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A pilot study for the application of one- and two-stage tube settlers as a secondary clarifier for wastewater treatment

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Abstract

Secondary clarifiers with large areas are widely applied in wastewater treatment plants. A pilot study was conducted to examine the possibility of applying one and two-stage inclined tube settlers instead of conventional secondary clarifiers. Tube diameter in the first stage of the two-stage settler was wide as the conventional ones, but in the second stage, it was narrow to improve the efficiency. The results indicated that in short detention times, the tube settler was more effective in shorter detention time than the conventional secondary sedimentation basin, and its effluent of TSS and turbidity was acceptable to discharge into the surface waters. The average removal of TSS, BOD5, and COD, in a 20-minute detention time in the tubes, in the one-stage tube settler pilot plants was 97.6%, 96.4%, and 96.36%, respectively, while in the conventional secondary sedimentation basin was 98.2%, 99%, and 98.6%, respectively. There was a good agreement between theoretical analyses and experimental results of the pilot plant. Two-stage tube settlers in the series could improve hydraulic condition and removal efficiency of TSS, in comparison with the one-stage tube settler. The average TSS removal, in shorter detention times than that the one-stage, was 97.8%.

Keywords: *Wastewater treatment, Sedimentation, Tube settlers, Solids and turbidity removal, Two-stage tube settler.*

1. Introduction

The activated sludge technique is one of the most commonly used processes in municipal wastewater treatment plants, and a secondary sedimentation basin is one of the main units of this process. Most of the clarifiers and wastewater treatment plants are designed according to the average daily flow, and they represent a low-cost system for wastewater treatment, but they need large areas and are not able to remove all small particles. Whenever wastewater treatment plants receive high amounts of inlet flow, conventional sedimentation basins are facing overloading problems which results in poor performance.

Besides, achieving more stringent effluent quality standards, forces designers to examine more efficient methods for removing solids from wastewaters.

In 1904, Hazen presented that the efficiency of a settling basin depends primarily on overflow rate and maximum particle settling distance, and removal efficiency is independent of the depth and hydraulic detention time [1,2]. Feri (1941) found an increase of TSS removal efficiency from 41 to 61 percent with three horizontal plates in primary sedimentation in the wastewater treatment process [3].

Fischerstorm (1955) concluded from experimental work that the Reynolds number was another important variable for shallow depth sedimentation, and when laminar flow conditions were maintained, good performance levels could be achieved[4]. Tube settling is a process that has received more attention because of high-rate gravity sedimentation [5]. Jimenez and Ramos (1997) showed that the use of flocculants such as alum can help to achieve better solid removal efficiency even in peak flow rates in wastewater treatment[6] . Saleh and Hamoda (1999) stated that high-rate settlers, which show much better performance than conventional settlers, have a good potential for upgrading of the sedimentation basins, especially during the peak flows[7]. Sarkar et al. (2007) showed that the angle of inclination of 45 degrees for co-current systems is optimal [8]. Some researchers have shown that the tube settlers improve the performance of secondary sedimentation in activated sludge processes [3,5,6,7].

Shevidi et al. (2011) introduced a new arrangement of tube settlers in series. They used a two-stage tube settler for the removal of turbidity from water. In their design,

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tube diameter of the first stage was wide as the conventional tube settlers; while in the second stage, tube diameter was narrow to improve the efficiency. They showed that the two-stage tube settler was more efficient than the single-stage one[9].

Although several attempts have been made to use high rate settlers as the secondary clarifiers, it seemed that the efficiency of a two-stage tube settler for the clarifying of secondary treated wastewater had not been investigated. Therefore, a study was aimed to disclose the efficiency of the two-stage tube settling for the removal of the suspended solids from mixed liquor.

1.1. Theory of Sedimentation Basins

Camp (1946) described the theory of settling pattern of discrete particles in an ideal rectangular basin as straight lines where all particles with similar settling velocities move in parallel paths. Figure 1 shows the settling pattern which is identical for all longitudinal sections. All particles having settling velocities, Vs, greater than V_c (critical velocity of settling particles) will fall through the entire depth, h_0, and be removed. The portion of particles with settling velocities $V_s < V_c$, which will be removed, is equal to the ratio of the velocities, V_s/V_c. Figure 1 shows that the particles with $V_s < V_c$ could be removed completely if a horizontal tray is inserted at the height of h. Without such trays, a basin with a length much greater than L_0 would be required to capture these particles [10].

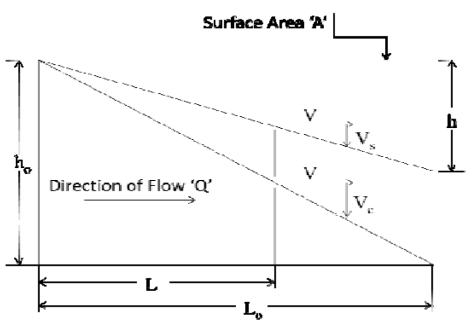

Fig. 1 Ideal settling paths of discrete practices in a horizontal flow basin

As shown in Figure 1, as the interval h is reduced, the required size of a basin to remove a given percentage of the incoming settleable material is decreased. Critical velocity of settling particle is given by Eq. (1):

$$V_c = SLR = \frac{h_o}{t} = \frac{h_o Q}{h_o A} = \frac{Q}{A} \quad (1)$$

Where Q, A, V_c, t, SLR and h_o are flow rate (m^3/s), horizontal area of the basin (m^2), critical settling velocity (m/s), detention time (s), surface loading rate (m/s), and height of the basin (m), respectively.

Theory of sedimentation basin and the ratio of Q/A show that the efficiency of a sedimentation basin depends on surface loading rate (SLR), and as effective surface area is increased, the SLR is decreasing.

The following equations apply for inclined plate settler design [11]. Figure 2 shows a schematic of inclined pipes.

The Reynolds number is specified by Eq. (2):

$$R = \frac{V_o d_H}{\upsilon} \quad (2)$$

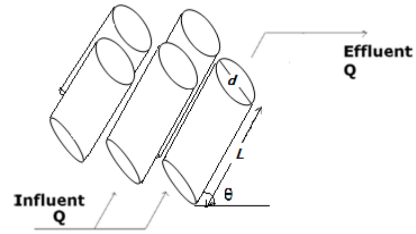

Fig. 2 Schematic of inclined tubes.

Where R, V_o, d_H and υ are the Reynolds number, average flow velocity (m/s), hydraulic diameter of the channel (m), and kinematic viscosity of water (m^2/s), respectively.

Where the hydraulic diameter of the channel is given by Eq. (3):

$$d_H = 4\frac{A}{P} \quad (3)$$

Where A and P are sectional area (m^2) and wetted perimeter of the channel (m), respectively.

The average flow velocity is given by Eq. (4):

$$V_o = \frac{Q}{NA} = \frac{Q}{N\frac{\pi d^2}{4}} \quad (4)$$

Where N and d are the number of tubes and the diameter of tubes (m), respectively.

The surface loading rate of high rate settlers is given by Eq. (5):

$$SLR = \frac{Q}{A_E} \quad (5)$$

Where A_E is the effective surface area (m^2) which is given by:

$$A_E = Ld\cos\theta \quad (6)$$

Where, L and θ are the length of tubes (m) and the angle of tubes relative to horizontal (degree), respectively.

According to American Water Work Association [11,12], the Reynolds number should be remained below 800 to ensure laminar flow and optimal particle settling.

Some other researchers, such as Feri (1941) [3], Yao (1970) [13], Tebbutt (1979) [14], Mendis and Benedek

(1980) [5], Oswald and Nurdogan (1996) [15], Jimenez and Ramos (1997) [6], Saleh and Hamoda (1999) [7], Sarkar et al. (2007) [8], Navarro et al. (2008) [16], Jardin et al. (2008) [17], and Silva et al. (2009) [18], showed advantages of the high-rate sedimentation in their works.

2. Materials and Methods

2.1. Pilot Plants

One - and two-stage tube settler pilot plants were utilized concurrently. The main body of the settlers was made of a polyvinyl chloride (PVC) with 20 cm in diameter and an angle of 45 degrees related to horizontal. The pilot plants were installed at the Ekbatan wastewater treatment plant (EWTP), close to the aeration basin number 2. The tubes diameter in the two-stage tube settler had an inner diameter of 5 and 1.2 centimeters in the first and second stages, respectively. Tube length was 60 cm in both stages. A submersible pump was used to deliver the effluent from the activated sludge aeration basin to the pilot plants. The effluent of the pilot plants and the settled sludge were returned to the inlet of the aeration basin. The sketch of the experimental set-up is shown in Figure 3. The samples were taken at the inlet and outlet of each stage separately.

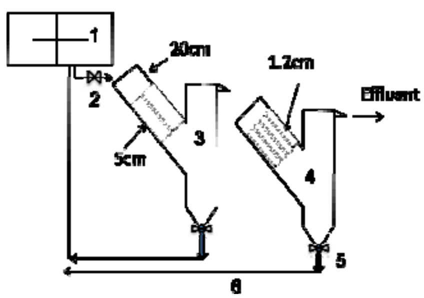

Fig. 3 Experimental set-up of the two-stage tube settler. (1) Aeration basin, (2) Manual value to control feed to inclined tube settlers, (3) first stage, (4) second stage, (5) Value to remove settled sludge, 6) return sludge line into aeration basin

The pilot plants were operated at different flow rates to determine the effect of various hydraulic residence time (HRT) and the SLR on the performance of the inclined tube settlers. The samples were collected in different operation periods. The effluent samples from the first and second stage were analyzed according to the procedures outlined in "Standard Methods for the Examination of Water and Wastewater" [19] to determine the following parameters: MLSS of the aeration basin. For monitoring of turbidity and TSS of the wastewater of the pilot plant a standard turbidimeter (HACH-2100P) and spectrophotometer (HACH DR-5000) were applied, and subsequently the results were compared with the consequence of the EWTP's secondary sedimentation basin effluent (number 2), simultaneously.

First of all, the possibility of the sedimentation in the two–stage tube settler was investigated by the using of the theoretical equations. The value of the average flow velocity (Eq. (4)) and the Reynolds number (Eq. (2)) were calculated for the first and second stage of the pilot plants in the different detention times [11,20].

2.2. Study Site

The EWTP which is located in the west of the capital of Iran, Tehran, is a 600 m^3/h conventional activated sludge treatment plant with the A_2O system. The EWTP has two aeration basins (15 hour detention times, 8930 m^3 volumes) and two circular secondary sedimentation basins (36.6 diameters, 6-8 hour detention times). In design flow, surface loading is 0.57 m/h and weir loading rate is 5.22 m^3/m.h.

3. Results and Discussions

3.1. Evaluation of the Reynolds Number

Figure 4 shows the results of the calculation of the Reynolds number [9]. As shown in this Figure, the two stages are in laminar flow limit, because the Reynolds number was less than 800.

In spite of the increases in the amounts of average flow velocity in the second stage, the amount of the Reynolds number was decreased because of a reduction in diameter of tubes in this stage [9].

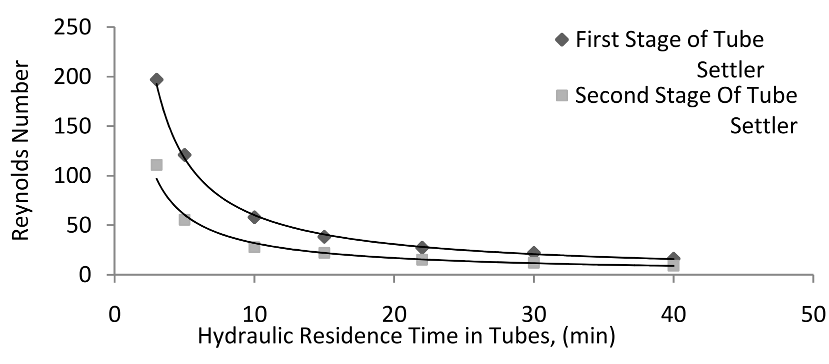

Fig. 4 The relationship between the Reynolds number and hydraulic residence time, kinematic viscosity of water is 0.864×10^6 m^2/s at 27°C [9]

3.2. Evaluation of the SLR

Sedimentation basins are normally designed on the basis of the SLR called "surface loading rate" which is expressed as cubic meter per square meter of surface area per day ($m^3/m^2/d$) [21]. Figure 5 shows that while the HRT is increased, the SLR is declined. The amount of surface loading of the second stage tube settler is less than that of the first stage. As shown in Figure 5, the largest difference between the first and second stage occurred in short HRT. Because HRT of tube settler basins commonly is short, the second stage can help to capture small particles; therefore, the two-stage tube settler is expected to be more efficient than the one-stage in short HRT.

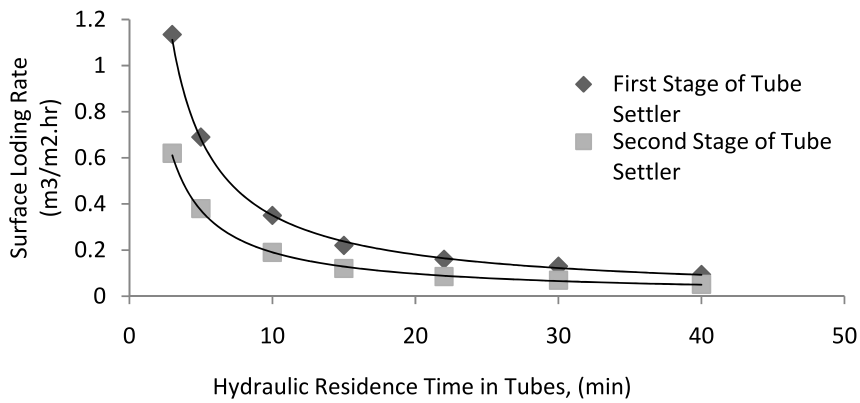

Fig. 5 The relationship between surface loading rate and hydraulic residence time

3.3. Pilot Plants Operation

The pilot plants were operated at different flow rates to determine the effects of various of the HRT and the SLR on the performance of the inclined tube settlers. The results of HRT at 5, 10, 15, 20, and 40 minutes are shown in Tables 1 to 5, respectively.

As shown in the Tables, despite the increases in the amount of average flow velocity in the second stage, the effluent turbidity and removal efficiencies of TSS in the two-stage unit, in all cases, is less than those of the one-stage unit. This may be caused by a reduction in the diameter of the tubes and the improvement of hydraulic conditions in the second stage of the tube settler, which offset the increase of the average flow velocity. In fact, the presented results in Tables 1 to 5 of the pilot plants confirm the analytic formulations.

The maximum removal percent of the second stage belonged to HRT of 5 minutes in the tubes, and it was 43.4%. This result may show the advantage of the two-stage tube settler in comparison with the one-stage at the short detention times (Table 1).

Table 1 The performance results of inclined tube settlers in the hydraulic residence time of 5 min in the tubes.

	MLSS mg/l	Percentage of TSS removal of the one-stage unit	TSS removal belongs to the second stage unit	Percentage of TSS removal of the two-stage unit	TSS removal of the Ekbatan sedimentation	turbidity of the one-stage unit (NTU)	turbidity of the two-stage unit (NTU)	turbidity of the Ekbatan sedimentation basin (NTU)	Percentage of BOD$_5$ removal of the one-stage unit	Percentage of COD removal of the one-stage unit	Percentage of BOD$_5$ removal of the Ekbatan sedimentation basin	COD removal of the Ekbatan sedimentation
	1260	96	48.6	97.9	96.9	---	---	---	---	---	---	---
	880	94.9	50	97.4	95.6	---	---	---	---	---	---	---
	1580	97	36.2	98.1	97.5	---	---	---	---	---	---	---
	660	93.8	22	95.2	98.5	---	---	---	87.9	94	---	---
	1260	95.9	44.3	97.7	99.4	44	19	5	81.7	87	99.3	99.5
	1060	96.4	52.6	98.3	99.6	28	9	4	92.9	93.3	98.6	97.7
	1100	95.1	42.4	97.2	99.1	40.5	20	5	---	---	---	---
Average	1114	95.6	42.3	97.4	98.1	37.5	16	4.7	87.5	91.4	99	98.6

Table 2 The performance results of inclined tube settlers in the hydraulic residence time of 10 min in the tubes.

	MLSS mg/l	Percentage of TSS removal of the one-stage unit	Percentage of TSS removal belongs to the second stage unit	Percentage of TSS removal of the two-stage unit	Percentage of TSS removal of the Ekbatan sedimentation basin	The effluent turbidity of the one-stage unit (NTU)	The effluent turbidity of the two-stage unit (NTU)	The effluent turbidity of the Ekbatan sedimentation basin (NTU)	Percentage of BOD_5 removal of the one-stage unit	Percentage of COD removal of the one-stage unit	Percentage of BOD_5 removal of the Ekbatan sedimentation basin	Percentage of COD removal of the Ekbatan sedimentation basin
	1260	96.3	40.4	97.8	96.9	---	---	---	---	---	---	---
	880	95.5	22.5	96.5	95.6	---	---	---	---	---	---	---
	1580	97.5	22.5	98	97.5	---	---	---	---	---	---	---
	660	---	---	---	98.5	---	---	---	---	---	---	---
	1260	96.8	52.5	98.5	99.4	18	9	5	---	---	99.3	99.5
	1060	---	---	---	99.6	---	---	4	92.2	93.8	98.6	97.7
	1100	---	---	---	99.1	---	---	5	---	---	---	---
Average	1114	96.5	34.5	97.7	98.1	18	9	4.7	92.2	93.8	99	98.6

Table 3 The performance results of inclined tube settlers in the hydraulic residence time of 15 min in the tubes

	MLSS mg/l	Percentage of TSS removal of the one-stage unit	Percentage of TSS removal belongs to the second stage unit	Percentage of TSS removal of the two-stage unit	Percentage of TSS removal of the Ekbatan sedimentation basin	The effluent turbidity of the one-stage unit (NTU)	The effluent turbidity of the two-stage unit (NTU)	The effluent turbidity of the Ekbatan sedimentation basin (NTU)	Percentage of BOD_5 removal of the one-stage unit	Percentage of COD removal of the one-stage unit	Percentage of BOD_5 removal of the Ekbatan sedimentation basin	Percentage of COD removal of the Ekbatan sedimentation basin
	1260	96.9	41	98.2	96.9	---	---	---	---	---	---	---
	880	95.5	30	96.8	95.6	---	---	---	---	---	---	---
	1580	97.6	26.3	98.2	97.5	---	---	---	---	---	---	---
	660	93.9	35	96.1	98.5	---	---	---	95.2	97.5	---	---
	1260	96.9	50	98.5	99.4	17	7	5	95	95	99.3	99.5
	1060	97.5	44.4	98.6	99.6	15	7	4	96.4	95.2	98.6	97.7
	1100	96.7	43.5	98.1	99.1	18	9	5	---	---	---	---
Average	1114	96.4	38.6	97.8	98.1	16.7	7.7	4.7	95.5	95.9	99	98.6

Table 4. The performance results of inclined tube settlers in the hydraulic residence time of 20 min in the tubes

	MLSS mg/l	Percentage of TSS removal of the one-stage unit	Percentage of TSS removal belongs to the second stage unit	Percentage of TSS removal of the two-stage unit	Percentage of TSS removal of the Ekbatan sedimentation basin	The effluent turbidity of the one-stage unit (NTU)	The effluent turbidity of the two-stage unit (NTU)	The effluent turbidity of the Ekbatan sedimentation basin (NTU)	Percentage of BOD_5 removal of the one-stage unit	Percentage of COD removal of the one-stage unit	Percentage of BOD_5 removal of the Ekbatan sedimentation basin	Percentage of COD removal of the Ekbatan sedimentation basin
	1260	97.3	38.2	98.3	96.9	---	---	---	---	---	---	---
	880	95.7	31.6	97	95.6	---	---	---	---	---	---	---
	1580	97.8	38.6	98.6	97.5	---	---	---	---	---	---	---
	660	96.1	23	97	98.5	---	---	---	94.2	95.5	---	---
	1260	98.3	36.4	98.9	99.4	18	6	5	97.7	97	99.5	99.5
	1060	97.9	36.4	98.7	99.6	11	6	4	97.4	96.6	98.6	97.7
	3420	99.3	43.1	99.6	99.7	12.8	6.7	6.5	---	---	---	---
	1100	98	26	98.5	99.1	11	8	5	---	---	---	---
Average	1402.5	97.6	34.2	98.3	98.2	13.2	6.7	5.1	96.4	96.36	99	98.6

Table 5 The performance results of inclined tube settlers in the hydraulic residence time of 40 min in the tubes

	MLSS mg/l	Percentage of TSS removal of the one-stage unit	Percentage of TSS removal belongs to the second stage unit	Percentage of TSS removal of the two-stage unit	Percentage of TSS removal of the Ekbatan sedimentation basin	The effluent turbidity of the one-stage unit (NTU)	The effluent turbidity of the two-stage unit (NTU)	The effluent turbidity of the Ekbatan sedimentation basin (NTU)	Percentage of BOD_5 removal of the one-stage unit	Percentage of COD removal of the one-stage unit	Percentage of BOD_5 removal of the Ekbatan sedimentation basin	Percentage of COD removal of the Ekbatan sedimentation basin
	1060	98.1	34	98.8	99.6	7	5.4	4	98.6	97.7	98.6	97.7
	1100	98	24	98.5	99.1	10	7	5	---	---	---	---
	1540	98.6	30.2	99	99.4	10.7	7	5.8	---	---	---	---
Average	1233	98.2	29.4	98.8	99.4	9.2	6.5	4.9	98.6	97.7	98.6	97.7

However, as the HRT increases, the difference between removal efficiency of TSS in the first and second stages reduces. It may be as a result of occurrence of large and heavy floc in the first stage which causes an increase in sedimentation velocity and opportunity for more particle sedimentation. Hence, the efficiency of the two-stage tube settler in short HRT may be higher than the one-stage.

Figure 6 shows the relationship between the HRT and average TSS removal efficiencies. As shown in Figure 6, when the HRT increases, the TSS removal efficiency augments. This result has a good agreement with the results of some researchers such as Saleh and Hamoda (1999) on the pilot plant studies in wastewater treatment[7]. In additional, in all cases the effluent of the two-stage tube settler has a better quality than that of the one-stage one.

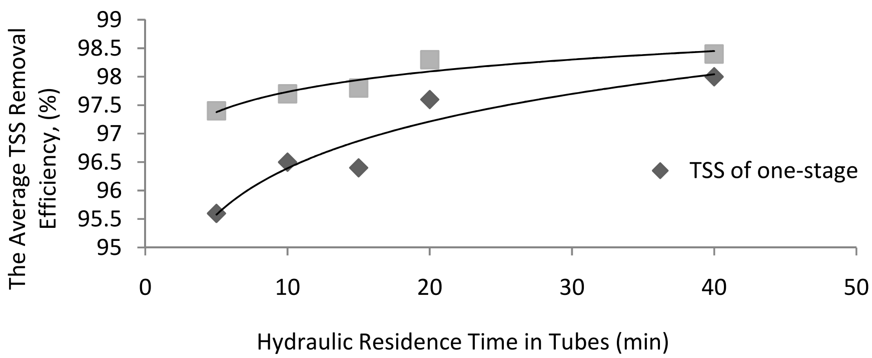

Fig. 6 The effect of HRT on efficiency of total suspended solid removal.

Figure 7 illustrates the relationship between the HRT in the tubes and the average effluent turbidity. The Figure demonstrates that while HRT increases, the average effluent turbidity decreases, and the two-stage unit has better effluent quality than the one-stage one in all cases. After 20 minutes in the tubes of the one-stage unit and after 15 minutes in the tubes of the two-stage unit, there is no significant difference in the effluents, and the curves tend to be flattened out as HRT is increased. Therefore, it seems that HRT of 15 min in the tubes is adequate for settling in the two-stage tube settler pilot plant. The average TSS removal efficiency of 20 minutes in the tubes in the one-stage, of 15 minutes in the tubes in the two-stage and of the EWTP's conventional sedimentation basin is 97.6%, 97.8%, and 98.2%, respectively.

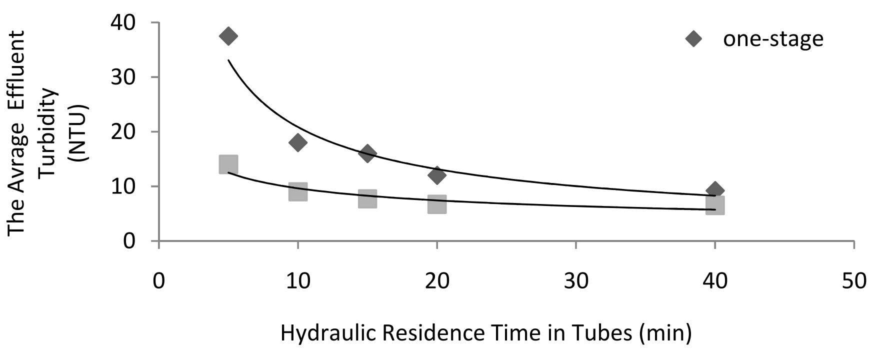

Fig. 7 The relationship between hydraulic residence time and the average effluent turbidity

Figure 8 shows the relationship between the average effluent turbidity and the Reynolds number. As shown in Figure 8, while the Reynolds number increases, the average effluent turbidity increases, and the two-stage tube settler are more effective than the one-stage for removal of the turbidity of wastewater. This result has a good agreement with the results of Shevidi et al. (2011) on pilot plant studies[9].

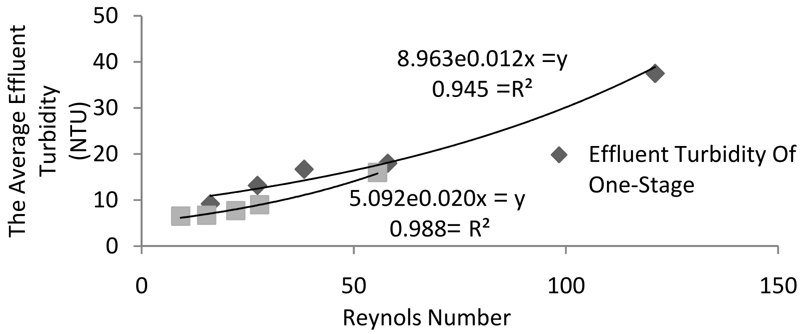

Fig. 8 The relationship between the average effluent turbidity and Reynolds number

The relationship between the average effluent turbidity and the Reynolds number for the one- and two-stage unit could be explained by Eqs. (8) and (9):

$$\text{The average effluent turbidity of one - stage (NTU)} = 8.963e^{0.012\times R} \quad (8)$$

$$\text{The average effluent turbidity of one - stage (NTU)} = 8.963e^{0.012\times R} \quad (9)$$

Figure 9 shows the relationship between MLSS and the average TSS removal efficiencies of 5, 15, and 20 minutes in the one-stage unit, which is clear that the removal efficiency increases as MLSS of the pilot plant increases. Nonetheless, the effluent of TSS is increasing as a result of high MLSS. The reason for this could be due to a high concentration of MLSS and influence of particles together (type 3 of sedimentation) and; hence, the removal efficiencies have been increased.

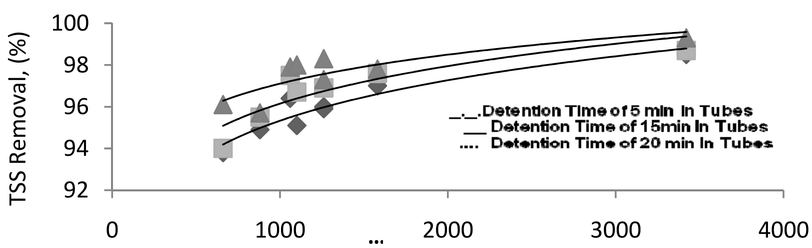

Fig. 9 The relationship between the percentage of TSS removal and MLSS

3.3.1. Evaluation of BOD and COD Removal Efficiencies

The effluent BOD of the activated sludge process depends on the solids removal in the clarifier. Dick stated that one mg/l of solids lost over the weir of the final settling basin commonly increases the effluent BOD by about 0.6 mg/l[23]. Figures 10 and 11 show the relationship between the SLR and the percentage of BOD removal, and the relationship between the SLR and the percentage of COD removal for the one-stage tube settler, respectively.

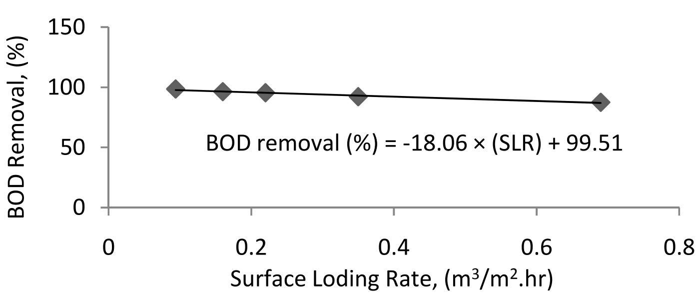

Fig. 10 The relationship between the percentage of BOD removal and SLR

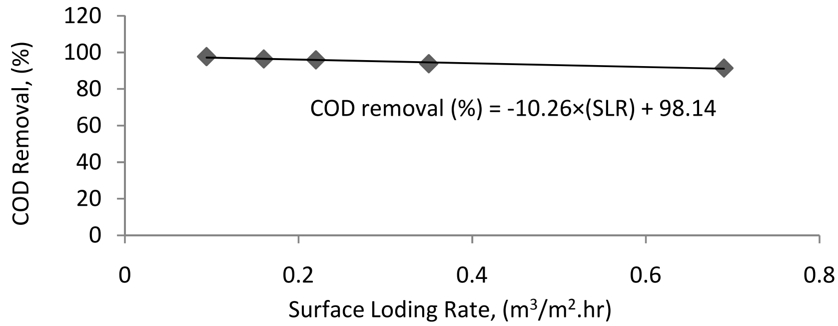

Fig. 11 The relationship between the percentage of COD removal and SLR

In both figures, while SLR increases, the percentage of BOD and COD removal decreases. The average BOD and COD removal percentages of 20 minutes in the tubes were 96.4% and 96.36%, and for the EWTP's conventional sedimentation basin (with HRT of 6-8 hour) were 99% and 98.6%, respectively. In all cases, experiments show that BOD and COD removal efficiencies for the one-stage at a detention time of 20 minutes in the tubes were in the standard range for Iran for discharge to the surface waters [24] [Department of Environment (DOE)]. The results of this study, as illustrated in Figures 9 and 10, have a good agreement with the consequences of Saleh and Hamoda (1999) on pilot plant studies in wastewater treatment[7].

4. Conclusion

The results of the study indicate that the effluent of the tube settler pilot plant, with HRT of 20 minutes in the tubes, meets the Iranian standard of TSS and turbidity for discharging to the surface waters. The average removal efficiencies of TSS, BOD_5, and COD, at 20 minutes in the tubes, in the one-stage pilot plant were 97.6%, 96.4%, and 96.36%, respectively, while the effluent of the secondary conventional sedimentation basin of EWTP,s with HRT of 6-8 hours, were 98.2%, 99%, and 98.6%, respectively. Theoretical analyses and experiments in the pilot study had a good agreement. The pilot plant study outcomes showed that the two-stage tube settler had better hydraulic conditions than the one-stage tube settler. It may be as a result of reduction of the diameter of the tubes in the second stage. In addition, the Reynolds number was improved in the second stage. Thus, the two-stage tube settler may overcome the hydraulic shortcomings existing in large conventional basins. Additionally, the results indicated that the two-stage tube settler had better effluent quality than the one-stage one with shorter residence time (i.e., 15 minutes in the tubes). The optimal residence time for the two-stage unit was found to be 15 minutes in the tubes with the average TSS removal efficiency of 97.8%. In general, tube settlers may be used to reduce required areas and to minimize the pollutions in emergency conditions, such as wet weather conditions. Also, it may be used instead of secondary conventional sedimentation basin.

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5. Notation

The following symbols and abbreviations are used in this paper:

A_2O: Anaerobic, Anoxic, Aerobic system;
BOD: Biochemical Oxygen Demand;
COD: Chemical Oxygen Demand;
HRT: Hydraulic Retention Time;
MLSS: Mixed Liquor Suspended Solids;
SLR: Surface Loading Rate;
TSS: Total Suspended Solid;
t: hydraulic residence time in tubes;
V_f: average flow velocity;
V_s : particle settling velocity;
A: cross-section area (perpendicular to the flow);
A_E: effective sedimentation area;
d_h : hydraulic diameter of the channel;
L: length of the tubes;
N: number of cells
P: perimeter of channel;
Q: flow rate through the device;
R: Reynolds number;
θ: angle of the tube relative to horizontal;
υ: cinematic viscosity

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