Journal of Environmental Management 133 (2014) 388–396

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

A numerical flow analysis using the concept of inflow age for oxidation pond design

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ARTICLE INFO

Article history:
Received 24 July 2012
Received in revised form
21 October 2013
Accepted 28 October 2013
Available online 13 January 2014

Keywords:
Oxidation pond
Acid mine drainage
Inflow age
Retention time

ABSTRACT

A numerical flow analysis for the design of an oxidation pond was conducted to investigate the optimal flow characteristics. This analysis includes the inflow rate and the shape and depth of the oxidation pond. The total area and maximum depth of the pond were 500 m^2 and 3 m, respectively. We defined the retention time, retention time ratio, homogeneity index, and inflow exchange efficiency in order to choose the optimal conditions. The optimum width to length ratio and depth of the pond were found to be 1:5 and 2 m, respectively.

1. Introduction

After mining minerals, the exposed rocks come into contact with water and oxygen. Acid mine drainage (AMD) is the result of the oxidation of minerals that contain reduced forms of sulfides [pyrite or its polymorph, marcasite (both FeS_2), pyrrhotite (FeS), galena (PbS), sphalerite (ZnS), and chalcopyrite ($FeCuS_2$)], which commonly occur when the sulfide bearing minerals in the rocks are exposed to air and water, transforming the sulfides into sulfuric acid. This means that the greater the surface area of the rock that is exposed, the greater the amount of acid (Silva et al., 2006). The acidic water leaches out the surrounding heavy metals and so contaminates the AMD (Tiwary, 2001). AMD, along with these contaminants, has been recognized as a major environmental pollution problem over the past few decades (Letterman and Mitsch, 1978; Kleinmann et al., 1981; Gray, 1997).

An oxidation pond stores the AMD for a given period of time, allowing for the precipitation of the ferric hydroxide found within it, so that the remediation of the contaminated effluents can be accomplished. The key to the design of an oxidation pond is to ensure that the retention time of the AMD in a pond is sufficiently long for the iron precipitates to settle out effectively. In the past, the retention time recommendations for such purposes have ranged from as little as 8 h to more than 72 h. Additional guidance on retention time of mine water can be drawn from studies conducted in the United States (Lin et al., 2003; Keefe et al., 2004), in U.K. reducing and alkalinity producing systems (Wolkersdorfer et al., 2005), and modeling studies (Goebes and Younger, 2004).

Studies have revealed the existence of a relatively robust linear relationship between the percentage reduction in the influent iron concentration and nominal hydraulic retention time (Parker, 2003). In the UK Coal industry, the basic water treatment design guidance for engineers was set out by National Coal Board (1982). The total pond volume and flow rate are often designed on the basis of a 48 h retention time (Laine and Jarvis, 2003) and 100 m^2 pond surface area for every l/s of drainage. The length to width ratio is designated to be within the range of 2:1–5:1 (National Coal Board, 1982). The depth of the pond is usually set at around 3 m to prevent the re-suspension of the settled particles due to the effects of the wind (PRAMID Consortium, 2003). The theoretical maximum concentration of ferrous iron that can be oxidized in a single aeration cascade is 50 mg/l. However, practical experience suggests that 30 mg/l is a more realistic figure (National Coal Board, 1982). This implies that for discharges in excess of 30 mg/l, it will be necessary to have a series of aeration cascades, with oxidation ponds in between them.

Until now, the nominal retention time was calculated simply as the ratio of the volume of AMD stored in the pond to the flow rate. The flow distribution characteristics in the pond vary with its shape and depth and with the flow rate of the AMD, so that more sophisticated techniques, such as the application of the physics represented by the Navier–Stokes equation, are needed.

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http://dx.doi.org/10.1016/j.jenvman.2013.10.026

2. Computational method

2.1. Concept of inflow age

The concept of “air age” in the field of mine ventilation was introduced to estimate the retention time of the airflow in a mine drift. Air age is defined as the time taken for the inflow air to move to point P, as shown in Fig. 1. The term “retention time” is defined as the time it takes for air to flow completely through the system. The fluid of this study is not air but mine drainage, thus the term air age was renamed “inflow age”.

2.2. Suggestions for estimating the indices for an oxidation pond design

To optimize the design of the oxidation pond, the retention time, stagnant level, distribution level, and exchange level for the AMD in the oxidation pond need to be defined. We propose to solve this problem by defining the following concepts: the retention time, retention time ratio, homogeneity index, and inflow exchange efficiency.

- Retention time

  The retention time, t_a, is generally defined as the time needed for the inflow AMD from the inlet to reach the outlet and is defined in this study as the average inflow age at the exit, as determined by computational analysis.
- Retention time ratio, R

  The retention time ratio, R, is a guideline, showing how long the inflow AMD stays in the pond and is defined as the ratio of the nominal retention time, t_n, to the retention time, t_a. A retention time ratio closer to 1 indicates that the flow of the inflow AMD is more stagnant.

$$R = \left|1 - \frac{t_n}{t_a}\right| \tag{1}$$

- Homogeneity index, H

  The homogeneity index H is defined as the value of the minimum areal retention time, t_{aeral}, divided by the volume average retention time, t_{vol}. A homogeneity index closer to 1 indicates that the distribution of the inflow age is more homogeneous.

$$H = \frac{t_{aeral}}{t_{vol}} \tag{2}$$

- Inflow exchange efficiency, E_i

  The inflow exchange efficiency, E_i, is defined as the shortest time it takes for the pond’s contents to be exchanged with the fresh inflow AMD and is further defined as the ratio of the nominal retention time, t_n, to the inflow exchange time, t_e.

$$E_i = \frac{t_n}{t_e} \times 100\ (\%) \tag{3}$$

2.3. The oxidation pond design cases

Fig. 2 shows a schematic of a rectangular oxidation pond. The inlet and outlet size of the oxidation pond was set to 0.3 m × 0.3 m in all cases with an area of 500 m^2. The flow rate at the inlet was based on a pond surface area of 100 m^2 for every l/s of AMD, as defined by National Coal Board (1982). Table 1 shows 19 cases with different flow rates, shapes, and depths of the oxidation ponds.

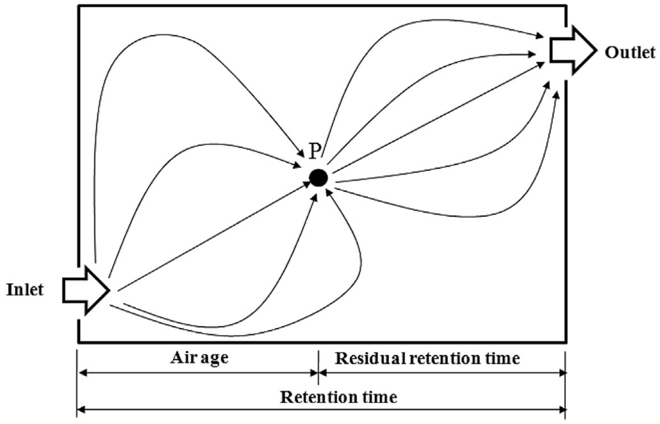

Fig. 1. The concept of air age.

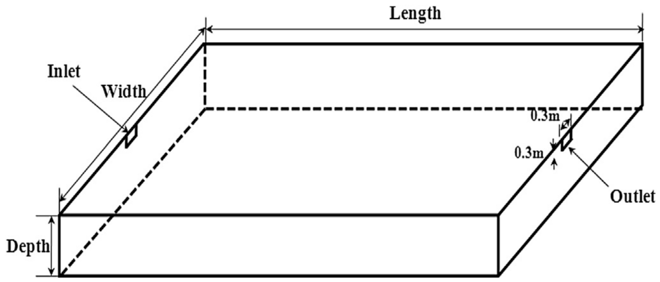

Fig. 2. Schematic of oxidation pond.

2.4. Grid constructions

In the case where both sides of the pond are symmetrical with the same shape and flow conditions, the analysis model was made for one side only. The meshes were denser near the inlet and outlet and the grid sizes were increased gradually as the model approached the middle of the pond. The total number of grids in selected cases was up to 1.2 million (Fig. 3).

2.5. The numerical analysis method

Computational analyses were performed for the three governing equations: the continuity equation, the momentum equation, and the turbulent dissipation equation. These are used to predict

Table 1
Cases of oxidation pond.

Case	Width:length	Flow rate (l/s)	Width (m)	Length (m)	Height (m)
Case 1	1:3	1	12.90	38.73	3
Case 2	1:3	5	12.90	38.73	3
Case 3	1:3	10	12.90	38.73	3
Case 4	1:3	15	12.90	38.73	3
Case 5	1:3	20	12.90	38.73	3
Case 6	1:2	5	15.81	31.62	3
Case 7	1:4	5	11.18	44.72	3
Case 8	1:5	5	10.00	50.00	3
Case 9	Circle	5	25.23	–	3
Case 10	1:2	5	15.81	31.62	2
Case 11	1:3	5	12.90	38.73	2
Case 12	1:4	5	11.18	44.72	2
Case 13	1:5	5	10.00	50.00	2
Case 14	Circle	5	25.23	–	2
Case 15	1:2	5	15.81	31.62	1
Case 16	1:3	5	12.90	38.73	1
Case 17	1:4	5	11.18	44.72	1
Case 18	1:5	5	10.00	50.00	1
Case 19	Circle	5	25.23	–	1