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Study on Scale Formation in Leachate Transport Pipelines Based on System Dynamics(SD)

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Abstract. This study investigates the scaling process in landfill leachate collection and transportation pipelines. A system dynamics model was established to predict pipeline scaling, employing a combined approach of orthogonal experiments， and simulation techniques to account for the nonlinear coupling effects of crystallisation kinetics and thermodynamics, among other factors. Different parameters were adjusted to study variations in scaling behaviour. The results show that the model predictions of scale formation changes are basically consistent with the experimental scale formation changes. The scale formation shows a rapid increase followed by a decrease， and then gradually stabilises and fluctuates. The water quality factors are ranked as Ca^{2+} > COD > pH > Humus substances. The effect of temperature on scale formation can be divided into two stages. This study provides new insights into pipeline scale formation research.

Keywords: Leachate transport pipeline; scaling; system dynamics; water quality factors; thermodynamic.

1. Introduction

Landfill leachate is characterized by a complex composition. Transportation pipelines are susceptible to scaling due to factors that promote the development of scaling. These organisms are frequently threatened by the risk of scaling[1]. A substantial body of research has been conducted by scholars in the field regarding the causes of scaling in transport pipelines and treatment structures, with a particular focus on wastewater quality factors[1-2]. The objective of this study is to conduct in-depth research on the mechanisms that influence scaling. A number of scholars have undertaken the analysis of the etiology of scaling. To this end, they have employed theoretical models and numerical simulation methods to study the mechanisms of scaling control. The objective is to unveil the dynamic patterns of scaling from multiple perspectives. It is imperative to provide comprehensive support for interdisciplinary research endeavors encompassing the domains of thermodynamics, fluid dynamics and pipeline materials, in conjunction with engineering practice.

Currently, some progress has been made in the simulation study of scale formation in wastewater transport pipelines. Langelier proposed the Langelier Saturation Index method based on the dissolution equilibrium principle of $CaCO_3$. Stiff et al. (1952) developed the Davis-Stiff Saturation Index method by integrating the weak ionisation equilibrium of carbonic acid and thermodynamics, determining scaling tendencies through the Saturation Index (*SI*) derived from the relationship curve between ionic strength and water temperature[3]. Oddo et al. (1982) introduced a modified approach based on the Davis-Stiff saturation index method, incorporating pressure, dissolved salts, and dissolved CO_2 factors to enhance methodological reliability[4]. Nebot et al. (2007) employed the Kern-Seaton model to investigate the effects of flow velocity and temperature on scaling deposition and removal rates for two metallic pipe materials, proposing the $t_{1/2}$ scaling concept to elucidate the inflection point of the S-curve[5]. Mesticou et al. (2014) constructed deposition and erosion kinetic models based on experimental data to simulate multiphase transport of salts and particles within pipes. These models successfully predicted particle adhesion and erosion phenomena at constant

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flow rates under varying ionic strengths, demonstrating favourable simulation outcomes[6]. Ahmadi et al. (2015) developed a pipe scaling prediction model centred on internal pressure and temperature, revealing that scaling increases progressively with decreasing pressure and temperature[7]. Zhao (2023) established a CFD model using experimental data to simulate the scaling process of leachate in straight pipes and 90º elbows, analysing the influence of factors such as temperature and flow rate[8]. Khodabakhshi & Bijani (2024) employed machine learning algorithms to optimise reservoir scaling prediction, investigating the impact of parameters including temperature, pressure drop, and ion concentration on prediction accuracy[9].

The Kern-Seaton model is currently one of the most widely used scaling models. It uses scale thickness to calculate deposition rates, but the difficulty in quantifying scale thickness limits the application of this model. The model disregards numerous operational parameters, complicating the elucidation of intricate scaling phenomena. This study is founded on the findings of earlier research on scale formation simulation. It considers water quality factors and thermodynamic synergies to investigate the combined effects of different control factors on scale formation. The present study aims to provide a theoretical basis for predicting scale formation in wastewater transport pipelines.

2. Fouling Experiment

2.1 Orthogonal Experimental

Based on landfill site surveys, literature reviews and preliminary experimental data, the main components of sediment deposits are calcium compounds. The critical value ranges for the water quality factors pH, COD, Ca^{2+} and humic substances must be determined[1-2], an orthogonal experimental plan must be designed (see Table 1). The medicines are divided into two categories. Analytical pure reagents include anhydrous glucose (Xilong Chemical), $CaCl_2$, NaCl (Chengdu Kelong Chemical), sodium bicarbonate (Xilong Chemical) and pH buffer (Xilong Chemical). Chemical pure reagents include humic acid (Xilong Chemical). It has been demonstrated that an elevated scaling rate in the experimental evaluation indicators is associated with a more pronounced impact on pipe scaling[1-2].The formula is $Fouling\ Rate = \frac{(Pipe\ Fouling\ Weight - Pipe\ Weight)}{Pipe\ Weight} * 100\%$.

Table 1. Experimental protocol

Experiment No.	Key Water Quality Factors (mg/L)			
	pH (dimensionless)	COD	Ca^{2+}	Humus
1	4.00	30000	5000	1000
2	4.00	19000	3500	500
3	4.00	8000	2000	100
4	6.86	30000	3500	100
5	6.86	19000	2000	1000
6	6.86	8000	5000	500
7	9.18	30000	2000	500
8	9.18	19000	5000	100
9	9.18	8000	3500	1000

2.2 Basic Model of Scaling

The present study investigates the flow of the most common generalized time-independent non-Newtonian fluid in pipes within industrial applications. As leachate moves through the system, its pollutants concentrations are gradually diluted by the water body through convection and molecular diffusion. The two elements play a dominant role in the migration and attenuation process of wastewater pollutants. The former is attributed to the head pressure differential that exists before and after the pipeline, while the latter is predominantly governed by the gradient of pollutant concentration. During the flow of leachate within the pipe, the concentration of solutes

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undergoes changes due to the effects of flow velocity, lateral and longitudinal diffusion coefficients, molecular diffusion and other factors. The concentration field control equation is[2,10]:

$$R_d=\frac{\partial(\varnothing\ C_w)}{\partial t}=div\left(\varnothing\ D_{i,j}gradC_w\right)-V_n(p)divC_wD$$

In the equation, C_w—Solute concentration in the fluid, kg/m^3;$V_n(p)$—Average flow velocity, m/s;R_d—Stagnation coefficient;$D_{i,j}$—Hydrodynamic diffusion coefficient Tensor, transverse and longitudinal diffusion coefficients are $D_{i,j}=\alpha_i v+D,\alpha_i(i=1,2)$;$D$—Molecular diffusion coefficient,m^2/s.

The flow of leachate within the pipe is classified as slow flow and can be described using Darcy's law[2,11]:

$$\frac{\partial\varepsilon\rho_w}{\partial t}+\nabla\cdot\rho_w u=0$$

$$\mathrm{u}=\frac{k}{\mu_w}(\nabla p+\rho_w g\nabla \mathrm{h})$$

In the formula,ρ_w—Fluid density，kg/m^3;t—Time，s;ε—Porosity;u—Darcy velocity，m/s,Darcy velocity depends on permeability k;μ_w—Fluid dynamics;p—Fluid pressure,Pa;g—Gravitational acceleration，m^2/s;h—Height in the vertical coordinate direction,m.

Since fluctuations in wastewater density$\rho_0$and salt concentration C_S (mol/m^3) alter the density of the water flow[2,12]:

$$\rho_\omega=\rho_0+\beta c=\rho_0+\frac{\rho_s-\rho_0}{C_S-C_0}$$

The decay rate coefficient, ion concentration, pipe length, temperature and reaction rate all exert a significant influence on the scale formation reaction process inside the pipe.

3. Results Analysis and Model Construction

3.1 Analysis of Experimental Results

Following the experimental period, significant differences in scaling rates were observed among the different experimental groups (see Fig. 1). Neutral solutions are not prone to scaling. The extent of scaling was found to be maximized at elevated levels of humic substance concentration. This phenomenon is hypothesized to be attributable to the complexing effect of humic substances. It is recommended that humic substances be removed from neutral water. Alkaline solutions demonstrated a greater propensity for scaling, while the addition of humic substances to acidic solutions resulted in an increased scaling response.

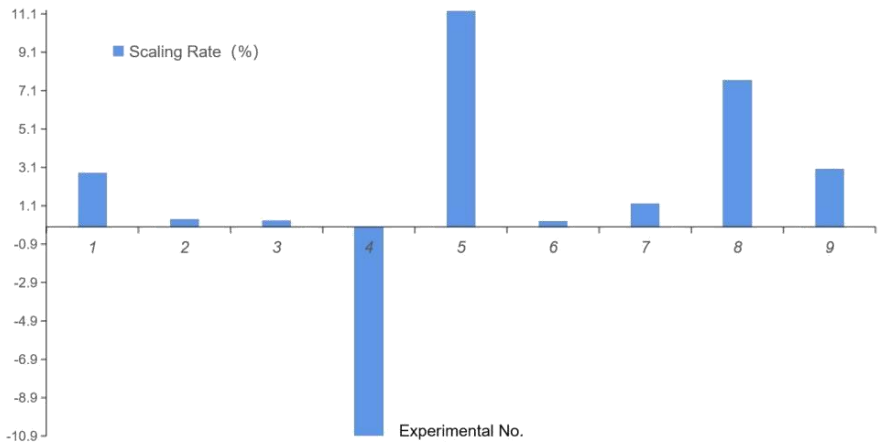


Fig. 1 Scale rate for each experimental group

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The utilization of range analysis is imperative for the subsequent analysis of the results, identification of the combinations of scaling levels that are both the easiest and most difficult and determination of the order of importance of each factor's impact on scaling(see Table 2). The following analysis will examine the impact of each level of the four factors on the experimental indicators. The impact of A1 is reflected in experiments 1, 2 and 3. The formula is $K_{ni}=\sum k_{ni}/3$,n=A、B、C、D; i=1、2、3. The range R_j indicates the range of variation in the experimental evaluation index values within the range of values for that factor. The magnitude is used to determine the primary and secondary effects of each factor on the experimental evaluation index. The calculation formula is as follows $R_j=max(\overline{K}_i)-min(\overline{K}_i)$.

Table 2. Results of extreme value analysis

Factors	Level	Impact Reflection on EGN	k_{ni}	K_{ni}	R_j	Levelmost prone	Level least prone
A(pH)	A_1(=4)	1、2、3	3.5632	1.1817	3.7354	A_3	A_2
	A_2(=6.86)	4、5、6	0.6827	0.2276			
	A_3(=9.18)	7、8、9	11.8889	3.9629			
B(COD)	B_1(=8000)	3、6、9	3.6673	1.2224	6.7439	B_2	B_3
	B_2(=19000)	2、5、8	19.2982	6.4327			
	B_3(=30000)	1、4、7	-6.8309	-2.2770			
C(Ca^{2+})	C_1(=2000)	3、5、7	12.7909	4.2636	8.7097	C_1	C_2
	C_2(=3500)	2、4、9	-7.4411	-2.4804			
	C_3(=5000)	1、6、8	10.7851	3.5951			
D(Humus)	D_1(=100)	3、4、8	-2.9302	-0.9767	6.6842	D_3	D_1
	D_2(=500)	2、6、7	1.9425	0.6475			
	D_3(=1000)	1、5、9	17.1225	5.7075			

Based on the calculation data, it can be determined that the impact of scale formation on pipes is as follows: $k_{A_3} > k_{A_1} > k_{A_2}$, $k_{B_2} > k_{B_1} > k_{B_3}$, $k_{C_1} > k_{C_3} > k_{C_2}$, $k_{D_1} > k_{D_2} > k_{D_3}$. When water quality is alkaline, with COD at 19000, Ca^{2+} at 2000 and humic substances at 1000, scaling is more likely to occur. In the event that the water quality is neutral, with a COD of 30000, a calcium ion (Ca^{2+}) concentration of 3500 and a humic substance concentration of 100, the pipes are less prone to scaling. The ranking of water quality factors affecting scaling is Ca^{2+} > COD > pH > Humic substances. This result provides guidance for effective scale prevention.

3.2 Scale Formation Model Construction

The reaction process leading to the formation of scale in landfill leachate is primarily influenced by factors such as temperature within the pipes, ion concentration and reaction rate. Scale-forming salts such as $CaCO_3$ and $MgCO_3$ are commonly produced. These reactions are typically endothermic. The scaling process is primarily controlled by ion concentration gradients. The concentration of scaling ions in wastewater gradually decreases through convection and molecular diffusion. It is possible to infer the mass of scale formed in the solution based on the changes in the scaling chemical reaction. If other factors in the wastewater are not considered, the maximum scale formation rate is predominantly determined by the concentration of Ca^{2+} in the solution. The actual fouling reaction rate is affected by the concentration of other ions in the solution, temperature and operating conditions.

The system cause-and-effect loop diagram controlled by solution ion concentration is shown in Fig. 2. As the concentration of pollutants in wastewater increases, the concentration of scale-forming ions in the pipe increases and the concentration of CO_3^{2-} increases. The rate of

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chemical reactions increases. The amount of scale formed in the solution increases. The extent of scale deposition is influenced by factors such as adhesion, scale properties, and pipe material properties. Therefore, the amount of scale formed does not equal the amount deposited. Furthermore, the crystal particles generated require a certain induction time to settle. An increase in particulate matter generated by the reaction leads to an increase in the amount of scale deposited on the wall surface. Temperature promotes an increase in the reaction rate, indirectly reducing the ion concentration in the solution.

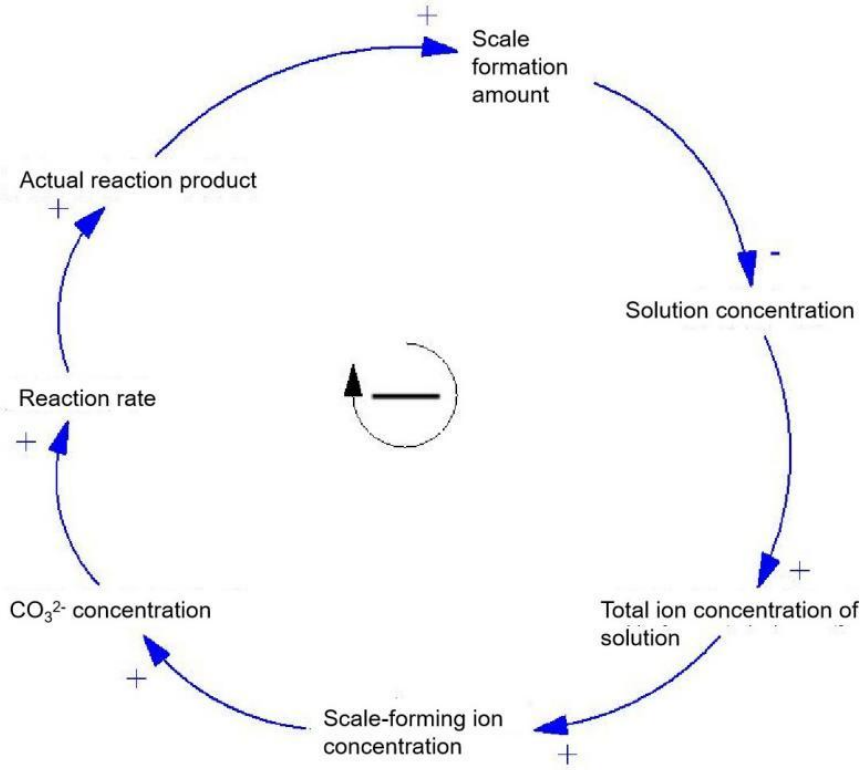


Fig. 2 SD System causal loop diagram

Create a stock flow diagram as shown in Fig. 3. In the event of alterations in both time and environmental temperature, the CO_3^{2-} concentration fulfills the criteria for the comprehensive manifestation of the scaling reaction. The maximum Ca^{2+} concentration in the solution inside the pipe determines the maximum target scale formation. A multitude of factors may impede the formation of scale, while an augmentation in reaction products can precipitate an increase in deposits on surfaces. The total ion concentration of the solution gradually decreases as scaling chemical reactions occur. The decay rate is a metric of the extent of pollutant reduction. The rate of decay increases in proportion to rising temperature. Reaction rate can be used to measure the speed at which a chemical reaction proceeds. An increase in reaction rate accelerates the formation of scale particles. Factors influencing scaling are divided into internal and external causes. The former refers to the properties of the reactants and the reaction process as determining factors, while the latter refers to concentration, pressure, temperature, etc. The reaction rate increases in proportion to the increase in both reactant concentration and temperature. Generally, every 10℃ increase in temperature can increase the chemical reaction rate by 2 to 4 times. This increase in frequency can be attributed to the elevated energy levels of ions at elevated temperatures, thus enhancing the probability of effective collisions. The specific model variables of the system are listed in Table 2.

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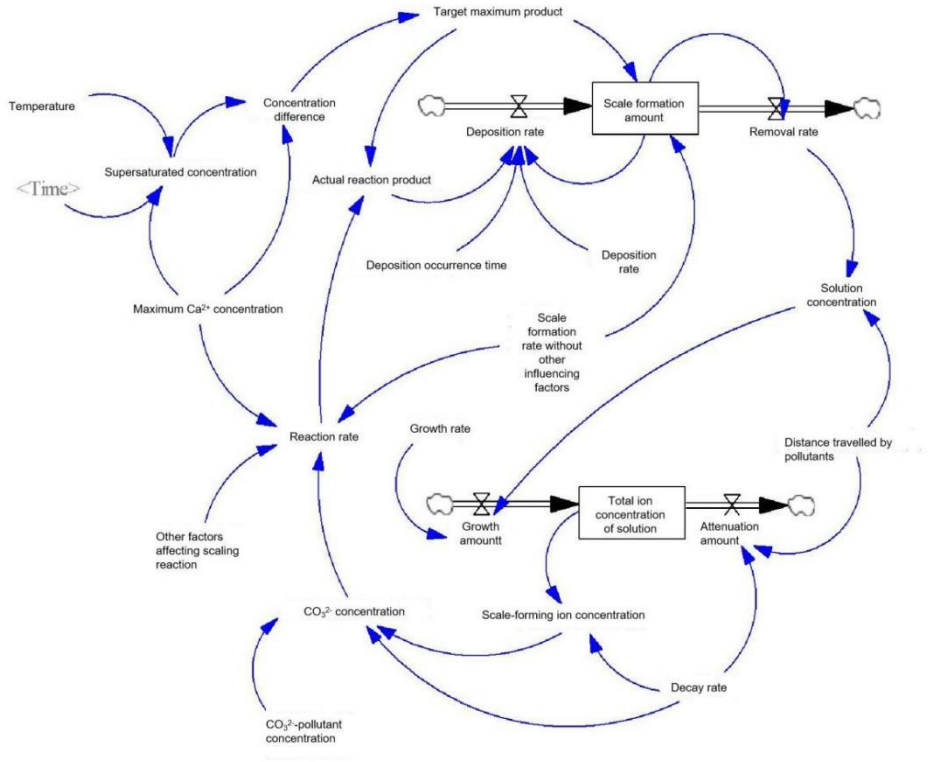


Fig. 3 SD Model stock traffic chart

Table 2. SD Model Variable Properties

Variable	Property	Variable	Property	Variable	Property
Scale formation amount	L	Solution concentration	A	Total ion concentration of solution	A
Scale-forming ion concentration	L	CO_3^{2-} concentration	A	Reaction rate	A
Actual reaction product	A	Deposition rate	R	Removal rate	R
Target maximum product	A	Concentration difference	R	Temperature	C
Supersaturated concentration	A	Deposition occurrence time	C	Deposition rate	R
Maximum Ca^{2+} concentration	C	Scale formation rate without other influencing factors	C	Other factors affecting scaling reaction	C
Attenuation amount	R	Growth amount	R	Growth rate	R
CO_3^{2-}-pollutant concentration	C	Decay rate	C	Distance travelled by pollutants	C

Note: L represents stock, R represents flow, A represents auxiliary variable, C represents constant.

4. Analysis of Model Prediction Results

4.1 Initial State Analysis

Consider the effects of crystallisation kinetics and thermodynamic factors on scale formation on the inner walls of pipes. External factors include temperature, while internal factors include scale-forming ions and total ion concentration. Tian et al. (2025) found that the crystallisation process involves the formation of low-solubility salt molecules by cations and anions, which continuously grow and develop into microcrystals through crystallisation. These crystals

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accumulate to form scale[13]. The primary factors influencing the composition and morphology of scale deposits are temperature, solution ion concentration and Ca^{2+} concentration. Research shows scale deposits are mainly sulphate-type and carbonate-type. The subject of this study is landfill leachate. The wastewater contains a complex mix of ions and has a high degree of mineralisation. Environmental conditions affect the chemical equilibrium of the system. When ions in a solution become imbalanced and reach a state of supersaturation, carbonates precipitate out to form particles that settle in transport pipelines and form scale deposits. The main component of carbonate scale is $CaCO_3$. The deposition process is shown in Fig. 4.

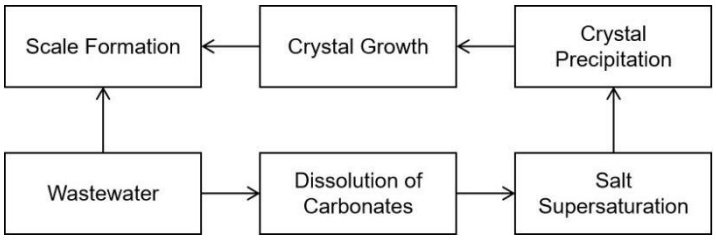


Fig. 4 Carbonate scaling deposition process

Fig. 5 shows the initial state prediction results of the model. The maximum Ca^{2+} concentration of the model is 3 g/L, the temperature is 15℃ and the flow rate is 0.1 m/s. The amount of scale formation exhibited a fluctuating pattern over time, following a pattern of "increase-decrease-stabilization." The maximum amount of scale formation is approximately 1.46 g. When the initial concentration of scale-forming ions is high, the reaction rate is faster, resulting in a significant increase in the amount of scale formation. However, given the reversibility of the scaling reaction, the resulting scale is challenging to fully precipitate due to the influence of temperature, other ion concentrations and diffusion decay. When the concentration of contaminants inside the pipe remains constant, the rate of scaling decreases gradually as the concentration of scaling ions decreases. Consequently, the amount of scale deposited on the surface begins to decrease. Model validity testing is used to study the degree of deviation between model predictions and actual results. The average relative error between the model's scale prediction results and the experimental results was 5.8% (<20%), indicating that the model is valid(see Table 3). Adjust various factors and conduct an in-depth analysis of their impact on scale formation on the walls of transport pipes.

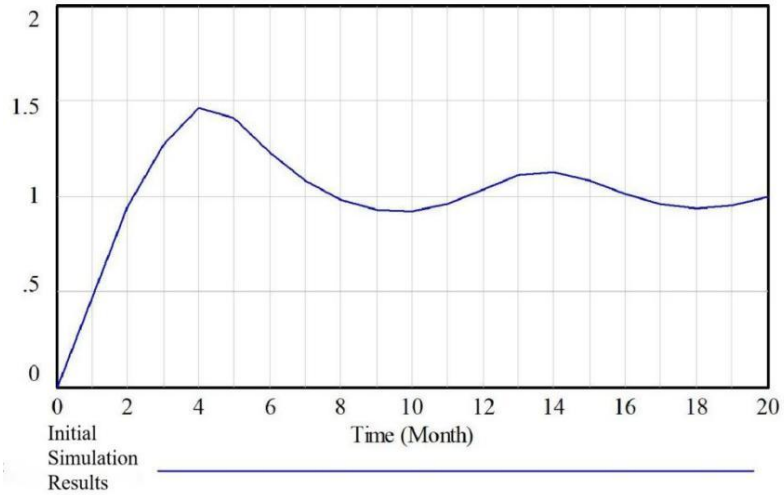


Fig. 5 SD Model Initial prediction results for scale formation

Table 3. System effectiveness test results (%)

Month	2	4	6	8	10	12	Average Relative Error
SD	13.54	16.95	1.580	1.231	0.6713	0.6896	5.777

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4.2 Analysis of Influencing Factors

4.2.1 Effect of Ca^{2+} on Pipe Scaling

Assuming all other variables are at their initial values, the simulation compares the effects of different Ca^{2+} concentrations on the scaling process(see Fig. 6). In actual leachate, physical, chemical and biological reactions continuously occur during the flow process. The survey results indicate that the actual Ca^{2+} concentration ranges approximately from 0.5 to 5 g/L. The concentration gradient was divided into six gradients: 0.5, 1, 2, 3, 4 and 5 g/L. The amount of scale formation in the model system increases gradually with increasing Ca^{2+} concentration. This indicates that scale formation is primarily influenced by reaction rate and ion concentration. Additionally, it is affected by the diffusion decay effect of ion concentration within the pipe, temperature, solution properties and fluid dynamics. When the ion concentration reaches saturation, precipitation occurs. The higher the concentration, the more crystal particles are precipitated. Li et al.(2024), Chen et al.(2025) discovered that the formation of scale involves a mutually reinforcing process between scale-forming ions and non-scale-forming ions. $CaCO_3$ scale serves as the nucleation site required for the precipitation of non-scaling ions. Salt precipitation enhances ion activity, thereby promoting the precipitation rate of $CaCO_3$[14-15].

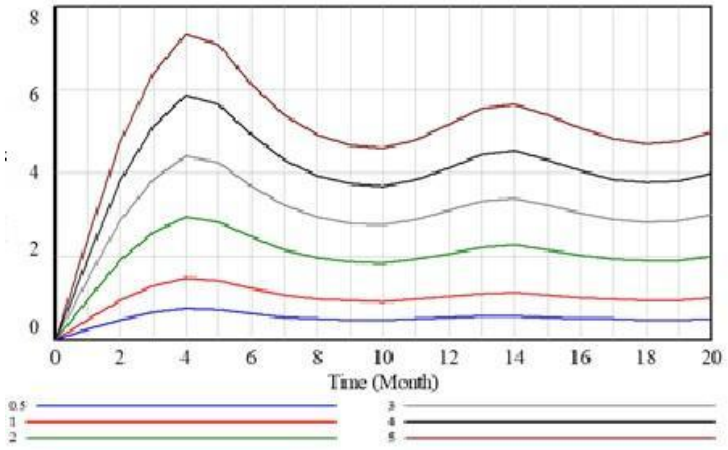


Fig. 6 The effect of Ca^{2+} changes on scale deposition

4.2.2 Effect of Temperature on Pipe Scaling

Leachate collection and transportation at landfill sites operate year-round across different seasons. Studies find it hard to maintain consistent temperatures over long periods. Even if achievable, this would require significant human, material and financial resources. Researchers found that there are significant differences in the impact of winter and summer seasons on scale formation in transport pipelines. The simulation of temperature-induced scale accumulation in transportation pipelines over extended operational periods offers valuable insights for the study of actual pipeline scaling processes.

The temperature simulation range is set to approximately 0~25℃, based on actual operating conditions. The remaining variables are set to their initial values, with an interval of 5. The effect of temperature on scale formation on walls can be categorized into two stages(see Fig. 7). In the first stage (0~10℃), the scaling rate remained largely consistent over the first four months as temperature increased. Higher temperatures result in greater maximum scaling amounts. Research indicates that the solubility of salts decreases as temperature increases. As time progresses, scaling amounts reach a peak before gradually entering a stable fluctuating state. Temperature promotes scale deposition. The second stage occurs between 10℃ and 25℃, with maximum scaling amounts of 1.439 g, 1.447 g and 1.445 g, respectively. The scaling amount remains relatively constant as the temperature rises. However, elevated temperatures have been shown to reduce the induction period of the scaling process. At temperatures of 15℃, 20℃ and 25℃, the maximum scaling amounts

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occur in the 8th, 6th and 5th months, respectively. As the temperature rises, the solubility of calcium carbonate decreases. Precipitation accelerates. This finding aligns with the observations reported by Fleming et al. (2004), who noted a substantial scaling phenomenon in leachate during winter months, accompanied by a decline in CO_2 content and $CaCO_3$ solubility as temperature increased[16].

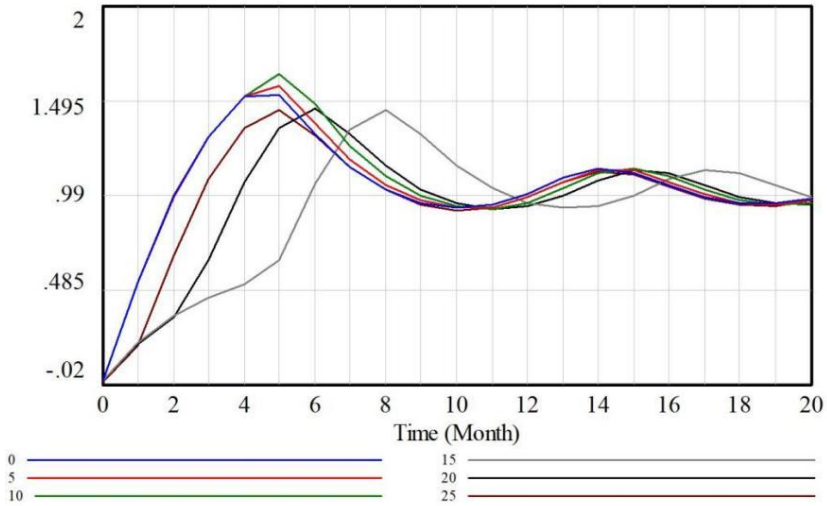


Fig. 7 The effect of temperature changes on scale deposition

4.2.3 Sensitivity Analysis

To ensure the reliability and accuracy of the pipe scaling model results, a sensitivity analysis was employed to test and evaluate the model constant parameter values[17]. The trends in scaling amounts after changes in Ca^{2+} concentration and temperature are shown in Fig. 8. The model remains within a reasonable variation range of ± 0.001 (<1%), indicating that the model has a certain degree of robustness.

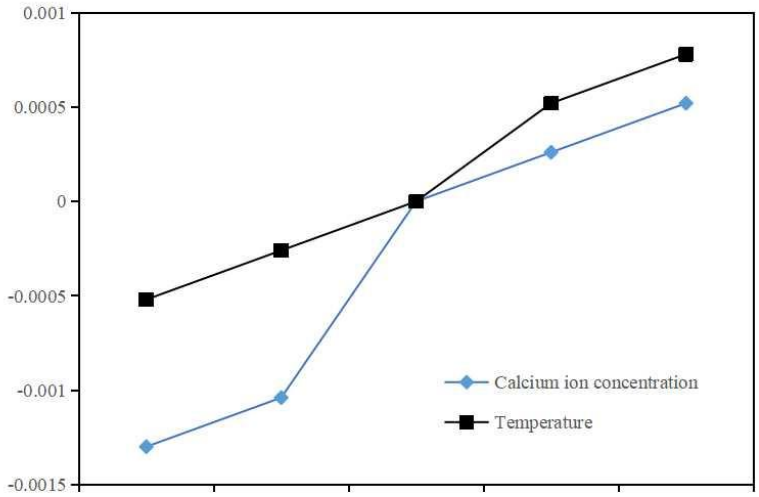


Fig. 8 Sensitivity analysis

5. Summary

The present study developed a pipe scaling prediction model based on orthogonal experiments, taking into account three factors: the diffusion and decay process of wastewater in pipes, thermodynamics and the characteristics of deposited scale. The results showed that the amount of scale formation increased rapidly at first, then decreased and gradually stabilised. The amount of

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scale formation increased gradually with increasing Ca^{2+} concentration and temperature. The order of importance of water quality factors was Ca^{2+} > COD > pH > Humus substances. This method provides guidance for selecting water quality conditions that are least likely to cause scale formation on pipes, thereby providing guidance for effective scale prevention.

References

[1] Zhang L, Yang C, et al. Research on Scaling of Wastewater Transportation Pipes: A Review. IOP Conference Series: Earth and Environmental Science, 2023, 1146(1): 012005.

[2] Zhang L. Simulation Research on Scaling of Wastewater Transportation Pipes Based on System Dynamics. Southwest Jiaotong University, 2020.

[3] Stiff J, Henry A, Davis L E. A method for predicting the tendency of oil field waters to deposit calcium carbonate. Jouranal of Petroleum Technology, 1952, 4(9): 213-216.

[4] Oddo J E, Tomson M B. Simplified Calculation of $CaCO_3$ Saturation at High Temperatures and Pressures in Brine Solutions. Journal of Petroleum Technology, 1982, 34(07): 1583-1590.

[5] Nebot E, Casanueva J F, et al. Model for fouling deposition on power plant steam condensers cooled with seawater: Effect of water velocity and tube material. International Journal of Heat and Mass Transfer, 2007, 50(17): 3351-3358.

[6] Mesticou Z, Kacem M, et al. Influence of Ionic Strength and Flow Rate on Silt Particle Deposition and Release in Saturated Porous Medium: Experiment and Modeling. Transp Porous Med, 2014, 103: 1-24.

[7] Ahmadi M, Bahadori A, et al. A rigorous model to predict the amount of Dissolved Calcium Carbonate Concentration throughout oil field brines: side effect of pressure and temperature. Fuel, 2015: 154-159.

[8] Zhao R. Numerical Simulation on Scaling by Leachate Pipe Transport Based on CFD. Environmental Engineering, 2023.

[9] Khodabakhshi M J, Bijani M. Predicting scale deposition in oil reservoirs using machine learning optimization Algorithms . Results in Engineering, 2024, 22: 102263.

[10] Inoue M, Wiseman J. Transport, Mixing and Stirring Processes in a Louisiana Estuary: A Model Study. Estuarine, Coastal and Shelf Science, 2000, 50(4): 449-466.

[11] Masada T. Leachate Flow Mound Equations for Steady-State Flow Over a Landfill Geosynthetic Bottom Liner. Geosynthetics International, 1998, 5(4): 383-397.

[12] Pääkkönen T, Ojaniemi U, et al. CFD modelling of $CaCO_3$ crystallization fouling on heat transfer surfaces. International Journal of Heat and Mass Transfer, 2016, 97: 618-630.

[13] Tian R, Gao X, et al. Temperature Fluctuation‐Driven Salt Crystallization in Salt Lakes and Nearby Sands—Lab Emulations. Water Resources Research, 2025, 61(8).

[14] Li Y, Zhang J, et al. Ion association behaviors in the initial stage of calcium carbonate formation: An ab initio Study. The Journal of Chemical Physics, 2024, 161(1).

[15] Chen D, Shen Y, et al. Mechanisms of calcium carbonate scaling regulated by single and Multi-ion interactions: Insights from experiments and molecular dynamics Simulations. Journal of Environmental Chemical Engineering, 2025, 13(5): 117723.

[16] Fleming I R, Rowe R K. Laboratory studies of clogging of landfill leachate collection and drainage systems. Canadian Geotechnical Journal, 2004, 41(1): 134-153.

[17] Li M, Di Z, Duan Q. Effect of sensitivity analysis on parameter optimization: Case study based on streamflow simulations using the SWAT model in China. Journal of Hydrology, 2021, 603: 126896.