Application of low-mixing energy input for the coagulation process

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ABSTRACT

Rapid-mixing tanks with mechanical mixers are a common design used in treatment plants. Yet, the role of such rapid-mixing systems on the effectiveness of the coagulation performance is unclear. This study looked at optimizing the direct energy used in the coagulation process for removal of natural dissolved organic matter (DOM). The role of coagulation mixing intensity (G-value) on total organic carbon (TOC) and turbidity removal was examined for the water types with high organic content, with a specific ultraviolet absorbance (SUVA) of at least 2—2.5 units of m^{-1} of absorbance per mg/L. A standard jar test using ferric sulfate coagulant was performed to optimize the chemical condition in coagulation for removal of dissolved organics as well as particles. The jar test analysis at an acidic pH (4.5 ± 0.3) required an iron dose <0.3 mM to arrive at an optimal coagulant concentration and resulted in above 75% of TOC removal. The influence of coagulation mixing on TOC and turbidity removal was evaluated at G varying from 0 to 1500 s^{-1} at the optimized coagulant dose and pH conditions for enhanced coagulation. In this study, a combined effective removal of TOC and turbidity was achieved at a low-mixing intensity range of 110 s^{-1} < G < 450 s^{-1}. Coagulation operated at G greater than 450 s^{-1} showed negligible improvement in TOC removal. Minimizing energy consumption in enhanced coagulation is feasible at the proposed mixing intensity range (i.e., 110 s^{-1} < G < 450 s^{-1}), without sacrificing the effectiveness of DOM removal by coagulation. These findings represent an opportunity for energy savings for the water industry without sacrificing quality.

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1. Introduction

The water sector relies highly on energy-intensive processes to provide safe drinking water and reliable wastewater services to their customers (Leiby and Burke, 2011). Energy consumption in the water and wastewater utility accounts for approximately one-third of a city's total energy bill (USEPA, 2008), and by 2023 energy demand is estimated to increase by 20% due to projected population growth and more stringent water quality regulations (USEPA, 2008). There are ways to reduce the energy consumption of water utility operations. One example is the modification of several processes at the Metropolitan Syracuse Wastewater Treatment Plant (New York), including retrofitting motors and upgrading

impellers, that resulted in improved energy efficiency and an annual electricity savings of about 2.8 million kWh (EERE, 2005). Therefore, a thorough assessment of the energy performance of water treatment processes is important to optimize system efficiency and to achieve gains in energy conservation.

Energy usage in the water sector can be quantified in terms of power and cost per unit volume of treated water. Previous research on the David L.Tippin water treatment plant in Tampa, Florida (Santana et al., 2014) quantified the energy consumed at that facility through the calculation of the operational embodied energy. The authors defined it as the sum of the direct and indirect energies used exclusively during the operation and maintenance life stage. Direct energy is mostly related to the onsite consumption of fuel and electricity for pumping and process operations. It amounts to the use of high service pumps for transportation of water in and out of the treatment plant, power associated with mixing of motors and impellers, operation of processes (e.g. ozonation), and other equipment used onsite on a daily basis. The authors (Santana et al., 2014) estimated about 62.9% of the total operational embodied energy was primarily the direct consumption of energy at the plant. The remaining 37.1% was indirect energy associated with the chemicals used in the treatment process.

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The direct energy used in treatment plants is the largest contributor of the embodied energy. The current study examines one such application of direct energy in the coagulation process for removal of natural dissolved organic matter (DOM). Coagulation is a critical process used commonly in the surface treatment plants and facilitates the reduction of turbidity, pathogens, dissolved organic matter and inorganic particles from drinking water (Davis and Edwards, 2014). Humic substances, the major class of organic compounds in natural waters, comprise higher than 50% of dissolved organic carbon (Thurman, 1985). The removal of DOM during drinking water treatment is significantly important for water utilities due to the potential health risks associated with the formation of chlorinated disinfection byproducts (Amirtharajah et al., 1993). Presence of DOM in potable water is also linked to aesthetic issues, increased oxidant demand, membrane fouling, corrosion, and bacterial regrowth in the distribution systems (Davis and Edwards, 2014; Owen et al., 1995). Coagulation is often optimized to provide a substantial removal of DOM as well as particles (Volk et al., 2000). This process of application of effective coagulant doses to minimize residual DOM after coagulation in drinking water supplies is termed as enhanced coagulation (Xie et al., 2012).

Removal of DOM in coagulation occurs either by charge neutralization or by adsorption on precipitated metal hydroxide (Duan and Gregory, 2003). The primary mechanism of DOM removal is strongly related to the concentration of DOM, the coagulant dose and pH that controls the speciation of coagulant metal salts (Dempsey et al., 1984). Cationic hydroxyl species of aluminum or iron-based coagulants are predominant at pH less than 6.0 (Amirtharajah et al., 1993; Amirtharajah and Mills, 1982). In charge neutralization mechanism, the cationic species are suggested to chemically react with the soluble humic anions and give rise to strong association of complexes that form precipitation (Narkis and Rebhun, 1977) . Alternatively, the rate of amorphous metal hydroxide precipitates is favored at pH greater than 6.0 and at a relatively high coagulant dose (>0.03 mM as Fe or 0.05 mM as Al) (Jiang and Graham, 1998). This mechanism of rapid precipitation of metal hydroxides at a sufficient metal coagulant dose is referred as sweep-floc coagulation (Edzwald, 2013). Under such conditions, adsorption of DOM complexes on metal hydroxide precipitates and/direct adsorption of DOM onto the surface of precipitates is proposed to play a major role in removal of humic substances (Van Benschoten and Edzwald, 1990; Dempsey et al., 1984).

Rapid (or flash) mixing is used in coagulation to uniformly disperse the coagulant with the incoming water and to promote subsequent collision rates between the charge neutralized particles. Further aggregation of such particles is promoted in a flocculation stage to form large floc aggregates, which are removed from drinking water in subsequent solid—liquid separation processes (e.g. sedimentation/flotation, filtration) (Jiang and Graham, 1998). Design guidelines call for an intense mixing during coagulation with an average mixing intensity, measured as G-value, of $600-1000$ s^{-1} and a short detention time of $10-60$ s (AWWA and ASCE, 2012). The Ten State Standards (2012) recommends a maximum detention time 30 s with mixing equipment capable of imparting a minimum G of at least 750 s^{-1}. However, previous research suggests such a high-intense mixing operation is not necessary for the coagulation mechanism by precipitation (Edzwald, 2013; Amirtharajah and Mills, 1982). Amirtharajah and Mills (1982) found a low G of 300 s^{-1} made no significant differences in the settled water turbidity as that of operating at a high G of 750 s^{-1} for the optimal sweep-floc coagulation. Edzwald (2013) showed a reduction of one-tenth in power costs with the incorporation of low-mixing operations, which suggests that the size of rapid mixing tanks should be based on average daily flow rather than the maximum plant design flow.

Extensive research has focused on DOM removal by enhanced coagulation; there is a little understanding as to how a change in the coagulation mixing may influence the removal of humic substances. Siéliéchi et al. (2008) showed a drastic decrease in sediment volumes under low mixing intensity, suggesting the shrinkage of the humic/hydrolyzed-iron complexes. In the current study, the pH and coagulant dose were predetermined using jar test analysis to optimize the removal of total organic carbon (TOC), a surrogate parameter measured to quantify DOM removal. At the optimized coagulant dose and pH conditions for enhanced coagulation, we investigated the role of coagulation mixing on TOC removal at a range of G-values. This study focuses on minimizing the direct energy consumption in coagulation by determining the feasibility of using low-mixing intensity, without compromising the removal efficiency of DOM by enhanced coagulation.

2. Materials and methods

2.1. Source water

Two water types were used in the coagulation experiments: synthetic humic water and raw water from a lake source. Both waters have a high organic content, with a specific ultraviolet absorbance (SUVA) of at least $2-2.5$ units of m^{-1} of absorbance per mg/L. Detailed characterization of the water quality parameters for the two source water is outlined in Table 1.

2.1.1. Preparation of the synthetic humic water

Commercially available humic acid, sodium salt (containing $50-60\%$ as humic acid) was purchased from Alfa Aesar (Haverhill, Massachusetts). Elemental analysis of humic acid in the ECS 4010 CHNSO analyzer (Costech Analytical Technologies Inc., Valencia, California) indicated of the composition of 38.4% carbon (C), and 0.73% nitrogen (N). For the purposes of this study, hydrogen (H) was not analyzed. A stock solution was prepared by dissolving 0.030 g of humic acid in a liter of deionized (DI) water to produce a TOC concentration of (8.75 ± 0.64) mg/L. Alkalinity was introduced by adding 20 mg/L of 1 N sodium bicarbonate to the stock solution. The prepared stock solution was continuously mixed using a magnetic stirrer for approximately 2 h prior to the start of the experiment.

2.1.2. Freshwater source

Approximately 30 L of raw water was collected from the intake at the Louisbourg water treatment plant (Nova Scotia, Canada). The plant withdraws raw water from Kelly Lake, a protected watershed area located approximately a kilometer from the water treatment plant. The plant has a capacity of three million liters per day (MLD).

2.2. Chemicals used in the coagulation process

Ferric sulfate, MP Biomedicals (Fisher Scientific, Pittsburgh, Pennsylvania) was used as the coagulant. Fresh stock solution of 1 g/L of ferric sulfate was prepared prior to the coagulation and flocculation experiments. The stock solution was replaced every day to minimize aging or any metal precipitation. The concentration of iron in the stock solution was measured as 5 mM of iron (Fe), according to the Standard Method 3125 (APHA, 2012). Stock solutions of 0.2 N nitric acid and 1 M sodium hydroxide were used to adjust the pH to the desired pH condition.

2.3. Jar test apparatus

The coagulation and flocculation experiments were conducted at room temperature (21 ± 1 °C) in a 1-L square beaker using a