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

A novel process ‘coalescence-air flotation-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 air flotation 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 m³ d⁻¹, 3 m³ d⁻¹ and 2,000 m³ 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 m³ d⁻¹ the oil-water separation flotation column were a feeding speed of 0.042 m³ h⁻¹, an aeration rate of 0.10 m³ 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 air flotation process. In the 2,000 m³ 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-air flotation process, fine coal, flotation, oil-water separation flotation column

NOMENCLATURE

$g_1$ feeding speed (m³·h⁻¹)
$q_8$ aeration rate (m³·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 air flotation 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 air flotation (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...
separation because of the synergistic effect between the cyclonic separation and air flotation (Park et al. 2006). The coalescence-air flotation-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 air flotation separations. The oil-water separation efficiency of a flotation column consists of the cyclonic separation section and air flotation 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.

**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 air flotation 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 air flotation 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

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**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.
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 m³ 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 \( g_1 \) (m³ h⁻¹). Finally, the outflow was drained from the bottom of the flotation column via the control valve. The aeration rate, \( q_g \) (m³ 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 m³ d⁻¹ Oil-water separation experimental system

The 30 m³ 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.

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 m³ 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
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-air flotation-carrier preferential adsorption process on flotation column**

As shown in the results of the preliminary research, the coalescence-air flotation 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-air flotation process and the preferential-carrier-adsorption process, using a combined system within the flotation column.

The combined coalescence-air flotation-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-air flotation 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-air flotation 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-air flotation-carrier preferential adsorption are shown in Table 2.

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

Based on the research results, the coalescence-air flotation-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-air flotation separation system, the carrier preferential adsorption separation system, and an adsorbent preparation system and pressure filtration.

| Table 1 | The operational parameters of the coalescence-air flotation process |
|---------|-------------------------------------------------------------------|
| The feeding rate \(q_1\) (m\(^3\) h\(^{-1}\)) | The circulating pressure \(P\) (MPa) | Aeration rate \(q_2\) (m\(^3\) h\(^{-1}\)) |
| 1.25 | 0.20 | 1.5 |

![Figure 6](https://iwaponline.com/jwrd/article-pdf/8/1/111/240616/jwrd0080111.pdf) | The combined process of coalescence-air flotation-carrier preferential adsorption.
dewatering system. The key piece of equipment of coalescence-air flotation 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 m³ 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 m³ 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 m³ 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 m³ h⁻¹.

| Feeding rate $q_1$ (m³ h⁻¹) | Circulating pressure $p$ (MPa) | Aeration rate $q_g$ (m³ 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                  |

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

**Figure 7** | 2,000 m³ d⁻¹ industrial experimental system.
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<sub>coal</sub> g<sub>oil</sub><sup>-1</sup>

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<sup>-1</sup>. 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<sup>-1</sup>, 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<sup>-1</sup>

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<sup>3</sup> h<sup>-1</sup>.

### 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<sup>-1</sup>

The circulating pressure was 0.12 MPa, the feeding rate was 0.042 m<sup>3</sup> h<sup>-1</sup>, the powder coal consumption was 4 g<sub>coal</sub> g<sub>oil</sub><sup>-1</sup>, the frother dosage was 10 mg L<sup>-1</sup>, 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 1,564.14 mg L<sup>-1</sup>, the average SS concentration at the inlet was 88.00 mg L<sup>-1</sup>. After the oil-water separation using flotation column, the average oil concentration at the outlet was 22.24 mg L<sup>-1</sup> and the average SS concentration at the inlet was 29.59 mg L<sup>-1</sup>. 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<sup>3</sup> d<sup>-1</sup> oil-water separation experiment

Based on the results of the 1 m<sup>3</sup> d<sup>-1</sup> oil-water separation experiment, a 30 m<sup>3</sup> d<sup>-1</sup> 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<sup>3</sup> h<sup>-1</sup>, the powder coal consumption was 2 g<sub>coal</sub> g<sub>oil</sub><sup>-1</sup>, the frother dosage was 10 mg L<sup>-1</sup>, the
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 m³ d⁻¹ oil-water separation system. The average oil concentration at the outlet was 10.04 mg L⁻¹, the
The 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.

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              |

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-air flotation-carrier preferential adsorption process on flotation column

The circulating pressure was 0.16 MPa, the feeding rate was 1.25 m³ h⁻¹, the powder coal consumption was 2 gcoal L⁻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-air flotation-carrier preferential adsorption process and a conventional two-stage air flotation process is shown in Table 6. The following conditions were applied: treatment capacity of 30 m³ d⁻¹, coagulant of poly-aluminium chloride consumption is 600 mg L⁻¹, flocculent of polyacrylamide consumption is 1 mg L⁻¹.

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

Results of 2,000 m³ d⁻¹ oil-water separation experiment

The circulating pressure was 0.16 MPa, the feeding rate was 83.0 m³ h⁻¹, the powder coal consumption of column 2 was 1 gcoal L⁻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-air flotation 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
coalescence-air flotation-carrier preferential adsorption process provides a new and good way to treat the oily sewage.

CONCLUSIONS

The coalescence-air flotation-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 m³ 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 air flotation. The process contains two stages: the coalescence-carrier preferential adsorption and the air flotation 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 m³ d⁻¹ oil-water separation system experiments, the coalescence-airflotation-carrier preferential adsorption process using a

| 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       |

Table 6 | The cost comparison (unit, RMB yuan m⁻³)

| Sample time | Column 1 | Oil concentration at inflow (mg L⁻¹) | Oil concentration at outflow (mg L⁻¹) | Oil removal efficiency (%) | Column 2 | 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 air flotation process.

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