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Multistage Flocculation Technique of Gradual Velocity Gradient to Improve Turbidity Removal from Water

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Abstract—The removal of fine materials from surface water represents a challenge. This research tries to improve the efficiency of flocculation process of low turbidity water by dividing the process into stage of gradual descending velocity gradient. A three stages flocculator model of continuous flow was designed and constructed. Combinations of three levels of velocity gradient of 60, 45 and 30 sec^{-1} were applied in the experiments in descending order. Tigris river water was used as raw water with 8-12 NTU turbidity. Alum was used as a coagulant at the optimum dosage. Turbidity removal percent was considered as an indicator of flocculation efficiency. The results showed a significant increase in turbidity removal percent with the decrease of velocity gradient at stage III. On the other hand, velocity gradient at stage I shows a direct relationship with turbidity removal, while the relationship is not clear at stage II. The best turbidity removal percent of more than 80% was obtained by the combinations 60*30*30 and 45*45* 30 sec^{-1}. A regression model shows that velocity gradient at stage III was the most contributor to turbidity removal variation. The research recommended descending gradual velocity gradient flocculation at two stages.

Keywords— Flocculation, velocity gradient, turbidity removal, floc strength, floc breakage

1. Introduction

Water turbidity is resulted from the occurrence of clay and silt or it may result from the organic and inorganic materials, in addition to the algae and microorganisms. The size of these flocs ranged from 0.01 to 100 micron. The coarse materials can be removed easily from water by sedimentation and filtration. On the other hand, the fine materials of 0.01 to 5 micron represent the big challenge in water clarification, since it takes a long time to settle and it can pass through the filtration medias. To increase the efficiency of turbidity removal, the size of these flocs may be enlarged. This needs to release these flocs from their charge by using chemicals which called coagulation. After that these flocs may go in collision with each other by creating velocity gradient through slow mixing to form larger settleable ones known as flocculation. The velocity gradient must be optimized to form larger flocs with lower breakage. Floc strength is difficult to evaluate. It may be determined in terms of energy required to break the flocs under tension, compression or shear [1]. Other researchers measure that by applying an increasing shear force to the flocs through mixing in a vessel [2]. In practice, floc strength is often estimated in an experimental method by finding a relationship between floc size and applied shear force [2-4]. When a schedule of shear force was applied, flocs grown at shear rate of 50 sec^{-1} velocity gradient for 30 minute, then broken at 100 to 500 sec^{-1} for one minute and then regrown at velocity gradient of 50 sec^{-1} [5].

Shear force is often denoted by average velocity gradient (G) as:

$$G = \sqrt{\frac{P}{\mu V}} \qquad \dots\dots\dots\dots (1)$$

where P is the power dissipated in the tank, V is the volume of the tank and μ is the dynamic viscosity of the fluid.

The power dissipated depends on the characteristics of the mixing device and calculated as:

$$P = \frac{N_p}{\rho N^3 D^5} \qquad \dots\dots\dots (2)$$

where N_p is the power number of the impeller, N the impeller frequency, ρ the fluid density and D the impeller diameter. The improvement of flocculation may take another way through using new coagulants or coagulants aid. This was associated with the appearance of negative and positive organic and inorganic polymers which was used in the improvement of flocculation process compared with conventional ones [6]. The flocculation process of Prut river in Moldavia was improved by optimizing the velocity of mixing and the dosage of aluminum sulfate used as a coagulant [7]. Mixing conditions also influence the floc properties [8-11]. Flocculation of Tigris river water was improved by increasing the inclination angle of mixer blades with 60 sec^{-1} velocities gradient [12]. In Mosul city, Tigris river, which is the source of raw water of all the drinking water treatment plants, have low turbidity water as it comes from Mosul dam lake. This made the flocculation process inefficient in the conventional treatment plants of Mosul city. This research tries to improve flocculation by dividing the process into steps of gradual velocity gradient.

2. Materials and Methods

2.1 Raw Water

The raw water used in the experiments was supplied from Al-Ayser Old Treatment Plant. The raw water was taken from the room which receives the raw water drawn from the river by the low lift pumps. More than 100 liters was supplied to the research in the week. Raw water turbidity ranged between 8-12 NTU, 7.8-8.0 for pH and 402-438 μmos/cm for electrical conductivity.

2.2 Laboratory Model

A laboratory model was designed and manufactured to conduct the experiments. **Figure 1** shows a photograph for the laboratory model. It consists from these parts:

2.3 Rapid Mix Unit

Jar test apparatus Model ET 740 was used to conduct the rapid mix (see **Figure 2**). Alum was used as a coagulant at an optimum dosage of 20 mg/l.

2.4 Slow Mixing Unit (Flocculation Unit)

Flocculation unit includes a glass tank divided into three stages separated by perforated glass barriers. Each stage has a mixer with plate paddles. Motors were used to rotate these mixers with descending speed to obtain a gradual velocity gradient. The design calculations are as follows:

Flow rate = 27 liter/hr
Total slow mix time = 30 minutes
Area of paddles = 10-25% of the cross sectional of the tank [13]

Figure 1 A photograph showing the multistage flocculation model

Figure 2 A photograph showing jar test apparatus used in the research

Volume of the slow mix tank = 30 * 27/ 60 = 13.5 liter
By using three stages for flocculation, the volume of tank for each stage = 13.5/3 = 4.5 liter
Select the dimensions of the tank for each stage = 20 * 15 * 15 cm
Area of blades = 0.1 * 15 * 15 = 22.5 cm^2
By using two similar blades of same center, the area of each blade will be = 22.5/2 = 11.25 cm^2
The dimensions of the perforated baffles between the flocculation stages = 15 * 20 cm
The percentage of holes' area for each baffle = 6-8% of the baffle area [13]

Area of holes in the baffle = 0.08 * 15 * 20 = 24 cm^2 distributed as shown in **Figure 3**.

Figure 3 The distribution of the holes in the baffles separated the flocculation stages.

2.4 Sedimentation Unit

This unit consists of a rectangular tank provided with a baffle at the end to increase the efficiency of sedimentation. This tank was designed as follows:

Flow rate = 27 liter/hr
Over flow rate = 20 m^3/m^2/day [14]
Tank depth = 20 cm since the flow will be laminar by gravity
Surface area of the tank = 27 * 24 /20/1000 = 0.0324 m^2 = 324 cm^2
Using tank width equal to the flocculation tank width of 15 cm
Surface area = length * width
324 = length * 15
Tank length = 21.6 cm

As the depth used do not correspond to the actual depth used in water treatment plants, 60 cm depth will be used to obtain lower sedimentation time
Sedimentation time = 0.6 * 15 * 0.2/ (0.027 * 60) = 40 minute

This time is near from the lower limit of sedimentation time recommended (1 hr), [15].

3. Results and Discussion

Velocity gradient combinations for multistage flocculation showed variation in turbidity removal percent (Table 1). When using same velocity gradient at the three stages, turbidity removal percent decreased as velocity gradient increase more than 30 sec^{-1} (see combinations no. 1 vs. no. 2 vs. no. 3 in **Table 1**). This indicates that velocity gradient of 30 sec^{-1} is the balance point between floc breakage and aggregation and above this point floc breakage will overcomes floc aggregation [2 & 16]. Additionally, these results coincided with the results of Oliveira et al. [17] who found that flocs diameter decrease with velocity gradient increase, which lead to decrease turbidity removal. At the start of mixing, flocs will enlarge with velocity gradient increase. After that with the continuity of mixing, the enlarged flocs will expose to shear forces, which act to break up the flocs depending on their strength. At higher velocity gradient, the flocs will subjected to higher shear forces and will exhibit more breakage as aluminum hydroxide flocs are weak. Consequently, average floc size will be smaller at higher velocity gradients according to the equilibrium between floc strength and hydrodynamic stress or it will be less settleable [18].

Table 1 Comparison among different combinations of velocity gradient for multi-stage flocculation

Combination No.	Velocity gradient at stages 1^{st}-2^{nd}-3^{rd} sec^{-1}	Mean turbidity removal (%)	Standard deviation
1	60-60-60	55.65d*	2.78
2	45-45-45	55.43d	1.36
3	30-30-30	63.72c	0.82
4	60-60-45	73.60b	1.02
5	60-60-30	78.33a	1.52
6	60-45-45	77.59a	0.93
7	60-45-30	79.00a	2.56
8	60-30-30	80.24a	1.73
9	45-45-30	80.25a	1.19

* Different letters mean significant difference vertically at $p \leq 0.05$ using Duncan multiple range test

If a gradual velocity gradient is applied in the flocculation, is the improvement in the turbidity removal acceptable. The results in Table 1 show significant increase in turbidity removal percent by about 18% for the combination 60 * 60 * 45 sec^{-1} versus 60 sec^{-1} velocity gradient at all stages [see combinations no. 1 vs. 4 in Table 1]. When velocity gradient at stage III decreased more to 30 sec^{-1}, the increase in turbidity removal reached 23% over that of 60 sec^{-1} [see combinations no. 1 vs. 5 in Table 1]. At stage III as velocity gradient decreased to 45 sec^{-1}, the balance between flocs formation and breakage will differ to the benefit of floc formation and larger flocs of more settleable ability will be formed, as shear forces decreased with minor breakage [19]. For stage II, turbidity removal percent increased significantly by about 4% with velocity gradient decrease from 60 to 45 sec^{-1} and keeping it in stages I and III at 60 and 45 sec^{-1} respectively, (see combination no. 4 vs. no. 6 in Table 1). On the other hand, the increase in turbidity removal did not reach the level of significance (<1%) when the same decrease in velocity gradient occurred, but with stage III at 30 sec^{-1} (see combination No. 5 vs. No. 7 in Table 1). At combination no. 5, stage III will begin with smaller flocs than that at combination no. 7 and therefore slightly larger flocs will be obtained in this stage. Additionally, more power was dissipated in combination no. 5 than 7 which may produce smaller flocs since floc size distribution is determined by the distribution of the energy dissipated within the reactor [10]. The best improvement in flocculation was obtained by decreasing stage III velocity gradient from 45 to 30 sec^{-1} versus 45 sec^{-1} for all stages (combination no. 2 vs. no. 9 in table 1). An increase of about 25% in turbidity removal was recorded more than that of 45 sec^{-1} for all stages. The balance between floc formation and breakage at 30 sec^{-1} velocity gradient will produce flocs of larger diameter than that at 45 sec^{-1} and being more settleable. This explains the role of gradual velocity gradient or the multistage flocculation in the improvement of the efficiency of the process. Additionally, this indicates that velocity gradient at the last stage of flocculation is the key factor in the process. Velocity gradient at each stage of flocculation has different effect on turbidity removal (see Figure 4). At stage I, turbidity removal percent increased with velocity gradient within the range of the studied values but without significance. On the other hand, velocity gradient did not show a clear relationship with turbidity removal percent at stage II. In contrary to stage I, velocity gradient at stage III has a reverse effect with significance on turbidity removal percent, since turbidity removal increases when velocity gradient decrease. This coincided with the fact that floc diameter increases with velocity gradient decrease [10]. At stage I, higher velocity gradient is needed to make more collision among destabilized primary fine particles. After that, velocity gradient need to be dropped to avoid the breakage of flocculated flocs, as hydrogen bonds created between particles have weak cohesion [18]. **Table 2** shows the regression model constructed between turbidity removals percent as dependent variable versus velocity gradients at each stage as independent variables. The variation of velocity gradient at the three stages contribute in about 76% of the variation in turbidity removal with significance at $p<0.001$. Additionally, the variation in velocity gradient at stage III was the most contributor in turbidity removal variation as it has the higher standardized beta value of -0.819. It was higher than the effect of stage I by more than 32%, but oppositely. On the other hand, it is effect represent 74 times that of velocity gradient at stage II. As the velocity gradient at stage II has non-significant effect on turbidity removal variation.

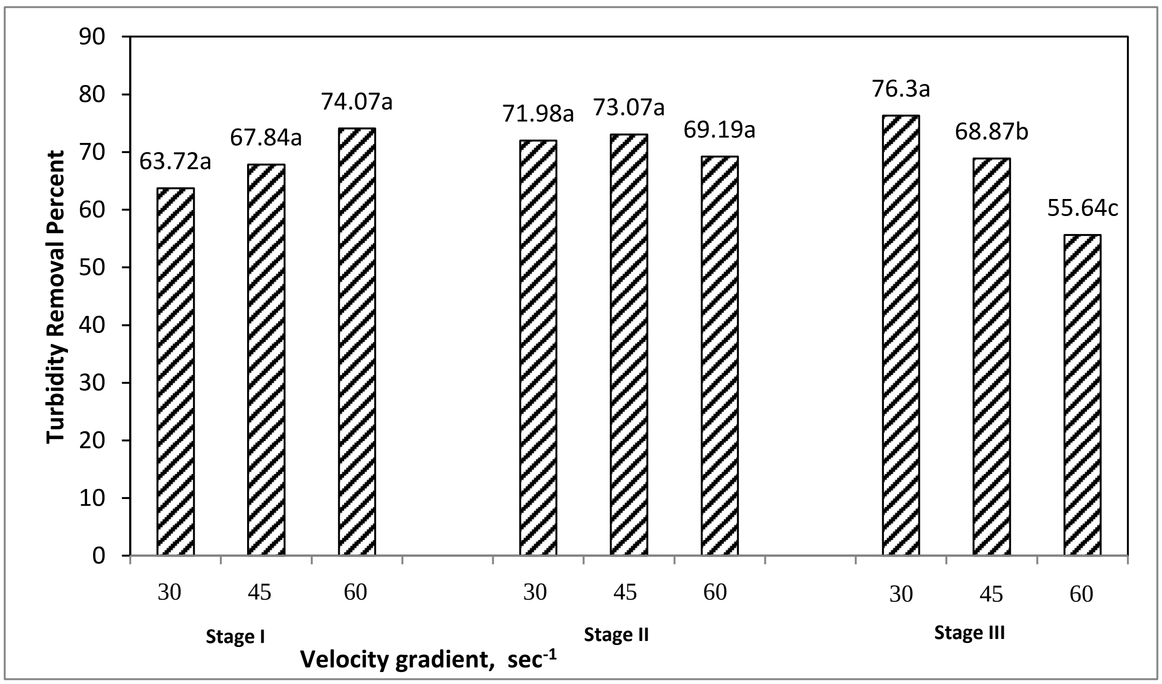

Figure 4 Comparison of velocity gradient effect on turbidity removal at each stage alone. (the values above the bars represents turbidity removal percent and the letters represents the results of Duncan multiple range test at $p \leq 0.05$).

Table 3 shows the distribution of turbidity removal percent levels according to the combinations of multistage velocity gradient. The descending gradual velocity gradient combinations produce the best results versus the same velocity gradient. Most of these best combinations start with 60 sec^{-1} at stage I and finish with 30 sec^{-1} at stage III. On the other hand, stage II has same or lower velocity gradient than stage I and higher or equal to stage III.

Table 2 Regression model for turbidity removal percent versus the velocity gradient at the three stages

Independent variables*	Coefficient (B)	Standardized Beta	t-value	p-value
Constant	70.52			
Velocity gradient at stage I	0.6000	0.621	5.130	<0.001
Velocity gradient at stage II	-0.0099	-0.011	-0.083	0.935
Velocity gradient at stage III	-0.7960	-0.824	-6.803	<0.001

* Coefficient of determination (R^2) = 0.772, p<0.001)

Table 3 Distribution of turbidity removal percent according to velocity gradient at each stage

No.	Velocity gradient/stage (sec^{-1})			Turbidity Removal Percent					
				50-65%		66-75%		76-85%	
	I	II	III	No.	%	No.	%	No.	%
1	60	60	60	3	100	0	0.0	0	0.0
2	45	45	45	3	100	0	0.0	0	0.0
3	30	30	30	3	100	0	0.0	0	0.0
4	60	60	45	0	0.0	3	100	0	0.0
5	60	60	30	0	0.0	0	0.0	3	100
6	60	45	45	0	0.0	0	0.0	3	100
7	60	45	30	0	0.0	0	0.0	3	100
8	60	30	30	0	0.0	0	0.0	3	100
9	45	45	30	0	0.0	0	0.0	3	100

4. Conclusions

From this study, it can be concluded that multistage flocculation with descending velocity gradient can improve turbidity removal by about 25%. It varied directly with velocity gradient at stage I non-significantly, while at stage III, the relationship became oppositely significant. The variation of velocity gradient at stage III was the most contributors in the variation of turbidity removal. It has more contribution than that of stage I by 32%. On the other hand, the contribution of velocity gradient variation at stage II has non-significant effect in turbidity removal. Therefore, the research recommends using two stages with descending velocity gradient to improve the efficiency of the flocculation.

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