Research Article

Research on Dynamic Dissolving Model and Experiment for Rock Salt under Different Flow Conditions

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1. Introduction


<table>
<thead>
<tr>
<th>Soluble substance</th>
<th>Insoluble substance</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>K₂SO₃</td>
</tr>
<tr>
<td>99.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Small amount of muddy</td>
</tr>
</tbody>
</table>

Table 1: Components of rock salt specimens (%).


Past research has yielded significant results for shape control of rock salt cavities and stability analysis. Dynamic dissolving properties of rock salt, however, require further in-depth analysis and research [25, 26]. In this paper, a dynamic dissolving experiment was designed for rock salt to research the dynamic dissolving process under different flow conditions. And according to experiment results, a dynamic dissolving model for rock salt was built with the finite-difference method applied to derive a numerical solution to the dynamic dissolving model. The Particle Swarm Optimization algorithm was then introduced to inverse parameters of the model. Comparison between the calculation results and experimental data demonstrates effectiveness of the established model and provides reference for the study of the rock salt dissolving mechanism.

2. Experimental Research on the Rock Salt’s Dynamic Dissolving Properties under Different Flow Conditions

2.1. Experimental Process. Natural rock salt from the Himalayan Mountains in Pakistan was utilized as the experimental specimen. The rock salt is located at a depth of 2000 to 3000 meters and exhibits coloring of white mixed with light red or glass white. Specimens are manufacturer-processed into test specimens of 50 × 100 mm for experimental purposes. Components of the specimens are comprised of 99.8% soluble substance with average density of 2959 kg/m³ as listed in Table 1.

A water-passage pinhole with 6 mm diameter is drilled at the center of the sample's axial position and processing conducted strictly in line with the experimental regulations. The processed sample size accuracy must be kept within the deviations. Figure 1 depicts rock salt samples prepared for hole-boring.

Rock salt dynamic dissolving experimental devices (Figure 2) have been designed for this paper. The component devices of the experiment include iron pedestal, beaker chain clip, 703 glue, two large beakers, fluid flowmeter (measuring range 6–60 L/h), facial tissue, air blower, high-precision electronic balance (the precision is 0.01 g), plastic flexible pipe with 6 mm outer diameter, and vernier calipers.

Test procedures are as follows.

1. Weigh the bored test sample utilizing the electronic balance and measure length and diameter by vernier calipers.
2. Seal the test sample utilizing the waterproof coating material “703 glue” and then weigh the sealed samples.
3. Adjust flow quantity with the water faucet switch to allow the flowmeter to display 20 L/h.
4. Attach the beaker chain clip to the waterproofed test sample, insert the water passage pipe into the test sample and begin timing.
5. Remote the water-passage pipe until three minutes run out and place the pipe into another large beaker for continuation of flow quantity. Then detach the test sample and dry the sample with facial tissue and the air blower and weigh with the electronic balance.
6. Adjust the flowmeter to display the flow quantity numbers of 30 L/h, 40 L/h, and 50 L/h. Repeat experiment procedures in (4) and (5).

2.2. Experimental Results. The rock salt dynamic dissolving curve is not a smooth curve but rather a slightly fluctuating curve as demonstrated in Figures 3 and 4.

Dissolving rate of rock salt accelerates with a larger value of flow quantity Q as demonstrated in Tables 2 and 3, revealing that solution movement accelerated the convection effect and diffusion effect of rock salt. The experiment studied rock salt samples in dynamic solution state, and rock salt specimen dissolving mass was recorded with different flow rates in different time to study the effect of flow quantity Q on the dissolving rate of rock salt. Experiment results reveal that in a certain range the dissolving rate of rock salt increases with increasing of flow quantity Q. Therefore, in practice, properly controlling the freshwater injection rate will have a better effect of mineral dissolution for rock salt.
Figure 2: Device for dynamic dissolving test for rock salt.
Table 2: Data of rock salt specimens.

| Serial number of the test sample | Diameter/mm | Length/mm | Mass of the test sample/g | Mass of the sample that has been sealed with waterproof coating materials/g | Density/g cm$^{-3}$ |
|----------------------------------|-------------|-----------|--------------------------|---------------------------------------------------------------------------|
| A1                               | 49.32       | 100.78    | 394.25                   | 434.01                                                                     | 2.0797             |
| A2                               | 51.84       | 101.08    | 432.54                   | 464.3                                                                      | 2.0284             |
| A3                               | 50.92       | 101.96    | 441.22                   | 480.62                                                                     | 2.156              |
| A4                               | 52.56       | 101.38    | 446.39                   | 482.25                                                                     | 2.0572             |

Table 3: Results of dynamic dissolving test for rock salt (g).

<table>
<thead>
<tr>
<th>Time/min</th>
<th>20 L/h</th>
<th>30 L/h</th>
<th>40 L/h</th>
<th>50 L/h</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>A4</td>
</tr>
<tr>
<td>0</td>
<td>434.01</td>
<td>464.3</td>
<td>480.62</td>
<td>482.25</td>
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<td>458.07</td>
<td>472.94</td>
<td>472.61</td>
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<tr>
<td>6</td>
<td>424.81</td>
<td>448.93</td>
<td>460.94</td>
<td>458.62</td>
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<td>9</td>
<td>419.08</td>
<td>437.85</td>
<td>449.2</td>
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<tr>
<td>12</td>
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<td>423.76</td>
<td>434.81</td>
<td>421.86</td>
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<tr>
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<td>412.15</td>
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<td>402.34</td>
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<td>18</td>
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<td>400.18</td>
<td>401.54</td>
<td>377.38</td>
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<tr>
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<td>387.63</td>
<td>382.57</td>
<td>351.8</td>
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<tr>
<td>24</td>
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<td>374.89</td>
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<td>36</td>
<td>325.35</td>
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<tr>
<td>39</td>
<td>311.13</td>
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</tr>
</tbody>
</table>

3. Rock Salt’s Dynamic Dissolving Model under Different Flow Conditions

Ideal conditions are assumed for rock salt samples as follows. (1) Rock salt samples are considered homogeneous with isotropic properties and no interlayer. (2) The seepage in dynamic dissolution is considered as laminar flow. (3) Insoluble residuals flow with the fluid and do not subside in the pinhole. (4) Insoluble residuals have a negligible effect on the diffusion process. (5) The influence by temperature difference and variations is ignored.

The diffusion effect can be described according to the First Diffusion Laws of Fick: the diffusion coefficient is directly proportional to the gradient of concentration, described as follows (1):

$$J = -D \frac{\partial C}{\partial n},$$  \hspace{1cm} (1)

where $J$ represents the diffusive flux (mol·cm$^{-2}$·s$^{-1}$), $C$ refers to the material concentration (mol·L$^{-1}$), $D$ represents the diffusive coefficient (cm$^2$·s$^{-1}$), and, under normal circumstances, the diffusive coefficient is relevant to the solvent and temperature of solute.

Micro units $dx$ can be derived according to the mass balance principle and by referring to Figure 5:

$$Jdxdtdx = \frac{\rho_s}{M}dRdx,$$  \hspace{1cm} (2)

where $\rho_s$ refers to the density of rock salt (cm$^3$·s$^{-1}$), $M$ represents the molar mass of rock salt (g·mol$^{-1}$), $R$ is...
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The dissolving process of rock salt is also influenced by the fluid's flow rate $v$ and the pinhole diameter $d$. Establishing the dissolving equilibrium equation of rock salt then necessitates the assumption that $m_x$ is the mole number of solution that passes through the pinhole section $x$ within the time period $dt$, $m_{x+dx}$ refers to the mole number of solution passing through the seepage section $x + dx$ within the time period $dt$, and $d$ is the diameter of pinhole. The equations are as follows:

$$m_x = C_{st} \frac{\pi}{4} (d + 2R_{xt})^2 v_{st} dt,$$

$$m_{x+dx} = \left( C_{st} + \frac{\partial C}{\partial x} dx \right) \frac{\pi}{4} (d + 2R_{xt})^2 v_{st} dt. \tag{7}$$

Disregarding changes in the fluid volume inside the pinhole caused by rock salt dissolution, it is discovered, according to the mass balance principle, that the difference between $m_{x+dx}$ and $m_x$ is the mole number of the rock salt that has dissolved within the time period of $dt$ at the section $dx$ or

$$m_{x+dx} - m_x = \frac{\rho_s}{M} \pi (d + 2R_{xt}) \frac{\partial R}{\partial x} \ dt. \tag{8}$$

Presuming the flow loss is not considered, then

$$Q = \frac{\pi}{4} (d + 2R_{xt})^2 v_{st}. \tag{9}$$

where $Q$ represents the flow quantity (cm$^3$·s$^{-1}$).

Combining (7), (8), and (9), we have the following reorganization:

$$\frac{\partial C}{\partial x} = \frac{\rho_s}{MQ} \pi (d + 2R_{xt}) \frac{\partial R}{\partial t}, \tag{10}$$

where signs mean the same as those appearing before.

Partial differential equations are composed of (6) and (10):

$$\frac{\partial R}{\partial t} = \frac{2D}{\delta} \frac{M}{\rho_s} (C_s - C_{xt}),$$

$$\frac{\partial C}{\partial x} = \frac{2D}{\delta Q} \pi (d + 2R_{xt}) (C_s - C_{xt}), \tag{11}$$

where $C_{st}$ represents the initial concentration of the solution (mol·L$^{-1}$).

4. Numerical Solutions and Results

Analysis of Rock Salt Dynamic Dissolving Model under Different Flow Conditions

4.1. Numerical Solution. Among the rock salt dynamic dissolving models, the partial differential equations (11) are non-linear, creating challenges for obtaining an analytic solution.
A proper difference scheme is thus established to discretize the partial differential equations (11). A computerized analytic solution can then be derived.

A difference grid is established as Figure 6, where the step length of \( x \) axis is \( h \) and the step length of \( t \) axis is \( \tau \). The equation system then is

\[
\begin{align*}
R(x,t) &= R(nh,i\tau) = R^i_n \\
C(x,t) &= C(nh,i\tau) = C^n_i \\
\frac{\partial R(x,t)}{\partial t} &= \frac{\partial R}{\partial t} \\
\frac{\partial C(x,t)}{\partial x} &= \frac{\partial C}{\partial x}.
\end{align*}
\]

The difference scheme that is built from (11) is as follows:

\[
\begin{align*}
\frac{R(nh,(i+1)\tau) - R(nh,i\tau)}{\tau} &= \frac{2}{\delta} \frac{M}{\rho_s} (C^i_s - C(nh,i\tau)) \\
\frac{C((n+1)h,i\tau) - C(nh,i\tau)}{h} &= \frac{2D}{\delta Q} \pi (d + 2R(nh,i\tau)) (C^i_s - C(nh,i\tau)).
\end{align*}
\]

Assuming that \( (2M/\rho_s)C_s \tau = a \), \( (2M/\rho_s)\tau = b \), \( (2/Q)\pi C_s h = A \), and \( (2/Q)\tau h = B \), then after reorganizing:

\[
\begin{align*}
R^n_{i+1} &= \frac{D}{\delta} (a - bC^n_{i+1}) + R^n_i \\
C^n_{i+1} &= \frac{D}{\delta} (A - BC^n_{i+1}) (d + 2R^n_i) + C^n_i
\end{align*}
\]

then we can get:

\[
\begin{align*}
R^n_i &= \frac{D}{\delta} (a - bC^n_{i-1}) + R^n_{i-1} \\
C^n_i &= \frac{D}{\delta} (A - BC^{n-1}_i) (d + 2R^n_{i-1}) + C^{n-1}_i.
\end{align*}
\]

and, further,

\[
\begin{align*}
R^n_0 &= \frac{D}{\delta} (a - bC^n_{i-1}) + R^n_{i-1} \\
C^n_0 &= \frac{D}{\delta} (A - BC^{n-1}_i) (d + 2R^n_{i-1}) + C^{n-1}_i.
\end{align*}
\]

Owing to known initial conditions, \( R(x,0) = 0 \) and \( C(0,t) = C_0 \), it is determined that \( R^n_0 = 0 \) and \( C^n_0 = C_0 \). Since the \( R^n_0 \) and \( C^n_0 \) are known, from the recursion formula, we can also calculate \( R^n_i \) and \( C^n_i \). So the initial conditions \( R^n_0 \), \( C^n_0 \), \( R^n_i \), and \( C^n_i \) will be known.

As known from the recursion equation (15), \( R^n_i = (D/\delta)(a - bC^n_{i+1}) + R^n_{i-1} \) is an explicit difference form; in other word, \( R^n_i \) is directly calculated from \( R^n_{i-1} \) and \( C^n_{i+1} \). According to initial conditions, \( R^n_0 \) has known, and \( R^n_i \) can be calculated through the explicit difference form. Therefore, through the chasing method, from \( \{C^n_{i-1}, R^n_{i-1}\} \), calculations are made for \( \{C^n_i, R^n_i\} \), above is the realization process of the numerical solution.

Parameters of the experiment are as follows: \( M = 58.5 \, g/mol, C_s = 0.0054 \, mol/cm^3, \) and \( d = 0.6 \, cm, \rho_s \) and \( Q \) can be derived from the experiment and their value referred to in Tables 2 and 3. The parameters \( a, b, A, \) and \( B \) can then be calculated. The initial concentration of solution in this paper is \( C_0 = 0 \, mol/cm^3 \). The diffusion coefficient \( D \) and the boundary layer’s thickness \( \delta \), as determined from the research above, result in the dissolving radius \( R \) with the above finite-difference recursion formula applied.

4.2 Parameters Inversion. Particle swarm optimization (PSO), a type of artificial-intelligence algorithm, is introduced in this research to conduct parameters inversion of the rock salt dynamic dissolving model.

Particle swarm optimization is a new Evolutionary Algorithm (EA) developed in recent years. PSO is similar to the Simulated Annealing Algorithm as both originate from random solutions and seek to find optimal solutions through recursion. PSO also evaluates the quality of solutions through fitness value, but is simpler than the Genetic Algorithm rules as it does not have operations such as “Crossover” and “Mutation.” PSO simply searches for the global optimum through the found optimal value and is even known for its simplicity, high precision, and quick convergence while demonstrating advantages in the solving of practical problems.

The inverse programs will be realized in the MATLAB software and include three parts (Figure 7). The first part, referred to as cc.Mat, is the random initialization and includes both velocity matrix and position matrix.

The second part, according to the M file, solves the dissolving radius through applying the finite-difference method programmed on the basis described in Section 4.1 and is referred to as Numerical.m. This part mainly includes the random velocity matrix and random position matrix which are generated in the first part to calculate the dissolving radius \( R \).
The third part, referred to as “main.m” is the main program written based on the particle swarm optimization. The program’s major steps include:

1. retrieve the cc.Mat file; obtain the random displacement matrix and velocity matrix; implement the Numerical.m file to calculate the dissolving radius $R$; apply the calculated results to the fitness function to attain the fitness value of each particle;
2. compare the value of each particle’s fitness; retrieve the global optimal solution (or the minimum); and record value and position of the global optimum;
3. update the velocity matrix and position matrix according to the particle swarm optimization; save the renewed data and create overlay for the part one file cc.Mat;
4. implement the Numerical.m file again after the renewed particle velocity and position matrix and calculate the dissolving radius $R$ and the fitness value of each particle;
5. compare the fitness value of each particle after renewed. If the upgraded fitness value is smaller, save and record the corresponding value and position. If the value is larger, do not save;
6. compare the fitness value of each particle after renewed with the global optimum. If the fitness value of the particle with renewed information is smaller, then save and record the value and position. If the value is larger, do not save;
7. repeat steps (4) to (6) until the conditions for seeking solution are satisfied.

Ren et al. [28] establish the calculation formula of the rock salt’s mass and the dissolving radius:

$$ R(k) = \sqrt{\frac{m(k)}{\rho_s l \pi} + \frac{d^2}{4} - \frac{d}{2} - R}, $$

(17)

where $R(k)$ is the rock salt dissolving radius at the time of $k$, $l$ is the height of the test specimen, and $m(k)$ is the dissolving mass at the time of $t$.

Fitness function can be established as follows:

$$ f = \frac{1}{N} \sum_{k=1}^{N} \left( \sqrt{\frac{m(k)}{\rho_s l \pi} + \frac{d^2}{4} - \frac{d}{2} - R} \right), $$

(18)
where $N$ is the experiment recording times and, as the experiment is recorded every 3 minutes, the total time of the experiment then is $t = N \times 180$ (s).

Parameters of rock salt dynamic dissolving models are inversed under different flow conditions according to the particle swarm optimization in this research effort (see Figures 8, 9, 10, and 11). Table 4 details that, with flow $Q$ quantity changing, the increase in flow quantity $Q$ can accelerate the diffusion rate of the rock salt minerals.

5. Conclusions

An in-depth and systematic research effort was conducted on the properties of the rock salt dynamic dissolving model and tests under difference flow conditions drawing the following conclusions.

(1) Experimental research on the rock salt dynamic dissolving processes under different flow conditions was conducted by adopting a self-designed rock salt dynamic dissolving experimental set-up. Dynamic
dissolving test data of the rock salt was obtained under various flow conditions with varying dissolution time. The dynamic dissolving curve for rock salt was discovered as a fluctuating curve and the dissolving rate of rock salt increased with the increasing of flow quantity Q in a certain range.

(2) According to the dissolving properties of rock salt, the study reasonably simplifies and hypothesizes the rock salt dynamic dissolving process. The study accounts for combined conditions involving the dissolution effect and seepage effect changes of rock salt to establish the rock salt dynamic dissolving model.

(3) The study introduces the particle swarm optimization (PSO) to inverse parameters on the model established by applying the finite-difference method to calculate the numerical solution for the rock salt dynamic dissolving model. Calculation results were found to relatively coincide with the experimental data, indicating the rock salt dynamic dissolving model established is capable of effectively describing the dynamic dissolving process and dissolving mechanisms for rock salt.

**Conflict of Interests**

The authors declare that there is no conflict of interests regarding the publication of this paper.

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