate distribution, misdirection in water distribution schemes, and might even negatively impact the development efficiency of the oil layer and the production benefits of the oil field. In establishing a mathematical model of injection column for a single stratum, this paper takes account of the pressure loss along the path to enhance the model's accuracy and application effectiveness.

The relationship between differential pressure and flow rate at the throttling elements (wellhead valve, nozzles) is as follows:

$$q_v = C\sqrt{\Delta p} \tag{1}$$

where C is the opening coefficient of the wellhead valve, which is given by

$$C = \frac{\pi C_m d_1^2}{4}\sqrt{\frac{2}{\rho\left(1-\beta^4\right)}} \tag{2}$$

In the model, C_m is the flow coefficient, and ρ represents the density of water, with units in kg/m^3. β can be considered as the ratio of the throttling element's open area to the pipeline area. d_1 is the valve opening diameter, measured in meters. The relationship between post-nozzle pressure and flow rate can be determined according to the water intake characteristics curve of the stratum:

$$P_{11} = k_1 Q_1 + b_1 \tag{3}$$

where k_1 is the water absorption index of the first stratum, b_1 is the minimum opening pressure of the stratum, and the joint (1) formula can be obtained:

$$P_1 = \frac{Q_1^2}{C_1^2} + k_1 Q_1 + b_1 \tag{4}$$

$$Q_0^2 = C^2(P_0 - P) \tag{5}$$

Neglecting the nozzle loss, the pressure loss along the surface pipeline, and strata, and considering the pressure loss along the vertical pipeline, then

$$P_1 = P + \rho g H_1 - \frac{128\mu H_1 Q_0}{\pi d^4} \tag{6}$$

where μ is the viscosity coefficient of the fluid in Pa-s, g is the acceleration of gravity in m/s^2, and d is the diameter of the injection pipeline in m. Since the model is a single stratum, $Q_0 = Q_1$, and the association of Equations (4) and (6) yields

$$Q_1' = \frac{-\left(k_1 + \frac{128\mu H_1}{\pi d^4}\right) + \sqrt{\left(k_1 + \frac{128\mu H_1}{\pi d^4}\right)^2 - 4\left(\frac{1}{C_1^2} + \frac{1}{C^2}\right)(b_1 - P_0 - \rho g H_1)}}{2\left(\frac{1}{C_1^2} + \frac{1}{C^2}\right)} \tag{7}$$

where Q_1' is the branch flow rate when the single stratum is activated, and also the total flow rate in m^3/h. In this paper, considering constant pressure injection, the wellhead pump is a centrifugal pump, and the incoming water characteristic curve of the pump:

$$P_0 = m_1 n^2 - m_2 Q_0^2 \tag{8}$$

where m_1 and m_2 are the scale factors of the pump machine and n is the rotation speed.

3. **Mathematical Model of Layered Water Injection Pipeline in Multiple Strata.** Similar to the single stratum case, the number of water injection branches increases in multiple strata conditions, as shown in Figure 4. Given that the water intake characteristics vary across different strata, the steady-state characteristics of pressure and flow rate changes become more complex compared to the single stratum case.

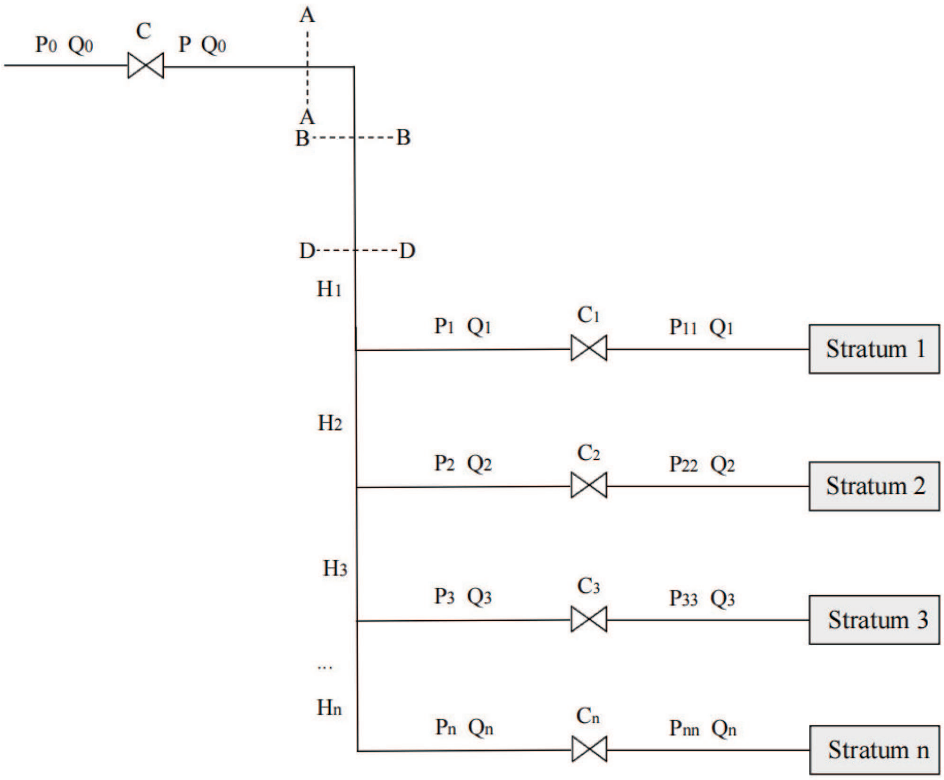

Figure 4. Pipeline model of multiple strata

The stratigraphic properties satisfy the following primary functional relationship:

$$P_{nn} = k_n Q_n + b_n \tag{9}$$

where k_n denotes the water absorption index of the nth stratum, reflecting its water absorption capability, while b_n represents the minimum opening pressure of the nth stratum. The condition for strata injection flow rate is that the pressure behind the nozzles should not be less than the minimum opening pressure of that strata. According to the stratigraphic properties, to ensure the simultaneous opening of each stratum in layered water injection, the minimum pressure behind all the water distributors should not be less than the maximum value of the minimum opening pressure across all strata, i.e.,

$$\min\{P_{ii}\} \geq \max\{b_i\}, \quad i = 1, 2, \ldots, n \tag{10}$$

Starting from the classical theory of fluid mechanics, considering the disturbance characteristics under multiple strata conditions for the entire well, and combining fluid physical parameters, wellbore structure, and strata characteristic parameters, a spatial distribution model for pressure and flow rate under stable water injection conditions at a fixed opening is established. When the nozzles of multiple strata are open simultaneously, the flow rate in the main and branch flow rates satisfies the following relationship:

$$Q_0 = Q_1 + Q_2 + \cdots + Q_n \tag{11}$$

From Equation (5), we can see that

$$P = P_0 - \frac{Q_0^2}{C^2} \tag{12}$$

The relationship between the pressure in front of the water distributor nozzle and the incoming water pressure in each stratum is as follows:

$$P_1 = P_0 - \frac{Q_0^2}{C^2} + \rho g H_1 - h_{f1} \tag{13}$$

$$P_2 = P_0 - \frac{Q_0^2}{C^2} + \rho g (H_1 + H_2) - h_{f1} - h_{f2} \tag{14}$$

$$P_n = P_0 - \frac{Q_0^2}{C^2} + \rho g (H_1 + H_2 + \cdots + H_n) - h_{f1} - h_{f2} - \cdots - h_{fn} \tag{15}$$

Among them,

$$h_{f1} = \frac{128\mu H_1 Q_0}{\pi d^4} \tag{16}$$

$$h_{f2} = \frac{128\mu H_2 (Q_0 - Q_1)}{\pi d^4} \tag{17}$$

$$h_{fn} = \frac{128\mu H_n \left(Q_0 - \sum_{i=1}^{n-1} Q_i\right)}{\pi d^4} \tag{18}$$

The relationship between pressure and flow rate after the nozzle of each stratum is

$$P_{11} = k_1 Q_1 + b_1 \tag{19}$$

$$P_{22} = k_2 Q_2 + b_2 \tag{20}$$

$$P_{nn} = k_n Q_n + b_n \tag{21}$$

Coupling Equations (19), (20), and (21) with Equation (1) yields

$$P_1 = \frac{1}{C_1^2} Q_1^2 + k_1 Q_1 + b_1 \tag{22}$$

$$P_2 = \frac{1}{C_2^2} Q_2^2 + k_2 Q_2 + b_2 \tag{23}$$

$$P_n = \frac{1}{C_n^2} Q_n^2 + k_n Q_n + b_n \tag{24}$$

Combining Equations (22), (23), and (24) with Equations (13), (14), and (15) yields

$$Q_1 = -\frac{k_1 C_1^2}{2} + \frac{C_1^2}{2}\sqrt{k_1^2 - \frac{4}{C_1^2}\left(b_1 - P_0 + \frac{Q_0^2}{C^2} - \rho g H_1 + h_{f1}\right)} \tag{25}$$

$$Q_2 = -\frac{k_2 C_2^2}{2} + \frac{C_2^2}{2}\sqrt{k_2^2 - \frac{4}{C_2^2}\left(b_2 - P_0 + \frac{Q_0^2}{C^2} - \rho g\left(H_1 + H_2\right) + h_{f1} + h_{f2}\right)} \tag{26}$$

$$\begin{aligned} Q_n = &-\frac{k_n C_n^2}{2} \\ &+ \frac{C_n^2}{2}\sqrt{k_n^2 - \frac{4}{C_n^2}\left(b_n - P_0 + \frac{Q_0^2}{C^2} - \rho g\left(H_1 + H_2 + \cdots + H_n\right) + h_{f1} + h_{f2} + \cdots + h_{fn}\right)} \end{aligned} \tag{27}$$

When the multiple strata are activated at the same time, the relationship between the flow rate in the main and branch flow rates is

$$\begin{aligned} Q_0 &= Q_1 + Q_2 + \cdots + Q_n \\ &= -\frac{k_1 C_1^2}{2} + \frac{C_1^2}{2}\sqrt{k_1^2 - \frac{4}{C_1^2}\left(b_1 - P_0 + \frac{Q_0^2}{C^2} - \rho g H_1 + h_{f1}\right)} \\ &\quad -\frac{k_2 C_2^2}{2} + \frac{C_2^2}{2}\sqrt{k_2^2 - \frac{4}{C_2^2}\left(b_2 - P_0 + \frac{Q_0^2}{C^2} - \rho g\left(H_1 + H_2\right) + h_{f1} + h_{f2}\right)} \\ &\quad -\frac{k_n C_n^2}{2} + \frac{C_n^2}{2}\sqrt{k_n^2 - \frac{4}{C_n^2}\left(b_n - P_0 + \frac{Q_0^2}{C^2} - \rho g\left(H_1 + H_2 + \cdots + H_n\right) + h_{f1} + h_{f2} + \cdots + h_{fn}\right)} \\ &= -\frac{1}{2}\sum_{i=1}^{n} k_i C_i^2 + \frac{1}{2}\sum_{i=1}^{n} C_i^2 \sqrt{k_i^2 - \frac{4}{C_i^2}\left(b_i - P_0 + \frac{Q_0^2}{C^2} + \sum_{m=1}^{i} h_{fm} - \rho g \sum_{m=1}^{i}\left(H_m\right)\right)} \end{aligned} \tag{28}$$

where C_2 is the opening coefficient of the 2nd stratigraphic nozzle, and the rest of the parameter units refer to Section 2.

The above is the pressure-flow characteristic curve of multiple strata and the total route established considering the vertical height of the pipeline interlayer height, and the pressure loss along the path. During the water injection operation, the pressure before the wellhead valve is generally provided by the pump room, i.e., P_0 remains constant. As can be seen from Equations (25) to (28), changes in the nozzle opening of a certain stratum cause changes in the fluid environment, leading to changes in the total demand flow characteristics, prompting the steady-state operating points of the remaining strata to readjust.

4. Analysis of the Feasible Range of Flow Rate for the Layered Water Injection.

4.1. Study on the re-evaluation of strata nozzles opening under simultaneous activation conditions of multiple strata. When multiple strata are activated simultaneously, the overall fluid dynamic environment changes significantly compared to when a single stratum is activated. Even though each nozzle opening remains constant, the flow rate of each stratum changes due to the interlayer interactions. Specifically, the flow rate corresponding to each opening of the nozzle when a stratum is activated individually cannot be directly used to determine the flow rate corresponding to each opening of that nozzle when multiple strata are activated simultaneously. This is because the resistance characteristics of the entire system change when multiple strata are activated simultaneously, thereby affecting the flow rate distribution. Although this issue is of great practical significance for optimizing water injection efficiency, no scholars have conducted in-depth research on it to date. Therefore, this section employs the PSO algorithm to meticulously analyze and validate that the sum of the flow rates when multiple strata are activated independently under various opening combinations of nozzles is greater than the total branch flow rate when the strata are activated simultaneously [30,31]. This underscores the necessity to reassess the flow rate corresponding to each opening combination of nozzles when multiple strata are activated concurrently, leading to the requirement for the feasible range of flow rates in the strata.

4.1.1. *Modeling.* Based on the field water injection process of oilfields, the demand for water injection flow rates in the entire water injection system is maintained for an extended period once determined. Taking the three-strata layered water injection model as an example, when the three strata are activated independently, it can be deduced from Equation (7) that the relationship between the flow rate and nozzle opening for the second and third stratum is as follows:

$$Q_2' = \frac{-\left(k_2 + \frac{128\mu H_1}{\pi d^4}\right) + \sqrt{\left(k_2 + \frac{128\mu H_1}{\pi d^4}\right)^2 - 4\left(\frac{1}{C_2^2} + \frac{1}{C^2}\right)\left(b_2 - P_0 - \rho g\left(H_1 + H_2\right)\right)}}{2\left(\frac{1}{C_2^2} + \frac{1}{C^2}\right)} \tag{29}$$

$$Q_3' = \frac{-\left(k_3 + \frac{128\mu H_1}{\pi d^4}\right) + \sqrt{\left(k_3 + \frac{128\mu H_1}{\pi d^4}\right)^2 - 4\left(\frac{1}{C_3^2} + \frac{1}{C^2}\right)\left(b_3 - P_0 - \rho g\left(H_1 + H_2 + H_3\right)\right)}}{2\left(\frac{1}{C_3^2} + \frac{1}{C^2}\right)} \tag{30}$$

The total branch flow rate approximation when the nozzles in the three strata are activated at the same time is

$$Q_0' = \frac{-\frac{k_1 C_1^2}{2} + \frac{C_1^2}{2}\sqrt{k_1^2 - \frac{4}{C_1^2}\left(b_1 - P_0 + \frac{25}{C^2} - \rho g H_1 + \frac{640\mu g H_1}{\pi d^4}\right)} - \frac{k_2 C_2^2}{2} + \frac{C_2^2}{2}\sqrt{k_2^2 - \frac{4}{C_2^2}\left(b_2 - P_0 + \frac{25}{C^2} - \rho g\left(H_1 + H_2\right) + \frac{640\mu H_1}{\pi d^4}\right)}}{1 + \frac{\left(\frac{10}{C^2} - \frac{128\mu H_1}{\pi d^4}\right)}{\sqrt{k_1^2 - \frac{4}{C_1^2}\left(b_1 - P_0 + \frac{25}{C^2} - \rho g H_1 + \frac{640\mu H_1}{\pi d^4}\right)}} + \frac{\left(\frac{10}{C^2} - \frac{128\mu H_1}{\pi d^4}\right)}{\sqrt{k_2^2 - \frac{4}{C_2^2}\left(b_2 - P_0 + \frac{25}{C^2} - \rho g(H_1 + H_2) + \frac{640\mu H_1}{\pi d^4}\right)}} + \frac{\left(\frac{10}{C^2} - \frac{128\mu H_1}{\pi d^4}\right)}{\sqrt{k_3^2 - \frac{4}{C_3^2}\left(b_3 - P_0 + \frac{25}{C^2} - \rho g(H_1 + H_2 + H_3) + \frac{640\mu H_1}{\pi d^4}\right)}}}$$
$$+ \frac{-\frac{k_3 C_3^2}{2} + \frac{C_3^2}{2}\sqrt{k_3^2 - \frac{4}{C_3^2}\left(b_3 - P_0 + \frac{25}{C^2} - \rho g\left(H_1 + H_2 + H_3\right) + \frac{640\mu H_1}{\pi d^4}\right)} - 5}{1 + \frac{\left(\frac{10}{C^2} - \frac{128\mu H_1}{\pi d^4}\right)}{\sqrt{k_1^2 - \frac{4}{C_1^2}\left(b_1 - P_0 + \frac{25}{C^2} - \rho g H_1 + \frac{640\mu H_1}{\pi d^4}\right)}} + \frac{\left(\frac{10}{C^2} - \frac{128\mu H_1}{\pi d^4}\right)}{\sqrt{k_2^2 - \frac{4}{C_2^2}\left(b_2 - P_0 + \frac{25}{C^2} - \rho g(H_1 + H_2) + \frac{640\mu H_1}{\pi d^4}\right)}} + \frac{\left(\frac{10}{C^2} - \frac{128\mu H_1}{\pi d^4}\right)}{\sqrt{k_3^2 - \frac{4}{C_3^2}\left(b_3 - P_0 + \frac{25}{C^2} - \rho g(H_1 + H_2 + H_3) + \frac{640\mu H_1}{\pi d^4}\right)}}} + 5 \tag{31}$$

The following assumptions have been made:

1) The physical parameters of the injected fluid are considered to be constant;
2) The fluid is assumed to exhibit a laminar flow;
3) The pressure before the wellhead valve is considered constant, without considering the variation of the pressure before the wellhead valve;
4) The stratigraphic properties remain constant.

4.1.2. *Objective function.* In this study, an optimization mathematical model is established to minimize the difference between the sum of flow rates when multiple strata are activated individually and the total branch flow rate when all strata are activated simultaneously. In this model, C_1, C_2, and C_3 represent the opening coefficients of the nozzles in each stratum. The objective is to find the optimal combination of C_1, C_2, and C_3 that minimizes the objective function.

$$\min F(C_1, C_2, C_3) = Q_1' + Q_2' + Q_3' - Q_0' \tag{32}$$

$$\text{s.t. } C_1 \in [0,1],\ C_2 \in [0,1],\ C_3 \in [0,1] \tag{33}$$

In this context, Q_1', Q_2', Q_3', and Q_0' are determined by Equations (7), (29), (30), and (31), respectively. Q_1' represents the total flow rate when only the first stratum is activated, measured in m^3/h. Q_2' signifies the total flow rate when only the second stratum is activated, also in m^3/h. Similarly, Q_3' indicates the total flow rate when the third stratum alone is activated, in m^3/h. Q_0' represents the total branch flow rate when the three strata are activated concurrently, denoted in m^3/h. Equation (33) serves as the constraint, which outlines the range of the nozzles opening coefficients for each stratum.

4.1.3. *Principle of PSO algorithm.* PSO algorithm is an intuitive method of global optimization, and its inspiration stems from the social behavior of bird flocking while foraging. Each particle traverses within the search space, striving for the optimal solution. Assume within an F-dimensional target search space, a swarm is comprised of N particles, where the ith particle is denoted by an F-dimensional vector $x_i = (x_{i1}, x_{i2}, \ldots, x_{iF})$, $i = 1, 2, \ldots, N$, representing its position within the F-dimensional search space. The "flight" velocity of the ith particle is also an F-dimensional vector, denoted as $v_i = (v_{i1}, v_{i2}, \ldots, v_{iF})$, $i = 1, 2, \ldots, N$. The best position thus far located by the ith particle is represented as $p_i = (p_{i1}, p_{i2}, \ldots, p_{iF})$, and the most optimal position the entire swarm has found to date is represented as $p_g = (p_{g1}, p_{g2}, \ldots, p_{gF})$ [32-34]. Herein are the main steps of the algorithm.

1) Initialization: Initialize a swarm of particles, each with a random position and velocity.

2) Evaluation: In each iteration, the fitness of the position of each particle is assessed.

3) Update: Each particle updates its velocity and position based on its historical best position p_i and the best position of the swarm p_g. The updated formulas are as follows:

$$v_i = wv_i + c_1 r_1 (p_i - x_i) + c_2 r_2 (p_g - x_i) \tag{34}$$

$$x_i = x_i + v_i \tag{35}$$

where w is the inertia weight, c_1 and c_2 are the learning factors, and r_1 and r_2 are random numbers between $[0, 1]$.

4) Loop: Repeat steps 2) and 3) until the termination conditions are met, such as when the number of iterations reaches a preset value, or when the fitness of the swarm's best position meets the requirements of the problem.

4.2. **Study of the feasible range of flow rates in the strata.** In the implementation of layered water injection technology, "the feasible range of flow rates in the strata" refers to the range of flow rate combinations corresponding to possible nozzles settings of each stratum under given operating conditions. Within this range, the possibility of flow rate combinations for each stratum is defined as a feasible range, and all flow rate combinations within this range are achievable, whereas those beyond this range are not feasible. This concept assists engineers in understanding the potential combinations of flow rates that can be realized under specific conditions, offering theoretical backing and operational guidelines for achieving better water-oil ratio control and improving oil field recovery rates. The theoretical analysis and solving of the feasible range are of crucial importance for effective layered water injection management and optimization.

For the feasible range of flow rate in the single stratum, using the scenario where only the first stratum is activated as an example, and taking account of the pressure loss along the path, the operating point corresponding to this stratum will change accordingly as per Equation (7), when the first stratum nozzle opening changes. When considering the constraints of the maximum injection pressure in the strata, the feasible range of flow rate in the strata under the limit of maximum injection pressure corresponds to the flow rate range associated with the range of nozzle openings.

When analyzing the feasible range of flow rates in the strata, the pressure loss along the path between the stratum is ignored in the calculation due to the significant difference in distance between the interlayer and the distance H_1 from the surface to the first stratum. Only the pressure loss from the surface to the first stratum is considered. When the nozzles of multiple strata are activated simultaneously, the changes in the combination of nozzle openings for each stratum will cause changes in the total branch flow rate, further leading to changes in the steady-state operating points of each stratum.

Combining Equations (22), (23), and (24) with Equations (13), (14), and (15) yields

$$C_1 = \frac{Q_1}{\sqrt{P_0 - \frac{Q_0^2}{C^2} + \rho g H_1 - h_{f1} - k_1 Q_1 - b_1}} \tag{36}$$

$$C_2 = \frac{Q_2}{\sqrt{P_0 - \frac{Q_0^2}{C^2} + \rho g \left(H_1 + H_2\right) - h_{f1} - k_2 Q_2 - b_2}} \tag{37}$$

$$C_n = \frac{Q_n}{\sqrt{P_0 - \frac{Q_0^2}{C^2} + \rho g \left(H_1 + H_2 + \cdots + H_n\right) - h_{f1} - k_n Q_n - b_n}} \tag{38}$$

Taking account of the maximum injection pressure for each stratum, during the water injection process, the pressure behind the stratum nozzle should not exceed the maximum injection pressure of that stratum. If it does, it would lead to a breakthrough of the injected water and an increase in water cut. Let the maximum injection pressure for the first stratum be $P_{11\max}$, for the second stratum be $P_{22\max}$, and for the nth stratum be $P_{nn\max}$. Considering the maximum injection pressure constraint, we obtain

$$P_0 - \frac{Q_1^2}{C_1^2} \le P_{11\max} + \frac{Q_0^2}{C^2} - \rho g H_1 + h_{f1} \tag{39}$$

$$P_0 - \frac{Q_2^2}{C_2^2} \le P_{22\max} + \frac{Q_0^2}{C^2} - \rho g \left(H_1 + H_2\right) + h_{f1} \tag{40}$$

$$P_0 - \frac{Q_n^2}{C_n^2} \le P_{nn\max} + \frac{Q_0^2}{C^2} - \rho g \left(H_1 + H_2 + \cdots + H_n\right) + h_{f1} \tag{41}$$

Equations (25), (26), and (27) establish a pipeline model considering interlayer pressure loss along the path, reflecting the change of steady-state operating point caused by nozzles opening variation. In the study of the feasible range of flow rates in the strata, the interlayer pressure loss is disregarded, and we obtain from Equations (25), (26), and (27):

$$\bar{Q}_1 = -\frac{k_1 C_1^2}{2} + \frac{C_1^2}{2}\sqrt{k_1^2 - \frac{4}{C_1^2}\left(b_1 - P_0 + \frac{\bar{Q}_0^2}{C^2} - \rho g H_1 + \frac{128\mu H_1 \bar{Q}_0}{\pi d^4}\right)} \tag{42}$$

$$\bar{Q}_2 = -\frac{k_2 C_2^2}{2} + \frac{C_2^2}{2}\sqrt{k_2^2 - \frac{4}{C_2^2}\left(b_2 - P_0 + \frac{\bar{Q}_0^2}{C^2} - \rho g \left(H_1 + H_2\right) + \frac{128\mu H_1 \bar{Q}_0}{\pi d^4}\right)} \tag{43}$$

$$\begin{aligned} \bar{Q}_n = & -\frac{k_n C_n^2}{2} \\ & + \frac{C_n^2}{2}\sqrt{k_n^2 - \frac{4}{C_n^2}\left(b_n - P_0 + \frac{\bar{Q}_0^2}{C^2} - \rho g \left(H_1 + H_2 + \cdots + H_n\right) + \frac{128\mu H_1 \bar{Q}_0}{\pi d^4}\right)} \end{aligned} \tag{44}$$

where $\bar{Q}_1$, $\bar{Q}_2$ and $\bar{Q}_n$ denote the branch flow rate of the first stratum, the branch flow rate of the second stratum, and the branch flow rate of the nth stratum in m^3/h, respectively, ignoring the pressure loss along the path between the first stratum and the nth stratum.

From Equation (28), we have the total flow rate:

$$\begin{aligned} & \bar{Q}_0 \\ = & \bar{Q}_1 + \bar{Q}_2 + \cdots + \bar{Q}_n \end{aligned}$$

$$= -\frac{k_1 C_1^2}{2} + \frac{C_1^2}{2}\sqrt{k_1^2 - \frac{4}{C_1^2}\left(b_1 - P_0 + \frac{\bar{Q}_0^2}{C^2} - \rho g H_1 + \frac{128\mu H_1 \bar{Q}_0}{\pi d^4}\right)}$$
$$-\frac{k_2 C_2^2}{2} + \frac{C_2^2}{2}\sqrt{k_2^2 - \frac{4}{C_2^2}\left(b_2 - P_0 + \frac{\bar{Q}_0^2}{C^2} - \rho g (H_1 + H_2) + \frac{128\mu H_1 \bar{Q}_0}{\pi d^4}\right)}$$
$$-\frac{k_n C_n^2}{2} + \frac{C_n^2}{2}\sqrt{k_n^2 - \frac{4}{C_n^2}\left(b_n - P_0 + \frac{\bar{Q}_0^2}{C^2} - \rho g (H_1 + H_2 + \cdots + H_n) + \frac{128\mu H_1 \bar{Q}_0}{\pi d^4}\right)} \quad (45)$$

When the stratum nozzle opening changes, the total flow rate $\bar{Q}_0$ will be affected correspondingly. In strata water injection models, determining the total flow rate under various nozzle opening combinations is crucial. Given the non-linear characteristics of the model, direct solutions using conventional methods are challenging. For this reason, this paper employs the Newton method. The Newton method is an iterative numerical technique aimed at approximating the solution to this problem [35,36], offering a practical tool for flow rate management after adjusting each stratum nozzle opening. Utilizing the Newton method enables us to predict and control the total flow rate changes during the layered water injection process with greater accuracy, thereby optimizing the water injection process. The procedure of the Newton iterative method is demonstrated in Figure 5.

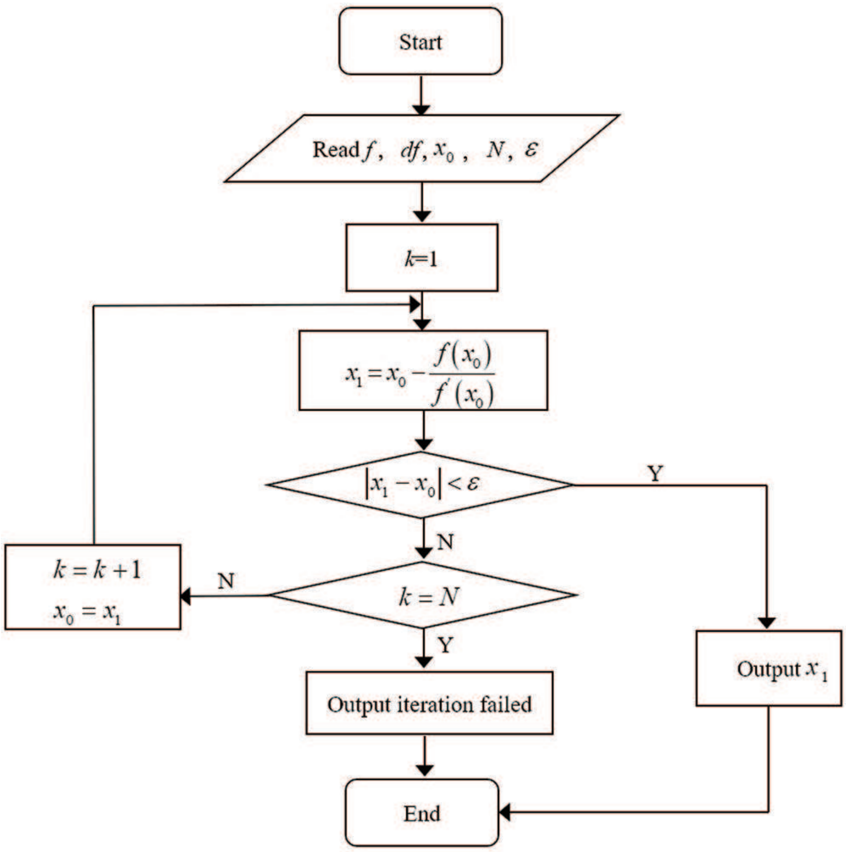

FIGURE 5. Newton method for $\bar{Q}_0$

In Figure 5 the objective function f is determined by Equation (45), that is, $f = \bar{Q}_1 + \bar{Q}_2 + \bar{Q}_3 - \bar{Q}_0$, df represents the derivative of f with respect to $\bar{Q}_0$, where $\bar{Q}_0$ is denoted as x, x_0 is the initial estimate, ε is precision, and N represents the maximum number of iterations. The core of the Newton method is to use the current estimate and its corresponding function value and derivative value to obtain the next estimate that is closer to the true solution, i.e.,

$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)} \tag{46}$$

Comparing the newly obtained total flow rate estimate x_1 with the previous estimate x_0, if the difference between them is less than a predefined precision ε, it can be inferred that the estimate is sufficiently close to the true total flow rate, terminating the iteration. Otherwise, if the maximum iteration count is not yet reached, the new estimate x_1 replaces x_0, proceeding to the next iteration. In certain instances, even after N iterations, the algorithm may not achieve the desired precision. Under such circumstances, it becomes pertinent to reconsider adjusting the initial estimate or enhancing the maximum iteration limit.

Through the aforementioned iterative process, estimates of the total flow rate for various opening combinations of nozzles can be obtained. This method is not only efficient but also accounts for the non-linear characteristics of the model. Based on the total flow rate estimates for each opening combination of nozzles, using Equations (42) to (44), the flow rates for each stratum are derived, denoting the feasible range of flow rates in the strata. Concurrently, the critical constraint of the maximum injection pressure for each stratum must be considered. By analyzing all potential opening combinations of nozzles and excluding those that do not meet the constraints, a more practical feasible range of flow rates that incorporates the maximum injection pressure constraint can be established.

5. **Simulation.** This section presents a study where the simultaneous opening of nozzles across three strata is considered. Simulation experiments were conducted to verify the mutual disturbance characteristics of the steady-state operating points among the strata. The experiments provided insight into how alterations in the nozzles opening in the first, second, and third stratum respectively impact the steady-state operating points of the other strata. Building on the foundation of interlayer interference, and following the theoretical derivations of the feasible range of flow rates in the strata, constraints regarding the maximum injection pressure of the strata were incorporated into the analysis. This led to a simulation-based analysis of the feasible range of flow rates in the strata.

5.1. **Simulation of strata steady-state operating point mutual disturbance characteristics.** In scenarios where only a single stratum is activated, consider the case where only the first stratum is activated. Given the known incoming water characteristic and a constant pressure injection scenario, when the wellhead valve opening coefficient C is fixed and the first stratum nozzle opening coefficient C_1 changes, the pressure-flow relationship before the nozzle can be obtained from Equation (4), as illustrated in Figure 6.

As depicted in Figure 6, the water injection layer section 1-1 curve represents the pressure-flow relationship of the stratum when the nozzle opening coefficient is 50%. The point of intersection between this curve and the total flow pressure characteristics curve represents the steady-state operating point, labeled as point a. When the nozzle opening coefficient decreases to 25%, the steady-state operating point of the stratum shifts from point a to point c, causing a reduction in the flow rate under the same pre-nozzle pressure conditions. Conversely, when the nozzle opening coefficient increases to 75%, the steady-state operating point of the stratum shifts from point a to point b, resulting in an increased flow rate under the same pre-nozzle pressure.

When the nozzles of three strata are concurrently activated, considering the incoming water characteristic is known, and the injection condition is constant pressure injection,

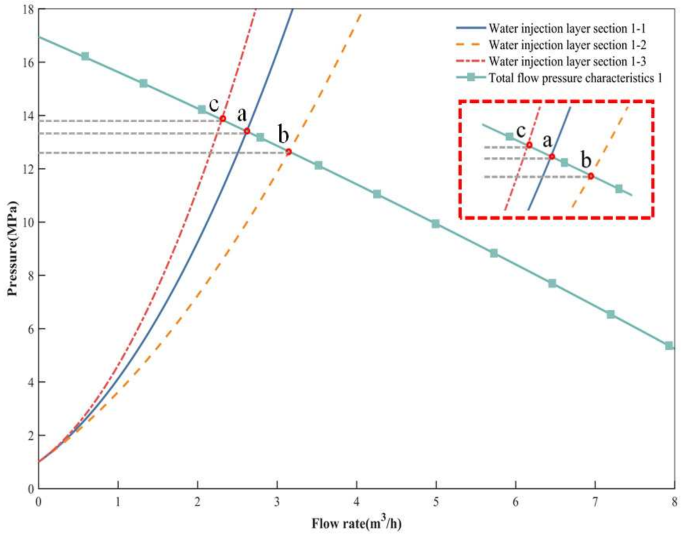

Figure 6. Variation of the steady-state operating point of the first stratum when its opening coefficient is changed

the pre-nozzle pressure-flow relationship for each stratum can be obtained from Equations (22), (23), and (24) when the wellhead valve opening coefficient C remains constant, while the nozzles opening coefficients C_1, C_2, and C_3 respectively increase or decrease. These relationships are illustrated in Figures 7 to 12.

Figures 7 to 12 illustrate the flow-pressure curves of pre-nozzle for each stratum under constant pressure injection conditions, obtained by individually varying the nozzles opening coefficients for the first, second, and third strata. Taking the example of increasing or decreasing the nozzle opening coefficient for the first stratum, the change is illustrated in the steady-state operating points of the remaining strata when the nozzle opening coefficient of certain stratum changes. As depicted in Figures 7 and 8, the total flow pressure characteristics 1, 2, and 3 curves are obtained by calculating the total flow rate and pressure from the surface to the bottom of the well. The water injection layer section 1-1 curve represents the flow-pressure characteristics when the nozzle opening coefficient of the first stratum is at 50%. The water injection layer section 1-2 curve corresponds to

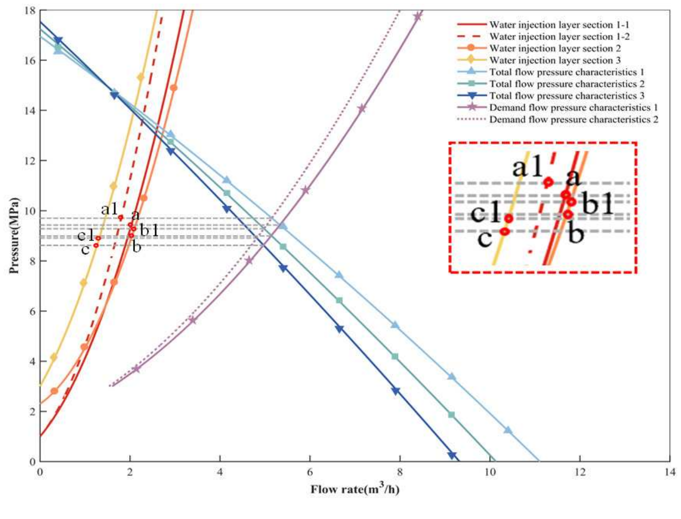

Figure 7. Variation of the steady-state operating point of each stratum when the opening coefficient of the first stratum is reduced

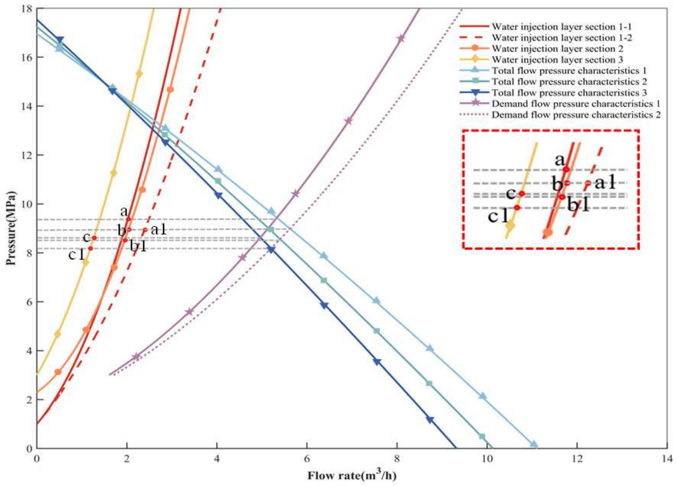

FIGURE 8. Variation of the steady-state operating point of each stratum when the opening coefficient of the first stratum is increased

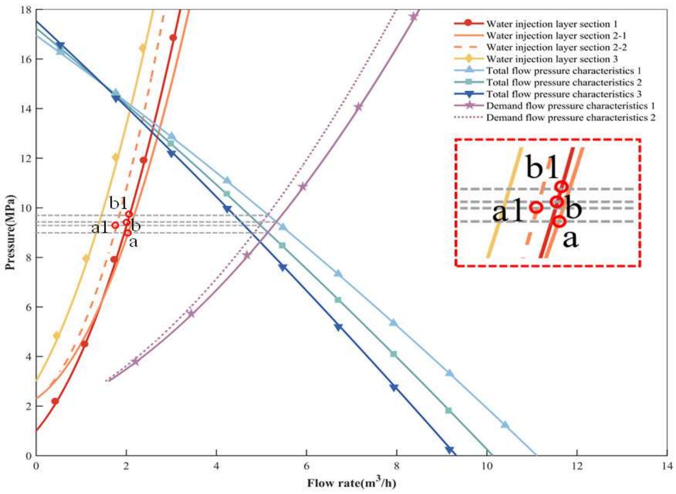

FIGURE 9. Variation of the steady-state operating point of each stratum when the opening coefficient of the second stratum is reduced

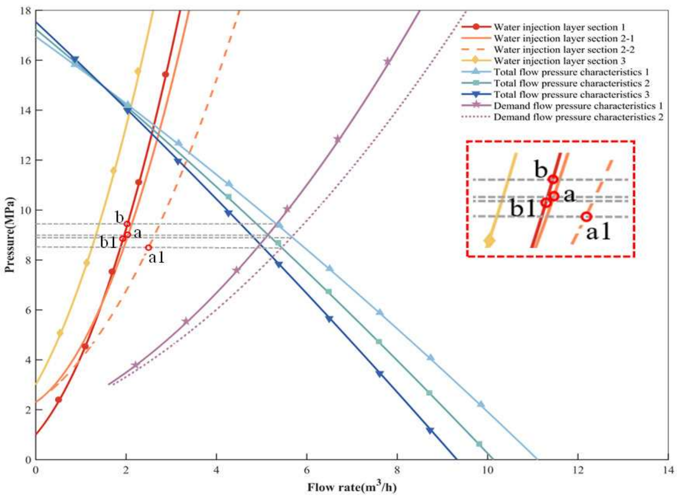

FIGURE 10. Variation of the steady-state operating point of each stratum when the opening coefficient of the second stratum is increased

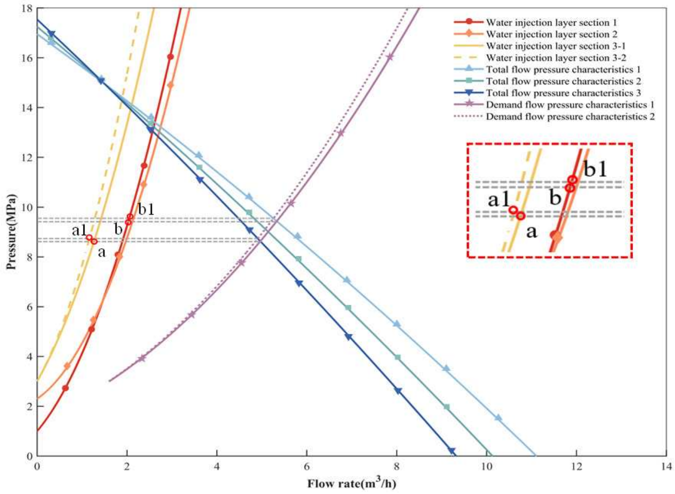

FIGURE 11. Variation of the steady-state operating point of each stratum when the opening coefficient of the third stratum is reduced

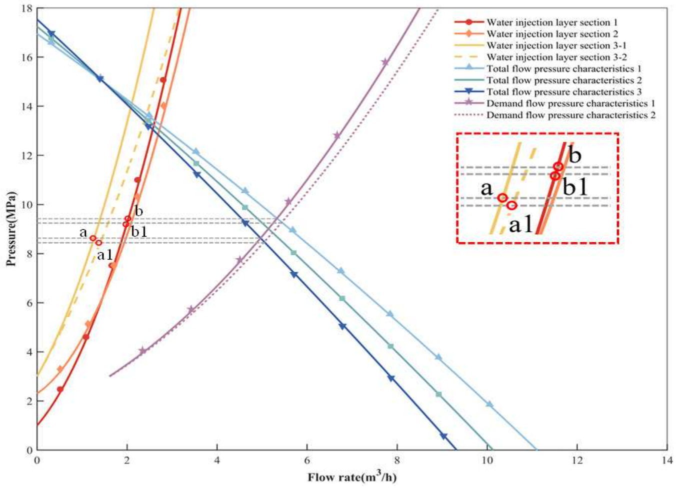

FIGURE 12. Variation of the steady-state operating point of each stratum when the opening coefficient of the third stratum is increased

the flow-pressure characteristics when the nozzle opening coefficient increases or decreases by 25%. The water injection layer section 2, and 3 curves represent the flow-pressure characteristics when the nozzles opening coefficients of the second and third strata are both at 50%. The demand flow pressure characteristics 1, and 2 curves illustrate the total flow pressure characteristics before and after changes in the opening coefficient of the first stratum's nozzle when three strata are operating simultaneously. With the nozzles opening coefficients of the first, second, and third strata all being 50%, the steady-state operation points for these strata are respectively at points a, b, and c. As shown in Figure 7, when the nozzle opening coefficient of the first stratum decreases by 25%, the steady-state operation point of this stratum transitions from point a to point a1. Under identical pre-nozzle pressures, this stratum's flow rate decreases. At the same time, the steady-state operation points of the second and third strata move from points b and c to points b1 and c1, suggesting that under the same pre-nozzle pressure, the flow rates for these strata increase. Similarly, as illustrated in Figure 8, when the nozzle opening coefficient for the first stratum increases by 25%, under the same pre-nozzle pressure, the flow rate of this stratum increases, while the flow rates of the second and third strata decrease.

These results align with the fundamental understanding of fluid dynamics, corroborating the accuracy of the mathematical model of the layered water injection pipeline.

5.2. **The feasible range of flow rates in the strata simulation.** In this section, the PSO algorithm is employed for simulation analysis to reassess the issue of water injection opening configuration. During this process, each particle represents a possible opening configuration, incorporating three parameters: C_1, C_2, and C_3. PSO algorithm attempts to find an optimal set of parameters that minimize the objective function in Equation (32) by iteratively moving particles within the parameter space. Specifically, the "particleswarm" function in the MATLAB environment is used, with the number of particles set to 100 and the maximum number of iterations set to 200. For each particle, a three-dimensional search space is defined, where the range for parameters C_1, C_2, and C_3 is $[0.01, 1]$.

During each iteration, the fitness of every particle is evaluated, that is, the current position of the particle (values of C_1, C_2, and C_3) is plugged into the objective function, which represents the influence of the opening coefficient of the three strata on system performance. Moreover, each particle updates its velocity and position, taking consideration of its best historical position and the best historical position of the entire swarm, among others. These elements collectively guide the movement of particles within the search space, aiding the algorithm in finding the global optimum. The changes in the optimal function value during each iteration process are shown in Figure 13.

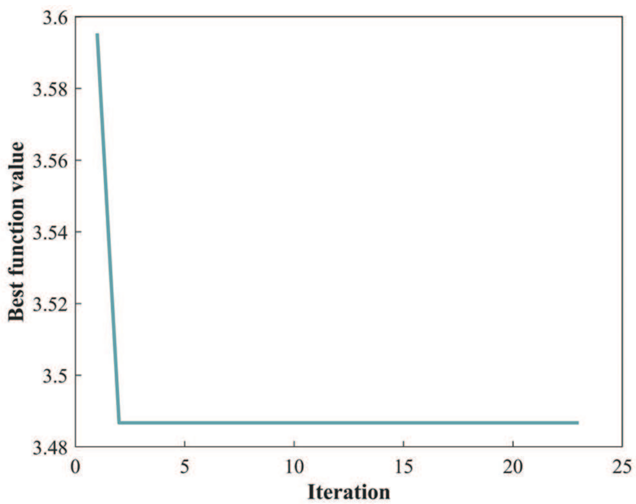

FIGURE 13. Variation of optimal function values

As illustrated in Figure 13, the best function value of all particles is stored during each iteration. This best value represents the minimum of the objective function at the current position of the swarm. As the number of iterations increases, the optimal function value eventually stabilizes, implying that the algorithm is nearing a global optimum. The stabilized value is a positive number, suggesting that the sum of flow rates when each stratum is independently activated at any opening combination exceeds the total branch flow rate when all strata are simultaneously activated. This indicates that the flow rate corresponding to each nozzle opening when a stratum is independently activated cannot directly determine the flow rate corresponding to each nozzle opening of that stratum when multiple strata are activated simultaneously. The analysis of the feasible range of flow rates in the strata is, therefore, of paramount importance.

In Section 4.2, the theoretical derivation part, this study introduced the concept of the feasible range of flow rates in the strata. The relationships between the flow rate of each stratum, nozzles opening, pressure loss, and other factors are derived, taking account of the constraint of maximum injection pressure. Concurrently, the Newton method was used to solve for the total branch flow rate under different opening combinations. In this section, the theoretical understandings and mathematical models are applied in conjunction with specific data and parameters for simulation analysis. Based on actual geological structures and working conditions, simulate the layered water injection process, calculate, and present the feasible range of flow rates in the strata, as shown in Figure 14.

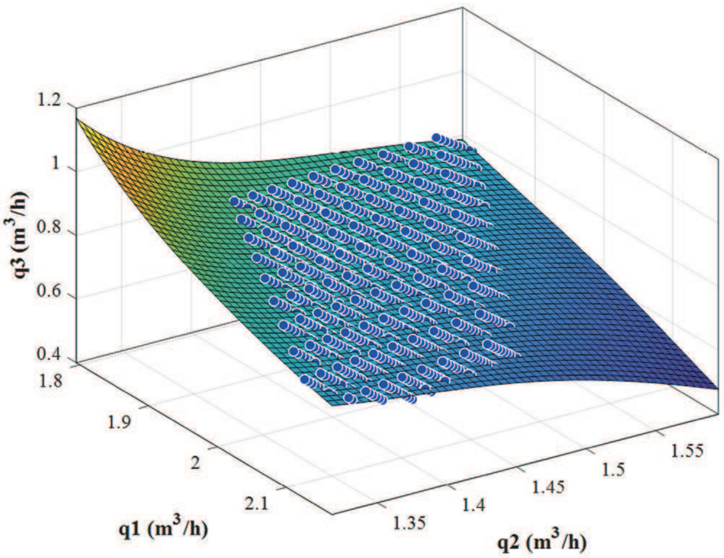

Figure 14. The feasible range of flow rates in the strata under constraint

As depicted in Figure 14, the X, Y, and Z axes represent the flow rates of the three strata, respectively, and the scatter points represent various possible flow rate combinations, forming the feasible range. By traversing all possible combinations of strata nozzles opening, the flow rate combinations are within a specific region. Specifically, the range of q1 is between 1.8 m^3/h and 2.15 m^3/h, the range of q2 is between 1.3 m^3/h and 1.6 m^3/h, and the range of q3 is between 0.5 m^3/h and 1.18 m^3/h. No outliers are observed. Water distribution schemes should be within this feasible range. If not, it indicates that the water distribution schemes are unfeasible and need to be adjusted promptly; otherwise, it would lead to a decline in the water injection success rate. In numerical simulations, by traversing all possible opening combinations and calculating the total flow rate under these combinations, the flow rate of each stratum is computed. The flow rates of the three strata are represented in a scatter plot. The changing trend and relationship of the feasible range are obtained by approximating the scattered points. Based on the feasible range that comprehensively considers all constraints, a more accurate determination of the possible flow rate range of each stratum during the actual layered water injection process can be made. This aids in optimizing the water injection process, thereby improving the water injection success rate of oilfields.

6. **Conclusion.** Addressing the issue of the feasibility of water distribution schemes during simultaneous multiple strata operation in layered water injection and the need to improve the water injection success rate, this study carries out theoretical derivations to establish the relationship between nozzle opening and flow rate for each stratum during layered water injection. The study then uses simulation analysis to understand the

changing laws of the steady-state operating points of the remaining strata when the nozzle opening of certain stratum changes. Comprehending this mechanism of mutual influence is crucial for optimizing the layered water injection process. Building upon the theoretical derivation, due to the difference in fluid dynamics between individual stratum operation and simultaneous multiple strata operation, this paper employs the PSO algorithm. This demonstrates that the flow rate corresponding to each nozzle opening during a single stratum operation cannot be directly used to assess the flow rate corresponding to the same nozzle opening of that stratum when multiple strata are simultaneously in operation. This work introduces the concept of the feasible range of flow rates in the strata, conducting theoretical and numerical research into the feasible range of flow rates in the strata. This provides a basis for judging the feasibility and adjustment of water distribution schemes, aiding in optimizing the fourth-generation layered water injection technology and enhancing the efficiency of oilfield development. In the future, further studies should be directed towards the following two areas: 1) Given the complexity of geological formations, it is imperative to extend the scope to more intricate strata structures and heterogeneities, to further validate and optimize the model's adaptability; 2) Incorporating field experimental data for comparative analysis against simulation results will bolster the validation of the methods proposed in this study. Moreover, refining and optimizing the model in a real-world setting is pivotal. Such research directions hold promise for fostering technical innovations and enhancing benefits in oilfield development.

REFERENCES

[1] S. Yuan and Q. Wang, New progress and prospect of oilfields development technologies in China, *Petroleum Exploration and Development*, vol.45, no.4, pp.698-711, 2018.

[2] X. Zheng, J. Shi, G. Cao, N. Yang, M. Cui, D. Jia and H. Liu, Progress and prospects of oil and gas production engineering technology in China, *Petroleum Exploration and Development*, vol.49, no.3, pp.644-659, 2022.

[3] X. Wang, H. Dang and T. Gao, Method of moderate water injection and its application in ultra-low permeability oil reservoirs of Yanchang Oilfield, NW China, *Petroleum Exploration and Development*, vol.45, no.6, pp.1094-1102, 2018.

[4] J. Xia, C. Yang, F. Tan et al., Current status and prospect of zonal water injection technology in Huabei Oilfield, *Oil Drilling & Production Technology*, vol.37, no.2, pp.74-78, 2015.

[5] D. Jia, H. Liu, J. Zhang et al., Data-driven optimization for fine water injection in a mature oil field, *Petroleum Exploration and Development*, vol.47, no.3, pp.674-682, 2020.

[6] H. Liu, L. Zheng, Q. Yang et al., Development and prospect of separated zone oil production technology, *Petroleum Exploration and Development*, vol.47, no.5, pp.1103-1116, 2020.

[7] H. Liu, X. Pei, D. Jia, F. Sun and T. Guo, Connotation, application and prospect of the fourth generation separated layer water injection technology, *Petroleum Exploration and Development*, vol.44, no.4, pp.644-651, 2017.

[8] X. Zhang, R. Zhu, G. Li et al., Application of wireline intelligent separate-layer water injection technology in Huabei Oilfield, *Journal of Physics: Conference Series*, vol.1983, no.1, 012043, 2021.

[9] B. Yao, L. Yang, J. Yu, Z. Ji and G. Hu, Digital layered water injection based on wave code communication, *China Petroleum Machinery*, vol.48, no.5, pp.71-77, 2020.

[10] L. Zheng, J. Yu, Q. Yang, Y. Gao and F. Sun, Vibration wave downhole communication technique, *Petroleum Exploration and Development*, vol.44, no.2, pp.321-327, 2017.

[11] T. Jiang, Z. Huang, J. Li et al., Internal flow mechanism of cone-straight nozzle, *Petroleum Science*, vol.18, no.5, pp.1507-1519, 2021.

[12] M. Jalali, J. M. Embry, F. Sanfilippo et al., Cross-flow analysis of injection wells in a multilayered reservoir, *Petroleum*, vol.2, no.3, pp.273-281, 2016.

[13] Z. Cheng, Y. Xu, C. Gu and Z. Liu, Research on pressure wave and communication of real-time testing and adjustable system in oilfield layered water injection, *Proc. of the Asia-Pacific Conference on Intelligent Medical 2018 & International Conference on Transportation and Traffic Engineering (APCIM & ICTTE)*, New York, USA, pp.208-212, 2018.

[14] H. Cheng, D. Yang, C. Lu et al., Intelligent oil production stratified water injection technology, *Wireless Communications and Mobile Computing*, pp.1-7, 2022.

[15] G. Du, Research and application of cable controlled layered water injection technology in Daqing Oilfield, *IOP Conference Series: Earth and Environmental Science*, vol.384, no.1, 012068, 2019.

[16] E. Ming, J. Yu, L. Zheng et al., Transmission model of transient flow wave signal in intelligent layered water injection system, *Journal of Petroleum Exploration and Production Technology*, pp.1-16, 2023.

[17] T.-C. Che, H.-F. Duan and P. J. Lee, Transient wave-based methods for anomaly detection in fluid pipes: A review, *Mechanical Systems and Signal Processing*, vol.160, 107874, 2021.

[18] Y. Hou, Y. Peng, Z. Chen et al., Investigation on the controlling factors of pressure wave propagation behavior induced by pulsating hydraulic fracturing, *SPE Journal*, vol.26, no.5, pp.2716-2735, 2021.

[19] Y. Li, X. Hu, F. Zhou et al., A new comprehensive filtering model for pump shut-in water hammer pressure wave signals during hydraulic fracturing, *J. Pet. Sci. Eng.*, vol.208, 109796, 2022.

[20] E. Ming, C. Li, H. Lan et al., Modeling wave transmission for transient flow and amplitude-frequency characteristics of tubular string in a water injection well, *Appl. Sci.*, vol.13, no.6, 3917, 2023.

[21] Y. Zhou, S. Lei, X. Du et al., Injection-production optimization of carbonate reservoir based on an inter-well connectivity model, *Energy Exploration & Exploitation*, vol.39, no.5, pp.1666-1684, 2021.

[22] Y. Yue, H. Wen, X. Zuo, M. Sheng and F. Sun, Output fusion of MPC and PID and its application in intelligent layered water injection of oilfield, *International Journal of Innovative Computing, Information and Control*, vol.19, no.3, pp.737-762, DOI: 10.24507/ijicic.19.03.737, 2023.

[23] H. Liu, L. Zheng, J. Yu et al., Development and prospect of downhole monitoring and data transmission technology for separated zone water injection, *Petroleum Exploration and Development*, vol.50, no.1, pp.191-201, 2023.

[24] B. Wu, C. Hua, G. Ren et al., Downhole parameter prediction method based on multi-layer water injection model and historical data-based model parameter identification, *Heliyon*, 2023.

[25] G. Chen, K. Zhang, L. Zhang et al., Global and local surrogate-model-assisted differential evolution for waterflooding production optimization, *SPE Journal*, vol.25, no.1, pp.105-118, 2020.

[26] W. Zhao, A. Shen, S. Hu et al., Geological conditions and distributional features of large-scale carbonate reservoirs onshore China, *Petroleum Exploration and Development*, vol.39, no.1, pp.1-14, 2012.

[27] C. Esene, N. Rezaei, A. Aborig and S. Zendehboudi, Comprehensive review of carbonated water injection for enhanced oil recovery, *Fuel*, vol.237, pp.1086-1107, 2019.

[28] W. Kang, S. Shao, H. Yang et al., The effect of stepwise increasing of water injection rates on enhanced oil recovery after preformed particle gel treatment, *Journal of Petroleum Science and Engineering*, vol.182, 106239, 2019.

[29] L. Liu, Y. Liu, J. Yao et al., Mechanistic study of cyclic water injection to enhance oil recovery in tight reservoirs with fracture deformation hysteresis, *Fuel*, vol.271, 117677, 2020.

[30] X. Song and Y. Li, Optimum development options and strategies for water injection development of carbonate reservoirs in the middle east, *Petroleum Exploration and Development*, vol.45, no.4, pp.723-734, 2018.

[31] Q. Lei, D. Weng, B. Guan et al., A novel approach of tight oil reservoirs simulation based on fracture controlling optimization and design, *Petroleum Exploration and Development*, vol.47, no.3, pp.632-641, 2020.

[32] M. Razghandi, A. Dehghan and R. Yousefzadeh, Application of particle swarm optimization and genetic algorithm for optimization of a Southern Iranian Oilfield, *Journal of Petroleum Exploration and Production*, vol.11, pp.1781-1796, 2021.

[33] Y. Yu, Y. Wang, D. Xu, Z. Dou and M. Yang, Research on charging and discharging strategy of electric vehicles in park micro-grid based on pigeon-inspired optimization algorithm, *International Journal of Innovative Computing, Information and Control*, vol.19, no.3, pp.721-735, 2023.

[34] D. Wang, M. Li and W. Song, A kind of information granular fuzzy broad learning system based on the Takagi-Sugeno model, *International Journal of Innovative Computing, Information and Control*, vol.19, no.1, pp.279-287, 2023.

[35] K. Mishchenko, Regularized Newton method with global convergence, *SIAM Journal on Optimization*, vol.33, no.3, pp.1440-1462, 2023.

[36] N. Doikov and Y. Nesterov, Gradient regularization of Newton method with Bregman distances, *Mathematical Programming*, pp.1-25, 2023.

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