Effect and applicability of different phosphates on inhibiting iron release in water distribution system

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ABSTRACT

Phosphate inhibitors added is a method to control iron release from the pipes. This paper studied the effect of different phosphates on controlling iron release in different pipes and different water bodies. A multi-factor fitting method was used to fit a series of models of the iron release rate constant K and the main influencing factors after adding five kinds of phosphates to two different types of iron pipes and two kinds of water, respectively. The inhibition effects of phosphates on iron release were compared according to the predicted values of K under conventional water quality and fluctuating water quality. The results show that Na_2HPO_4 can inhibit the release of iron with the most extensive application. In a gray iron pipe, turbidity has the greatest impact on K and negative correlation with K. However, in a ductile iron pipe, dissolved oxygen has the same effect on K comparing with turbidity.

Keywords: Iron release; Phosphate inhibitors; Rate constant K; Water distribution system

1. Introduction

At present, iron pipelines compose more than 70% of the urban water distribution system in China. Expansion of water supply network, replacement of pipe segments and different water sources will cause fluctuations in water quality, destroy the original equilibrium state and increase iron release [1]. In particular, when desalinated seawater used in some coastal cities, it is very different from the original water and very unstable in the pipe network. Then, it will increase the possibility of "red water" [2–4].

Physical and chemical methods can be used to control iron release in the water distribution system. The physical methods, including blending methods and velocity-control methods [1], are used more than chemical methods in China. They can be "_in situ_ repair" without introducing

new pollutants but taking a long time to form a new balance. Simple and effective chemical methods, widely adopted abroad, mainly refer to add phosphates and other inhibitors to water [5]. Phosphates are apt for human consumption and have no negative impact to the environment under low concentrations. In a 2001 survey of medium and large US utilities, 56% of corrosion inhibitor was used as phosphate-based. In recent years, some scholars have also studied the inhibition of iron, copper and zinc release from the water distribution system by phosphate [6–8].

Phosphates inhibitor used to control iron release from drinking water mainly include orthophosphates and polyphosphates. The mechanism of orthophosphate controlling iron release is to react with iron to form a precipitate, cover the surface of pipe scale, form a protective film and reduce

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iron release [9]. Polyphosphates can form chelates with iron ions and bond to the surface of scale, thus preventing the dissolution of iron compounds into water [10]. Phosphates affect iron release in pipelines mainly by changing water quality conditions and scale characteristics and affect the release mechanism of a molecule and dissolved iron.

Some studies have shown that phosphate can control iron release from the pipeline network well, and obviously reduce the turbidity of water in the pipeline network [11]. However, some studies have shown that the effect of phosphate on the iron release is not obvious, and even accelerates iron release in some cases [12]. Although different mechanisms depending on specific conditions, the relative effects of phosphate always depend on: (1) water quality conditions (such as pH, natural organic matter concentration, ion concentration, temperature, etc.); (2) types of phosphate; (3) dosage of phosphate; (4) hydraulic conditions.

There are many studies on pH, temperature and so on, and the conclusions are similar. However, there is no definite conclusion about which type of phosphates has better inhibition effects and can by widely applied. For example, Alshehri et al. [13] found that blended orthophosphate minimized total iron release, while Zhang et al. [14] thought tripolyphosphate and hexametaphosphate were more effective than orthophosphate in reducing the iron release rate. Therefore, this paper tries to investigate the performance of various phosphate on the inhibition of iron release for two kinds of water bodies and two kinds of iron pipes and to get better inhibitors from the phosphates, which can be the basis for practical applications.

In the past, many studies compared the effects of phosphates by the curves of iron release with time, but time is an unknown quantity in the actual pipe networks. It can be considered that the rate of iron release at any time is independent of time but affected by water quality parameters. According to the [Fe]~t curve ([Fe] indicates total iron concentration), which approximates a logarithmic curve, the iron release process in the tube section is approximately a first-order kinetic reaction [15], and the release rate constant K represents the rate of iron release per unit concentration, which can reflect the speed of iron release and changes in the main influencing factors, such as dissolved oxygen (DO), Temperature (T), pH, and turbidity. Though many scholars have used the control variate method to study the effect of a single variate on iron release in a water supply network [16], this paper attempts to analyze the influence of multiple factors on the K value, which is a multivariate problem and much more difficult because there is no unified system of evaluation.

Thus, this paper attempts to use the "multi-factor fitting method" to fit the linear models of the iron release rate constant K with DO, T, pH, and turbidity. Other factors such as Cl^- and SO_4^{2-} are not considered, because they are almost unchanged with time in the experiment. The K values under different water quality conditions can be calculated according to the fitted models. Based on the reason, the inhibition effects of phosphates on iron release were compared according to the predicted K values under conventional water quality and fluctuating water quality. In order to phosphate selected with a good application, the SPSS multiple regression method is used to further analyze the factors that

have the greatest impact on K after adding the phosphate selected. This can be used as the basis for the application of water quality control.

2. Materials and methods

Desalinated seawater and conventional tap water are used as the main research bodies. The desalinated seawater is from a desalination demonstration enterprise on an island in the south of China. The enterprise has been in normal operation for many years by using reverse osmosis technology to produce desalinated seawater. The desalinated water from the factory is mainly used for daily water supply on the island. Tap water is from water supply networks in south of China and the water source is surface water. Some index of water is shown in Table 1.

Through the analysis of the test results, it can be seen that the quality of desalinated seawater is excellent. All indicators can meet the national standards and can meet the requirements of industrial and domestic water quality; compared with conventional tap water, desalinated seawater has the characteristics of low alkalinity, low hardness, and high chloride ion content, which is due to a large amount of chloride ion in seawater.

The two kinds of pipes used in this study, including gray cast iron pipe and ductile cast iron pipe lined with cement mortar, are taken from the municipal pipe network for 10 y of service in Zhejiang province in China.

It can be seen that there are many pipe scales on the inner wall of the two kinds of pipes. The surface of the pipe scale contacting with water body is brown, and the side close to the pipe wall is ferrous material. Energy-dispersive X-ray spectroscopy (EDS) analysis was carried out on the scale samples of two kinds of pipes. The results of EDS scanning are shown in Tables 2 and 3, respectively.

From the results of energy spectrum analysis and scanning, it can be seen that the main elements of pipe scale are iron and oxygen. The main material of the pipe scale is iron oxide, which reacts with the main body water after contacting to cause iron release phenomenon, and the change of some water quality parameters of the main body water can also cause iron release rate on the pipe wall. X-ray projection

Table 1
Index data of test water

Index	Desalinated seawater	Tap water
T, °C	26.4	28.3
pH	8.53	7.82
DO, mg/L	7.28	4.59
Turbidity, NTU	0.44	0.48
Conductivity, μS/cm	752.0	189.1
Alkalinity, mg/L	1.0	46.5
Total hardness, mg/L	35.0	68.1
Total iron, mg/L	/	/
Soluble iron, mg/L	/	/
Chloridion, mg/L	194.9	14.2
Bromide, mg/L	1.3	/

Table 2
Results of EDS scanning on the scale samples of ductile cast iron pipes

Element	Weight (%)	Atom number (%)
O	32.42	61.49
Al	0.69	0.77
Si	1.75	1.89
S	0.85	0.8
Ca	0.44	0.33
Fe	63.86	34.71

Table 3
Results of EDS scanning on the scale samples of gray cast iron pipe

Element	Weight (%)	Atom number (%)
O	30.32	59.85
Si	0.76	0.86
Ca	1.43	1.13
Fe	67.48	38.16

diffraction analysis was carried out on the scale sample, and the results are shown in Figs. 1 and 2.

It can be seen from Fig. 1 that the scale compounds of ductile cast iron pipe mainly exist in the form of Fe_3O_4 and Fe_2O_3, including silica and calcium iron garnet. This is because the long-term hydraulic erosion has damaged the cement mortar lining and formed the corrosion tumor with cement mortar lining materials.

In addition to Fe_3O_4, there are also α-FeO(OH) and γ-FeO(OH) compounds in the pipe scale of gray cast iron. α-FeO(OH) and γ-FeO(OH) are very stable iron compounds.

The inner wall of the pipes transported from the site should be washed for several hours with tap water to remove debris and dust attached to the scale. After flushing, the tube should be cut into a number of small tubes with a length of 200 mm. The cut section of the small tubes should be coated with epoxy resin not to contact with water. Then, it should be connected with a Plexiglas base and cover plate to form a "pipe segment simulation reactor." The micromotor drives the impeller to stir the water in the reactor, and the longitudinal flow conditions in the actual pipeline are simulated by the transverse circulation produced by the stirring. The experimental device is shown in Fig. 3. For a period of contact between the water and the corrosion scale, the chemical ions in the water react with the scale, resulting in metal ions released from the scale. The concentration of dissolved oxygen should be maintained within the range of 5–8 mg/L. As sodium hypochlorite was used as a disinfectant for a certain time, there is a certain residual concentration of free chlorine in the reactor. The decay of the residual chlorine with time was measured.

Five different kinds of phosphates, including sodium tripolyphosphate, sodium hexametaphosphate, sodium orthophosphate, sodium dihydrogen phosphate, and disodium hydrogen phosphate (analytical pure, Macklin), were added to the reactor of gray cast iron pipe and ductile cast iron pipe respectively, and the concentration was 1 mg/L. There was continue operation for 48 h, and the sampling times were 1, 3, 6, 9, 12, 24, 36, and 48 h.

The main water quality indexes include DO, T, pH, and turbidity. It is known that (1) within a certain range, the concentration of oxidants increasing in water and flowing conditions maintaining can reduce the amount of iron release from corroded iron pipes [17]; (2) temperature impacts many critical parameters to pipe corrosion, including the physical properties of the solution, thermodynamic and physical properties of corrosion scale, chemical rates,
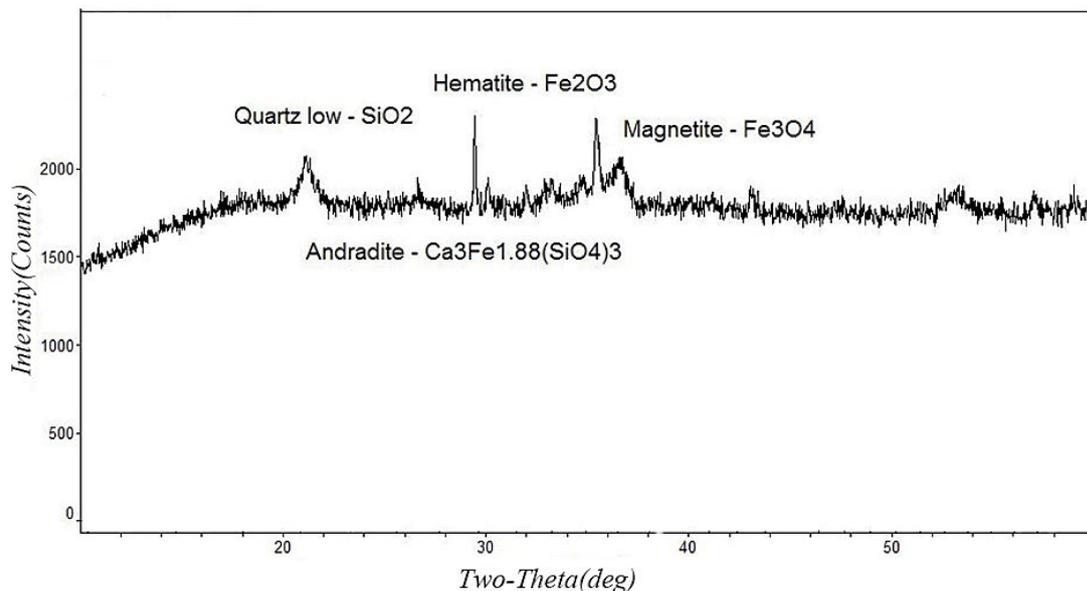

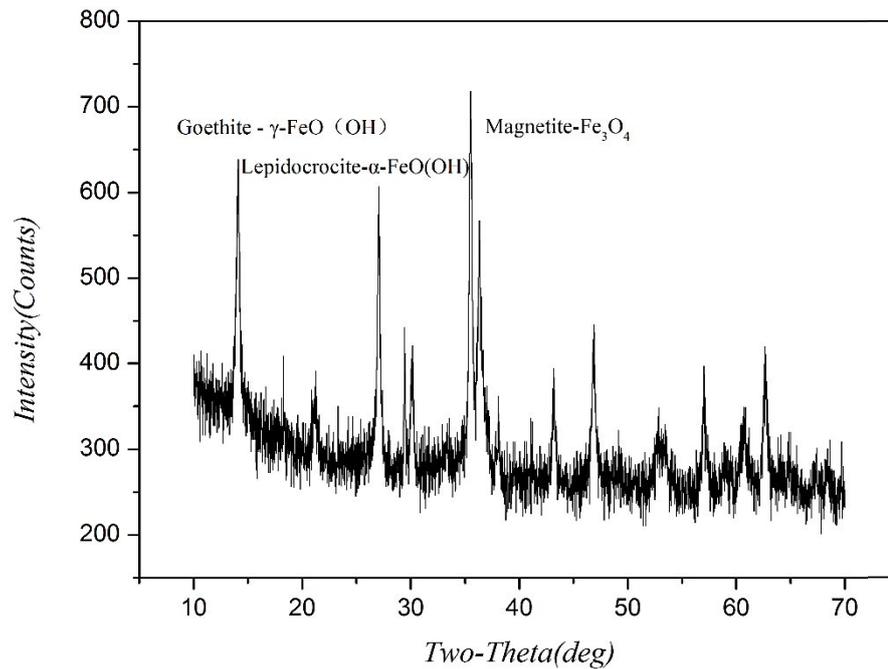Fig. 1. XRD analysis results of pipe scale of ductile cast iron pipe.

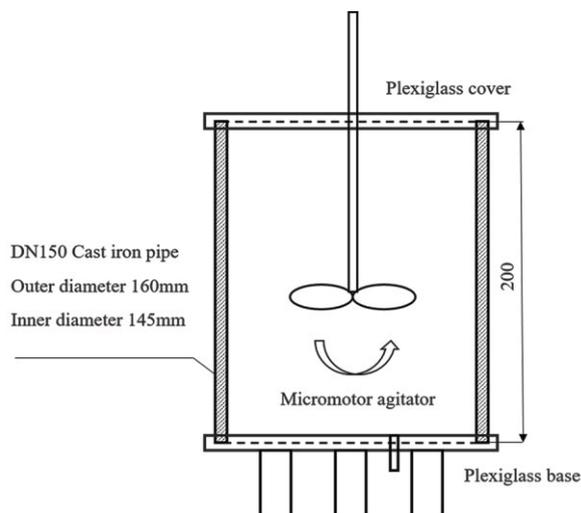Fig. 2. XRD analysis results of pipe scale of gray cast iron pipe.

Fig. 3. Schematic diagram of an experimental device.

and biological activity [18,19]; (3) the iron release rate and turbidity decreased significantly with pH and alkalinity increasing; and (4) turbidity mainly affects the dissolution equilibrium during iron release [3].

3. Results and discussion

According to the experimental water and pipe materials, the research objects are divided into four categories including No corrosion inhibitor (G_{i0}), sodium tripolyphosphate (G_{i1}), sodium hexametaphosphate (G_{i2}), sodium orthophosphate (G_{i3}), sodium dihydrogen phosphate (G_{i4}), and disodium hydrogen phosphate (G_{i5}), i = 1, 2, 3, 4.

Therefore, the experiment is divided into four categories and 24 groups, as shown in Table 4.

3.1. K-model fitting results

The process of iron release in pipe sections can be simplified as:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \tag{1}$$

$$Fe^{2+} \rightarrow Fe^{3+} + e^{-} \tag{2}$$

Table 4
Group table for research on iron release control

Category	Water species	Pipe type	Group
Category I	Tap water	Gray cast iron pipe	G_{10}–G_{15}
Category II	Tap water	Ductile iron pipe	G_{20}–G_{25}
Category III	Desalinated seawater	Gray cast iron pipe	G_{30}–G_{35}
Category IV	Desalinated seawater	Ductile iron pipe	G_{40}–G_{45}

According to the [Fe]~t curve ([Fe] indicates total iron concentration), which approximates a logarithmic curve, this process approximately conforms to the first-order kinetic reaction equation, so (Fig. 4):

$$\frac{d[Fe]}{dt} = K[Fe] \tag{3}$$

The integral of the above formula can be obtained: $Ln[Fe]_t - Ln[Fe]_0 = Kt$, i.e.,

$$Ln[Fe] = Kt + B \tag{4}$$

where the iron release rate constant K represents the rate of iron release per unit concentration, which can reflect the speed of iron release.

A series of water quality indicators in the 24 groups can be measured, including the total iron concentration [Fe], DO, T, pH, and turbidity. In this study, the "multi-factor fitting method" was adopted. The specific methods are as follows:

- Use MATLAB to fit the Ln[Fe]~t curve obtained in the experiments and find the K value corresponding to each state point.
- According to the obtained K values, the linear models of each group of K for DO, T, pH, and turbidity can be fitted:

$$K = b_1 X_{DO} + b_2 X_T + b_3 X_{pH} + b_4 X_{tur} + b_5 \tag{5}$$

Where b_i is the index coefficient obtained by fitting; X_{DO} is the value of DO (mg/L); X_T is the value of T (°C); X_{pH} is the value of pH; X_{tur} is the value of turbidity (NTU). Within a very small range of variation, it is considered that DO, T, pH is a linear relationship with K.

The fitting result can be measured by the determinable coefficient R^2 and R^2 is close to 1. The better the fitting degree of the regression line is to the observed.

Taking the first category (tap water, gray cast iron pipe) without the corrosion inhibitor group (G_0) as an example, the Ln[Fe]~t curve and the fitting results were as follows:

We have deduced that:

$$Ln[Fe]_{10} = K_{10}t + B \tag{6}$$

The fitting results are as follows:

$$Ln[Fe]_{10} = -0.0014t^2 + 1.1210t - 0.3663 \tag{7}$$

By derivation, we can get:

$$K_{10} = -0.0028t + 1.1210 \tag{8}$$

The results show that K_{10} changes with time. When $t > 35$ h, K_{10} is less than 0. Theoretically, we believe that the change of K is not directly caused by time, but by the change of water quality parameters (turbidity, dissolved oxygen, etc.) with time. If the water quality parameters are constant, K is constant and the fitting result of Ln [Fe] ~ t will be a straight line. In addition, the decrease of K with time is consistent with the gradual decrease of iron release. When $t > 35$ h, the effect of iron deposition and adsorption is greater than that of release, and K_{10} is less than 0. The linear fitting results of K_{10} on DO, T, pH, and turbidity are as follows:

$$K_{10} = -0.0018 \times X_{DO} - 0.0040 \times X_T + 0.0029 \times X_{pH} - 0.0006 \times X_{tur} + 0.1736 \tag{9}$$

$R^2 = 0.965$, the fitting effect is good.

In this study, the K linear fitting was performed for the 24 groups, and it was found that all R^2 values were greater than 0.9. The R^2 values for 23 groups (>95%) were greater than 0.95, which indicated that the fitting results were good. The specific fitting results are shown in Appendices Table S1.

In addition, the K-models proposed in this study can be used to estimate the iron release rate of the pipe network. In the actual water supply network, the total iron concentration [Fe], DO, T, pH, and turbidity can be measured to estimate the iron release rate $v = K \cdot$[Fe], which can also be used in the "red water" warning system of the pipe network.

3.2. Effect of phosphate

The water quality parameters of drinking water fluctuate at the normal value. In this study, the predicted K values of each group were compared according to the "normal state point" (all water quality indicators are normal values) and the "experimental state points" (all water quality indicators are experimental value). Moreover, the effects of phosphates on iron release were analyzed. Among them, the normal state point mainly simulates the iron release under the conventional water supply state and the experimental points mainly simulate the water quality fluctuation under the changes in water supply quality.

3.2.1. Normal state point-conventional water quality

- According to the water quality standard for drinking water in China (GB5749-2006), pH should be no less than

6.5 and no more than 8.5. Turbidity should be no more than 1 NTU, and there are no special regulations on DO and T.

- According to experience, in general, take $X_T = 20$ for room temperature and $X_{DO} = 7$ for dissolved oxygen.
- Considering the difference of water quality between the two water bodies in Table 1, tap water: $X_T = 28.3$, $X_{pH} = 7.82$, $X_{DO} = 4.59$, $X_{tur} = 0.48$. Desalinated seawater: $X_T = 26.4$, $X_{pH} = 8.53$, $X_{DO} = 7.28$, $X_{tur} = 0.44$.

Taking a, b, and c into account, the "normal state point 1" of tap water is defined as $X_T = 20$, $X_{pH} = 7.5$, $X_{DO} = 7$, $X_{tur} = 1$, and the "normal state point 2" of desalinated seawater is defined as $X_T = 20$, $X_{pH} = 8.5$, $X_{DO} = 7$, $X_{tur} = 1$. Then, the normal state point value can be substituted into the corresponding K linear models, and the inhibition effects of each phosphate can be directly compared according to the values of K.

3.2.2. Experimental state points- fluctuating water quality

The water quality parameters of drinking water fluctuate up and down at the normal value. In this study, a series of DO, T, pH, and turbidity values measured without a corrosion inhibitor were used to simulate the fluctuation state of water quality and were defined as a series of "experimental status points." The corresponding K_{i0}, K_{i1}, K_{i2}, K_{i3}, K_{i4}, and K_{i5} values can be obtained by substituting each "experimental state point" into the corresponding K_{ij} model, and then the fluctuation curve of K_{ij} can be made. The K_{i0} curve is the control curve without a corrosion inhibitor, and the curve below the K_{i0} curve indicates that the phosphate added has the effect of inhibiting iron release.

3.2.1. Category I (tap water, gray cast iron pipe)

3.2.1.1. Comparison of normal state point ($X_{DO} = 7$, $X_T = 20$, $X_{pH} = 7.5$, $X_{tur} = 1$)

It can be seen from Table 5 that in the normal state, except for sodium tripolyphosphate, all the other four phosphates have the effect of inhibiting iron release in the tap water of grey cast iron pipe.
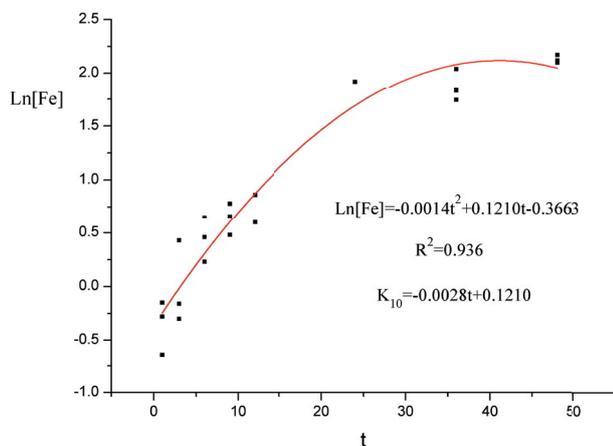

Fig. 4. The Ln[Fe]~t curve of G_{10}.

3.2.1.2. Comparison of experimental status points

Firstly, DO, T, pH, and turbidity were measured without a corrosion inhibitor (Table 6) and were, respectively, substituted into the expressions of the six K_{1j} models of Category I (j = 0, 1, 2, 3, 4, 5, the same as Category II, III, IV). Secondly, the K_{1j} values corresponding to each state point were calculated. Finally, the curves were drawn to compare the K values and the effects of phosphates on iron release.

In addition, generally, when cloudy or "red water" occurs, the turbidity value is much higher than 1, so the turbidity data greater than 1 in Table 6 are meaningful.

It can be seen from Fig. 5 that except for sodium dihydrogen phosphate, the other four phosphates have certain inhibiting effects on the iron release in the tap water of gray cast iron pipe. Among them, sodium hexametaphosphate, disodium hydrogen phosphate, and sodium orthophosphate all showed inhibitory effects at five state points. Sodium hexametaphosphate had the best inhibitory effect at state point 1, and the K value decreased by 0.04 (33%). Disodium hydrogen phosphate had the best inhibitory effect at state point 2, and the K value decreased by 0.03 (26%). Sodium orthophosphate had the best inhibitory effect at state point 2, and K decreased by 0.02 (20%). Sodium tripolyphosphate showed an inhibitory effect on iron release at the last three state points and had the best inhibitory effect at the state point 5 and K value decreased by 0.04 (42%).

Table 5
Comparison table of K values at normal state point

| Category	Group	K_{1j}	Value	Comparison
Category I	G_{10}	K_{10}	0.10215	
	G_{11}	K_{11}	0.12945	$>K_{10}$
	G_{12}	K_{12}	0.0698	$<K_{10}$
	G_{13}	K_{13}	0.0199	$<K_{10}$
	G_{14}	K_{14}	−0.0033	$<K_{10}$
	G_{15}	K_{15}	0.01875	$<K_{10}$
Category II	G_{20}	K_{20}	0.40785	
	G_{21}	K_{21}	0.07855	$<K_{20}$
	G_{22}	K_{22}	−0.2381	$<K_{20}$
	G_{23}	K_{23}	0.06635	$<K_{20}$
	G_{24}	K_{24}	−0.46295	$<K_{20}$
	G_{25}	K_{25}	−0.3374	$<K_{20}$
Category III	G_{30}	K_{30}	0.4342	
	G_{31}	K_{31}	0.195	$<K_{30}$
	G_{32}	K_{32}	0.13125	$<K_{30}$
	G_{33}	K_{33}	0.05245	$<K_{30}$
	G_{34}	K_{34}	0.05935	$<K_{30}$
	G_{35}	K_{35}	0.0809	$<K_{30}$
Category IV	G_{40}	K_{40}	0.25285	
	G_{41}	K_{41}	0.2826	$>K_{40}$
	G_{42}	K_{42}	0.73895	$>K_{40}$
	G_{43}	K_{43}	0.97745	$>K_{40}$
	G_{44}	K_{44}	1.52295	$>K_{40}$
	G_{45}	K_{45}	0.1375	$<K_{40}$
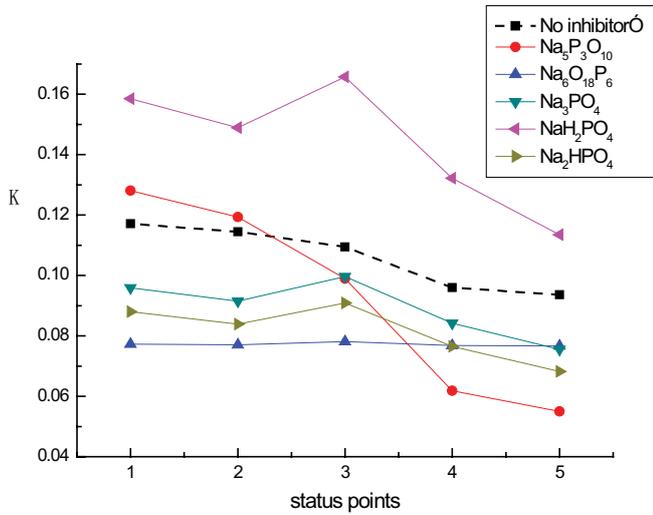
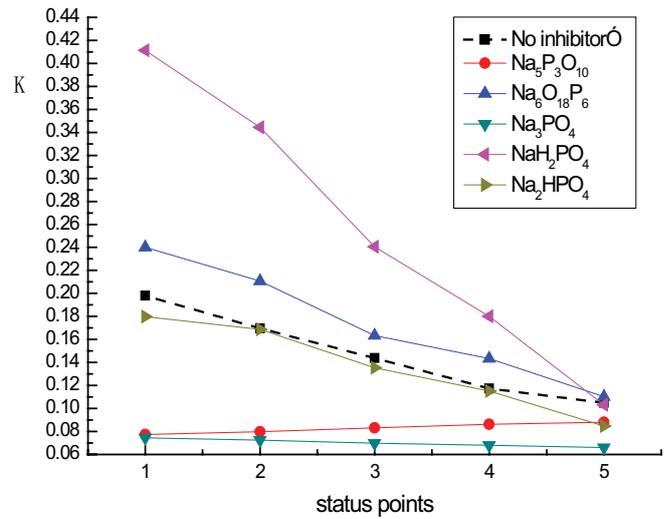Fig. 5. Fluctuation curve of experimental status points of Category I.

Fig. 6. Fluctuation curve of experimental status points of Category II.

3.2.2. Category II (tap water, ductile iron pipe)

3.2.2.1. Comparison of normal state point ($X_{DO} = 7$, $X_T = 20$, $X_{pH} = 7.5$, $X_{tur} = 1$)

It can be seen from Table 5 that when in a normal state, the five phosphates have inhibitory effects on iron release in ductile iron pipe, and sodium hexametaphosphate, sodium dihydrogen phosphate, and disodium hydrogen phosphate have the strongest effects.

3.2.2.2. Comparison of experimental status points

Fig. 6 shows that except for sodium hexametaphosphate and sodium dihydrogen phosphate. The other three phosphates have certain inhibiting effects on iron release in ductile iron pipe. Among them, disodium hydrogen phosphate has no obviously inhibitory effect on iron release, while sodium orthophosphate and sodium tripolyphosphate have good inhibitory effects at five state points. Both sodium orthophosphate and sodium tripolyphosphate had the best inhibitory effect on iron release at state point 1, and the K value decreased by 0.12 (60%).

3.2.3. Category III (desalinated seawater, gray cast iron pipe)

3.2.3.1. Comparison of normal state point ($X_{DO} = 7$, $X_T = 20$, $X_{pH} = 8.5$, $X_{tur} = 1$)

It can be seen from Table 5 that when in the normal state, the five kinds of phosphate all have inhibitory effects on iron release in the desalinated seawater of gray cast iron pipe, and sodium orthophosphate has the best effect.

3.2.3.2. Comparison of experimental status points

As shown in Fig. 7, all five phosphates have an inhibitory effect on iron release in the desalinated seawater of gray cast iron pipes. Among them, sodium hexametaphosphate has no obvious effect at state point 1, but its K value
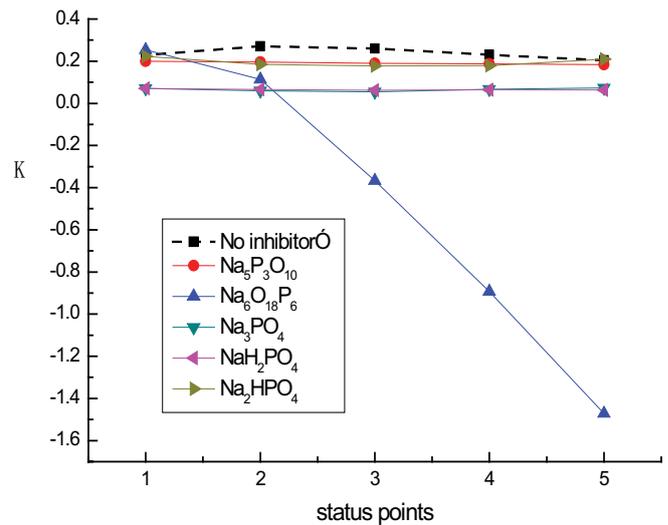

Fig. 7. Fluctuation curve of experimental status points of Category III.

decreases by 0.15 (60%) at state point 2, and its K value is less than 0 at the last three states. Sodium dihydrogen phosphate and sodium orthophosphate have similar effects, and they have better inhibitory effects than sodium triphosphate and disodium hydrogen phosphate; their K values decreased by 0.2 (70%) at state point 2.

3.2.4. Category IV (desalinated seawater, ductile iron pipe)

3.2.4.1. Comparison of normal state point ($X_{DO} = 7$, $X_T = 20$, $X_{pH} = 8.5$, $X_{tur} = 1$)

It can be seen from Table 5 that in the normal state, except for disodium hydrogen phosphate, the other four phosphates added into the desalinated seawater of ductile iron pipes may increase the iron release.

3.2.4.2. Comparison of experimental status points

As shown from Fig. 8, only disodium hydrogen phosphate inhibits iron release at all five state points in the desalinated seawater of ductile iron pipe, which has the best effect at state point 5, and its K value decreased by 0.18 (100%).

3.2.5. Effect of phosphate

Combined with the above analysis, the inhibition effects of five phosphates on iron release under different conditions were summarized, as shown in Table 7.

In the table, "×" means no inhibition, and "√" means inhibition. Therefore, under the same water quality, an equal amount of phosphate added, whether it is desalinated seawater or tap water, gray cast iron pipe or ductile cast iron pipe, disodium hydrogen phosphate (Na_2HPO_4) can inhibit iron release, which has the most extensive application.

3.3. Comparison of influencing factors

After selecting good and suitable phosphates, in order to compare the influence of various water quality factors on K, the experimental data should be standardized, and then the relationship between K and the processed data should be fitted.

Based on the above results, disodium hydrogen phosphate (Na_2HPO_4) was selected for the control of iron release in the water supply network, and various water quality factors would affect K_{i5}. Therefore, the effects of these factors on

K_{i5} were further analyzed. In this study, the SPSS multivariate regression method was used to determine the influence of various factors on K according to the absolute values of the standardized regression coefficient, and the results are shown in Table 8.

The data in Table 8 shows that after disodium hydrogen phosphate added, in the tap water (or desalinated seawater) of the gray cast iron pipe, turbidity has the greatest influence on K, and K is negatively correlated with turbidity. Moreover, DO has the greatest influence on K, and K is negatively correlated with DO. However, it can be seen from the observation of the least influencing factors that T has the least influencing on iron release in tap water and pH has the least influencing on iron release in desalinated seawater. Therefore, it can be concluded that the key factors greatly influencing iron release are DO and turbidity when disodium hydrogen phosphate is added.

4. Conclusions

To solve the problem of unclear effect and applicability of various phosphates in controlling iron release, the multi-factor fitting method was investigated in this paper to fit the linear models of the iron release rate constant K and the main influencing factors DO, T, pH, and turbidity. The effects of five phosphates (sodium tripolyphosphate, sodium hexametaphosphate, sodium orthophosphate, sodium dihydrogen phosphate, and disodium hydrogen phosphate) on the control of iron release in two kinds of iron pipes (gray iron pipe and ductile iron pipe) and two kinds of water bodies (tap water and desalinated water) were compared according to the K values. In addition, the K linear models established in this paper can be used in the estimation of the iron release rate of water supply pipe network and the early warning system for "red water."

The comparison results of the iron release rate constant K showed that the same amount of phosphate added under

Table 6
Experimental data

| Category	Status point number	DO	T	pH	Turbidity
	1	6.75	16.5	8.70	5.89
	2	6.75	16.5	8.65	10.10
Category I	3	6.75	16.5	8.87	19.60
	4	8.37	17.6	8.80	29.50
	5	6.63	17.2	8.62	40.40
	1	5.13	24.7	8.94	4.47
	2	5.59	24.6	9.07	4.38
Category II	3	6.12	24.4	9.15	5.63
	4	6.53	24.3	9.30	8.88
	5	6.95	24.0	9.38	9.99
	1	7.95	15.0	9.00	4.43
	2	7.63	16.1	9.15	12.3
Category III	3	7.46	16.0	9.31	41.7
	4	7.93	15.5	8.74	69.2
	5	7.40	14.9	8.75	103
	1	7.30	24.3	9.34	5.89
	2	7.51	24.7	9.18	10.10
Category IV	3	6.90	24.9	9.34	19.60
	4	7.00	24.6	9.18	29.50
	5	7.50	24.8	8.33	40.40
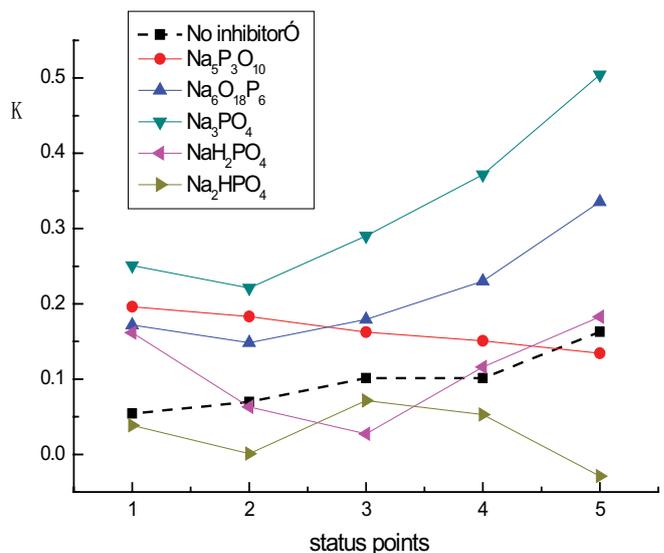
Fig. 8. Fluctuation curve of experimental status points of Category IV.

Table 7
Statistical table of the inhibiting effect of phosphate on iron release

Category		$Na_5P_3O_{10}$	$Na_6O_{18}P_6$	Na_3PO_4	NaH_2PO_4	Na_2HPO_4
Tap water	Gray cast	×	√	√	×	√
	Ductile cast	√	×	√	×	√
Desalinated seawater	Gray cast	√	√	√	√	√
	Ductile cast	×	×	×	×	√

Table 8
Standardized regression coefficient table of all factors with disodium hydrogen phosphate added (Na_2HPO_4)

Category	DO	T	pH	Turbidity
Category I	−0.141	−0.059	0.144	−0.893
Categories II	−0.694	0.193	0.475	−0.542
Categories III	−0.213	−0.220	−0.094	−1.107
Categories IV	−0.877	−0.040	0.009	0.046

the same water quality conditions. Whether it is desalinated seawater or tap water, gray cast iron pipe, or ductile cast iron pipe, Na_2HPO_4 has a good effect on inhibiting iron release.

The results of the analysis of influencing factors in SPSS indicate that after disodium hydrogen phosphate added in the gray cast iron pipe, tap water (or desalinated and seawater) turbidity has the greatest influence on K, and K is negatively correlated with turbidity. Moreover, DO has the greatest influence on K, and K is negatively correlated with DO in the ductile iron pipe and tap water (or desalinated seawater).

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Appendix

The K linear model obtained by MATLAB fitting is "$K = b_1 X_{DO} + b_2 X_T + b_3 X_{pH} + b_4 X_{tur} + b_5$", whose coefficients are shown in Table S1. The fitting degree can be measured by the determinable coefficient R^2, and the closer R^2 is to 1, the closer the fitting degree of the regression line is to the observed value.

Table S1
K_{ij} fitting coefficient table

Category	K_{ij}	b_1	b_2	b_3	b_4	b_5	R^2
Category I	K_{10}	−0.0018	−0.0040	0.0029	−0.0006	0.1736	0.965
	K_{11}	−0.0084	−0.0026	−0.0019	−0.0021	0.2566	0.995
	K_{12}	−0.0003	−0.0004	0.0050	0.0000	0.0424	0.997
	K_{13}	−0.0023	−0.0036	0.0540	−0.0004	−0.2966	0.964
	K_{14}	−0.0050	−0.0077	0.1150	−0.0009	−0.6759	0.964
	K_{15}	−0.0021	−0.0033	0.0493	−0.0004	−0.2699	0.964
Category II	K_{20}	−0.0662	−0.0610	−0.0321	−0.0002	2.3322	0.956
	K_{21}	0.0079	0.0043	−0.0053	0.0003	−0.0233	0.999
	K_{22}	−0.1228	−0.0089	0.2024	−0.0003	−0.7182	0.997
	K_{23}	−0.0047	−0.0001	−0.0001	0.0000	0.1020	0.996
	K_{24}	−0.2365	−0.0027	0.3173	−0.0035	−1.1297	0.983
	K_{25}	−0.0599	0.0418	0.1560	−0.0046	−1.9195	0.990
Category III	K_{30}	−0.0139	0.0375	−0.0068	−0.0003	−0.1604	0.916
	K_{31}	−0.0026	−0.0023	−0.0066	−0.0002	0.3155	0.961
	K_{32}	0.0291	−0.0166	0.1415	−0.0170	−0.9262	1.0
	K_{33}	−0.0083	−0.0080	−0.0273	−0.0001	0.5027	0.999
	K_{34}	−0.0009	−0.0032	−0.0071	−0.0001	0.1901	1.0
	K_{35}	−0.0443	−0.0400	−0.0276	−0.0005	1.4261	0.997
Category IV	K_{40}	−0.1353	0.0234	−0.1711	−0.0004	2.1867	0.990
	K_{41}	−0.0020	−0.0162	−0.0088	−0.0018	0.6972	0.991
	K_{42}	−0.1248	−0.0826	−0.2105	0.0005	5.0533	0.966
	K_{43}	−0.1748	−0.1106	−0.2515	0.0026	6.5482	0.996
	K_{44}	−0.1098	−0.2634	−0.2241	−0.0015	9.4659	1.0
	K_{45}	−0.1334	−0.0133	0.0032	−0.0009	1.3110	0.979