Quasi-Equilibrium and Unsteady Mass Transfer of Low-Grade Bloedite in the Process of Static Water Dissolution

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Featured Application: The unsteady mass transfer model and kinetic investigation presented in this work are useful for optimizing the hydrometallurgical recycling of waste resources of low-grade bloedite.

Abstract: Hydrometallurgical extraction and treatment of bloedite waste is one necessity for the sustainable development of sodium sulfate subtype salt lake mining areas, but the industrial dissolution of bloedite is not stable. One of the reasons for this is the unsteady mass transfer of dissolved electrolytes in water according to the diffusion model and static water dissolution experiment in this work. The diffusion behaviors of aqueous Na₂SO₄ and MgSO₄ released from bloedite in water are similar, and their mass transfer coefficients decrease in a nonlinear manner as the diffusion process continues. Within 720 h of dissolution time, there is a quasi-steady-state quasilinear stage of rapid increase in the solute concentration of leaching water, and a water depth of 20–40 mm is recommended as the optimal dissolution depth. Under such operating conditions, the amount of evaporated water required for salt production decreases in a quasi-linear manner with respect to dissolution time. However, after 720 h of dissolution and extraction time, the growth rate of brine concentration slows. The information provided by the model can be used in practice as a quantitative reference for bloedite recycling.

Keywords: low-grade bloedite; quasi-equilibrium; unsteady mass transfer; kinetic model; dissolution

1. Introduction

Water solution mining activity in salt lake mining areas is an important factor that affects water quality and mineral quality. Low-grade bloedite (mNa₂SO₄·nMgSO₄·xH₂O) is a sediment [1] of sodium-magnesium sulfate in salt lake areas [2,3]. It is also a low-grade soluble evaporite mineral that remains after sun salting, and its use is necessary for balancing the exploitation of salt lake minerals with sustainable development of the mining area. Bloedite has a microstructure that can undergo substitution reactions [4] and it can be used to assist in the preparation of electrode materials [5] and whiskers [6]. In addition to Na₂SO₄ and MgSO₄, bloedite in tailings also contains insoluble substances and a small amount of NaCl. Thus, it needs to be purified, and its purification generally uses water-soluble mining methods that are commonly used in salt mines [7], such as open-pit leaching, in-situ leaching, and underground tunnel mining [8]. However, the chemical components and concentration of resulting brine (the aqueous solution of bloedite) are usually variable, and a
mechanism to explain the variation in the dissolution process is lacking. This is one of the problems that inhibits the recycling and use of low-grade bloedite.

One of the most common topics is the dissociation mechanism at the solid–liquid interface in the study of salt dissolution. There is generally no real-time change in the concentration at the solid–liquid interface. In this case, it can be presumed that the instability of the concentration of the leached solution results from the difference in solute diffusion and mass transfer in the bulk liquid phase. This phenomenon is more obvious in the immersion-type dissolution process in static water [9], resembling element leaching in a flooding irrigation [10]. This phenomenon is specifically manifested in the changes in chemical composition or concentration of the resulting solution at different times, even when the original ore remains unchanged. This leads to uncertainties in the later purification, crystallization, and separation processes.

In-situ water dissolution of bloedite is a static exploitation method because stirring does not occur, and this is also what enables diffusion to affect concentration changes in the aqueous solution. The problem of how the dissolution process changes over time has attracted more attention in the research of evaporite dissolution. The dissolution process of salt is not a steady-state process [11]; the dissolution rate constant changes over time [12], and the ratio of solutes in the dissolution liquid phase is also affected by operating conditions [13]. For example, in static water dissolution of mixed evaporites, such as halite (NaCl)-epsmite (MgSO4·7H2O) or Glauber’s salt (Na2SO4·10H2O)-bischofite (MgCl2·6H2O) [9], the amount of dissolved electrolytes continuously changes over time. Because the diffusion rate of Na+ is higher than that of other ions, the composition of the resulting water solution is not stable. Similarly, in the process of dissolving solids, such as polyphosphate [14], the bulk water phase also experiences real-time changes in solute concentration.

Most dissolution research has focused on the solid–liquid equilibrium [15] or phase diagram [16,17] or thermochemical characteristics of the phase transition [18]. The experimental methods used to study phase diagrams are all based on equilibrium systems [19], but nonequilibrium data are usually required in the actual dissolution and crystallization processes [20]. Changes in the solute concentration of the resulting solution in the dissolution process are different from those in the evaporation process. Furthermore, the predictability of these changes is poor because the water solution is not saturated at this point, and calculation methods, such as the Pitzer model [21], are inconvenient to apply. Compared with the dissociation that occurs on the surface of solid-phase salt, studies have shown that the diffusion of the salt component in the liquid phase after dissociation under static conditions is the process control step [13,22]. Research on the diffusion and mass transfer kinetics of salt solutes in the liquid phase has mostly focused on the steady-state process of single-component salts or simple salt–water systems, and the obtained diffusion constant is usually a fixed average value [23]. In contrast, in these studies, the actual hydrostatic extraction of soluble salt is not a steady mass transfer process. Furthermore, the local mass transfer rate, local concentration, and mass transfer driving force at different locations all change in real time, and the actual dissolution mining system is a mixed-salt system. In a multicomponent liquid system, the dissolution, diffusion, mass transfer [24], and crystallization [25] of different components are mutually restricted. Some multicomponent mineral leaching experiments [26] can indirectly prove the complexity of similar solute diffusion processes. Non-steady diffusion of solutes in a single-salt solution or in a quaternary interaction system that contains two anions and two cations was investigated [9], but a simple ternary system that contains the same cations or anions has not been involved. It is inferred that without the interactive influence of the oppositely charged ions, the ternary simple system may not be able to distinguish between the diffusion of different ions as clearly as the quaternary interactive system can. On the whole, the diffusion behavior of the ternary simple system is still worthy of further investigation.

Bloedite is an example of such a simple ternary system. It is clear that its dissolution mining process is unstable, but the law of instability and quantitative prediction methods are still unclear. In response to this problem, this work attempts to establish a kinetic model that has a clear physical meaning for studying the unsteady mass transfer kinetics of multiple solutes in the water phase of bloedite under static dissolution and under diffusion conditions; this work also attempts to explain
how the chemical composition in aqueous solution changes over time and how to use this rule in practice.

2. Materials and Methods

The physical model of this work (Figure 1b) is based at the mining site of Yuncheng Salt Lake (Figure 1a). As a sodium sulfate subtype salt lake, there are bloedite deposits in the Yuncheng mining area. It is assumed that the bloedite dissolves and forms a concentration gradient during static water dissolution, which can be modelled in the laboratory (Figure 1c). The dissolution and diffusion experiments of single-component salt and bloedite were carried out in an air-conditioned room at a constant temperature of 20 °C. To avoid the occurrence of convective mass transfer and the interference of fluid flow in the dissolution and diffusion processes, it is necessary to ensure that the dissolution and diffusion processes are as slow as possible in a static environment. Therefore, either Na₂SO₄·10H₂O or MgSO₄·7H₂O (analytically pure, Sinopharm Chemical Reagent Co., Ltd., Shanghai, China), or bloedite (taken from the Yuncheng salt lake, Shanxi Province, China) were placed in a 1-L graduated cylinder. The amount of salt placed in the cylinder was 300 g. A 60–80-mm high cylindrical piece of foamed plastic was placed above the salt layer, which was about 75–90 mm in height in the graduated cylinder, and then ice cubes were placed on top of that (Figure 1d). After the ice melted, the water flowed down slowly from the gap between the foamed plastic and the inner wall of the graduated cylinder and soaked the salt layer below (Figure 1e). Once the water and salt came into contact, the timer started and the diffusion process of the solute in the liquid phase was timed. At the same time, the foamed plastic floated up (Figure 1f), and finally, the salt layer was fully immersed in water (Figure 1g). The initial distance from the water surface to the salt–water interface was about 225–240 mm.

![Figure 1. The experimental setup of the diffusion test: (a) project site of dissolution mining of bloedite; (b) schematic diagram of dissolution mining on-site; (c) schematic diagram of dissolution in the laboratory; (d) experimental step one—placed ice and foamed plastic on the salt; (e) experimental step two—the melted ice water soaked the salt; (f) experimental step three—the ice melted and the plastic floated to the top of the water; (g) experimental step four—removed the plastic and started sampling.](image-url)
When the salt layer is soaked, the processes of dissolution and diffusion are very slow. Therefore, it can be assumed that the saturated solubility of the salt is maintained at the solid–liquid interface; thus, the influence of the particle size of the salt on the dissolution and diffusion processes is neglected. After a certain period of time of dissolution, sampling by using a long–needle syringe and analysis were carried out at a specific height above the salt–water interface to determine the solute concentration.

In order to accurately test, the bloedite (Na₂SO₄·MgSO₄·4H₂O) specially used in this experiment was 95.74% in purity, a grade which was higher than that of bloedite in common salt lake tailings. The impurities in the bloedite sample were mainly insolubles. The resulting solution was used to define the aqueous solution that resulted from the dissolution of bloedite. The concentrations of Na⁺, Mg²⁺, and SO₄²⁻ (S) were analyzed using inductively coupled plasma emission spectroscopy (ICP-OES, Thermo ICAP 6000, Waltham, MA, USA), and the concentration of Cl⁻ was determined via chemical titration using the argentometry method. The saturation degree was used to characterize the amount of salt dissolution, which is expressed as the ratio of the concentration of dissolved electrolyte to its theoretical saturation value.

3. Dynamics Model of Unsteady Mass Transfer

It is assumed that there is sufficient contact between the salt and water at the interface. When the solid phase is a mixed salt, it is assumed that the contact area between each salt component and water at the salt–water interface is proportional to the dry-based mole fraction of the different salt components. Assuming that the solution behaves ideally, solute transfer is only due to diffusion and electron migration under a concentration gradient. Because diffusion is very slow, the interfacial mass transfer resistance between salt and water is neglected, and only the mass transfer process in the bulk solution is considered [22], as shown in Figure 2.

![Figure 2. Schematic diagram of the diffusion model.](Image)

At this point, solute transfer is an unsteady diffusion mass transfer process, and the bulk water solution is not flowing. According to Fick’s second law [23], the mass transfer can be calculated as follows:

\[
\frac{\partial c_A}{\partial \theta} = D_{AB} \left( \frac{\partial^2 c_A}{\partial x^2} + \frac{\partial^2 c_A}{\partial y^2} + \frac{\partial^2 c_A}{\partial z^2} \right)
\]

where \( \theta \) is the diffusion time; \( x, y, \) and \( z \) are the diffusion directions; \( c_A \) is the salt concentration in the liquid phase; and \( D_{AB} \) is the diffusion coefficient of the salt component in water. Assuming that the diffusion direction is one-dimensional (i.e., diffusion only occurs in the vertical \( y \) direction), Equation (1) can be transformed into the following form:
\[ \frac{\partial c_A}{\partial \theta} = D_{AB} \frac{\partial^2 c_A}{\partial y^2} \]  

(2)

The initial conditions and boundary conditions of Equation (2) are as follows:

\[ \theta = 0, \; c_A = c_{AB} \; \text{(for any y)} \]  

(3)

\[ y = 0, \; c_A = c_{AS} \; \text{(when } \theta > 0) \]  

(4)

\[ y \to \infty, \; c_A = c_{AB} \; \text{(when } \theta > 0) \]  

(5)

where \( c_{AB} \) is the initial concentration in the bulk liquid phase, \( c_{AS} \) is the salt concentration at the salt–water interface, \( c_{AB} \) has a value of zero, and \( c_{AS} \) is assumed to be equal to its saturation concentration.

Equation (2) can be solved using the synthetic variable method to substitute the partial derivatives of synthetic variables with respect to \( y \) and \( \theta \) into Equation (2). Furthermore, the partial differential equation of Equation (2) can be transformed into an ordinary differential equation:

\[ \frac{d^2 c_A}{d \left( \frac{y}{\sqrt{4D_{AB}\theta}} \right)^2} + 2\eta \frac{d c_A}{d \left( \frac{y}{\sqrt{4D_{AB}\theta}} \right)} = 0 \]  

(6)

The boundary conditions can thus be transformed as follows:

\[ \left( \frac{y}{\sqrt{4D_{AB}\theta}} \right) = \infty, \; c_A = c_{AB} \]  

(7)

\[ \left( \frac{y}{\sqrt{4D_{AB}\theta}} \right) = 0, \; c_A = c_{AS} \]  

(8)

Equation (6) is integrated twice, and the integral constants that appear in the integration process are determined according to Equations (3) and (4). Finally, the error function can be used to obtain Equation (9):

\[ \frac{c_A - c_{AS}}{c_{AB} - c_{AS}} = \text{erf} \left( \frac{y}{\sqrt{4D_{AB}\theta}} \right) \]  

(9)

Equation (9) shows the relationship between diffusion time, diffusion location, and local salt concentration.

The diffusion coefficient \( (D_{AB}) \) can be roughly derived using the Stokes equation [9]. In this calculation, some of the basic physicochemical constants are used, including Boltzmann’s constant \( (k = 1.380649 \times 10^{-23} \text{ J/K}) \), thermodynamic temperature \( (T) \), the Stokes–Einstein radius \( (r_A) \) of solute \( A \), and the dynamic viscosity of the solvent \( (\eta) \).

4. Results and Discussion

4.1. Dissolution and Diffusion Processes of a Single Electrolyte

Figure 3 shows the changes in the concentration profile of various single-electrolyte salts at different times when they were dissolved in static water. Generally, although the dissolution of a soluble salt is slow, it does occur in static water. In static water, the dissolution equilibrium time of soluble salts may be as long as one year [9]. In the case of unsteady diffusion, the solute has a normal profile [27] that reflects the concentration gradient, and this is suitable for calculations made using Fick’s second law [28]. Except for subtle differences, the diffusion trends of MgSO_4 and Na_2SO_4 are roughly similar, as shown in Figure 3a,b, respectively. To directly compare the diffusion behaviors of MgSO_4 and Na_2SO_4 in aqueous solution, Figure 3c shows the calculated results of their saturation degree profiles at different diffusion times. Because the change in solute concentration or saturation degree is mainly caused by solute diffusion, it is concluded from the saturation degree that the diffusion ability of Na⁺ is slightly stronger than that of Mg²⁺. Compared to Mg²⁺, in the process of cation diffusion, the atomic weight of Na⁺ is smaller, the atomic radius is smaller, and the valence is lower; thus, the hydration ability of Na⁺ is weaker than that of Mg²⁺, and this leads to the smaller
diffusion resistance. From this rule, the Na$_2$SO$_4$ components diffuse slightly faster than MgSO$_4$, as shown in Figure 3c. This phenomenon is more obvious when the diffusion time is long.

The difference between the experimental (Exp.) and calculated (Calc.) results in Figure 3a,b is due to the deviations in the calculation process. According to Equations (1)–(9), it is assumed that the parameters (e.g., $D_{ab}$) are not accurate as expected, which makes the calculation error larger at longer durations of dissolution and diffusion. However, the calculation is still reliable in practice because the calculated results are close enough to the experimental data even after nearly 3000 h of diffusion.

Figure 3. Profiles of saturation degree over time (in the dissolution and diffusion processes of single electrolyte in water): (a) MgSO$_4$; (b) Na$_2$SO$_4$; (c) calculated results of MgSO$_4$ and Na$_2$SO$_4$.

Figure 4 shows changes in saturation degree at different distances from the solid–liquid interface over time, and this indicates that the diffusion of soluble salts in static water is not stable. The process of static dissolution is roughly divided into three stages. The first stage is until about 720 h of dissolution. The saturation degree changes during this period of dissolution and diffusion processes are close to linear, and this indicates that the mass transfer is roughly steady. The second stage is from about 720 to 7000 h. During this period of the diffusion process, the saturation degree change is nonlinear and specifically has the form of a power function; the diffusion rate gradually decreased, and this indicates that the mass transfer entered an unsteady state. The third stage is after 7000 h, when the diffusion rate decreased further and the saturation degree change or the mass transfer process developed into a slow quasi-linear form and finally reached an unsaturated steady state. It is worth mentioning that such unsteady state mass transfer phenomena are common in molecular diffusion in condensed matter systems, and this is similar to the transport [29] in cementitious materials. Among the three stages of dissolution and diffusion in Figure 4, the dissolution mining in
practice mainly occurs in the first stage; hence, the law of diffusion at the first stage is the most important.

![Figure 4. Local saturation degrees of solute at different times and locations (in the dissolution and diffusion processes of single electrolyte in water): (a) MgSO₄; (b) Na₂SO₄.](image)

### 4.2. Dissolution and Diffusion Processes of Bloedite

Changes in the saturation degree profiles of bloedite are shown in Figure 5, and changes in the solute saturation degree at different water depths are shown in Figure 6. The diffusion capacities of Na₂SO₄ and MgSO₄ in water are very close, and the local saturation degree of the two is related to the composition of the original ore. The specific manifestation is that the concentration ratio of the two solutes in water is roughly equal to the molar ratio of Na₂SO₄ and MgSO₄ in the original ore. However, there is still a slight difference between the saturation degree or concentration profiles of the two, and this is manifested in the diffusion rate of Na⁺ being slightly faster than that of Mg²⁺. It is reasonable to expect that when the time for dissolution and diffusion is sufficient, the difference between the concentrations of Na₂SO₄ and MgSO₄ above the water layer will be significant enough for this approach to be used for engineering separation.

The general rule is that during short-term dissolution, the concentration of different solutes in the bottom water will be slightly different; if the dissolution time is extended indefinitely, the solute concentration of the upper brine will have a greater difference. This phenomenon is generally similar to that in an interactive system [9], but they are still slightly different. The main difference is that in the interactive system, especially in the “1-1 + 2-2” type of mixed-salt systems (such as the mixed salt of “NaCl + MgSO₄”), the difference in the mass transfer rates of the two salt solutes is more obvious. This makes it possible for the Mg²⁺ concentration to be close to zero somewhere above the solid–liquid interface; however, the Na⁺ concentration is high, and thus, the two salts can be separated after a certain diffusion time when the resulting solution is pumped out from a certain water depth. However, when the mixed salt of Na₂SO₄ and MgSO₄ was used, both of the salts are the “2-2” type, and their mass transfer rates are not much different. Therefore, it is not possible to achieve separation unless the dissolution and diffusion time is as long as about one year. Figure 7 shows the quantitative relationship between the average concentration of resulting solution and different immersion depths. When the water immersion depth increases, the total amount of dissolved solute increases because of the increase in water volume; however, the concentration of the resulting solution decreases. Considering factors such as the total amount of dissolution and solute concentration, it is recommended that an immersion depth of 20–40 mm is the optimal value.
**Figure 5.** Local saturation degrees of solutes at different diffusion times in the dissolution and diffusion process of bloedite.

**Figure 6.** Local concentrations of solute at different times and locations in the dissolution and diffusion processes of bloedite; the experimental data after 2000 h are the test results in the salt pond of Yuncheng Salt Lake, China.

**Figure 7.** Saturation degrees and dissolved solute amounts of resulting solution at different times and immersion depths (in the dissolution and diffusion processes of bloedite).
4.3. Distribution of Local Mass Transfer Coefficients in a Mixed Electrolyte System

Using the concentration profile shown in Figure 5 and the model in Figure 2, the local mass transfer coefficient when the electrolyte diffuses was calculated, and the results are shown in Figure 8. These results provide two pieces of information. First, the mass transfer coefficient of Na⁺ is greater than that of Mg²⁺, although the actual difference between the two is not very big. Second, the mass transfer coefficient is attenuated as diffusion continues, and the amount of variation for the two electrolytes is also different. These two phenomena are consistent with the changes in concentration shown in Figures 3 and 5 and reflect the inherent reason for the difference between the rates of diffusion for the different salt components. Because Mg²⁺ has a strong hydration ability in aqueous solution, it is a structure-making ion of water [30], and this can aggravate the internal cross-linking of the salt–water system. Thus, it can significantly increase the viscosity and decrease the mass transfer coefficient. In this case, the mass transfer coefficient of Mg²⁺ is smaller than that of Na⁺. Figures 5 and 8 shows that the mass transfer coefficient and the saturation degree are negatively related. For the mass transfer coefficient, when the salt–water interface is farther away, the diffusion coefficient is greater — this is because the solute concentration and viscosity are small, and this causes the mass transfer resistance to be smaller. Such a phenomenon is also consistent with the general law in the diffusion of salt solutes in aqueous solutions [23,31].

![Figure 8](image_url)

Figure 8. Calculated local mass transfer coefficient profiles at different times in the dissolution and diffusion processes of bloedite.

Figure 9 shows that the mass transfer coefficients of the mixed-electrolyte system are smaller than those of the single-electrolyte system. It is speculated that this reflects the interactive influence that the difference in transferability between Na⁺ and Mg²⁺ has on the diffusion rates. Because the diffusion of ions is mutually restricted, the presence of multiple ions must have an influence on the kinetics of the diffusion process [14]. Therefore, compared to the single-electrolyte system, the mass transfer coefficients in the mixed-salt system decrease.
Figure 9. Comparison of mass transfer coefficients between mixed-electrolyte (Na$_2$SO$_4$-MgSO$_4$-H$_2$O system from the bloedite dissolution) and single-electrolyte systems.

4.4. Phase Diagram Analysis and Process Optimization Strategy

As seen in the phase diagram shown in Figure 10, the dissolution of soluble salts containing Na$_2$SO$_4$ and MgSO$_4$ basically follows the rule that the solute composition in the liquid phase is consistent with the solid ore composition. The slow and incomplete dissolution of Na$_2$SO$_4$ and MgSO$_4$ from bloedite causes the increase in the solute concentration at different heights and different times to gradually slow down; thus, the concentration of the resulting solution will slowly stagnate in a certain area of Figure 10. This means that the resulting solution does not reach the traditional saturation line in the phase diagram. This is consistent with the actual situation on a project site.

Figure 10. The composition of the resulting solution in the phase diagram in the dissolution and diffusion processes of bloedite.

For example, in engineering practices, the dissolution mining time of 2160 h is roughly equivalent to an extensive mining time in autumn and winter; that is, flood irrigation begins in autumn, brine collection begins in spring, and freezing time in winter is excluded if there is no freezing Glauber’s salt. In this case, when the depth of the dissolving water was 100 mm, the concentration reached half of the saturation values of solutes. Except for the influence of seasonal
temperature changes, this phenomenon in practice is consistent with the predicted values shown in Figure 10.

Figures 6 and 10 provide references for actual solution mining. If the water source is sufficient, the dissolution can be stopped at 720 h and new fresh water can be introduced to continue solution mining, because the increase in concentration of resulting solution begins to slow down after 720 h of dissolution. However, the disadvantage of this solution extraction method is that the subsequent evaporation and crystallization processes consume more water. Figure 11 shows the amount of water that must be evaporated when the resulting solution is concentrated to a saturated state and begins to precipitate salt product under the conditions of different dissolution times and water depths. The results shown in Figure 11 are related to the technological economy of the dissolution and salt production processes; it is expected that the amount of evaporated water decreases so that the enthalpy consumption of the production process is also reduced. Figure 11a shows that as the depth of dissolving water increases, the amount of water that must be evaporated in the subsequent evaporation process also increases. As seen in Figure 11b, when the optimized brine depth is 40 mm (Figure 7), the required amount of evaporated water decreases roughly linearly with respect to time within the first 720 h; when the dissolution time is more than 720 h, the amount of evaporated water generally tends to be stable with respect to time, and this indicates that it is meaningless to extend the dissolution in terms of process optimization. When the dissolution time is long, such as from autumn to the following spring, it is better for the dissolution time to be controlled to be about 2160 h, because the amount of evaporated water is not further reduced even if the dissolution time is further extended. The information provided in Figure 11 can be used as a quantitative reference for industrial dissolution mining processes.

![Figure 11](image_url)

**Figure 11.** Technological performance under different dissolution conditions of bloedite: (a) amounts of dissolved solute per square meter of dissolution area; (b) evaporated water per unit of resulting solution.

5. Conclusions

Bloedite is one of the wastes produced by sodium sulfate subtype salt lakes. The dissolution process of bloedite is unstable, but the mechanism to explain this has been lacking for years. It is proposed that the instability of the dissolution process originates from the unsteady mass transfer of soluble salts. Using Fick’s second law, a mass transfer kinetics model was established. The viewpoint of unsteady solution mining was confirmed through the dissolution experiment of bloedite in static water and the mass transfer kinetics model. For dissolution and extraction in static water, the diffusion behaviors of the Na₂SO₄ and MgSO₄ that are released from bloedite in water are roughly similar, except that the diffusion ability of Na⁺ is slightly stronger than that of Mg²⁺. This is because of the smaller atomic radius, lower valence, and smaller diffusion resistance of Na⁺. The mass transfer coefficient of Na⁺ is greater than that of Mg²⁺, and the mass transfer coefficient in the bulk water phase is greater than that at the salt–water interface. The mass transfer coefficient is attenuated as diffusion
continues, and the variation range is different for different electrolytes. Because of the reciprocal interaction of different ions, the mass transfer coefficients of electrolytes in the mixed-electrolyte system are smaller than those in the single-electrolyte system. Although the diffusion of a soluble salt in static water does not undergo steady deceleration, there is a quasi-steady linear concentration stage within the first 720 h, and this is also the most important stage for dissolution engineering. The relationship between the average concentration of resulting solution and dissolution time and dissolving water depth was quantitatively predicted using the kinetics model. With an increase in the depth of dissolving water, the amount of evaporated water in the subsequent evaporation-crystallization process also increased. Considering factors such as the total amount of dissolved solutes and concentration, it is recommended that a water depth of 20–40 mm is optimal. The modelling calculations show that under the conditions of static water dissolution, cross-season dissolution mining does not obtain a saturated water solution, and the concentration of resulting solution is roughly equivalent to half of the actual saturation value. When the brine depth was 40 mm, the required amount of evaporated water decreased in a roughly linear manner within the first 720 h of dissolution time. When the dissolution time was more than 720 h, the increase in the concentration of resulting solution gradually slowed with respect to time, and the amount of evaporated water generally tended to be a stable value in the subsequent evaporation-crystallization process. Therefore, 720 h of dissolution time is the recommended dividing line for replacing the water with new dissolving water. The information provided by the model can be used as a quantitative reference for industrial dissolution of bloedite.

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