Research Paper: Design and Development of Municipal Wastewater Treatment Systems by Fe(VI) and Computation of System's Economic Navigation

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ABSTRACT

Objectives: In spite of numerous studies on Fe(VI) capacity in treating wastewater, no equations are presented yet for the design of a Fe(VI) treatment facility. In most studies, Fe(VI) has been mentioned as the most effective substance for wastewater treatment; however, none is currently available about the operation costs in treatment facilities. This paper aims to introduce the necessary equations for the design and development of facilities that use Fe(VI) through the electrolysis methods and conduct the necessary calculations regarding its navigation costs.

Materials & Methods: As the first step, a pilot plant test was conducted to find the basic information for municipal wastewater treatment by Fe(VI). Then, all the costs pertaining to electricity, acid and sodium hydroxide used in the treatment process were calculated to evaluate the total navigation costs.

Results: Our results indicate that treatment of every cubic meter of municipal wastewater would bear the following costs: US $1.17 for Fe(VI) production, US$ 2.52 for reducing the pH below 2 and US$ 146 for the production of 14 M sodium hydroxide solution. The overall costs for such facility would be equal to US$ 149.7.

Conclusion: As it is demonstrated, the generation of 14 M sodium hydroxide solution is the most expensive element in the treatment process. It appears that the aforementioned cost is very high for the municipal treatment facilities; however, it might be appropriate for wastewaters that are resistant to biological methods. Nevertheless, more research is still needed to address this issue.

1. Introduction

Coagulation, chemical oxidation and disinfection are the most important processes in wastewater treatment [1-4]. Coagulants attach the suspended particles to each other, leading to much larger particles. In some cases, these larger particles are capable of absorbing the dissolved pollutants in wastewater transfer lanes. The larger particles will in turn get eliminated through the process of sedimentation or filtration. The disinfection process is designed to eliminate the harmful microorganisms for

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human health [5, 6]. The disinfection process can also be applied to eliminate or control the odor-causing substances in wastewaters [7].

A wide range of coagulants, disinfectants and oxidizers can be applied for the wastewater treatment procedures [8]. Chloride, sodium hypochlorite, chloride dioxide and ozone are among the most important disinfectants and coagulants. The application of chloride in wastewater chemical oxidation is difficult due to the generation of carcinogenic by products like trihalomethanes [5]. The application of chloride dioxide and ozone produce no such by products but are very costly [9]. The pollution of water sources are increasing and so are the standards for the distribution of drinking water and the discharge of wastewater. Therefore, introduction of new and more affective compounds to achieve these standards is deemed necessary [10]. Such compounds must ideally possess: 1. Disinfection capacity in water; 2. Some capacity to decompose organic and inorganic impurities in water and wastewater; 3. The capability to remove heavy iron suspended particles in water; and 4. Produce no toxic compounds in chemical reaction with existing substances in wastewater [5].

Ferrate (VI) which is known as Fe(VI), with the chemical formula of (FeO^{2-}_{Δ}) is illegible for all the above criteria [11]. Fe(VI) is a very potent oxidizer which is superior to all other applied oxidizers and disinfectants in treatment procedures with regard to oxidation and reduction capacity in acidic conditions [12]. It is converted to ferric hydroxide in the course of time and be highly ideal for all three subsequent procedures of treatment, i.e., the oxidation of pollutants, disinfection and elimination of suspended particles, all in one operational unit with a single injection of this substance [13]. Some of the advantages of this compound includes the capacity to operate in the absence of hypochlorite ion and the possibility to generate on-demand within the treatment unit [14].

Numerous studies have successfully evaluated Fe(VI) capacities in treating wastewater [5, 12, 13, 15, 16]; however, no studies are currently available on providing the necessary equations for the design and set up of a treatment facility supported by Fe(VI). In most studies, Fe(VI) has been identified as the most effective method in treating the wastewater but the operational costs are still unexplored. This study aims to develop necessary equations for the design of such treatment units. The operational costs inflicted by the unit are also explored thus neglecting other expenditures such as tanks, pumps, mixers, electrodes, etc. It is recommended for the future studies to take into account the secondary expenses as well.

2. Materials and Methods

At first, we explored all the previous related research and gathered their results. These results were then subjected to the necessary analysis to develop the required equations to design and develop Fe(VI) supported treatment facilities. In the end, all the costs pertaining to electricity, acid and sodium hydroxide used in the treatment process were calculated in order to evaluate the navigation costs. The treatment system supported by Fe(VI) is composed of three distinct segments, including the Fe(VI) production segment, storage tank and chemical oxidation reactor segment (Figure 1). In this study a pilot plant was made and used to treat municipal wastewater. Then collected data were utilized to evaluate the navigation costs and develop required equations for designing Fe(VI) supported treatment facilities for municipal wastewater. As can be seen in Figure 1, Fe(VI) is entered into oxidation tank with the flow rate of 0.01 L/min along with municipal wastewater with the flow rate of 0.016 L/min. The hydraulic retention time in oxidation tank is 20 min. The row wastewater COD was 900 mg/L which after treatment in oxidation tank, was reduced to 530 mg/L. In this study, an electric current of 1.9 A and 7 v was utilized for treatment of municipal wastewater.

Fe(VI) generation system is one of the important parts of the treatment system supported by Fe(VI). Several parameters should be considered to design Fe(VI) generation system, including 1) the electrolyze reactor material, 2) the electrolyze reactor volume, 3) the wastewater flow rate of the input electrolyte fluid into the electrolyze reactor, 4) the concentration of the input Fe(VI) into the reactor and finally 5) the pH value of the reactor. The acid storage tank is another part of the treatment system supported by Fe(VI). The only necessary parameter in determining the dimensions of the acid storage tank is the volume of the consumed acid throughout the day. The design process began with the development of necessary equations supported by data provided by experimental tests and used similar approach in estimating the operational costs.

3. Results

The results showed that the total costs of treatment by Fe(VI) is US$ 149.7 for each cubic meter of wastewater. This cost includes US$ 1.17 for the generation of Fe(VI), US$ 2.52 for the reduction of pH to under 2 and US$ 146 for the generation of sodium hydroxide 14 M solution. Evidently, the maximum expenses belong to Fe(VI) generation segment and the purchase of sodium hydroxide 14 M solution. Biological treatment is a well-known

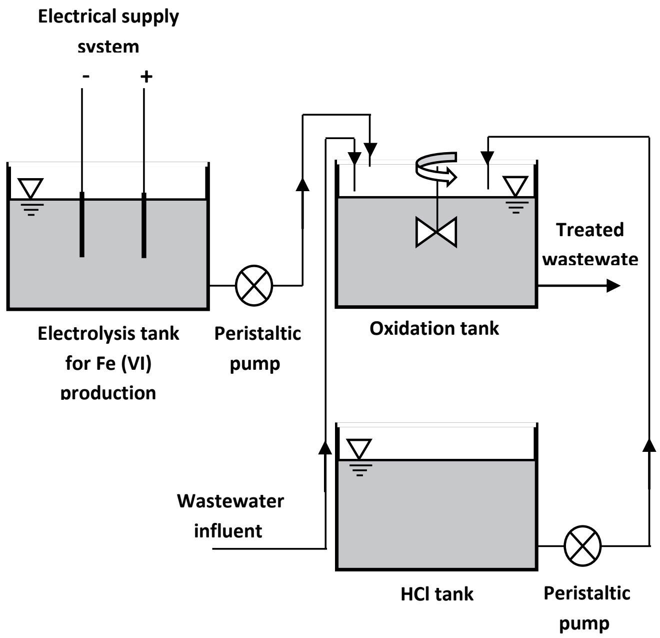

Figure 1. An overview of the treatment system supported by Fe(VI)

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method to treat municipal wastewater. Although operation cost of biological methods is not high, the cost of its constructing is expensive. Unlike biological method, wastewater treatment using Fe(VI) do not need high cost of construction but it has a high operation cost.

4. Discussions

Oxidation tank design and Fe(VI) production cost

In this study, deterioration of COD and variations of ΔH were investigated by using mass balance and energy balance, respectively to calculate the consumed electrical energy in a full scale wastewater treatment plant (Equation 1).

$$(1)\ v_0 CA_0 - v_0 CA - (r_{CA})(V) = 0$$

Where CA is COD concentration after treatment by Fe(VI) at steady state condition in g/L, CA_0 refers to initial concentration of COD in g/L, v_0 is wastewater flow rate in g/L, r_{CA} denotes deterioration rate of COD in g/L min and V is the volume of reactor in liter. By solving the Equation 1, r_{CA} was found as high as 0.02 g/L min. Equation 2 shows the energy balancing of reactor.

$$(2)\ \frac{dE}{dt} = 0 = H_0 - m^\circ H + Q^\circ - W^\circ$$

Q is equal to zero if the system is assumed to be adiabatic. Therefore, Equation 2 can be converted to Equation 3.

$$(3)\ W^\circ = -m^\circ (H - H_0) = -m^\circ \Delta H$$

Relation between reaction's temperature and ΔH is shown in Equation 4.

$$(4)\ \Delta H = H - H_0 = C(T_r - T_0) + \Delta H_{rxn(Tr)} + C(T - T_0)$$

It is assumed that specific heat capacity (C) of the wastewater is constant. Therefore, Equation 4 can be rewritten as Equation 5.

$$(5)\ \Delta H = C(T - T_0) + \Delta H_{rxn}$$

Since in the laboratory tests, T_0 is approximately equal to T and T_r is equal of 25C°, Equation 5 can be rearranged to Equation 6.

$$(6)\ \Delta H = \Delta H_{rxn(Tr)} = \Delta H_{rxn(T)}$$

Therefore, Equation 7 can be formed from laboratory tests and energy equation:

$$(7)\ m^\circ \Delta H = m^\circ \Delta H_{rxn} = -W^\circ$$

Equation 8 can be achieved from rearrangement of Equation 7.

$$(8)\ \Delta H_{rxn} = \frac{-W}{m^\circ}$$

Based on laboratory data, amount of W° is calculated by Equation 9. As, m° and ΔH_{rxn} are known, amount of ΔH_{rxn} can be determined by Equation 8.

$$(9)\ W^\circ = I \times v$$

Results of this study illustrated that amounts of W° and ΔH_{rxn} are equal to -13.3 j/s and 30.9 j/g, respectively (the minus sing is due to consumed work).

Amount of electrical power in the full scale plant

Assuming that the full scale plant of wastewater treatment by using Fe(VI) like laboratory scale is utilized the same CA and T, by using Equation 10 the parameter of W° can be calculated.

$$(10)\ W^{\circ}=-m^{\circ}\Delta H=-m^{\circ}\Delta H_{rxn}$$

Total consumed electrical power for Fe(VI) production by using electrolysis method in a year can be calculated by Equation 11. Then by multiplying the consumed electrical power and electrical power cost, amount of electrical power cost for a year is calculated.

$$(11)\ W=(W^{\circ})(2400)(7200)$$

Because the cost of electrical power in Iran is US$ 0.0127 for each KW, amount of electrical power cost for producing of Fe(VI) by using electrolysis method is calculated as high as US$ 1.17. One must be aware that the electricity costs are not the only source of expenditure in a Fe(VI) supported treatment unit. In order to achieve the maximum levels of oxidation, the pH level of the wastewater must be reduced to under 2. Research shows that in order to reduce the pH level of every cubic meter of normal municipal wastewater to under 2, approximately 150 liters of 19% chlorhydric acid is required. Since every liter of output liquid from the electrolysis tank contains only 0.2 g of Fe(VI), 8750 liters of liquid containing Fe(VI) must be produced in order to treat 1 m^3 of municipal wastewater. The cost of every liters of 30% industrial chlorhydric acid is US$ 0.045 which could be converted into 19% by dilution thus reducing the cost to over US$ 0.0285. As a result, the reduction of pH levels of municipal wastewater to under 2 would lead to a total cost of US$ 2.52.

In addition to the electricity and pH reduction costs, large volumes of sodium hydroxide 14 M are required for the production of electrolysis solution. In order to produce sodium hydroxide 14 M, 500 g of it must be dissolved in one liters of water. Therefore to generate 1 m^3 of sodium hydroxide 14 M, 500 kg of it must be dissolved in water. The cost of every kg of sodium hydroxide in Iran is US$ 0.47. The generation of 1 m^3 of 14 M solutions, a total cost of US$ 146 is inflicted.

By considering all the total costs (US$ 1.17 for the generation of Fe(VI), US$ 2.52 for the reduction of pH to under 2 and US$ 146 for the generation of sodium hydroxide 14 M solution), the treatment of every m^3 of municipal wastewater by Fe(VI) would amount to US$ 149.7. Evidently, the maximum expenses belong to Fe(VI) generation segment and the purchase of sodium hydroxide 14 M solution.

Determination of oxidation tank volume

Fe(VI) is known as the most oxidative compound under acidic condition [5]. The highest oxidation ability of Fe(VI) appears when pH is lower than 2 [2, 5, 9]. Oxidation tank is a container that wastewater remains in it for a certain time. Since Fe(VI) needs to be in a highly acidic environment to have the highest oxidation ability, the oxidation tank must be resistant to acidic condition. Otherwise, the oxidation tank will be gradually corroded and must be replaced. Therefore, using a wide range of metals such as iron or steel to make oxidation tank is impossible. Polyethylene and fiberglass are two materials which can be utilized to make oxidation tank. Such materials are light and inexpensive and their costs depends on tank volume. Assuming that wastewater treatment plant in full scale uses the same CA and T of laboratory pilot, Equation 12 can be used to determine the oxidation tank volume.

$$(12)\quad V=\frac{v_0(C_{A0}-C_A)}{r_{(c_{A,T})}}$$

5. Conclusion

In conclusion, wastewater treatment using Fe(VI) would require 1.17 dollars for the generation of Fe(VI), 2.52 dollars for the reduction of pH to fewer than 2 and 146 dollars for the generation of sodium hydroxide 14 molar solution which would amount to a totality of 149.7 dollars. In this study, we explored the various equations applied in the determination of Fe(VI) generation rates in electrolysis method while also specifying the various dimensions of such treatment units. As regards to the inflicted expenditures, we discovered that such unit would require US$ 1.17 for the generation of Fe(VI), US$ 2.52 for lowering pH value to under 2 and US$ 146 for the generation of sodium hydroxide 14 M solution which would amount to a total of US$ 149.7. Obviously, the most expensive part of the system is the Fe(VI) and sodium hydroxide production segments. It appears that the obtained cost is very high for the municipal treatment units to apply, however acceptable for the treatment of wastewater resistant to biological decomposition. Nevertheless this subject still requires more exploration in future studies.

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Authors are aware of and comply with best practice in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, figures manipulation, competing interests and compliance with policies on research ethics. Authors adhere to publication requirements that submitted work is original and has not been published elsewhere in any language.

Conflict of Interest

The authors declared no conflicts of interest that would prejudice the impartiality of this scientific work. All authors have equally contributed in data collection, data analyses and manuscript writing.

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