Research of novel process route and scale-up based on oil-water separation flotation column

Gen Huang, Hongxiang Xu, Lun Wu, Xiaobing Li and Yongtian Wang

ABSTRACT

A novel process 'coalescence-airflotation-carrier preferential adsorption' utilising an oil-water separation flotation column with a unique structure was used in the oil-water separation field. The oil-water separation flotation column contains the cyclonic separation and airflotation separation which has advantages in oily sewage treatment, especially in polymer-flooding-drive oily sewage treatment. In this paper, different dimensions of flotation column with 1 $m^3\ d^{-1}$, 30 $m^3\ d^{-1}$ and 2,000 $m^3\ d^{-1}$ oil-water separation systems were investigated. In addition, several operating parameters which impact separation, such as feeding speed, aeration rate, circulating pressure, adsorbents consumption and frother consumption were also investigated. The optimum operating parameters determined for 1 $m^3\ d^{-1}$ the oil-water separation flotation column were a feeding speed of 0.042 $m^3\ h^{-1}$, an aeration rate of 0.10 $m^3\ h^{-1}$, a coal consumption of 4 (g coal)·(g oil)$^{-1}$, a frother consumption of 10 mg L^{-1}, and a circulating pressure of 0.12 MPa. The novel process cost reduced 55.8% than conventional two-stage airflotation process. In the 2,000 $m^3\ d^{-1}$ oil-water separation experiment, the oil concentration and the oil removal efficiency of outlet are 23.39 mgL^{-1}, 97.70%, respectively. Sediment is not produced during the oily sewage treatment using the novel process and flotation column.

Key words | carrier preferential adsorption process, coalescence-airflotation process, fine coal, flotation, oil-water separation flotation column

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NOMENCLATURE

g_l feeding speed ($m^3{\cdot}h^{-1}$)
q_g aeration rate ($m^3{\cdot}h^{-1}$)
p circulating pressure (MPa)

INTRODUCTION

Currently, many domestic oilfields are in the medium, high or extra-high water cut stage of the mid-to-late petroleum exploitation period, where polymer flooding and ternary complex flooding have been widely applied in the oilfield (Tavera *et al.* 2001; Emamjomeh & Sivakumar 2009; Watcharasing *et al.* 2009). Thus, oily sewage treatment has become a key issue in the oilfield industry with particular regard to environment protection (Rubio *et al.* 2002; Capponi *et al.* 2006; Li *et al.* 2007). In recent years, the technology of cyclonic separation and airflotation have been extensively applied to oilfield ground engineering (Wang 1999), but the oily sewage treatment effect is unsatisfied by the separate use of either cyclonic separation or airflotation (Du 1999; Gao 2000; Zhu *et al.* 2001). An oil-water separation flotation column with a unique structure has been introduced to the oil-water separation field (Watcharasing *et al.* 2008) and has shown a great advantage in oil-water

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separation because of the synergistic effect between the cyclonic separation and airflotation (Park *et al.* 2006). The coalescence-airflotation-carrier preferential adsorption process has been introduced to the oil-water separation field (Li *et al.* 2010).

The oil-water separation flotation column is a complicated separation process comprising of both commonly used cyclonic and airflotation separations. The oil-water separation efficiency of a flotation column consists of the cyclonic separation section and airflotation section, which are significant in the further improvement the oil-water separation efficiency of the oil-water separation flotation column (Gu & Chiang 1999; Tang *et al.* 2000; Ran *et al.* 2013).

OIL-WATER SEPARATION FLOTATION COLUMN

Structure

The multi-flow patterns and the structure of the oil-water separation flotation column are shown in Figure 1. The oil-water separation flotation column is a combination of a flotation column and a common static hydraulic cyclone. The main components are a cylinder, a circulating pump, a bubble generator and a sieve plate. The brown color section shown in the middle of the column in Figure 1 is filled with the coalescent pack.

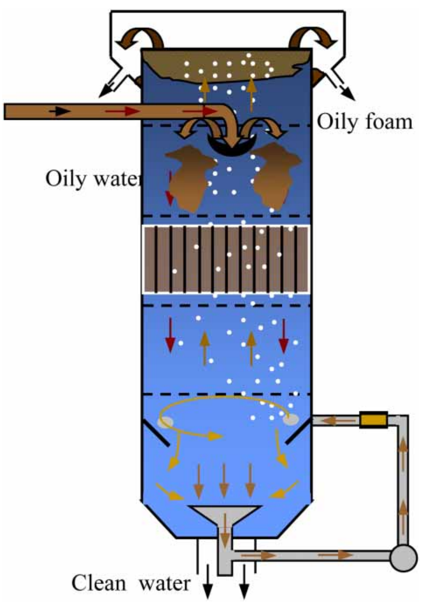

Figure 1 | Cyclone-static microbubble flotation column (ZL 201020164545.3). Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wrd.2017.090.

Process

The experimental system connections are shown in Figure 2. The experimental system includes the flotation column separation system and measurement control system. The measurement control system is composed of the gas flow meter, liquid flow meter, electric control valve, Pid digital regulator, and gas holdup meter. The automatic control system for the liquid surface of the flotation column is composed of the pressure transmitter, electronic control valve for straight travel, and Pid digital regulator.

As Figure 2 shows, oily sewage is either pumped or flows automatically into the flotation column. The clean water which is separated by flotation is discharged from the bottom of the flotation column, the oily scum which is composed of oil, bubble, oil-bubble complex and suspended solids (SS) is collected by foam tank and then discharged. Droplets with good floatability are effectively separated at the column flotation stage. The droplets of poorer floatability get into the bottom of the column prior to cyclone separation, whereupon they are pulled out tangentially by the circulating pump, through a connecting line and bubble generator, into the middle of the column. These droplets have high collision probability with bubble due to the pipe flow coalescence and cyclone separation effect, resulting in separation with stepwise intensification and multi-flow patterns on the oil-water separation.

The droplets are also coalesced when they pass through the sieve plate in flotation column. The effect is improved oil-water separation. The emulsification oil droplets are transported from the cyclone separation zone to the airflotation separation zone by the oil-gas complex which formed through the transportation role of the microbubbles, the oil-water separation has finished (Moruzzi & Reali 2010). The airflotation separation area has a static separation effect of the 'long and narrow' environment with 'quiet' fluid dynamics (Xu *et al.* 2014).

The oil-water separation flotation column is integrated with the cyclonic and flotation separation technology (Lee

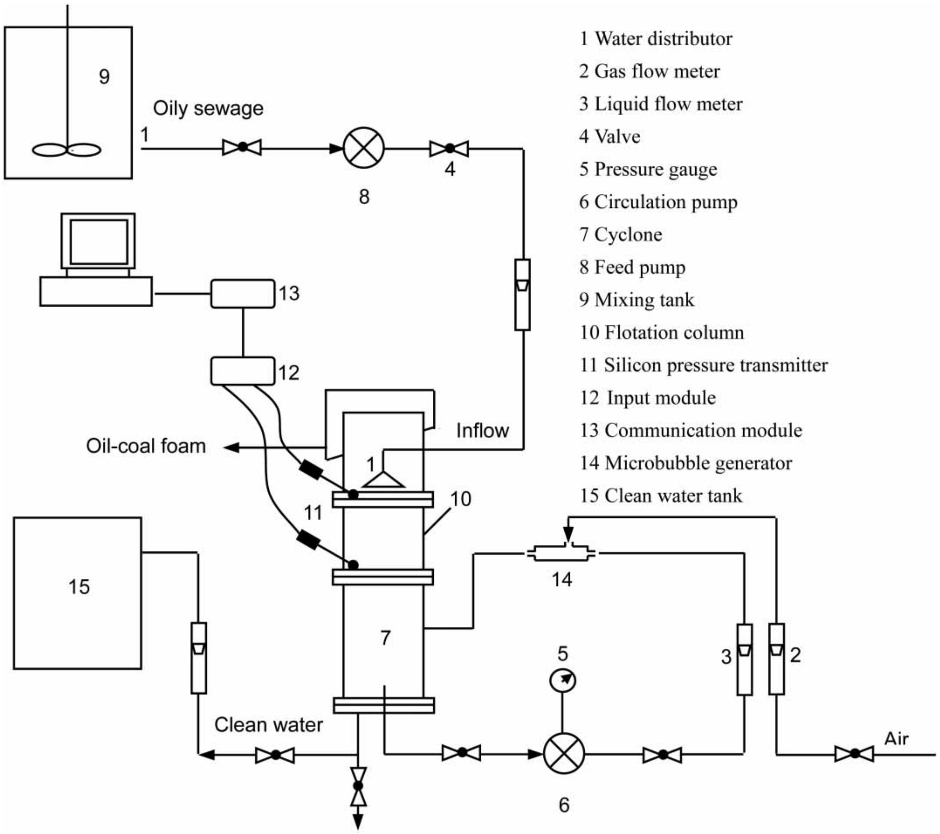

Figure 2 | The diagram of experimental equipment connections.

et al. 2007). In addition, the synergistic effect of multiple separation modes reinforces the separation effect and expands the size range of the oil concentration in the oily sewage for flotation separation. The advantages of the oil-water separation flotation column compared with the common hydraulic cyclone and common flotation column are the low effective flotation size, short separation time, large handling capacity and low operating cost.

METHODS

Experimental method

In the experiment, the oil removal efficiency was used to evaluate the oil-water separation efficiency of the flotation column. Samples were taken from the sampling point of the feeding port, the sampling point of purified underflow outlet, and the oil concentration at these three points is C_1 (oil concentration of inlet, mg L^{-1}) and C_2 (oil concentration of outlet, mg L^{-1}). The SS concentrations are m_1 and m_2 for the SS concentration at the inlet and outlet, respectively.

The oil removal efficiency R_1 is:

$$R_1 = \left(1 - \frac{C_1}{C_2}\right) \times 100\% \quad (1)$$

The SS removal efficiency R_2 is:

$$R_2 = \left(1 - \frac{m_1}{m_2}\right) \times 100\% \quad (2)$$

The oil concentration was measured using UV-4802S by ultraviolet spectrophotometer method (Zhu et al. 2012). Petroleum ether was used as extraction agent. The 256 nm wavelength was used in the spectrophotometer UV method. The working curve method was applied to the determination and blank solution was used as reference (Pang et al. 2002).

1 m^3 d^{-1} Oil-water separation experimental system

The flotation column in this experimental system has a diameter of 100 mm, height of 2,000 mm, and is made of stainless steel.

Firstly, the oily sewage from the primary separation tank entered into the mixing tank and its flow was regulated. The sorbent of powder coal (2% of concentration) also entered into the mixing drum by pump. After fully mixing, the inflow was supplemented from the mid-upper part of the flotation column via the feeding pump with feeding speed g_l (m^3 h^{-1}). Finally, the outflow was drained from the bottom of the flotation column via the control valve. The aeration rate, q_g (m^3 h^{-1}), was measured and regulated by the gas flowmeter and the circulating pressure, p (MPa), was regulated by adjustment of the circulating pump speed (Liu et al. 2013). The experimental equipment connections and experimental system are shown in Figures 2 and 3, respectively.

30 m^3 d^{-1} Oil-water separation experimental system

The 30 m^3 d^{-1} oil-water separation experimental system is shown in Figure 4. The flotation column in this experimental system has a diameter of 400 mm, height of 4,000 mm, and is made of stainless steel. The experimental set-up includes the flotation column separation system, measurement control system and liquid level automatic control system. The measurement control system is composed of the gas flowmeter, liquid flowmeter and gas holdup meter. Liquid level automatic control system contains electric control valve, Pid digital regulator and pressure transmitter.

Figure 4 | 30 m^3 d^{-1} Oil-water separation experimental system.

Figure 3 | 1 m^3 d^{-1} Oil-water separation experimental system.

The process on flotation column

Step 1 – Experimental system of the coalescence-airflotation process on the flotation column

The flotation column in this experimental system has a diameter of 100 mm, height of 2,000 mm, and is made of stainless steel.

The experimental system of the coalescence-airflotation process is the same as 30 m^3 d^{-1} oil-water separation experimental system, but the flotation column in this system is filled by coalescent pack which is shown in Figure 5. The

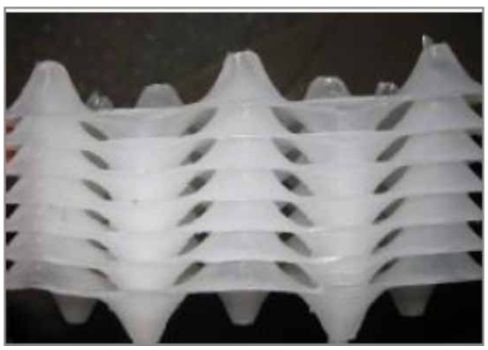

Figure 5 | Coalescent pack of flotation column.

coalescent is filled in the brown color section shown in the middle of the column in Figure 1. The operational parameters are shown in Table 1.

Step 2 – The experimental system of coalescence-airflotation-carrier preferential adsorption process on flotation column

As shown in the results of the preliminary research, the coalescence-airflotation process is good for removing large oil droplets, but is not good for small oil droplets. The oil concentration at the outlet is in the range from 100 to 200 mg L^{-1} and so cannot meet the requirement for reinjection. In the carrier preferential adsorption process, coal consumption is proportional to the oil concentration at the inlet, so the coal consumption is large when the oil concentration of the inlet is high. On this basis, the proposal has arisen to combine the respective advantages of both the coalescence-airflotation process and the preferential-carrier-adsorption process, using a combined system within the flotation column.

The combined coalescence-airflotation-preferential-carrier-adsorption process using flotation columns is shown in the Figure 6. Firstly, the oily sewage, with or without a little frother, entered into the first mixing tank as the feeding sewage of the primary coalescence-airflotation process using the first flotation column. After flotation separation and coalescence oil removal, the oily scum (which is composed of oil, bubble, oil-bubble complex and SS) is collected by foam tank and then discharged. The effluent water of the primary coalescence-airflotation process with the sorbent (powder coal) then entered into the second mixing tank, to undergo the carrier-preferential adsorption process using the second flotation column, and after fully mixing was pumped into the flotation column. After thorough flotation separation, coalescence oil removal and carrier-preferential adsorption, the oily scum composed of oil, powder coal, bubble, oil-bubble complex and SS is collected by foam tank and then discharged. The clean water is discharged from the bottom of the second flotation column.

The operational parameters for the process of coalescence-airflotation-carrier preferential adsorption are shown in Table 2.

Table 1 | The operational parameters of the coalescence-airflotation process

The feeding rate q_l ($m^3\ h^{-1}$)	The circulating pressure P (MPa)	Aeration rate q_g ($m^3\ h^{-1}$)
1.25	0.20	1.5

2,000 $m^3\ d^{-1}$ Oil-water separation industrial experimental system

Based on the research results, the coalescence-airflotation-carrier-preferential adsorption process was used in the 2,000 $m^3\ L^{-1}$ oil-water separation industrial experimental system. The 2,000 $m^3\ L^{-1}$ industrial system diagram of the process is shown in Figure 7. The whole industrial system includes the coalescence-airflotation separation system, the carrier preferential adsorption separation system, and an adsorbent preparation system and pressure filtration

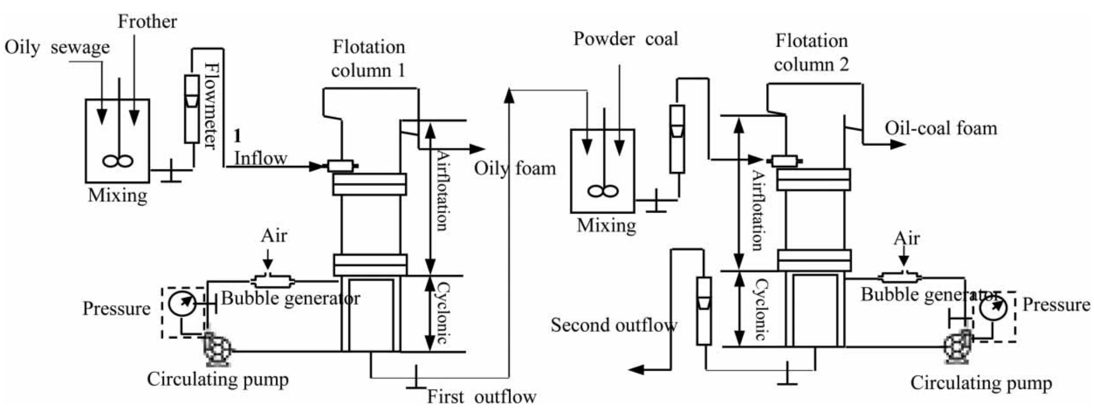

Figure 6 | The combined process of coalescence-airflotation-carrier preferential adsorption.

Table 2 | The operational parameters for the combined system on the flotation column

Feeding rate q_1 ($m^3\ h^{-1}$)	Circulating pressure p (MPa)	Aeration rate q_g ($m^3\ h^{-1}$)	Fine coal consumption (g coal)·(g oil)$^{-1}$	Frother dosage L min^{-1}
1.25	0.20	2.0	2.0	10.0

dewatering system. The key piece of equipment of coalescence-airflotation separation and carrier-preferential-adsorption separation systems is oil-water separation flotation column. Main technical index and structural parameters of the flotation column are shown in Table 3.

RESULTS AND DISCUSSION

Results of 1 $m^3\ d^{-1}$ oil-water separation experimental

Operational parameter optimization

This paper has investigated the impact of the factors, including feeding speed, aeration rate, circulating pressure, frother consumption and powder coal consumption, on the oil/water separation efficiency. The results are shown in Figure 8.

As shown in the Figure 8(a), with the increasing circulating pressure, the oil removal efficiency will gradually increase. When the circulating pressure reaches a certain value, the oil removal rate reaches a maximum; pressure continues increasing, and the oil removal efficiency then begins to fall. When the circulating pressure continues to increase with the power frequency, the centrifugal intensity becomes larger; so as the oil droplet is under a larger shearing force, small oil droplets are more easily formed and the cyclonic separation effect is adversely impacted, with those small oil droplets lack of powder coal for adsorption. The circulating pressure determined by the test is 0.28 MPa.

As shown in the Figure 8(b), with the increasing aeration rate, the oil removal efficiency increases initially and then decreases. The number of oil-bubble complexes is the key factor in the oil-water separation process. The high collision probability between oil drops, bubbles and powder coal increases the number of oil-bubble-coal complexes. When the aeration rate was under 0.1 $m^3\ h^{-1}$, the number of bubbles increases in the aeration section. The oil removal efficiency continuously increases and the oil concentration of the underflow outlet decreases because the collision probability between bubbles and oil droplets increases. After the aeration rate increased to 0.1 $m^3\ h^{-1}$, as the coalescence of bubbles in the cyclonic trends to tempestuous, the smaller diameter bubbles with the bigger capacity to capture oil droplets continuously decreases, thus the number of oil-bubble-coal complexes is reduced. Therefore, the oil removal efficiency decreases. The aeration rate determined by the test is 0.1 $m^3\ h^{-1}$.

Figure 7 | 2,000 $m^3\ d^{-1}$ Industrial experimental system.

Table 3 | Main technical index and structural parameters of the flotation column

Processing capacity ($m^3\ d^{-1}$)	2,000
Flotation column dimension(mm)	Ø 2,900 × 6,800
Diameter (mm)	2,000
Mixing tank dimension (mm)	Ø 2,000 × 4,700
Oily sewage	Oil concentration ≤3,000 mg/L SS concentration ≤200 mg/L
Circulating pump	Flow rate Q = 150 m^3/h Hydraulic head H = 40 m
Circulating pressure (MPa)	0.15–0.35
Residence time (min)	14

As shown in Figure 8(c), with increasing powder coal consumption, the oil removal efficiency showed a decreasing trend. With the increasing of powder consumption, the adsorption probability between the oil droplets and powder coal increases. This is advantageous for oil-water separation. Considering the requirements and cost, powder coal consumption determined by the test is 4 $g_{coal}\ g_{oil}^{-1}$.

As shown in Figure 8(d), with increasing frother consumption, the oil removal efficiency tended to increase, but decreased after the frother consumption was more than 15 mg L^{-1}. After adding the frother, the bubble size reduces and the bubble quantity increases and the collision probability between bubbles, oil droplets and powder coal increases. The frother can also increase the quantity of the hydrophobic groups of the oil droplets flocs, so the adhesive quantity and quality of the bubble were enhanced and the flotation effect was improved. However, after frother consumption was more than 15 mg L^{-1}, this generates too many microbubbles which has a negative influence on the flow condition of the flotation column, so the separation efficiency decreases. The frother consumption determined by the test is 10 mg L^{-1}.

As shown in Figure 8(e), with increasing feeding speed, the oil removal efficiency showed a decreasing trend. On increasing feeding speed, the collision probability between the oil droplets and bubble reduces since the separation time of oil-water coalescence is gradually shorted. This is a disadvantage of oil-water separation. The proper feeding flow determined by the test is 0.042 $m^3\ h^{-1}$.

Result of continuous operation experiment

Based on the operation parameters optimization, the 48 hours of continuous operation experiment was investigated for researching the reliabilities of the flotation column (Ø 100 mm × 2,000 mm) and the process. Water samples were taken every two hours, the water samples at the inlet and outlet were taken at the same time. The SS concentrations of inlet samples were tested every 16 hours and were 106, 74 and 84 mg L^{-1}.

The circulating pressure was 0.12 MPa, the feeding rate was 0.042 $m^3\ h^{-1}$, the powder coal consumption was 4 $g_{coal}\ g_{oil}^{-1}$, the frother dosage was 10 mg L^{-1}, and the experiment temperature was 20 °C. The results are shown in Figure 9. The results of the polymer retention effect are shown in Table 4.

As shown in Figure 9, the average oil concentration at the inlet was 1,364.14 mg L^{-1}, the average SS concentration at the inlet was 88.00 mg L^{-1}. After the oil-water separation using flotation column, the average oil concentration at the outlet was 22.24 mg L^{-1} and the average SS concentration at the inlet was 29.59 mg L^{-1}. The efficiencies of oil removal and SS removal were 98.37% and 66.38%, respectively. According to Table 4, the powder coal cannot remove all the polymers, most of the polymers are retained in the outlet water. So the adsorption of powder coal has selectivity, good adsorption efficiency for hydrocarbons (such as oil droplets), good adsorption efficiency for polymers and SS. According to the continuous experiment results, the process and flotation column can be used on the oily sewage treatment.

Results of 30 $m^3\ d^{-1}$ oil-water separation experiment

Based on the results of the 1 $m^3\ d^{-1}$ oil-water separation experiment, a 30 $m^3\ d^{-1}$ oil-water separation continuous operation experiment was investigated for researching the reliabilities of the flotation column (Ø 400 mm × 4,000 mm) and the process. Water samples were taken every two hours, the water samples at the inlet and outlet were taken at the same time.

The circulating pressure was 0.16 MPa, the feeding rate was 1.25 $m^3\ h^{-1}$, the powder coal consumption was 2 $g_{coal}\ g_{oil}^{-1}$, the frother dosage was 10 mg L^{-1}, the

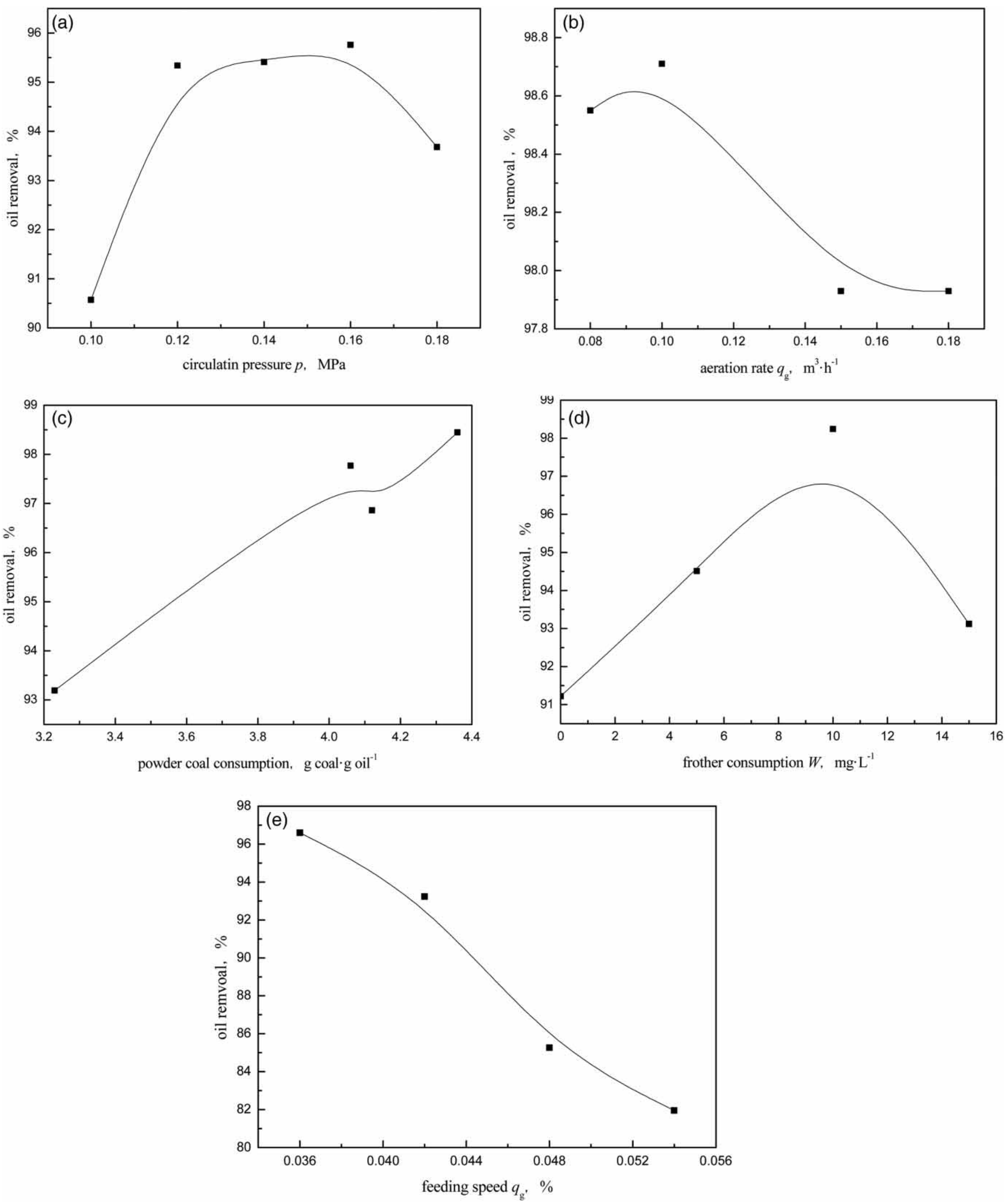

Figure 8 | The operational parameters impact on the oil/water separation efficiency.

experiment temperature was 20 °C. The experiment results are shown in Figure 10. The comparison between inlet and outlet samples is shown in Figure 11.

As shown in Figure 10, the water treatment effect is better than 30 $m^3\ d^{-1}$ oil-water separation system. The average oil concentration at the outlet was 10.04 $mg\ L^{-1}$, the

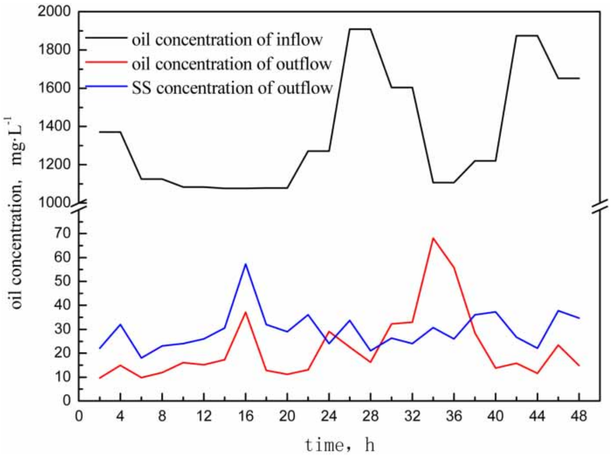

Figure 9 | The result of continuous operation experiment (1 m^3 d^{-1}, 48 hours).

Table 4 | The efficiency of polymer retention

No.	Inlet (mg L^{-1})	Outlet (mg L^{-1})	Retention rate (%)
1	107	56	52.3
2	112	63	56.2
3	120	73	60.8
Average	113	64	56.6

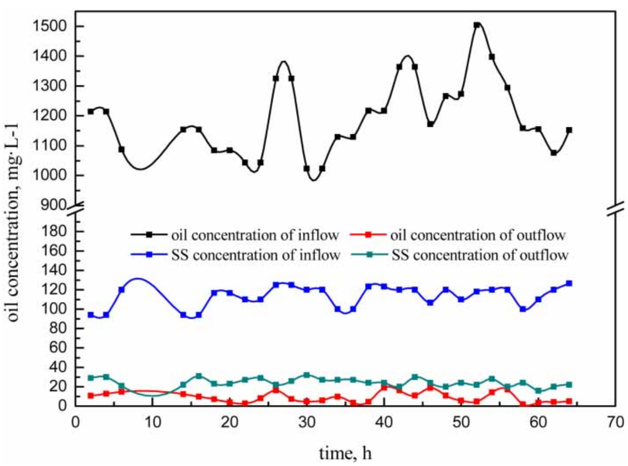

Figure 10 | The results of the 30 m^3 d^{-1} oil-water separation experiment.

average SS concentration at the outlet was 25.56 mg L^{-1}. The efficiencies of oil removal and SS removal were 99.14% and 76.88%, respectively. The two indexes meet the reinjection requirements of local oil deposits.

Figure 11 | Comparison between inflow and outflow samples.

Results of process experiments

Coalescence-airflotation process on flotation column

The circulating pressure was 0.16 MPa, the feeding rate was 1.25 m^3 h^{-1}, the frother dosage was 10 mg L^{-1}, experiment temperature was 20 °C. The experiment results are shown in Table 5.

As shown in Table 5, after the oily sewage was treated by the coalescence-airflotation process using the flotation column, the average oil concentration of the outlet samples was 263.05 mg L^{-1}, the average SS concentration of outlet samples was 47.33 mg L^{-1}. The efficiency of oil removal is more than 90% and SS removal efficiency reached 66.19%. So the coalescence-airflotation process by first using a flotation column in an industrial experiment was introduced and used to recycle the oil as much as possible.

Table 5 | The results of the coalescence-airflotation process on the flotation column

Sample	Oil concentration/ (mg L^{-1})	Oil removal efficiency (%)	SS concentration/ (mg L^{-1})	SS removal efficiency (%)
Inlet	2,873.86	/	140	/
Outlet 1	250.88	91.27	44.00	68.57
Outlet 2	270.43	90.59	48.00	65.71
Outlet 3	267.84	90.68	50.00	64.29
Outlet average	263.05	90.85	47.33	66.19

The system of coalescence-airflotation-carrier preferential adsorption process on flotation column

The circulating pressure was 0.16 MPa, the feeding rate was 1.25 $m^3\ h^{-1}$, the powder coal consumption was 2 $g_{coal}\ g_{oil}^{-1}$, the frother dosage for second flotation column was 10 $mg\ L^{-1}$, the experiment temperature was 20 °C. The experiment results are shown in Figure 12.

Cost comparison

A cost comparison between the coalescence-airflotation-carrier preferential adsorption process and a conventional two-stage airflotation process is shown in Table 6. The following conditions were applied: treatment capacity of 30 $m^3\ d^{-1}$, coagulant of poly-aluminium chloride consumption is 600 $mg\ L^{-1}$, flocculent of polyacrylamide consumption is 1 $mg\ L^{-1}$.

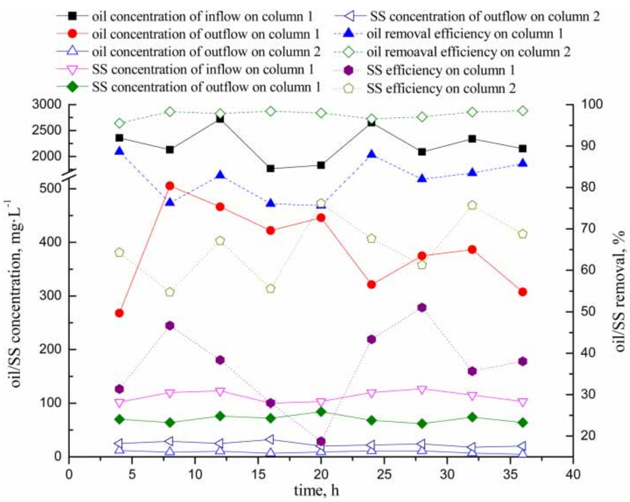

Figure 12 | Results of coalescence-airflotation-carrier preferential adsorption process experiment.

It can be seen from the Table 6, the cost of the coalescence-airflotation-carrier preferential adsorption process using a flotation column reduced the cost by 55.8% compared with a conventional two-stage airflotation process.

Results of 2,000 $m^3\ d^{-1}$ oil-water separation experiment

The circulating pressure was 0.16 MPa, the feeding rate was 83.0 $m^3\ h^{-1}$, the powder coal consumption of column 2 was 1 $g_{coal}\ g_{oil}^{-1}$, the experiment temperature was 20 °C. After the industrial experiment entered a stage of stable operation, the water samples were taken for four days. The experiment results are shown in Table 7.

As shown in Table 7, the average oil concentration of inlet samples was 1,017.18 $mg\ L^{-1}$, the average oil concentration of outlet samples through coalescence-airflotation process and carrier preferential adsorption process were 101.51 $mg\ L^{-1}$ and 23.39 $mg\ L^{-1}$, respectively. The total oil removal efficiency was 97.70%. It can be seen from Figure 13, the bubble size of column 1 is smaller than column 2 because the powder coal which makes the small bubbles has a greater probability of forming bigger oil-coal-bubble complexes.

With the scaling up of the flotation column, all of the oil removal efficiencies were more than 95%, so the oil-water separation flotation column has good stability and oil removal efficiency. The flotation column using the

Figure 13 | Oil-bubble complexes of column 1 and oil-coal-bubble complexes of column 2.

Table 6 | The cost comparison (unit, RMB yuan m^{-3})

Process name	Electric charge	Agent cost	Sediment treatment cost	Total cost
Coalescence-airflotation-carrier preferential adsorption process	1.04	0.06	0	1.10
Conventional two-stage airflotation process	0.30	1.81	0.38	2.49

coalescence-airflotation-carrier preferential adsorption process provides a new and good way to treat the oily sewage.

CONCLUSIONS

The coalescence-airflotation-carrier preferential adsorption process and oil-water separation flotation column were introduced to solve the problem which can arise during polymer-oily sewage treatment, namely that at high oil concentrations, large numbers of fine oil droplets can result in serious emulsification. The 1, 30 and 2,000 $m^3 d^{-1}$ oil-water separation systems were tested. The conclusions as follows.

The coalescence-airflotation-carrier preferential adsorption process is a novel water treatment process. This process arose from carrier flotation of mineral flotation. Powder coal as a carrier adsorbs the oil droplets which include large, fine and emulsified oil droplets in oily sewage. Thereafter the oil-coal complexes can be separated from oily sewage by airflotation. The process contains two stages: the coalescence-carrier preferential adsorption and the airflotation separation stage.

The oil-water separation flotation column is novel equipment. It is integrated with cyclonic and flotation separation technology. In addition, the synergistic effect of multiple separation modes reinforces the separation effect and expands the range of oil concentrations in the oily sewage suitable for flotation separation.

According to the results of the 1, 30 and 2,000 $m^3 d^{-1}$ oil-water separation system experiments, the coalescence-airflotation-carrier preferential adsorption process using a

Table 7 | Result of 2,000 $m^3 d^{-1}$ oil-water separation experiment for four days

	Column 1			Column 2	
Sample time	Oil concentration at inflow (mg L^{-1})	Oil concentration at outflow (mg L^{-1})	Oil removal efficiency (%)	Oil concentration at outflow (mg L^{-1})	Oil removal efficiency (%)
4:00	1,088.17	115.52	89.38	13.20	88.57
13:00	1,195.65	200.00	83.27	28.80	85.60
18:00	1,126.70	140.52	87.53	29.02	79.35
23:00	923.34	125.08	86.45	15.99	87.22
6:00	1,259.05	106.82	91.52	43.45	59.32
12:00	570.58	72.30	87.33	20.75	71.30
17:00	500.00	42.23	91.55	14.06	66.71
23:00	706.17	21.66	96.93	11.00	49.22
3:00	820.11	114.51	86.04	15.76	86.24
10:00	1,267.28	95.29	92.48	41.11	56.86
16:00	848.21	66.09	92.21	9.15	86.16
23:00	829.43	131.40	84.16	14.37	89.06
6:00	928.57	118.68	87.22	26.79	77.43
10:00	1,612.72	63.01	96.09	24.23	61.55
18:00	1,976.19	119.16	93.97	44.83	62.38
23:00	622.65	91.84	85.25	21.78	76.28
Average	1,017.18	101.51	89.46	23.39	73.95

flotation column has good reliability, stability and efficiency.

The oil removal efficiency is very good. In the 2,000 m^3 d^{-1} oil-water separation experiment, when the oil concentration of feed oily sewage is in the range 1,000 to 2,000 mg L^{-1}, the oil concentration and the oil removal efficiency at the outlet are 23.39 mg L^{-1} and 97.70%, respectively.

Finally, sediment is not produced during the oily sewage treatment using this novel process and flotation column. This is better in terms of both the environment and cost. The cost was reduced by 55.8% compared with a conventional two-stage airflotation process.

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REFERENCES

Capponi, F., Sartori, M., Souza, M. L. & Rubio, J. 2006 Modified column flotation of adsorbing iron hydroxide colloidal precipitates. *Int. J. Miner. Process.* **79**, 167–173.

Du, Y. B. 1999 Development of jet flotation device. *Oil-Gas Field Sur. Eng.* **18**, 32–35.

Emamjomeh, M. M. & Sivakumar, M. 2009 Review of pollutants removed by electro coagulation and electrocoagulation/flotation processes. *J. Environ. Manage.* **90**, 1663–1679.

Gao, G. C. 2000 A new type of oily sewage treatment equipment-jet flotation device. *China Offshore Oil and Gas (Eng.)* **12**, 57–59.

Gu, X. Q. & Chiang, S. H. 1999 A novel flotation column for oily water cleanup. *Sep. Purif. Technol.* **16**, 193–203.

Lee, B. H., Song, W. C. & Kim, H. Y. 2007 Enhanced separation of water quality parameters in the DAF (dissolved air flotation) system using ozone. *Water Sci. Technol.* **56** (10), 149–155.

Li, X. B., Liu, J. T., Wang, Y. T., Cao, Y. J. & Zhou, X. H. 2007 Separation of oil from wastewater by column flotation. *China Univ. Min. Technol.* **17**, 546–551.

Li, X. B., Zhang, C. J. & Liu, J. T. 2010 Adsorption of oil from waste water by coal: characteristics and mechanism. *Min. Sci. Technol.* **20**, 0778–0781.

Liu, J. T., Xu, H. X. & Li, X. B. 2013 Cyclonic separation process intensification oil removal based on microbubble flotation. *Int. J. Min. Sci. Technol.* **23**, 415–422.

Moruzzi, R. B. & Reali, M. A. P. 2010 Characterization of micro-bubble size distribution and flow configuration in DAF contact zone by a non-intrusive image analysis system and tracer tests. *Water Sci. Technol.* **61** (1), 253–262.

Pang, Y. H., Ding, Y. S. & Gong, W. M. 2002 Study of measurement of oil in water using UV spectrum. *Journal of Dalian Maritime University* **11**, 68–71.

Park, K. H., Lee, J. H., Bae, B. H., Kim, Y. H. & Choung, Y. K. 2006 Use of hydrocyclone and flotation column for reducing the volume of contaminated dredged material. *Water Sci. Technol.* **53** (7), 151–157.

Ran, J. C., Liu, J. T., Zhang, C. J., Wang, D. Y. & Li, X. B. 2013 Experimental investigation and modeling of flotation column for treatment of oily wastewater. *Int. J. Min. Sci. Technol.* **23**, 665–668.

Rubio, J., Souza, M. L. & Smith, R. W. 2002 Overview of flotation as a waste water treatment technique. *Miner. Eng.* **15**, 139–155.

Tang, H. X., Qian, Y. & Wen, X. H. 2000 *Characteristics and Control Technology Principle of Water Particles and Refractory Organic*. China Environ. Sci. Press, Beijing, P.R. China, pp. 50–65.

Tavera, F. J., Scudero, R. E. & Finch, J. A. 2001 Gas holdup in flotation columns: laboratory measurements. *Int. J. Miner. Process.* **61**, 23–40.

Wang, T. S. 1999 Status and prospects for oilfield water treatment equipment. *Pet. Mach.* **27**, l–4.

Watcharasing, S., Angkathunyakul, P. & Chavadej, S. 2008 Diesel oil removal from water by froth flotation under low interfacial tension and colloidal gas aprons conditions. *Sep. Purif. Technol.* **62**, 118–127.

Watcharasing, S., Kongkowit, W. & Chavadej, S. 2009 Motor oil removal from water by continuous froth flotation using extended surfactant: effects of air bubble parameters and surfactant concentration. *Sep. Purif. Technol.* **70**, 179–189.

Xu, H. X., Liu, J. T., Gao, L. H., Wang, Y. T., Deng, X. W. & Li, X. B. 2014 Study of oil removal kinetics using cyclone-static microbubble flotation column. *Sep. Sci. Technol.* **49**, 1170–1177.

Zhu, Y. Y., Zhang, Q. & Niu, Y. B. 2001 Development of a new high effective flotation device used for water treatment. In *SPE International Symposium on Oilfield Chemistry*, 13–16 February, Houston, Texas, pp. 589–592.

Zhu, D., Sun, S. Y., Liao, S. H. & Tian, C. M. 2012 Study on rapid determining oil in wastewater by using UV-spectrum. *Journal of Dail University* **10**, 28–30.

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