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Evaluation of Helical Tube Geometry on Hydraulic Flocculation Efficiency for Turbid Water Treatment

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The geometric configuration of helical tubes was assessed in relation to the hydraulic flocculation efficiency in the treatment of highly turbid water. The effect of evaluating different tube geometries (diameters of 0.019–0.025m), loop diameters (0.45–1 m) and flow rates ($7.5–25 \cdot 10^{-6}$ m^3/s) on head loss, camp number (Gt), and residence time was evaluated. The highest turbidity removal efficiency of 85.56% was achieved with the optimized configuration of a 0.019 m tube diameter with a 0.45 m loop. The performance was less if flow rates were higher, the tubes or loops were larger and the flow rates were higher due to inadequate turbulence and less time for particle interaction. Results validate that compact helical configurations aid in low turbulence condition improvement of mixing and particle collision. The helical flow devices were proven to be easy and low cost alternatives to these systems. Future work should focus on scaling and the optimizing the coagulant. The study illustrated that helical flow devices are easy and inexpensive alternatives to decentralized systems. Future work should focus on scaling and coagulant optimization.

Keywords: Spiral tube, Hydraulic flocculation, Artificial turbid water

Introduction

Access to clean drinking water remains a significant challenge in rural and remote areas due to the lack of adequate infrastructure, difficulties in applying appropriate treatment technologies, as well as extreme climatic conditions (Koop et al., 2022). Despite the fact conventional water treatment plants provide quality water, their high costs, the need for specialized technical expertise, and large operational spaces make their implementation difficult in developing countries (Alim et al., 2021). Accordingly, developing cost-effective, easily operated, and efficient water treatment technologies has become a major objective to secure reliable access to safe drinking water (Pichel et al., 2023). Within the conventional treatment units, coagulation and flocculation represent the fundamental stages responsible for reducing turbidity and improving water quality. The overall performance of these processes is strongly influenced by several operational and hydraulic parameters such as coagulant dosage, mixing intensity, residence time, and the hydraulic configuration of the flocculation unit (Razali et al., 2023).

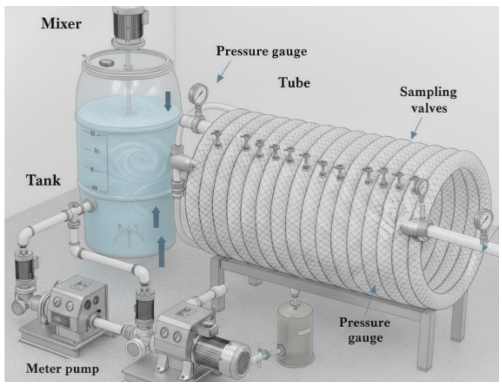
Recently, helically coiled tube flocculators (HCTFs) have gained attention as an energy-efficient, cost- effective and space-saving alternative (Thamer et al., 2025). Many authors (García-Ávila et al., 2024; de Oliveira and Donadel, 2024) have reported that HCTF systems can achieve high turbidity removal efficiencies at short retention times with minimal operational and maintenance requirements. Turbidity removal efficiencies of 72.4–78.5% (Cahyana et al., 2021) and more than 85% (de Oliveira and Teixeira, 2017) were achieved using HCTF. Despite these contributions, comprehensive experimental evaluations of the combined effects of geometric parameters (tube diameters and coil diameters) and hydraulic factors (flow rate and velocity gradient) on treating turbid water using HCTF remain limited. This study presents a new experimental assessment of HCTF performance for treating turbid water within settiling time of 30 minutes only, under 20 distinic geometric and haydraulic configurations that has not been previously reported. Unlike earlier studies that examined a very small-scale tube and loop diameters or relied on theoretical modeling, this work evaluates the combined effects of tube diameter (commercially available in markets), loop diameter, and flow rate under quasi-realistic conditions representative the turbidity level of Shatt Al-Arab, the primary water source for Basra Governorate, Iraq. Such a systematic evaluation provides both methodological contributions and practical design recommendations for researchers and practitioners working on decentralized flocculation systems. This offers future research and design of small-scale and decentralized hydraulic flocculation systems a constructive pathway.

Materials and Methods

Experimental setup

The process starts with a 180 L feed tank. This was used to prepare the influent artificial turbid water using kaolin clay. A mechanical mixer was installed inside the tank to mix the turbid water, with a shaft extending down to the bottom of the tank. Peristaltic pump BT300M was equipped with a digital display to control the required rate of flow accurately. Injection pump was used to dose the coagulant into the water stream before it enters the helical flocculator. Helical tube of different diameters (0.019 m), (0.025 m), (0.038 m), and (0.058 m) are coiled around circular frames (with diameters of 45 cm, 65 cm, 85 cm, and 1 m). Pressure gauges were installed at the inlet and outlet of the helical tube to measure the head loss during water flow. Plastic valves (sample ports) were distributed along the helical tube, with one valve located at each loop of the tube, as illustrated in *Fig 1*.

Fig. 1. *Graphic diagram of spiral flocculation unit*



Procedures

Initially, artificial turbid water was prepared by mixing tap water with kaolin clay. The mixture was stirred using a mechanical mixer inside the mixing tank (180 L capacity) to ensure complete dispersion of particles in the water. At the end of the mixing process, the average turbidity was measured at 150 ± 1 NTU, which was considered the initial turbidity value for all subsequent experiments. This value of initial turbidity was chosen to simulate the high turbidity level of Shatt- Al-Arab

Table 1. *Geometric and hydraulic characteristics of 80 HCTFs configurations*

No.	Case of HCTF	Tube Diameter (m)	Loop Diameter (m)	Tube Length (m)	Flow rate ·10^{-6} (m^3/s)	No.	Case of HCTF	Tube Diameter (m)	Loop Diameter (m)	Tube Length (m)	Flow rate ·10^{-6} (m^3/s)
1	a	0.019	0.45	31.101	7.5	11	a	0.019	0.85	21.362	15
	b	0.025	0.45	35.342	7.5		b	0.025	0.85	26.703	15
	c	0.038	0.45	50.893	7.5		c	0.038	0.85	37.384	15
	d	0.051	0.45	63.617	7.5		d	0.05	0.85	48.066	15
2	a	0.019	0.65	32.672	7.5	12	a	0.019	1	21.99	15
	b	0.025	0.65	34.714	7.5		b	0.025	1	28.27	15
	c	0.038	0.65	49.008	7.5		c	0.038	1	37.699	15
	d	0.051	0.65	59.219	7.5		d	0.05	1	47.123	15
3	a	0.019	0.85	26.703	7.5	13	a	0.019	0.45	21.205	20
	b	0.025	0.85	32.044	7.5		b	0.025	0.45	25.446	20
	c	0.038	0.85	48.066	7.5		c	0.038	0.45	36.756	20
	d	0.051	0.85	56.077	7.5		d	0.05	0.45	46.652	20
4	a	0.019	1	25.132	7.5	14	a	0.019	0.65	20.421	20
	b	0.025	1	31.416	7.5		b	0.025	0.65	26.546	20
	c	0.038	1	47.124	7.5		c	0.038	0.65	36.756	20
	d	0.051	1	56.549	7.5		d	0.051	0.65	42.882	20
5	a	0.019	0.45	26.861	10	15	a	0.019	0.85	18.692	20
	b	0.025	0.45	35.343	10		b	0.025	0.85	24.03	20
	c	0.038	0.45	49.48	10		c	0.038	0.85	34.71	20
	d	0.051	0.45	57.962	10		d	0.051	0.85	42.725	20
6	a	0.019	0.65	26.546	10	16	a	0.019	1	18.849	20
	b	0.025	0.65	32.673	10		b	0.025	1	21.99	20
	c	0.038	0.65	46.967	10		c	0.038	1	31.415	20
	d	0.051	0.65	55.135	10		d	0.051	1	40.84	20
7	a	0.019	0.85	26.704	10	17	a	0.019	0.45	18.378	25
	b	0.025	0.85	32.044	10		b	0.025	0.45	22.619	25
	c	0.038	0.85	45.396	10		c	0.038	0.45	31.101	25
	d	0.051	0.85	50.736	10		d	0.051	0.45	40.997	25
8	a	0.019	1	21.991	10	18	a	0.019	0.65	18.378	25
	b	0.025	1	31.416	10		b	0.025	0.65	22.462	25
	c	0.038	1	40.841	10		c	0.038	0.65	32.672	25
	d	0.051	1	50.265	10		d	0.051	0.65	38.799	25
9	a	0.019	0.45	24.033	15	19	a	0.019	0.85	18.692	25
	b	0.025	0.45	29.688	15		b	0.025	0.85	21.363	25
	c	0.038	0.45	42.411	15		c	0.038	0.85	26.704	25
	d	0.051	0.45	52.307	15		d	0.051	0.85	34.714	25
10	a	0.019	0.65	22.462	15	20	a	0.019	1	15.708	25
	b	0.025	0.65	28.588	15		b	0.025	1	21.991	25
	c	0.038	0.65	38.798	15		c	0.038	1	31.416	25
	d	0.051	0.65	49.009	15		d	0.051	1	31.416	25

Note: *No.; Arrangement number*

river in Basrah city, Iraq. This river is the main source of water in the city. A standard jar test was earlier performed to determine the optimum coagulant dose of aluminum sulfate solution (the dose was 40 mg/l corresponding to initial turbidity of 150 NTU), based on the selected concentration of turbidity. Following the addition of the selected coagulant dose in the dosing tank, the coagulant was injected into the tube while the water was passing through the flocculation unit using an injection pump. Pressure gauges were installed on the spiral tube, at the beginning and at the point of maximum turbidity removal (which obtained by preliminary tests), for each experiment. Water samples were subsequently collected via valves, and settled for 30 minutes in 100 ml beakers to measure the final turbidity. This experiment was repeated (80) times, to cover the effect of all the design parameters (flow rate, tube diameter, coil diameter), as presented in *Table 1*. The residence time (t) for each coil was calculated by dividing the water volume in the tube to the flowrate based on *equation 1*. The residence time varied among the experiments due to differences in tube diameter and flow rate across the various arrangements. The values of velocity gradient (G), camp number (Gt), and head loss (HL) are calculated according to de Oliveira and Teixeira (2017). The results are presented based on turbidity removal (EF) value based on *equation 2*.

$$t = \frac{Water\ volume}{flow\ rate} \quad (1)$$

$$\text{Ef}\ (\%) = \frac{Initial\ Turbidity\ - Final\ Turbidity}{Initial\ Turbidity} \cdot 100 \quad (2)$$

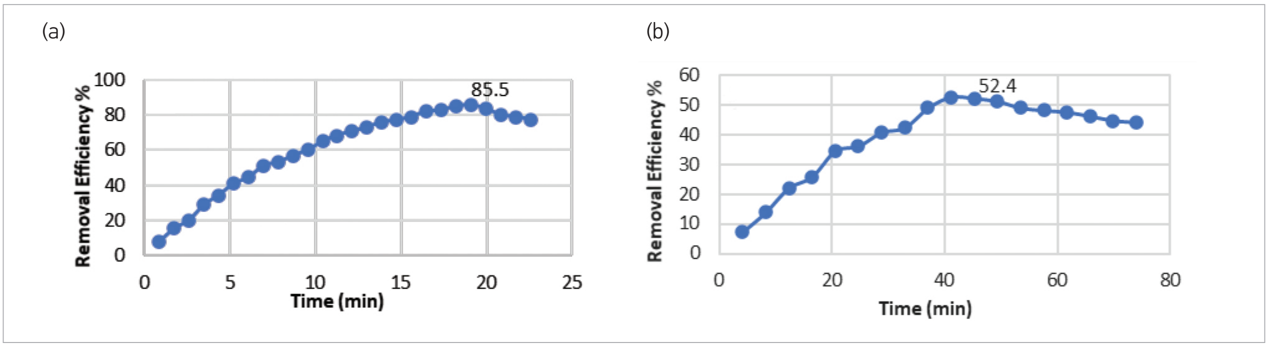
Results and Discussion

Spiral *flocculator* performance

A series of 80 experiments with different arrangements was conducted to evaluate the efficiency of the spiral flocculator in treating turbid water (Table 1). The performance of spiral flocculator showed a clear pattern of increasing turbidity removal efficiency reaching to a higher value and then decreasing, with increasing flocculation time. These findings are consistent with previous studies (Cahyana et al., 2021; de Oliveira and Donadel, 2019; Sartori et al., 2015). Author suggested that removal efficiency increases due to enhanced particle–particle collisions and floc formation during the early stages of flocculation. However, as flocculation time becomes prolonged, flocs are exposed to high shear forces within the helical tube, leading to floc breakup and a reduction in removal efficiency. The turbidity removal rates for all experiments (20 arrangements, 4 cases for each one) ranged between 85.56% and 52.47%. *Fig. 2* illustrates the case of optimum turbidity removal (geometric arrangement 1, case a) and the lower turbidity removal (geometric 20, case d). The other cases, for each arrangement, were presented in Supplementary file1, *Fig. 1* reflecting the maximum turbidity removal for each experiment in *Table 1*. For each arrangement, results showed that the removal decreases with increasing the tube diameter. The overall results of 20 arrangements showed that a flow rate of $7.5 \cdot 10^{-6}$ m^3/s, a tube diameter of 0.019 m, a loop diameter of 0.45 meters, and a residence time of 19.08 minutes produced the best turbidity removal efficiency (85.56%), *Fig. 2a*. However, at a flow rate of $25 \cdot 10^{-6}$ m^3/s, a tube diameter of 0.0508 m, a loop diameter of 1.0 m, and a residence time of 41.12 minutes, the lowest removal efficiency (52.47%) was observed, *Fig. 2b*. The improved efficiency of the tube with a diameter of 0.019 m and the loop with a diameter of 0.45 m is due to the specific hydrodynamic conditions these systems generate. Decreasing tube diameters increases the mean velocity gradient (G) and the strength of the dean vortices within the coil, leading to increased collisional activity and the enhanced rates of formation of microscopic agglomerates (or flocs). Similarly, a smaller loop diameter increases the strength of secondary flow, reduces dead zones, and creates a more even distribution of wall shear stress. It was also stated that best performance was achieved at mid Gt values, to contrast the extreme end values, signifying that mixing and residence, were balanced. This confirmed by the study of Kumar (2020).

The precise optimal level of removal efficiency may be different for other systems, but the greater efficiency of smaller tube and loop diameters in helical flocculation units is a trend that is easily recognizable. The plotted curves represent the highest turbidity removal achieved for each geometric arrangement, rather than all detailed measurements. This presentation style was adopted to highlight the optimum performance and to avoid overlap between multiple curves.

Fig. 2. *Turbidity removal efficiency and flocculation time for the best and worst case among the studied arrangements (Note: a, arrangement 1 (case a); b, arrangement 20 (case d); min, minute)*



The coiled flocculation system works best at low to medium flow rates. When flow rates get higher, Gt and t drop below ideal levels. This causes efficiency to decrease. To operate at higher flow rates, system designs need to focus on keeping enough t and generating proper turbulence by optimizing the system's geometry. The summary of optimal conditions is presented in *Table 2*.

Table 2. *Summary of optimal flocculation efficiency condition at various flow rates*

$Q \cdot 10^{-6}$ (m^3/s)	Efficiency (%)	Tube and loop diameter	$Gt \cdot 10^3$	t (min)	Remark
7.5	85.56	0.019 m, 0.45 m	9.68	19.08	Strong shear and adequate residence time
10	82.3	0.019 m, 0.45 m	8.43	12.36	High turbulence compensated short t
15	78.54	0.019 m, 0.45 m	7.69	7.37	Early decline in t noticeable
20	74	0.019 m, 0.45 m	6.92	4.87	Below Gt and t thresholds
25	68.7	0.019 m, 0.45 m	6.10	3.38	Severe performance reduction

Evaluation of key parameters

The design geometry affects the performance of helically flocculator due to the importance of each key parameter on the turbidity removal efficiency. These parameters reflect the flocculator configurations, including varying tube diameters (0.019 to 0.051 m), loop diameters (0.45–1 m), and flow rates (7.5–25·10^{-6} m^3/s). The following section presents the impact of these parameter on treatment efficiency, HL, Gt, and t.

Effect of tube diameter

Supplementary file 1, *Fig. 2a-e* showed the impact of tube diameter on the removal of turbidity at flow rates of (7.5–25·10^{-6} m^3/s), respectively. The results showed that tube with smaller diameter, 0.019 m gave better flocculation efficiency for all loops diameters (0.45–1 m) and flow rates (7.5–25·10^{-6} m^3/s). However, tube with bigger diameter 0.051 m gave lower removal efficiency for all loops flow rates. The optimum removal, among all studied cases of smaller tube diameter (0.019 m), was 85.56% (*Fig. 3*) corresponding to flow rate of 7.5·10^{-6} m^3/s and loop diameter of 0.45 m. Smaller tube create tighter spaces, which cause more turbulence and better mixing. These conditions are important for particle collisions and forming flocs, as confirmed by (Cahyana et al., 2021). Consequently, the Gt value is highest for the 0.019 m tube and decreases as the diameter increases. This provides a sufficiently high velocity gradient and residence time for effective floc formation.

Effect of loop diameter

Supplementary file 1, *Fig. 3a-e* show the effect of loop diameter on turbidity removal at flow rates of (7–25·10^{-6} m^3/s) respectively. The results showed that as the loop diameter increased, the efficiency decreased, Whereas, the smaller loop diameter, 0.45 m, resulted in stronger centrifugal forces and more active mixing. This helped provide a suitable for the growth and settlement of mud flocs (de Oliveira, 2022). It also caused, which improved mixing and thus helped increase removal efficiency. This was observed across all tube diameters (0.019–0.051 m) and flow rates (7.5–25·10⁻⁶ m³/s). The optimum removal, among all the studied cases for a 0.45m loop diameter, was 85.56% (*Fig. 4*), which corresponds to a flow rate of 7.5·10⁻⁶ m³/s and 0.019 m tube diameter. It is observed that the hydraulic losses inside the tube decrease with increasing tube diameter. Consequently, the Gt value is highest for the 0.45 m loop and decreases as the diameter increases. This provides a sufficiently high velocity gradient and residence time for effective floc formation.

Fig. 3. *Effect of tube diameter on removal efficiency at flow rate of 7.5 ·10⁻⁶ m³/s*

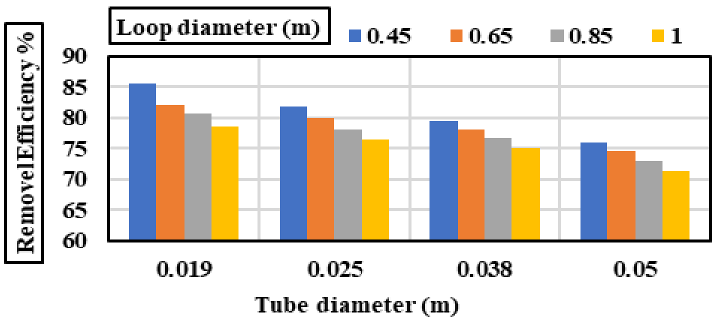
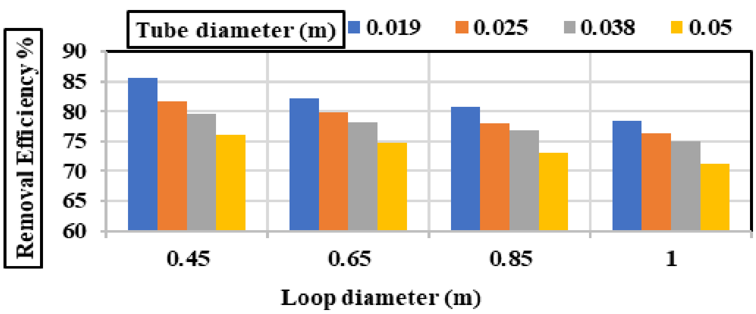


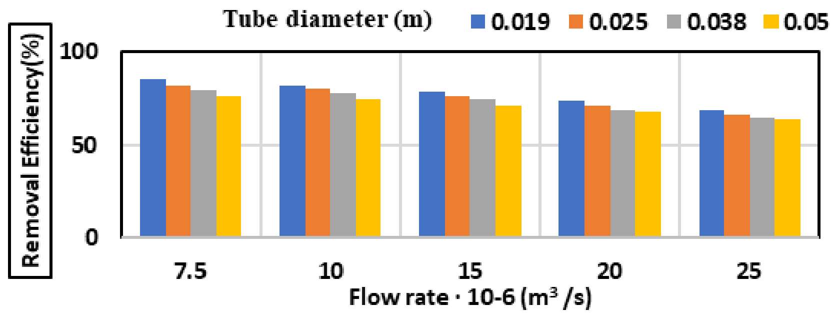
Fig. 4. *Effect of loop diameter on removal efficiency at flow rate of 7.5 ·10–6 m³/s*



Impact of flow rate

Raising the flow rate from 7.5 to 25·10⁻⁶ m³/s caused efficiency to decline. Turbidity removal efficiency dropped from 85.56 % at 7.5·10⁻⁶ m³/s to 68.7% at 25·10⁻⁶ m³/s. This happens because less residence time and lower Gt limit particles interaction and make it harder to form stable flocs (de Oliveira and Teixeira, 2017). Supplementary file 1, *fig. 4a-d* showed the impact of flowrates on the turbidity removal using different tubes diameter (0.019–0.051m) and loops diameter (0.45–1 m). The optimum removal, among all studied cases of 7.5·10⁻⁶ m³/s was 85.56 % (*Fig. 5*) corresponding to loop diameter of 0.45 m and tube diameter of 0.019 m. With the increase in flow rate, the hydraulic losses increased due to the higher flow velocity and greater frictional resistance. This leads to a reduction in the Gt value as a result of shorter residence time and lower G, thereby decreasing the overall performance efficiency since it reduces the opportunities for effective particle collision and aggregation (Vadasarukkai et al. 2011)

Fig. 5. *Effect of different discharge (·10⁻⁶) on removal efficiency.*



Comparative efficiency analysis and selection rationale

The analysis of the experimental data for all the operation cases not only identifies the operating conditions with the highest flocculation efficiency but also explains why some configurations were chosen while others were excluded, even when efficiency values were close to each other (*Table 3*). Therefore, the selection process considered residence time, hydrodynamic performance, and practical operational requirements to ensure optimal system performance, as explained below. The configuration corresponding to the case of lower tube diameter (0.019m) and lower loop diameter (0.45 m), the spiral flocculator at flowrate of 7.5 $\cdot 10^{-6}$ m^3/s, produced the highest efficiency (85.56%). This setup achieved strong turbulence and ensuring stable floc formation with adequate residence time (19 min), which was more than the published values in previous studies of between 3 to 5 min (Cahyana et al., 2021) for spiral flocculator, and less than the standard time in mechanical flocculator of 30 min (García-Ávila et al., 2024). The Gt value (9675) was within the allowable (5000 to 20000) and common reported (9000 to18000) values for spiral flocculator (Schutte, 2006), promoting effective particle collisions in smaller tubes and loops. The value of G was 8.48 s^{-1}, which is within the allowable range of (3.64–56.94) s^{-1} (García-Ávila et al., 2024). Therefore, this setup gives highest efficiency with adequate residence time, acceptable Gt**,** suitable velocity range, and minimal HL. At flow rate of $10\cdot10^{-6}$ m^3/s, the same configuration produced 82.3% efficiency with shorter residence time (12.36 min) compared with flowrate of $7.5\cdot10^{-6}$ m^3/s. The slightly lower efficiency was acceptable because higher turbulence compensated for the reduced retention time, maintaining effective mixing conditions and ensuring stable floc formation, as Gt value was (8438) within the allowable ranges for spiral flocculator. The value of G was 11.37 s^{-1}, which is within the allowable range. As for the hydraulic losses, they increased slightly due to the higher flow resistance inside the tubes. This made the setup operationally practical while sustaining good treatment performance. So, this setup provides balanced efficiency at moderate flow rates, with adequate residence time, allowable camp number (Gt). At flow rate of $15\cdot10^{-6}$ m^3/s, the same configuration exhibit 78.5% of turbidity removal with shorter residence time (7.37 min) compared with flowrate of 7.5 and $10\cdot10^{-6}$ m^3/s. This lower efficiency was achieved at allowable Gt value of 7695. This made the setup operationally practical while sustaining moderate treatment performance, with adequate residence time, allowable Gt. The G value reached 17.4 s^{-1}, which is within the allowable range.

However, as flow rate increased to 20 and $25\cdot10^{-6}$ m^3/s, removal efficiency dropped to 74% and 68.7%, respectively. The values of residence time of 4.87 min and 3.38 min were within the values achieved in literature (3 to 5 min) to recommend the utilization of spiral flocculator (García-Ávila et al., 2024; Cahyana et al., 2021). Also, the Gt values were 6915 and 6100 within the allowable range. But these setups were excluded due to the lower removal efficiency, which attributed to the low contact time and turbulence intensity that hindered stable floc formation. The G reached 23.66 and 30.7 s^{-1}, respectively, and was within the allowable range. The configuration corresponding to the cases of utilizing tube diameter between 0.025 and 0.051m and loop diameter between 0.85–1.0 m, the spiral flocculator produced lower efficiencies (71–76%) with longer residence times (120–277 min). The weaker shear forces and lower turbulence in these larger geometries allowed premature floc settling and insufficient particle collisions, leading to reduced performance. Greater residence time increases particulate collision and clot formation, but excessive time increases the likelihood of clot breakage and reduces efficiency. Thus, optimal time is necessary. Because of this, these configurations were set aside even if they had longer contact times, as the intensity of particle collision was too low.

Table 3. *Comparative efficiency analysis and selection rationale*

1. Selected configurations (best efficiency with practical conditions)						
$Q \cdot 10^{-6}$ m^3/s)	Efficiency (%)	Tube diameter (m)	Loop diameter (m)	$Gt \cdot 10^3$	t (min)	Reason for selection
7.5	85.56	0.019	0.45	9.68	19.08	Highest efficiency, acceptable t
10	82.3	0.019	0.45	8.43	12.36	Moderate efficiency, low t
2. Excluded configurations (lower times or lower efficiency)						
$Q \cdot 10^{-6}$ m^3/s)	Efficiency (%)	Tube diameter (m)	Loop diameter (m)	$Gt \cdot 10^3$	t (min)	Reason for exclusion
15	78.54	0.019	0.45	7.69	7.37	Lower t with limited efficiency improvement
20	74.0	0.019	0.45	6.92	4.87	Efficiency drops sharply despite higher flow
25	68.7	0.019	0.45	6.100	3.38	Lowest efficiency, excessive flow rate

Conclusion

The study concluded that smaller diameters of tubes and loops increased the intensity of turbulence, resulting in even greater collisions of the particles and leading to even greater efficiencies in the removal of turbid materials. The maximum removal of 85.6 % was obtained at optimal configuration of 0.019 m tube diameter, 0.45 m loop diameter and $7.5 \cdot 10^{-6}$ m^3/s. Increasing the flow rate to $25 \cdot 10^{-6}$ m^3 decreased removal efficiency to 68.7 % for the reason of shorter residence time combined with lower effective Gt values. The other larger configurations also performed worse than this. Therefore, the best conditions for the formation of flocs and the removal of turbidity were found to be in the smaller geometries and flow rates. Conversely, systems with higher discharge or bigger diameters suffered turbulence poor contact time short and or pointless extended residence time with no efficiency gain. Helically spiraled tube flocculators should be the replacement designed for primary water clarification. Expected next steps involve CFD (computational fluid dynamics) modeling of the discharge pattern in the coil tubes, tested field with Shatt al-Arab water, combining with coagulants for higher removal efficiency under fluctuating turbidity loads to be interlinked with field testing.

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