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A combined hydrocyclone - electrocoagulation treatment for different types of industrial wastewater

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Abstract: Every year, a large amount of mineral processing wastewater is discharged from various industries into the environment which is considered a challenging task not only because of its large volume, but more importantly, its hazardous components, while its reuse as feedwater without proper treatments causes great harm to the final product of these industries. Cost-effective methods are required to treat a wide range of industrial wastewater in a diverse range of conditions. In this study, a combined hydrocyclone-electrocoagulation system is tried to treat the wastewater for industries with high water consumption and high pollutants such as paper industry, iron and metal forming industry, and marble industry. The effects of the hydrocyclone operational parameters, such as feed inlet pressure and diameter, vortex finder diameter, apex diameter, and feed solids content, were investigated. In the case, wastewater of paper industry, the following optimum conditions (P = 4.5 bar, D_O = 15.8 mm, D_u = 6 mm, D_i = 4 mm and c_s = 2.3%) were achieved. An overflow of about 90.58% water recovery and 21.45% solid at 75.92% separation efficiency was obtained. The results showed that the hydrocyclone-electrocoagulation treatment has efficiently treated the three different types of industrial wastewater. The chemical oxygen demand (COD), biochemical oxygen demand (BOD), total solid (TS), total suspended solids (TSS), colour and turbidity, were reduced sharply and met the effluent discharge or reuse standards. Also, compared with the hydrocyclone-treated wastewater, the hydrocylone-electrocoagulation-treated wastewater was found to be more enhanced.

Keywords: hydrocyclone, electrocoagulation, paper industry, iron industry, marble and granite industry

1. Introduction

Treatment of mineral processing wastewater from different industries for meeting the effluent discharge standards is a challenging task not only because of its large volume, but more importantly, its hazardous components such as high chemical oxygen demand (COD) levels. Direct discharge of wastewater causes serious environmental pollution, while its reuse as feed water without proper treatments causes great harm to the final product of these industries (Araujo et al., 2005). Industrial effluents may contain toxic pollutants, which have to be reduced or eliminated to protect the environment, public health and the treatment plant (Yavuz and Ögütveren, 2018).

Paper industry, iron and metal forming industry and marble industry have been considered the largest water consumption industries in Egypt. They produce large amount of pollutant loads that discharged mostly into the River Nile and ground surfaces without proper treatment. Wastewater from that industries are generally high in biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, fatty acids, lignin, etc., (Toczyłowska-Mamińska, 2017; Colla et al., 2016; Domopoulou et al., 2015; Arslan et al., 2005). Water reuse has been dubbed as the greatest challenge of the 21st century as water supplies remain practically the same and water demands increase because of

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increasing population and industrial establishments (Kellis et al., 2013; Mahjouri et al., 2017). In recent years there has been an increasing interest in the use of cost-effective methods to treat a wide range of wastewater pollutants in a diverse range of conditions.

The hydrocyclone is a simple design and easy to operate apparatus. It has found wide application in various fields (Wills and Finch, 2006). Among the various applications, separation of solid-liquid suspensions is a crucial operation in the process industries. Many advantages associated with a separation cyclone, e.g., less residence time, low space, no moving parts, relatively low cost, high particulate removal efficiency, a compact treatment facility, does not require supplementary addition of chemicals, makes it promising for many wastewater treatments (Svarovsky, 1984; Habibian et al., 2008; Yang et al., 2004; Neesse et al., 2015; Braga et al., 2015).

As compared with traditional treatment methods, electrocoagulation provides a relatively compact and robust treatment alternative. The characteristics of the hydrocyclone-treated water can be enhanced by using electro-coagulation process. Electro-coagulation is an emerging technology that combines the functions and advantages of conventional coagulation, flotation, and electrochemistry in wastewater treatment (Normann, 2017). It has many benefits as compatibility, amenability to automation, cost effectiveness, energy efficiency, safety, and versatility (Nandi and Patel, 2017). The electro-coagulation process operates on the base of the principle that the cations produced electrically from iron or aluminum anodes which is responsible for the coagulation of contaminants from an aqueous medium (Chaturvedi, 2013). The flocculated particles attracted by small bubbles of oxygen and hydrogen generated from electrolysis of water. Thus, the flocculated particles float towards the surface (Sahu et al., 2014).

The present work aims to treat different types of real industrial wastewater produced from high water consumption industries and high polluted ones in Egypt to meet the effluent industrial wastewater discharge or reuse standards using a combined hydrocyclone-electrocoagulation treatment process.

2. Materials and methods

In the present work the experiments were carried out using three different types of real industrial wastewater produced from paper industry, iron and metal forming industry and marble and granite industry. These samples were collected from; Qena Company for paper industry located in Qus City, Qena, Egypt; Muhammadiyah company for the manufacture of iron and metal forming located in Badr city, Beheira, Egypt and El safwa company for marble and granite industry located in Cairo, Egypt. A head representative samples of about 1000 liters from each type (wastewater) were used in the experiments.

2.1. Experimental test rig

The treatment process of the wastewater was carried out using the 35 mm hydrocyclones followed by an Electro-coagulation unit in an attempt to enhance the treatment process. The hydrocyclones test-rig used in the experimental work is shown in Fig. 1 a and b. The Electro-coagulation unit used in the experimental work is shown in Fig. 2. It consists of a laboratory model DC power supply apparatus. The Electro-coagulation was conducted in a cylindrical glass cell of 400 ml in which wastewater sample of 300 ml was placed and slowly stirred with a magnetic bar at 120 rpm. A pair of aluminum plates of size 6 cm × 5 cm × 0.5 cm immersed to a 6 cm depth with an effective area of 30 cm^2. Each plate was used as electrodes in the experiments. The inter-electrode distance between the plates was 4 cm.

2.2. Experimental procedure

The present work was performed using a 35 mm hydrocyclone. A systematic set of experiments were carried out using paper industrial wastewater which contains the highest COD and BOD contents at different operating and design parameters of hydrocyclone. The other two industrial wastewater types, the iron and metal forming and marble and granite wastewater were also treated at the same optimum conditions which were obtained in the case of paper industry wastewater.

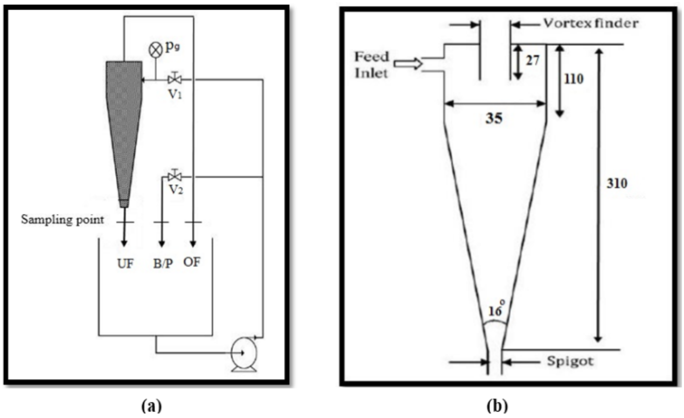

Fig. 1. (a) Hydrocyclone Test Rig (b) Hydrocyclone design dimension (in mm)

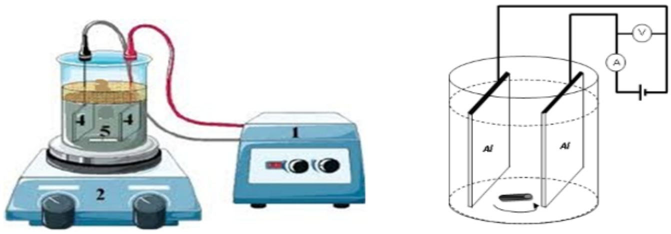

Fig. 2. The Electro-coagulation test rig. 1- DC power supply; 2- Magnetic stirrer; 3- Cylindrical glass 400 ml; 4- Aluminum electrodes; 5- A magnetic bar

In order to enhance the treatment process of paper industrial wastewater, the Electro-coagulation unit has been used after the hydrocyclone separation. The overflow stream which was produced by the hydrocyclone at the optimum conditions is fed to the Electro-coagulation unit at an operating voltage of 30 V and at an electric current of 1 Ampere for 10 min (Mahesh et al., 2016). The characterestics of the treated wastwater was carried out using the following units PH meter, BOD Trak (bottle), COD Reactor, Turbidity/Colorimetry, Density meter, TSS meter, DR 2010 Spectro photo meter, CG 855 Conductivity meter.

3. Result and discussion

3.1. Tests using paper industry wastewater

Fig. 3 shows the particle size distribution of the wastewater sample. Characterization of the sample is also shown in Table 1.

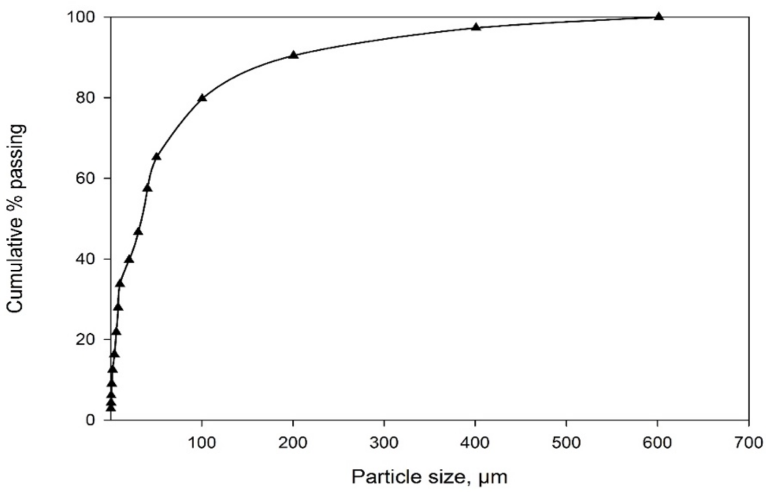

Fig. 3. Particle size distribution of the industrial wastewater sample of paper industry

Table 1. Characterizations of industrial wastewater from Qena Company for paper industry

Parameters	Unit	Value
PH		6.58
BOD	kg/m^3	2.900
COD	kg/m^3	0.650
Total Solid (TS)	kg/m^3	23.594
Total suspended solid (TSS)	kg/m^3	23.294
Oils and Grease	kg/m^3	0.050
Sulphides	kg/m^3	0.010
Phenols	kg/m^3	Non
Phosphate	kg/m^3	0.003
Fe	kg/m^3	0.007
Turbidity	(NTU)	498
Color	%	36

3.1.1. Hydrocyclone 35 mm

The effect of variable parameters; feed inlet pressure (P), feed inlet diameter (D_i), overflow diameter (D_o), underflow diameter (D_u) and feed solid content (cs) on the performance and separation efficiency of the hydrocyclone was investigated as illustrated in Table 2.

Table 2. Test program of paper industry wastewater

Parameter	value, mm
Inlet diameter, D_i	4, 6, 7.5, 8
Vortex finder diameter, D_o	6, 9.9, 14, 15.8
Underflow diameter, D_u	4, 6, 7.5, 8
Feed pressure (P), bar	1, 2, 3, 4, 4.5
Feed solid content, %(w/w)	2.3, 4, 6, 8, 10

3.1.1.1. Effect of feed inlet pressure (P)

Feed inlet pressure is an important operating parameter affecting the performance of the hydrocyclone. Fig. 4 and Fig. 5., show the effect of feed inlet pressure on both the water recovery and solid % in overflow stream and the separation efficiency (E_S) respectively.

From Fig. 4 and Fig. 5, it can be seen that the water recovery % in overflow stream and the separation efficiency (E_S) increase with increasing the feed inlet pressure, while overflow solid % decreases. This may be due to the increase in the feed throughput (capacity) and the centrifugal force of the suspension which are directly influenced by the feed inlet pressure. On the other hand, the overflow solid recovery decreases due to the decrease in the cut size (d_{50}) as it was previously shown in Eq. (1) for Schubert and Neesse (Schubert and Neesse, 1980) where the cut size (d_{50}) is inversely proportional to the feed inlet pressure (P). This result agrees with the results obtained by other authors (Neesse et al., 2015; Papacharalambous and Sun, 1963; Saengchan et al., 2009; Huang et al., 2013; Sabbagh et al., 2016; Hsu et al., 2011).

$$d_{50} = k\sqrt{\frac{\eta D ln\,[0.91(D_o/D_u)^3]}{(1-\varphi_p)^3\,(\rho_p-\rho_f)\sqrt{P/\rho_n}}} \tag{1}$$

where: d_{50} is the cut size, D_c is the hydrocyclone diameter, k is the experimental constant, η is the dynamic viscosity, D_o is the overflow diameter, D_u is the underflow diameter, φ_p is the solid ratio by wt., ρp is the solid density, ρ_f is the liquid density, P is the inlet pressure, and ρ_n is the suspension density.

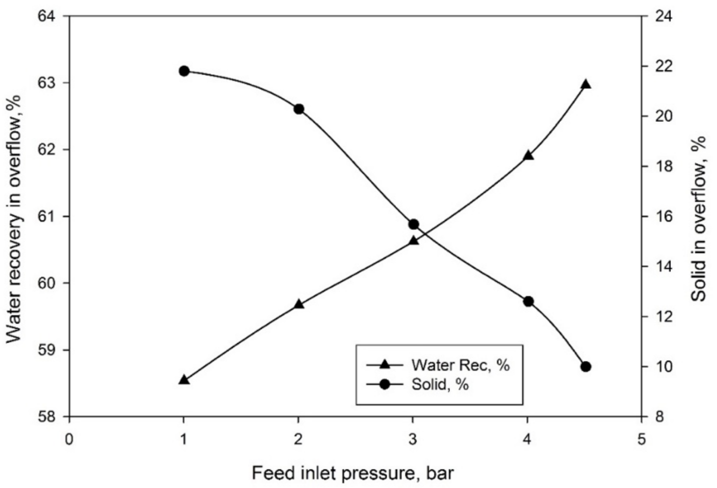

Fig. 4. Effect of feed inlet pressure on the water recovery and solid % in overflow at D_o = 9.9 mm, D_u = 8 mm and D_i = 8.75 mm

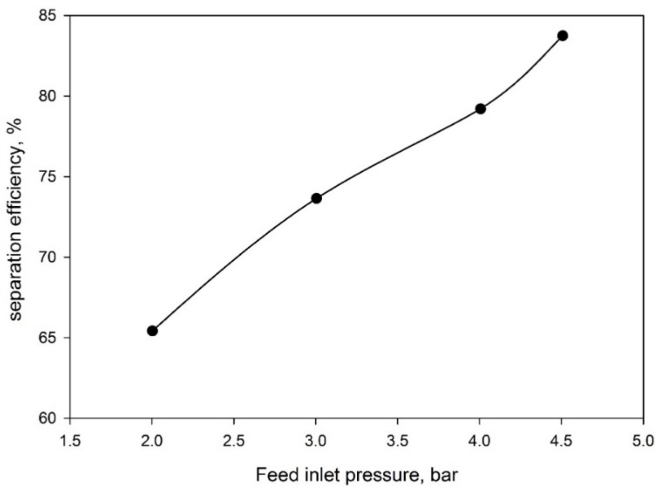

Fig. 5. Effect of feed inlet pressure on the separation efficiency (E_S), % at D_O = 9.9 mm, D_u = 8 mm and D_i = 8.75 mm

3.1.1.2. Effect of feed inlet diameter (D_i)

The effect of changing the feed inlet diameter (D_i) on water and solid recovery in overflow stream and the separation efficiency (E_S) is shown in Figs. 6 and 7. The results indicated that the overflow water recovery % and separation efficiency slightly deceases by increasing the feed inlet diameter, while overflow solid % slightly increases. Where the inlet diameter has a little influence on the volume split parameter (S) within the cyclone. This may be due to the decrease both the tangential velocity and centrifugal force with increasing feed inlet diameter.

According to Sabbagh et al. (2016) the increase feed inlet diameter decreases the inlet velocity, the tangential velocity and the centrifugal force consequently, the pressure drop decreases, and cut size (d_{50}) increases which in turn separation efficiency decreases. This result was also confirmed by other investigators (Vieira et al., 2016; Gawali and Bhambere, 2015).

3.1.1.3. Effect of vortex finder diameter (D_o)

It can be observed from Fig. 8 and Fig. 9, that the change in vortex finder diameter has a significant effect on hydrocyclone performance. An increase in the diameter of the vortex finder will result in more water and solids reporting to overflow. This can be attributed to the increase in overflow diameter increases the air core diameter. So, the overflow discharge (Q_{OF}) increases which lead to increasing of the volume split parameter (Q_{OF}/Q_{UF}) which means that more suspension is discharged through the overflow and less suspension is discharged to the underflow, and consequently the cut size (d_{50}) increases which reflecting to decreasing in the separation efficiency. A similar observation was found by other researchers (Sabbagh et al., 2016; Ahmed et al., 2009).

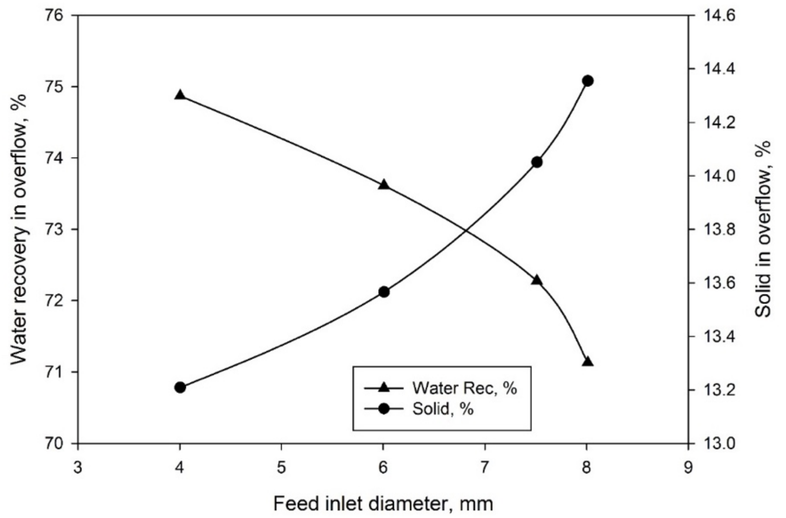

Fig. 6. Effect of feed inlet diameter on the water recovery and solid % in overflow at P = 4.5 bar, D_o = 9.9 mm and D_u= 6 mm

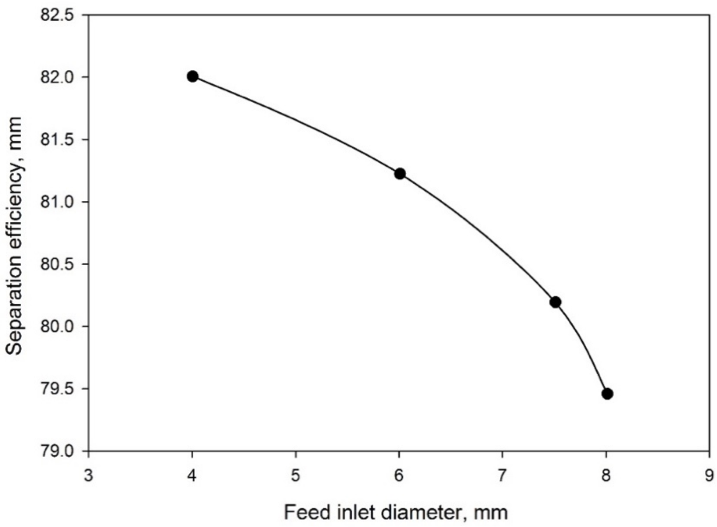

Fig. 7. Effect of feed inlet diameter on the separation efficiency (E_S), at P = 4.5 bar, D_o = 9.9 mm and D_u = 6 mm

3.1.1.4. Effect of underflow diameter (D_u)

The effect of the underflow diameter on water recovery and solid % in overflow stream is shown in Fig. 10. From this Figure it can be seen that the water recovery and solid % from the feed to overflow stream decrease with increasing the underflow diameter. This may be due to the increase in the discharge capacity of the apex leads to more feed water going to the underflow with more fines.

Fig. 11, reveals the effect of underflow diameter on the separation efficiency. The results indicated that the separation efficiency increases with increasing the underflow diameter (D_u). This can be explained by Eq. (1) of Schubert and Neesse (Schubert and Neesse, 1980) where the cut size (d_{50}) is inversely proportional to the underflow diameter (D_u).

As stated by many investigators (Ahmed et al., 2009; Farghaly et al.,2010; Plitt,1970) the increase in the underflow diameter decreases the cut size (d_{50}) according to the separation efficiency increases.

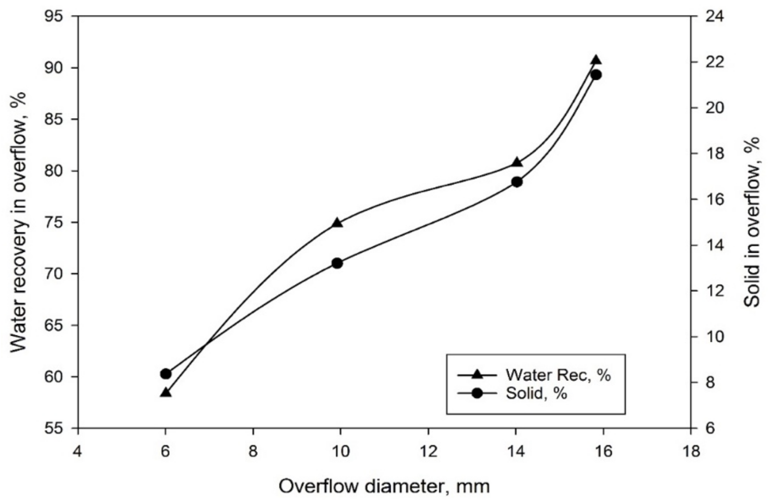

Fig. 8. Effect of overflow diameter on the water recovery and solid % in overflow at, P = 4.5 bar, D_u = 6 mm and D_i = 4 mm

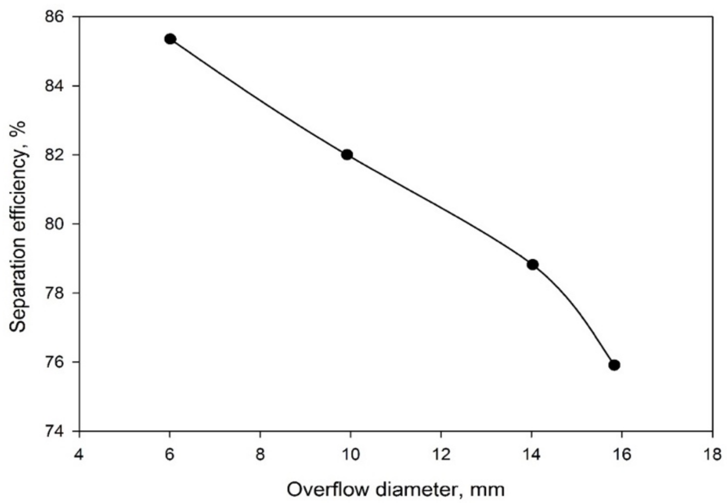

Fig. 9. Effect of overflow diameter on the separation efficiency at P = 4.5 bar, D_u = 6 mm and D_i = 4 mm

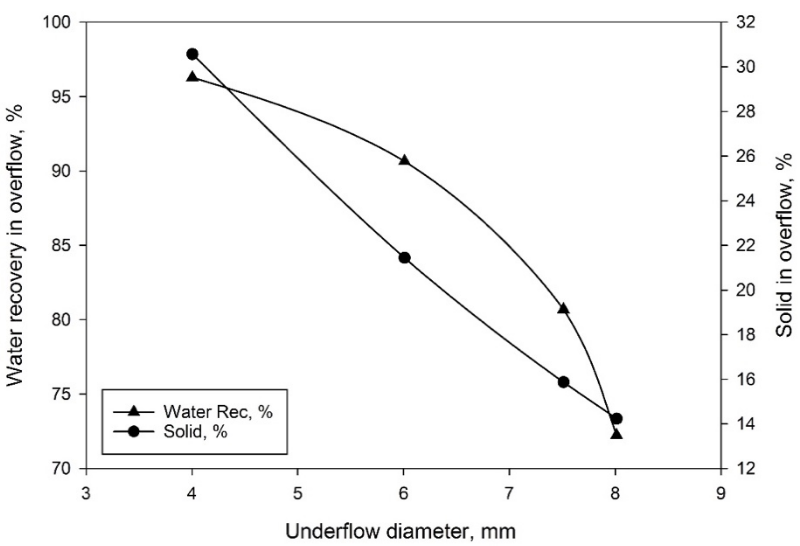

Fig. 10. Effect of underflow diameter on the water recovery and solid % in overflow at P = 4.5 bar, D_o = 15.8 mm and D_i = 4 mm

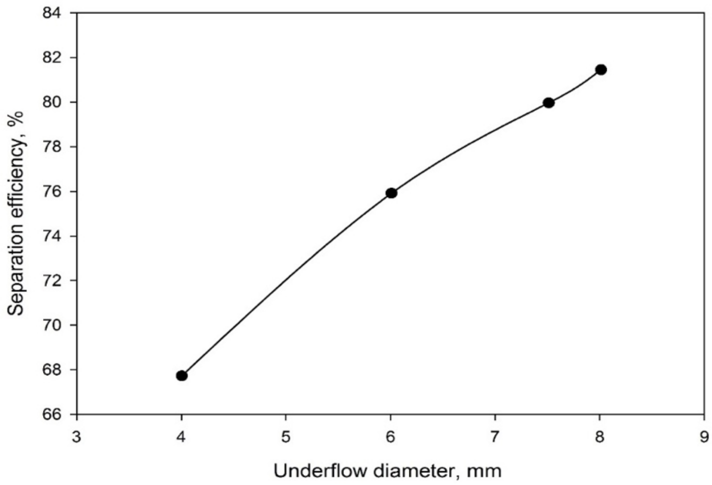

Fig. 11. Effect of underflow diameter on the separation efficiency at, p = 4.5 bar, D_o = 15.8 mm and D_i = 4 mm

3.1.1.5. Effect of feed solid content (C_S)

Fig. 12 and Fig. 13, show the effect of changing the feed solid content on the water recovery and solid % in overflow and the effect of changing the feed solid content on the separation efficiency respectively.

According to Dubey et al. (2017) the feed solid content directly affects the underflow discharge pattern. From Fig. 12 and Fig. 13, it can be seen that the overflow water recovery and separation efficiency decrease with increasing the feed solid content, while overflow solid recovery increases. As the feed content increases, underflow discharge pattern tends towards the roping condition or in other words, the discharge angle tends toward zero degrees (Dubey et al., 2017).

At higher feed solid content, particles' hindered settling condition prevails which does not conform to the Stokes' law and gravity force dominate the exit velocity profile. In dense flow separation (high solid content), more solids are stored in the conical part of the hydrocyclone and they are partially forced to the overflow. On the other hand, more water going to underflow. This result agrees with the results obtained by other investigators (Ahmed et al., 2009; Dubey et al., 2016; Dueck et al., 2014).

Based on the previous discussed results, the optimum conditions of the treatment process of the paper wastewater were as following (maximum water recovery with minimum solid % in overflow stream) were at feed pressure (P) = 4.5 bar, feed inlet diameter (D_i) = 4 mm, overflow diameter (D_o) = 15.8 mm, underflow diameter (D_u) = 6 mm and feed solid content (c_s)= 2.3 %.

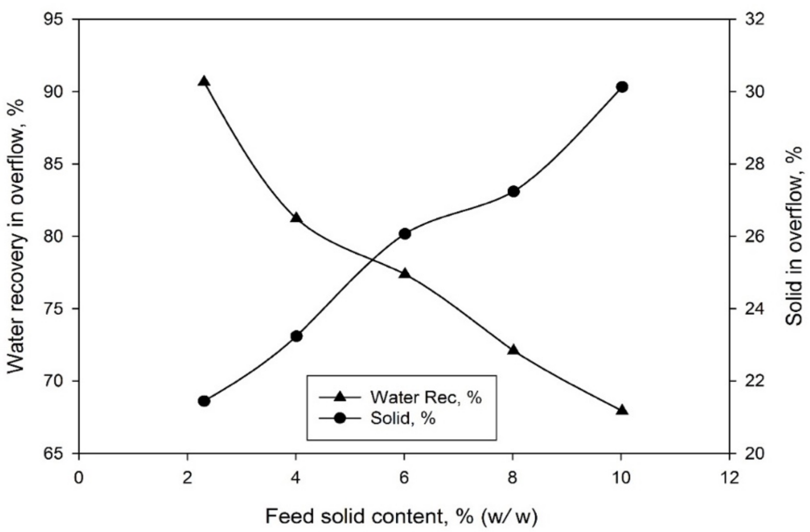

Fig. 12. Effect of feed solid content on the water recovery and solid % in overflow at P = 4.5 bar, D_o = 15.8 mm, D_u = 6 mm and D_i = 4 mm

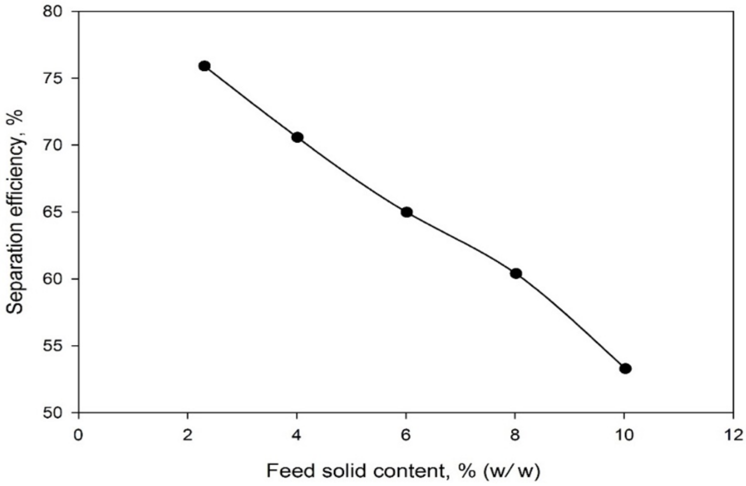

Fig. 13. Effect of feed solid content on the separation efficiency at P = 4.5 bar, D_o = 15.8 mm, D_u = 6 mm and D_i = 4 mm

3.1.2. Electro-coagulation process

In order to enhance the treatment process of paper industrial wastewater, the Electro-coagulation unit has been used after the hydrocyclone separation. The overflow stream which was produced by the hydrocyclone at the optimum conditions is fed to the Electro-coagulation unit at an operating voltage of 30 V and at an electric current of 1 Ampere for 10 min (Mahesh et al., 2016). The characterestics of the treated wastwater was carried out using the following units PH meter, BOD Trak (bottle), COD Reactor, Turbidity/Colorimetry, Density meter, TSS meter, DR 2010 Spectro photo meter, CG 855 Conductivity meter.

Table 3, shows the characteristics of the paper industrial wastwater before any treatment process (raw IWW), after the treatment process using only the 35 mm hydrocyclone and after treatment using the hydrocyclone and Electro-coagulation combination. From this table, it can be observed that the treatment process has a great potential to reduce the COD, BOD, TS, TSS, color and turbidity up to 98.2 %, 99.7 %, 99.8 %, 99.9%, 91.7 % and 96.8 % respectively.

Table 3. Characteristics of the IWW from paper industry before and after treatment process

Parameters	Raw IWW	After treatment by hydrocyclone only	After treatment by hydrocyclone Ec
PH	6.58	6.65	7.8
BOD, ($\mathbf{kg/m^3}$)	2.900	0.110	0.010
COD, ($\mathbf{kg/m^3}$)	0.650	0.121	0.012
TS, ($\mathbf{kg/m^3}$)	23.590	0.414	0.049
TSS, ($\mathbf{kg/m^3}$)	23.294	0.386	0.027
Oils and Grease, ($\mathbf{kg/m^3}$)	0.050	0.003	0.0003
Sulfides, ($\mathbf{kg/m^3}$)	0.010	0.006	0.00026
Phenols, ($\mathbf{kg/m^3}$)	Non	Non	Non
Phosphate, ($\mathbf{kg/m^3}$)	0.003	0.001	0.0001
Fe, ($\mathbf{kg/m^3}$)	0.007	0.0007	0.0003
Turbidity, (NTU)	498	84	16
Color,%	36	9	3

3.2. Tests using iron & metal forming and marble & granite industrial wastewater

In an attempt to investigate the treatment efficiency of the combined hydrocyclone-electrocoagulation process for iron and marble and granite industrial wastewaters, other experiments were carried out at the same optimum conditions which were obtained in the case of paper industry wastewater and the results are shown in Table 4.

From Table 4, it can be shown that the hydrocyclone has efficiently recovered about 90.58%, 90.02% and 89.5% from the treated water in paper, iron and marble and granite industries respectively. This would safe about 90% of the fresh water used daily in the production processes of the three tested industries.

The hydrocyclone overflow product of iron and marble industrial wastwater is then fed to the electro-coagulation unit. Table 5 shows the characteristics of the industrial wastewater of the paper, iron and marble and granite industries before treatment (raw IWW), after the treatment using only the hydrocyclone and after treatment using the combined hydrocyclone electro-coagulation. Table 5 shows also the allowed limits for safe discharge of the treated wastwater to the River Nile according to the standards of the Egyptian Ministry of Environment. It can also be seen that the combined hydrocyclone electrocoagulation process had efficiently treated the different types of industrial wastwater down to the acceptable limits of the Egyptian standards. The final treated water can also be reused again as a feed water in the industrial processes. This would safe more than 85% of the fresh water used in the production process in the three tested industries. Table 5 showed also that, compared with the hydrocyclone-treated wastewater, hydrocylone-electrocoagulation-treated wastewater was found to be closer to the acceptable limits of the Egyptian standards of wastewater safe discharge

Table 4. Characteristics of overflow product and separation efficiency obtained at the optimum operating conditions of the 35 mm hydrocyclone using paper industry, iron industry and marble industry

Parameters	paper industry industry	Iron	Marble industry
Overflow water recovery	90.58	90.02	89.5
Overflow solid %	21.45	10.03	11.8
Separation efficiency ($\boldsymbol{E_S}$)	75.92	88.62	85.5

4. Conclusions

The present study showed that the combined hydrocyclone-electrocoagulation has efficiently treated the industrial wastewater resulting from the paper, iron and metal forming and marble and granite industries. Using the suspension feed of paper industry wastewater, the following optimum conditions of the hydrocuclone were achieved ($P = 4.5$ bar, $D_O = 15.8$ mm, $D_u = 6$ mm, $D_i = 4$ mm and $c_s = 2.3$ %). At these conditions an overflow with 90.58 % water recovery, 21.45 % solid % and 75.92 % separation efficiency was obtained. The characteristics of the treated water of the paper industry was highly enhanced by using electro-coagulation process after the hydrocyclone treatment. Chemical analysis of the final treated wastewater showed that the combined hydrocyclone-electrocoagulation process had efficiently treated the three different types of industrial wastwater down to the acceptable limits of the Egyptian standards and reduced COD, BOD, TS, TSS, colour and turbidity up to 98.3 %, 99.7 %, 99.8 %, 99.9%, 91.7 % and 96.4 % respectively. Accordingally, the final treated water can be safely discharged or reused again as a feed water in the industrial processes. This would safe about 90% of the fresh water used daily in the production processes at the three investigated industries. In addition, compared with the hydrocyclone-treated wastewater, hydrocylone-electrocoagulation-treated wastewater was found to be more enhanced. This study confirmed that hydrocyclone-electrocoagulation is a promising method for the treatment of high-COD-containing wastewater, and it possesses great potential for wide range of industrial wastewater types.

Acknowledgments

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Table 5. Characteristics of the IWW of paper industry, iron industry and marble industry before treatment, after only hydrocyclone treatment, after combined hydrocyclone-electrocoagulation treatment and the allowable limits of wastwater discharg to the River Nile

Parameters	Paper industry			Iron industry			Marble and Granite industry			The allowed limits for the discharge of IWW to River Nile, according to Egyptian Ministry of Environment
	Raw IWW	After treatment by hydrocyclon e only	After treatment by hydrocyclone Ec	Raw IWW	After treatment by hydrocyclon e only	After treatment by hydrocyclone Ec	Raw IWW	After treatment by hydrocyclon e only	After treatment by hydrocyclone Ec	
PH	6.58	6.65	7.8	6.3	6.5	7.6	7.6	7.6	7.8	6 - 9
BOD, (kg/m^3)	2.900	0.110	0.010	0.081	0.039	0.010	0.0997	0.0468	0.011	0.030
COD, (kg/m^3)	0.650	0.121	0.012	0.361	0.050	0.012	0.215	0.0409	0.013	0.040
TS, (kg/m^3)	23.590	0.414	0.049	20.190	0.215	0.039	35.040	0.352	0.048	1.200
TSS, (kg/m^3)	23.294	0.386	0.027	0.547	0.0998	0.023	11.260	0.175	0.025	0.030
Oils & Grease, (kg/m^3)	0.050	0.003	0.0003	0.100	0.0021	0.0003	0.0029	0.0021	0.0002	0.005
Sulfides, (kg/m^3)	0.010	0.006	0.00026	Non	Non	Non	0.0121	0.0057	0.0003	0.0001
Phenols, (kg/m^3)	Non	Non	Non	Non	Non	Non	Non	Non	Non	0.000002
Phosphate, (kg/m^3)	0.003	0.001	0.0001	Non	Non	Non	0.0051	0.0018	0.0001	0.001
Fe, (kg/m^3)	0.007	0.0007	0.0003	0.023	0.0006	0.0003	0.0036	0.0007	0.0003	0.001
Turbidity, (NTU)	498	84	16	103	73	19	492	80	17	50
Color, %	36	9	3	13	8	2.5	49	10	3	3

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