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Effect of coagulation and sonication on the dissolved air flotation (DAF) process for thickening of biological sludge in wastewater treatment

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Abstract

Background: Dissolved air floatation (DAF) is one of the methods has been used for the sludge thickening in wastewater treatment plants. This study aimed to investigate the effects of coagulation and sonication processes as additional configurations on the efficiency of a lab-scale DAF process for thickening of the biological sludge of an industrial wastewater treatment plant in Kashan, Iran.

Methods: The required amounts of sludge samples were collected from a wastewater treatment plant and kept at temperature of 4°C. Variables, such as pressure (3, 5, and 7 atm), flotation time (5 and 10 minutes), ultrasonic irradiation power (0, 75, and 150 W), and presence/absence of Fe-based coagulant were considered on a sequencing batch reactor (SBR) included coagulation, flotation, and sonication processes, respectively.

Results: The use of ultrasonic waves led to an insignificant increase in the DAF efficiency ($P > 0.05$), however, the application of coagulant significantly increased the thickening efficiency ($P < 0.05$). The maximum efficiency of the process was achieved at flotation time of 5 min, pressure of 3 atm, and sonication power of 75 W.

Conclusion: According to the results, DAF has a proper efficiency for thickening of biological sludge. Coagulation compared to sonication has a greater effect on the efficiency of the process.

Keywords: Ultrasonic waves, Industrial effluent, Dissolved air flotation, Sonication

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Introduction

Sludge is a biomass produced in large quantities during the primary, secondary, and advanced municipal wastewater treatment (1). Sludge treatment and disposal are critical issues of each wastewater treatment plant. In addition, sludge production is expected to be increased due to the increase of wastewater and improvement of environmental regulations (2-4). Since the amount of water in the generated sludge is high, it must be reduced before further management. For this purpose, wastewater treatment plants employ a variety of units including sedimentation, filtering (filter press, vacuum filter, and belt filter), centrifuge, chemical processes, and floatation (5-8).

Floatation is a physicochemical process with advantages, such as short retention time, low demand of space, low cost, and flexible use. Among different types of floatation-based processes, dissolved air floatation (DAF) has been vastly used in water and wastewater treatment over the past six decades (9). Compared to other processes, such as typical primary and secondary clarifier, surface overflow rate of the DAF is 10-20 times higher, leads to a significant reduction in the retention time, however, unlike gravitational clarifiers, DAF requires higher energy consumption (10,11). DAF is primarily used to remove suspended solids and colloids. This method is widely used for municipal and industrial wastewater treatment purposes, such as sludge thickening, purification of algae-rich water, separating oil from water, treatment of refineries and poultry slaughterhouse wastewater, etc

(12,13). In a study conducted by Cagnetta et al, DAF combined or coupled with a high-rate activated sludge and showed a good performance for the removal of total suspended solids (TSS) and chemical oxygen demand (COD) (14).

In DAF systems, compressed air is injected into the sewage tank. As a result, air bubbles are composed, and adhere to fine particles inside the tank and make them float on the water surface. To enhance the efficiency of the process, chemicals and polymers are often used (15).

Several technologies, such as ultrasonic, thermal, microwave, and coagulants/flocculants addition have been applied to control and reduce the sludge problem. Since ultrasound waves have the ability to change the physical and chemical properties of sludge (16), sonication has been used in several studies for the wastewater treatment (17,18). Application of proper polymers (15) or coagulants in a DAF process can also reduce the zeta potential, and lead to maximum efficiency (9). Various chemicals can be used in DAF systems, including alum, poly-aluminum chloride, aluminum chloride, poly-aluminum sulfate, ferric chloride, bentonite, and organic polymers (19). In a study by Mohd Remy Rozainy et al, the use of chitosan and bentonite caused an average turbidity removal of 97% in the floatation tank. This study also proved the advantage of compounds, such as chitosan and bentonite as coagulant agents in DAF systems for water treatment (20). Common coagulants such as ferric chloride hydrolyze metal salts and neutralize the negatively charged colloids through the formation of cationic species (21). Several studies have mentioned the advantages of $FeCl_3$ for sludge conditioning (18,22).

Some studies have been conducted on DAF process for thickening of sludge that needs further investigation. However, the effect of application of ultrasonic waves on the DAF for sludge thickening has not yet been investigated. Given the importance of disposal and processing of sludge (7), as well as economic benefits and high efficiency of DAF systems (6), in this study, the simultaneous and individual effects of sonication and coagulation processes on the efficiency of a lab-scale DAF unit for thickening of the return activated sludge (RAS) of Amir Kabir industrial zone's treatment plant, were investigated.

Materials and Methods

Sludge samples

Amir Kabir industrial zone is located in the Southeast of Kashan city, located in the center of Iran. The industries like chemical, automotive, electronic, food, and textile are operating there. Combined industrial and sanitary wastewater produced in these industries contains 3800 and 1500 mg/L of COD and biochemical oxygen demand (BOD), respectively. An activated sludge process with a capacity of 350 m^3/d has been located within the town. In this study, the required amount of sludge samples was collected from the inlet of RAS to aeration tank, and transferred to the laboratory of School of Health, Kashan University of Medical Sciences. The samples were kept at temperature of 4°C.

Apparatus and procedure

As shown in Figure 1, the floatation tank (dimension of 10×10×35 cm) with the effective volume of 3 liters was placed on a 28 kHz ultrasonic generator with a power of 75 and 150 W. A sampling tap was placed at a distance of 3 cm from the bottom of the tank. The DAF system was operated as a sequencing batch reactor (SBR), and all the processes, including coagulation, flocculation, floatation, and sonication were taken place in the floatation tank, sequentially.

The study was performed in three main phases. The first phase included a jar test to determine the optimum dose of coagulant and pH. Ferric chloride ($FeCl_3$) was used as the coagulant in this experiment.

The second phase included the determination of the optimum recycling rate in the floatation tank using air-to-solid ratio (A/S). For solid thickening in wastewater treatment, it is usually assumed between 0.005-0.06 mL/mg. This ratio can be calculated according to the following equation (23,24).

$$\frac{A}{S}=\frac{1.3\times Sa(fP-1)R}{Su} \tag{1}$$

Where *Sa* is the solubility of air (mg/L), *f* is the ratio of air solubility in wastewater to the air solubility in water, *P* is pressure (atm), *R* is recycling rate (%), and *Su* is suspended

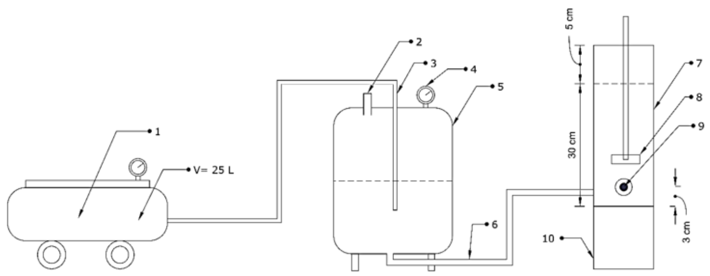

Figure 1. Schematic diagram of the DAF on a laboratory scale. 1) Air compressor, 2) Water transfer line, 3) Air transfer line, 4) Barometer, 5) Pressure tank, 6) Air-saturated water line, 7) Coagulation, flocculation, and floatation tank, 8) Mixer, 9) Sampling tap, 10) Ultrasonic wave generator.

solids concentration (mg/L). Since all the parameters are constant except pressure, recycling rate values depend on the pressure changes. *Sa* (ambient temperature), *f*, and *A/S* were considered 18.7 mg/L, 0.5, and 0.005 mL/mg, respectively. The average concentration of TSS was 9854 mg/L.

As presented in Eq. (2), the recycling rate can be calculated by dividing the volume of air-saturated water to the amount of inlet flow (24).

$$R = \frac{r}{v} \quad (2)$$

where *r* is the volume of recycled water (mL) and *v* is the volume of influent (mL) (r + v = 3000 mL).

The third phase included experiments to determine the efficiency of DAF system. First, a certain volume of water was put in the pressure vessel under different pressures of 3, 5, and 7 atm for 30 minutes. Simultaneously, a certain volume of sludge which was calculated at the second phase (Eq. 2), was poured into the floatation tank. Coagulation and flocculation stages were performed at 180 rpm for 1 minutes, and 30 rpm for 20 minutes, respectively. Then, air-saturated water was entered into the floatation tank with the average flow rate of 0.317 m^3/h (SOR = 31.7 m/h), and filled the tank up to 3 L. Two floatation times of 5 and 10 minutes were applied to the stream with and without sonication (75 and 150 W). Samples were taken from the sampling tap. It is noteworthy that all the processes (coagulation, flocculation, floatation, and sonication) were done in the presence and absence of coagulant. Finally, the TS concentration was measured and compared with that of primary diluted sludge to determine the efficiency of the floatation process. In order to increase the precision, the experiments were repeated three times.

Analytical method

Electrical conductivity (EC) and pH were measured using an EC meter (Metrohm 644; UK) and pH meter (Tajhizat Sanjesh, pH 262, Iran), respectively. Also, total solids (TS), COD, BOD, and TSS measurements were conducted according to the standard methods (16).

Statistical analysis

After data collection, Kolmogorov-Smirnov test was used to check the data normality. Finally, ANOVA test was used to analyze the results ($P < 0.05$). All the analyses were performed using SPSS version 16. Also, Grapher version 12 and Microsoft Excel version 2013 were used to draw the graphs.

Results

Optimization

Based on the results of jar test, coagulant concentration of 200 mg/L and pH = 7.5 were selected as the optimal conditions. However, there was no difference between optimal pH and natural pH. Hence, all experiments were conducted at $FeCl_3$ concentration of 200 mg/L and pH = 7.2.

Recycling rate

Considering the pressure values of 3, 5, and 7 atm, recycling rates were reported 400, 135, and 87%, respectively. Based on the recycling rates, the volume of air-saturated water and sludge sample was estimated using Eq. 2, and the results are shown in Figure 2 and Table 1. As can be observed, in a constant value of A/S ratio (0.005 mL/mg), with an increase in the pressure, the recycling rate decreased, and thus, the ratio of influent to air-saturated water increased.

The effect of time on the DAF efficiency

The removal efficiencies of DAF system at the retention times of 5 and 10 minutes were 73.52% and 71.13%, respectively.

The effect of pressure on the DAF efficiency

The average removal efficiencies under the pressures of 3, 5, and 7 atm were 81.13, 75.45, and 60.4%, respectively. The pressure and DAF efficiency had a significant inverse relationship at different retention times (Figure 3a).

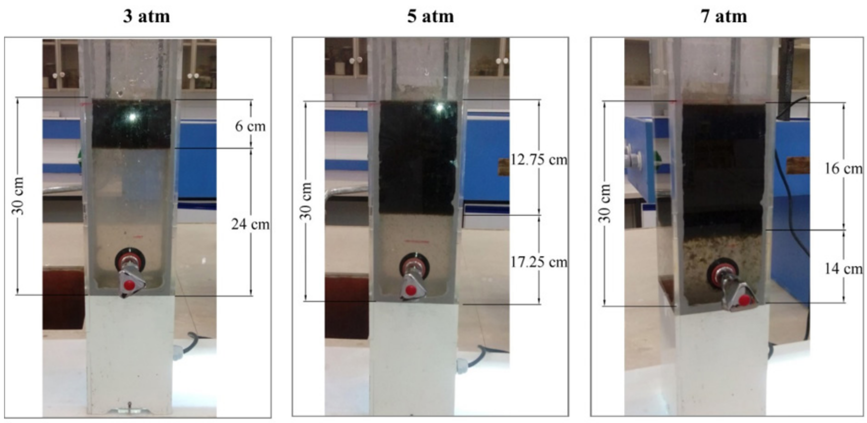

Figure 2. Volume ratio of sludge to saturated water at pressures of 3, 5, and 7 atm.

Table 1. The calculated values of R (recycling rate), r (volume of saturated water), and v (volume of sludge) in the flotation tank

P (atm)	3	5	7
R (%)	400	135	87
r (mL)	2400	1725	1400
v (mL)	600	1275	1600
Total volume (mL) (r + v)	3000	3000	3000

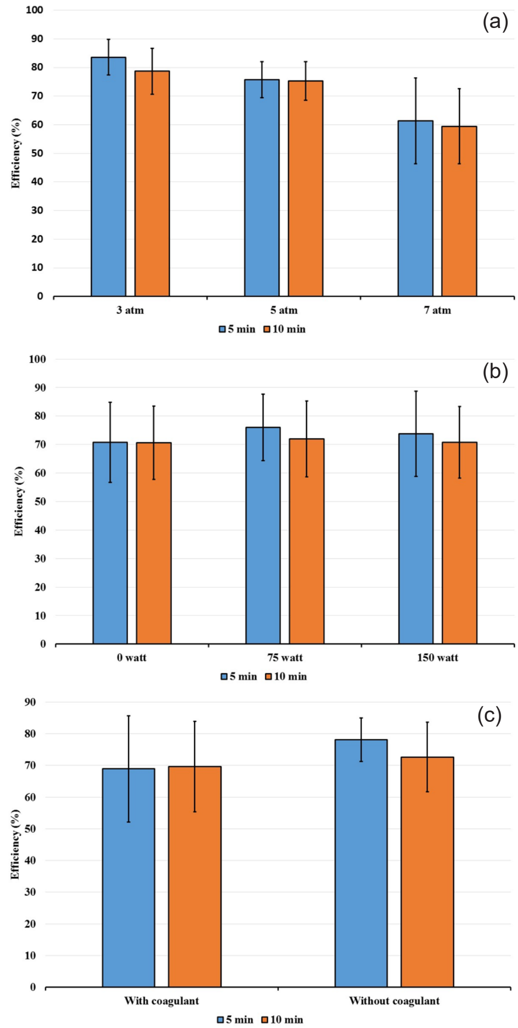

Figure 3. DAF efficiency based on a) pressure, b) sonication power, and c) coagulation status at retention times of 5 and 10 minutes.

The effect of ultrasonic waves on the DAF efficiency

The efficiency of the process in the absence of ultrasonic waves (silence mode) was 70.69%. When the ultrasonic waves were applied at 75 and 150 W, the removal efficiency reached 73.99% and 72.30%, respectively (Figure 3b).

The effect of coagulant on the DAF efficiency

In general, the injection of the optimum dose of ferric chloride to the process led to an increase in the removal efficiency from 69.27% to 75.38% (Figure 3c).

Efficiency of the DAF process in terms of time, pressure and coagulation status

The highest efficiency in terms of time, pressure and coagulation status was achieved to be 84.7% in the presence of coagulant, retention time of 5 minutes, and pressure of 3 atm.

Efficiency of the DAF process in terms of time, sonication power, and coagulation status

The highest efficiency in terms of time, sonication power and coagulation status was observed to be 80.3% in the presence of coagulant, sonication power of 150 W, and retention time of 5 minutes.

Discussion

In this study, the effects of flotation time, pressure, sonication irradiation, and coagulant addition on the DAF process for thickening of biological sludge were investigated. During the experiments, the removal efficiency was decreased with increasing the retention time. The main reason may be due to the shorter optimum time of floatation compared to the time of 5 minutes, or the low ability of the DAF for the floatation of flocs in the determined time periods. It may also be due to the reactor type. As the applied reactor was batch type, the air bubbles (flotation force) reduced over the time. However, it was revealed that longer retention time led to an increase in the thickening efficiency from 88% to 99% (25), which is consistent with the results of other studies (9,26,27).

As shown in Figure 3a, the efficiency of the DAF was significantly reduced with an increase in the pressure (P<0.001), while the air solubility in water increased linearly with increasing pressure, which subsequently improved the thickening efficiency (28). It was reported that the concentration of TSS was reduced from 25 mg/L to 12 mg/L as pressure increased from 0.1 MPa to 0.5 MPa (29). Another study showed that the removal efficiency of oil and grease increased from 25% to about 40% by an increase in pressure from 2 to 6 bar (27). According to Eq. 1, the recycling rate (R) and pressure (P) have a direct relationship with A/S, which is an important parameter for the contact of air bubbles' with suspended particles. Thus, under a fixed A/S, recycling rate increases as pressure decreases (Figure 2). According to Figure 3a, the pressure of 3 atm as the lowest pressure, led to the highest recycling rate and removal efficiency. On the other hand, the pressure of 7 atm showed the lowest efficiency. Because of the equilibrium between pressure and efficiency, it can be concluded that the recycling rate is a more important factor compared to pressure for flotation. High standard deviation changes in the pressure of 7 atm indicates the high sensitivity of this process at this pressure. This is possibly due to the impact of mixing area caused by ultrasonic waves on the flocs dispersion. This would reduce the efficiency of a DAF system. The type of formed flocs and high concentrations of TSS in the sludge samples could be a reason for the decrease in the efficiency as the pressure increases. A study by Adlan et al showed that the flow rate and pressure are not important for the leachate treatment by a DAF system (30).

The sonication with two different powers (75 and 150 W), and with or without coagulation had no significant impact on the thickening efficiency ($P = 0.057$). This comparison was made considering other factors, including time, pressure, and the application of coagulant. In a study by Videla et al, the efficiency of copper floatation was increased by 3.5% in comparison with the operation without ultrasonic waves (31). The results of another study by Heng et al showed that sonication can increase the removal efficiency of algae by 12.4%. In addition, increasing the power from 60 to 120 W resulted in a negative impact on the efficiency (32). Moreover, ultrasonic waves have shown a negative effect on the dewatering of the sludge resulted from water treatment (33). In the present study, the most negative effect of ultrasonic waves was observed at a retention time of 5 minutes, when power increased from 75 to 150 W. Within 10 minutes, no effect was observed (Figure 3b). This can be due to the effect of high power on the fluid turbulence, leading to a decrease in the efficiency.

In this study, the coagulation had a significant relationship with the increase in the efficiency within a 5-minute retention time ($P = 0.011$). However, in a 10-minute retention time, the average of efficiency was increased by 3%, which was not significant ($P = 0.39$). The effect of coagulant on the DAF efficiency has been evaluated in several studies by adding a variety of polymers, alum, ferric chloride, etc (34-36). In a study by Kim et al, the addition of coagulant increased the removal efficiency of suspended solids from 82% to 99% (37). In the present study, the process showed an acceptable efficiency (69.27%) without coagulation. This is possibly because of the extracellular polymeric substances, which accounts for 60-80% of the sludge mass. Based on the literature, the importance of extracellular polymeric substances on the sedimentation, flocculation, and dewatering of sludge has been identified (24).

The simultaneous effect of coagulation-time-pressure and coagulation-time-sonication are shown in Figure 4. As can be seen, with the addition of coagulant (Figure 4a), after 10 minutes and at pressure of 7 atm, the lowest efficiency was obtained. But at the same pressure and without the addition of coagulant, the lowest efficiency was obtained after 5 minutes (Figure 4b). Therefore, it can be concluded that the coagulant had no significant effect on the pressure. In association with coagulation-time-sonication, in the presence of coagulant, the lowest efficiency was obtained in 10 minutes and sonication power of 0 W. But in the absence of coagulant, there is an increase in the TS flotation over time and the lowest efficiency was observed in 5 minutes and sonication power of 0 W. So, according to Figure 4, it can be concluded that reducing the efficiency over time can be more likely due to the coagulant effect on the flocs drop.

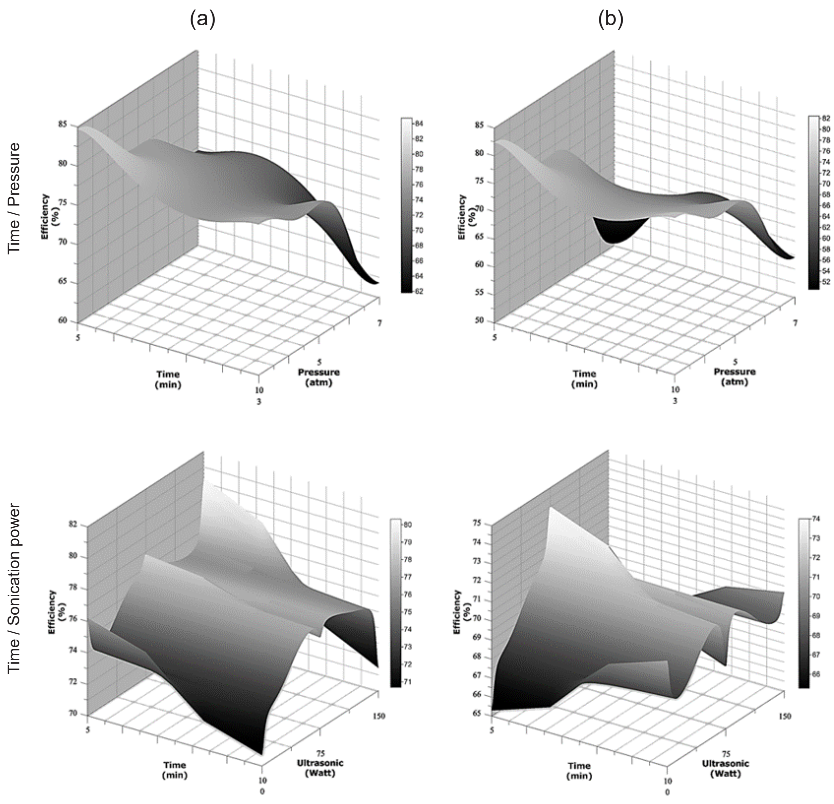

Figure 4. Simultaneous effect of time/pressure and time/sonication power on the DAF efficiency.

Conclusion

The unique innovation aspect of this study was the application of ultrasonic waves for the sludge thickening on the DAF process, which was not observed in the previous studies. The application of ferric chloride as a coagulant resulted in a significant increase in the process efficiency. However, the efficiency was still acceptable in the absence of coagulant. Thus, the use of coagulant can be avoided to minimize the operation costs. The optimum time, pressure, and sonication power were achieved to be 5 minutes, 3 atm, and 75 W, respectively. Due to the high concentration of the solids in samples, which required higher recycling rate, the lowest air-to-solid ratio was chosen. This low A/S ratio increased the sensitivity of the floatation process. Therefore, it can be recommended that DAF can be used for sludge samples with lower concentrations. In the full-scale applications, it is better to locate the ultrasonic generator near the outlet of subnatant in the floatation tank. This could provide enough time for solids to exit from mixing area of ultrasonic waves, and only be affected by the lifting force of waves. In addition, sonication can be coupled with the DAF as an SBR system for the full-scale purposes.

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Ethical issues

All authors certify that the data collected during the study are presented in this manuscript and no data from the study has been or will be published elsewhere separately.

Competing interests

All authors declare that they have no conflict of interests.

Authors' contributions

All authors have participated in all stages of the study including date collection, analysis, and interpretation, as well as the manuscript preparation.

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